_prototyping participation

3D Printing Co-Design into Healthcare

An Thesis Presented by
Josh Munn

acknowledgments_

A special thanks to my supervisors Stephen Reay and David White for all of their encouragement and advice during the year, my work colleagues Reid Douglas and Nick Hayes and my brother Luke Munn for their valuable input and the DHW Lab, AUT University and my wife Bridget for ongoing support.

abstract_

Increasingly accessible, affordable and technically viable, 3D printing is now being used for a number of high-end healthcare applications, including orthopaedic implants, prosthetics and dentistry casting. These applications, however, are largely driven by an industry that is often not embedded within the complex environments for which it is designing, therefore potentially lacking an in-depth understanding of the end-user. In contrast, this practice-based research operated within a hospital environment and alongside healthcare professionals who possessed a practical understanding of clinical requirements and the patient experience. Using a co-design methodology, a series of problems were identified and developed in workshops. Objects were designed and printed that not only leveraged the specific properties of 3D printing – rapid, iterative, and customisable – but also worked as a tool for co-design. These 'probes' were not a forerunner of the future product, but rather vehicles for observation, reflection, interpretation, discussion and expression. Probes helped to create a bridge between the worlds of design and health, acting as a common language between the designer and the participant in order to help establish a shared understanding. This shared understanding provided a stronger foundation for the collaborative identification and development of an optimal design opportunity, suitably linking a specific clinical problem with the capabilities of technology. In this way, 3D-printed probes helped co-design interactions evolve from passive exchanges of knowledge to active relationships. These more effective co-design relationships appear to provide a more reliable model for design outcomes in results-driven environments such as hospitals.

Keywords: 3D printing, design, healthcare, hospital, additive manufacturing, digital technologies, co-design, collaboration, end-users, human-centred design, probes, transparency, CAD, modeling, shared understanding, participatory design, 3D scanning, parametric design.

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figures_

All figures from other authors have been re-drawn by me in order to fit the overall aesthetic of this research document. The content and purpose of each figure has remained the same.

images_

All of the non-referenced images are photographs or digital media that have been created by me personally over the course of the research project.

attestation of authorship_

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgments or cited in the bibliography), nor material which, to a substantial extent, has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

Josh Munn Masters Student
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CHAPTER 01

introduction_

context_

Richard Seymour, one of Europe's best known product designers, defined design as "making things better for people" (Fisher and Thomas 2013, 158). This is a design philosophy that prioritises human behaviour and quality of life over and above the constraints or monetary endeavours of a manufacturer or distributor. The British Design Council (2015) describes how design is often portrayed only as an aesthetic consideration, reserved for the end of the development process. The council argues, however, that 'good' design derives from a much deeper level of inquiry, one that begins and ends with identifying and understanding the needs of the end-user. This approach is commonly referred to as human-centred design (HCD). Design researchers Norman and Stappers (2015, 84) highlight the growing importance for this type of design as designers continue to be more involved in complex socio-technical systems such as healthcare.

Co-design is an approach that goes one step beyond human-centred design, not only working to develop a better understanding of end-users, but also facilitating their involvement throughout the design process (Sanders and Stappers 2008, 8). However, design researcher Liz Sanders (2002, 1) points out co-design is more than a methodology but rather is a "belief that all people have something to offer to the design process and that they can be both articulate and creative when given appropriate tools with which to express themselves".

Cooperative design methods originated as early as the 1970s in Scandinavia (Bødker et al. 2000, 23). Only in the last decade, however, have they been formally adopted in healthcare services, first in the UK, then in New Zealand since 2008 (Boyd et al. 2012, 77). Boyd and her co-authors describe co-design as the facilitation of an ongoing working relationship between designers and end-users, where decisions for improvement or change are made together (2012, 78). In co-design, end-users are viewed as the greatest authority on their own experiences (Sanders and Stappers 2008, 6). The value of their role in co-design resides in their ability to help inform the design solution using this experiential information. One of the roles of designers is to facilitate this contribution and support end-users in engaging with the design problem – thereby helping them to better understand the context and the complexity of a problem.

For this engagement to occur, users need to be given the appropriate design tools to capture their thoughts and "express themselves" (Kristensson et al. 2004, 12). These tools may include traditional forms of communication such as verbal discussion or interviews. However, more visual tools, such as sketches and prototypes, often help users to gain a more accurate understanding of project direction. Storni et al. (2014, 149) highlight how the presence of physical objects, or 'things', give the user something tangible to observe, interact and communicate with. These 'things' allow designers to communicate more effectively by interpreting and bringing form to their ideas at a more practical level to be 'read' by collaborating participants. Sanders and Stappers (2014, 6) describe how the creative act of 'making' is also a way for non-designers to express themselves using design tools such as 'generative toolkits' – a variety of 2D and 3D components such as pictures, words and blocks that give non-designers a means with which to "participate as co-designers in the design process" (Sanders and Stappers 2014, 9).

Due to the affordable and rapid production possible with 3D printing, 3D-printed objects are becoming increasingly common examples of these physical 'things'. In 2015, as part of my work with the DHW Lab[1], 3D printing was used as a production tool in two design projects. The first, working with a principal pharmacist in medication safety, involved the design of an isoflurane anaesthetic adapter clip; the second, alongside clinical engineers and medical physicists, was the redesign of total body irradiation blocks (for more detail see 'Prior Contextual Work 1' in Appendix 1, page 140). Building upon the ideas formulated in these two projects, this research project aims to explore the role of the 3D printer and the objects manufactured by 3D printers as co-design tools, investigating how the use of the printer can help engage healthcare professionals with design.

1 Located inside Auckland City Hospital, the Design for Health and Wellbeing (DHW) Lab is designing better healthcare experiences for patients, families, and staff. A collaboration between the Auckland District Health Board and AUT's Faculty of Design and Creative Technologies, the DHW Lab was set up to develop products, services, systems, and experiences for the improved health and wellbeing of all hospital users.

intersection_

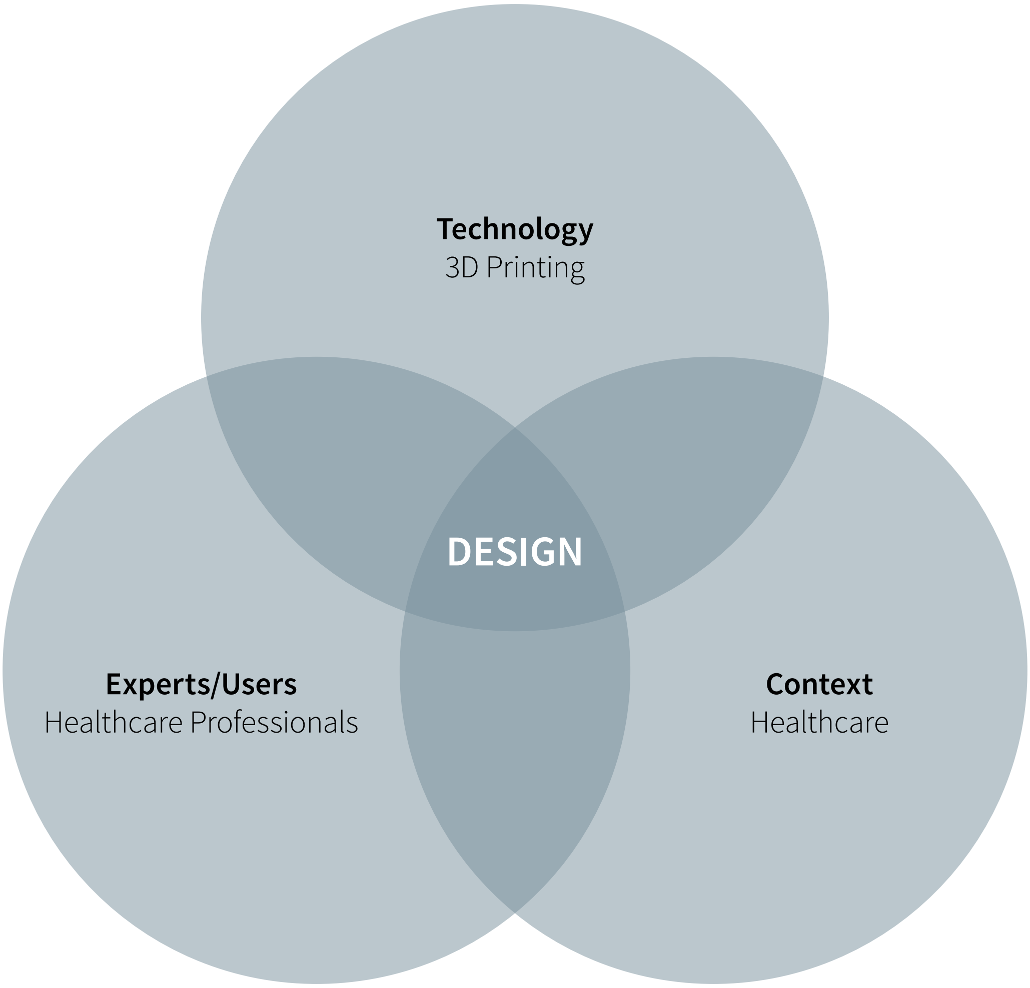


Figure 01. Research Intersection – Josh Munn

research question_

How can 3D printing be used as a design tool to help facilitate co-design in healthcare?

personal statement_

I have experienced healthcare both as a designer and as a patient. An arrhythmic heart condition and an assortment of accidents and sporting injuries have led to me spending a considerable amount of time in hospitals. I have also worked in a hospital as a designer with the DHW Lab for close to two years. Through these experiences I developed an understanding of just how problematic and complex healthcare really is. Hospitals are fast paced, alienating environments that are often confusing and scary for patients who are already feeling vulnerable and isolated. The busy, non-stop nature of healthcare services have made it difficult for healthcare professionals to cater for these challenging experiences, or fix common problems within their own practice. As a product designer, I feel obliged to use my skills to help improve these experiences and contribute to the wider improvement of healthcare delivery.

literature review_

3D Printing in Healthcare

3D printing refers to the creation of three-dimensional objects via a sequence of two-dimensional shapes printed layer by layer. The shape of each layer is governed by a digital file, normally produced using computer-aided design (CAD) or a 3D scan. This 'additive' form of manufacturing is what separates 3D printing from other 'subtractive' manufacturing methods that involve cutting or drilling (Lipson and Kurman 2013, 27-29). Originating in 1980s, 3D printing was first created as a prototyping technology for engineers and architects. The unique layering process allowed companies to rapidly produce, alter and test highly customised one-off designs without the need for expensive tooling associated with traditional mass manufacturing techniques (Lipson and Kurman 2013, 8). Recent advances in 3D printing technologies have led people to explore its use beyond conceptual prototyping, allowing people to create complex forms that simply weren't possible with common manufacturing methods (Lipson and Kurman 2013, 9).

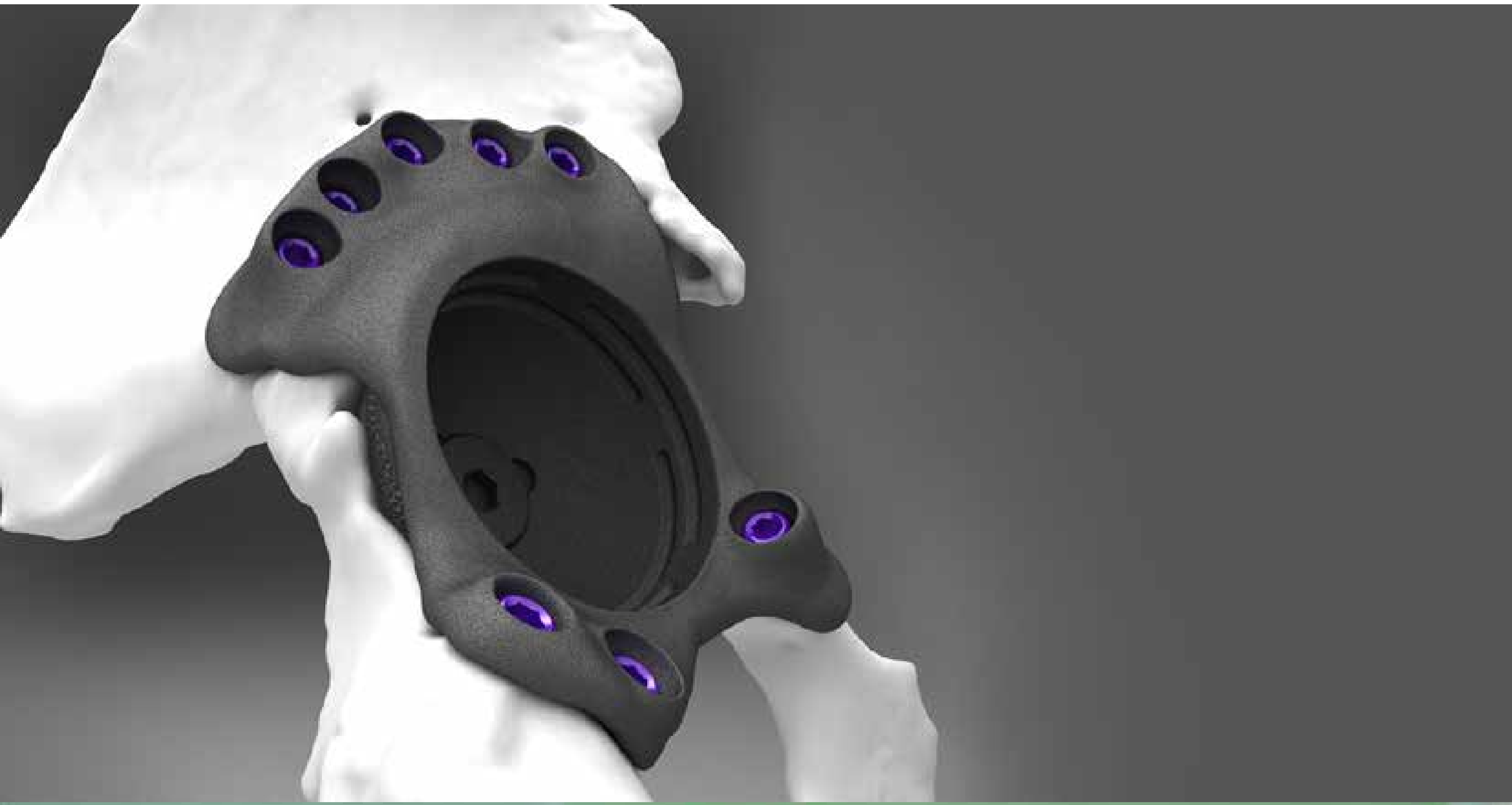
These advances have also seen 3D printers themselves evolve from a prototyping tool to an increasingly viable form of end-use manufacturing. 3D printing is now used in industries such as dentistry, healthcare, automotive, aerospace, fashion and construction (Davies et al. 2015, 2). In healthcare, 3D printing is being used to create end-use products in a range of clinical areas, including orthopaedics, prosthetics and surgical preparation (Lipson and Kurman 2013, 105). This trend has gained even further momentum from the rapid expansion of available materials (Ventola 2014, 704). Early 3D printers commonly used low-cost thermoplastics or resins that limited their usefulness beyond conceptual prototypes. Modern printers are now capable of printing in ceramic, glass and even titanium. New Zealand company Ossis Limited, for example, has appropriated the use of 3D-printed titanium for alloy bone and joint implants in orthopaedic surgery. Ossis works alongside surgeons to create custom-designed implants based on patient CT scan data, which reduce the complexity and length of surgery (ossis.com 2015).

However, this high-end use of 3D printing is considerably more expensive to produce. Products such as the Ossis 3D-printed implant are being produced using titanium 3D printers that cost upwards of $US1 million, while the prints themselves can cost anywhere between US$100 to US$200 for a part the size of a standard dice (gizmodo.com 2011). In prosthetics, there is also the need for 3D scanners, higher-end models being priced as much as US$400,000 (3dscanco.com 2015). Another form of high-end additive manufacturing is bio-printing – the 3D printing of living organs and tissues. The price of bio-printers is as high as US$250,000 (3ders.org 2015), while the cost of printing living cells using biological materials could reach US$300,000 (medicalphysicsweb.org 2016).

On top of production, regulatory approval is another significant cost. In a survey of more than 200 medical technology companies, the Advanced Medical Technology Association discovered that governing bodies such as the FDA mandate strict standards and an approval process that is both long and expensive. The approval of low to moderate-risk products such as hearing aids took an average of 10 months to process and cost an average of US$24 million (Makower et al. 2010, 6-7). As of 2015, the FDA had only approved 85 3D-printed medical devices (Leinauer 2015), suggesting either a high number of rejected devices, or a hesitancy from manufacturers to make such a considerable investment, particularly with the risk of products failing to meet requirements. The medical standards are even more of an obstacle for products that directly interact with the patient, for example, orthopaedic implants, known as Class II or Class III medical devices (Medsafe 2015). These products often require heavily tested 'biocompatible' materials – substances that won't be rejected by human cell cultures.

These high costs are a major barrier in a healthcare environment. Publicly funded services such as transport, education and hospitals often have limited funds (Page 2014, 219). Page (2014, 220) suggests technologies like 3D printing must come "at an economical cost and must satisfy a specific need" in order to be adopted. Consequently, million-dollar printers and considerable legal fees may not be an option for cash-strapped healthcare organisations. Leonard D'Avolio discusses how most hospitals often view designers as a "luxury afforded to consumer product companies" (informationweek.com 2015).

3D printed orthopaedic implant – *"Custom Orthopaedic Solutions." http://ossis.com/technology/. 2015.*



Bio-printed human nose and ear *– Charron, Kira. "3ders Monday Warm-Up: The Top 20 3d Bioprinters." http://www.3ders.org/articles/20151109-3ders-monday-warm-up-the-top-20-3d-bioprinters.html.*

A second major issue is market applicability. Here, applicability is measured by the number of people or situations for which an object is capable of being useful or relevant. The FDA's guide for premarket approval highlights applicability as a key determiner for a product's potential benefit (fda.gov 2015). The Ossis 3D-printed implants may reduce the risk of complication and therefore potential long-term cost, but, as Ventola points out, the number of applicable procedures in clinical areas such as orthopaedics is often low (2014, 705). One of the technology's greatest advantages is its on-demand model of manufacturing. Products are printed as they are needed. Unless the cost of the 3D printing titanium decreases or the number of hip replacements increases, it would be difficult for hospitals to justify the cost of niche products like a customised titanium implant. Scale and efficiency can only go so far in justifying high up-front cost. Jeroen Dille, director of Materialise's clinical unit, state: "There are a lot of niche applications where its value is huge but it won't suit everything," (ft.com 2014). Dille suggests healthcare organisations need to be mindful of the tension between cost and applicability before making decisions on whether to adopt 3D printing as part of their services. (See 'Matrix analysis' on page 22 for a visual example of this tension.)

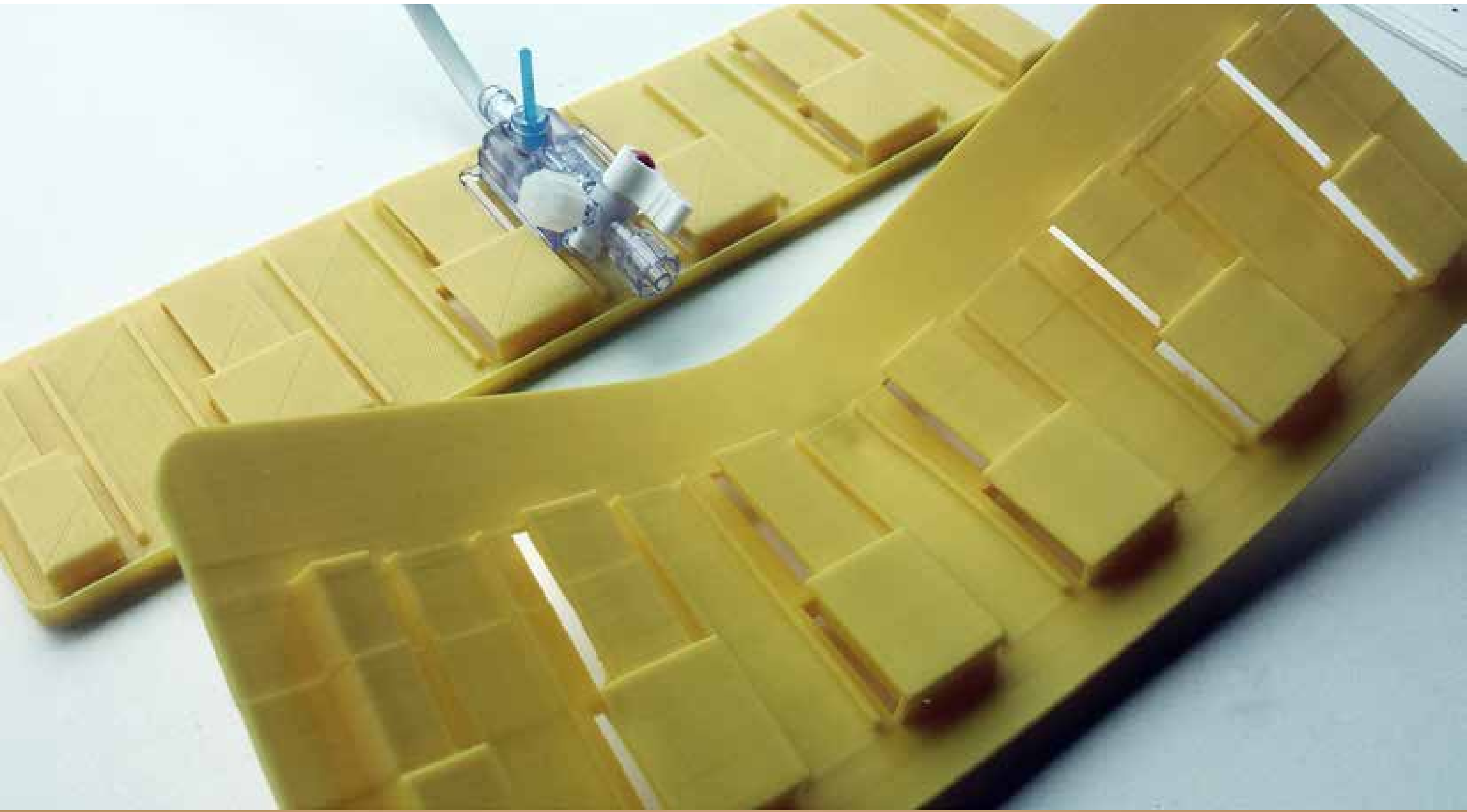
Considering these issues, it's difficult to understand why so much emphasis is placed on the development of 'high-end' 3D-printed applications. Jörg Lenz (tctmagazine.com 2015) describes how the 'hype' or excitement associated with additive technologies has created unrealistic expectations for what is actually possible with 3D printing, particularly in the medical industry. Lee Ventola (2014, 8) affirms this, explaining how exaggerated claims by the media, governments, and even researchers have led people to believe that 3D-printed applications such as prosthetics and implants are commonplace in the medical industry.

Ventola points out that despite recent progress, developments such as these are still in their infancy. The cost and complexity of these high-end devices will need to be reduced, and access to 3D printing services will need to be improved before widespread adoption is likely to occur. For example, in more sophisticated endeavours such as bio-printing – 3D-printing biocompatible materials have yet to be proven safe and effective (Ventola 2014, 8). Future prospects of high-end 3D printing may be exciting, but this excitement may be pushing the industry in a direction that fails to take full advantage of the technology in its current state.

While high-end printers may provide specialised manufacturing capabilities, there is also a growing trend of using smaller, low-cost printers in a range of areas including electrics, fashion and robotics. These low-end printers may have greater applicability in healthcare. This is not to say that high-end 3D printing should be avoided altogether. There are also potential disadvantages in designs for low-end, affordable consumer printers such as the MakerBot. One recent example is a transducer holder designed at DHW Lab (2015). This design was printed on a low-end desktop 3D printer. Issues occurred during the sterilisation process when high temperatures warped the 3D-printed device after a single use due to the low melting point of the material available (PLA). Functionally the design was effective, but the chosen material was unfit for sustainable 'end-use', suggesting the need for traditional manufacturing like injection moulding. 3D printing large quantities of the transducer was also likely to have been considerably more expensive than common mass manufacturing techniques. While the design was achievable, it failed to maximise the benefits that 3D printing offered.

An example that balances the tension between high-end and low-end 3D printing more effectively is a project by the University of Washington (washington.edu 2015). In this design, low-end 3D printing was used to create two-part moulds for pediatric rib cartilage models. The models themselves were moulded out of silicon in preparation for auricular reconstruction (ear replacement). For pediatrics with missing or underdeveloped ears, treatment involves using part of the child's rib cartilage to carve and construct the framework for a new ear. Cartilage models based on CT scans allow surgeons to practice the difficult procedure before actual surgery and thus improve the outcome for patients. Inexpensive, low-end 3D printers provided the university's bioengineering students with a way to create unique anatomical moulds for a fraction of the cost of traditional methods. The design took advantage of 3D printing's capability to produce highly customised models. Both the production and the regulatory costs were low due to desktop-style 3D printers and the low risk of a Class 1 medical device. This design technique is also highly applicable for a wide range of surgical procedures.

Transducer Holder warped from the sanitation process.



3D printed rib cartilage moulds for preparative surgery *– Langston, Jennifer. "3-D Printing Techniques Help Surgeons Carve New Ears." University of Washington, http://www.washington.edu/news/2015/09/30/3-d-printing-techniques-help-surgeons-carve-new-ears/.*

Given the advantages and disadvantages of high-end and low-end printing, as a central part of this research, it was important to determine how 3D printing technologies were going to be best integrated as a tool for collaboration and what this implied for co-design practice.

3D Printing and Co-Design

Co-design is a participatory approach that aims to create more informed design solutions by involving end-users in the design process. Users are invited not only to exchange their knowledge and experiences, but also to participate in design-related tasks such as drawing and model making (Sanders and Stappers 2008, 8). Research shows users are capable of communicating more effectively and contributing creatively if they are given the appropriate tools with which to express themselves.

Post World War Two, people's idea of value changed from cost to quality. The economic upturn allowed people to afford products of a nature and quality beyond the pressures of financial necessity. Instead of a 'one size fits all' mentality, businesses began applying research techniques that focused on gaining a better understanding of who their users were and how they experienced products or services (Friere and Sangiorgi 2010, 2). This user information was used to tailor products and services accordingly.

Within healthcare, Friere and Sangiorgi (2010, 3) describe how this participatory movement saw the delivery of services attempt to shift from a utilitarian model of mass production to a more personalised strategy driven by needs of the users. As a result, healthcare services started developing and adapting policies that were patient-led. This has seen an increase in the number of hospitals working with patients to support them with their health needs (Friere and Sangiorgi 2010, 2-3). England's Luton and Dunstable Hospital formally adopted co-design techniques in 2006. Since then, Australia and, more recently, New Zealand have also followed suit (Boyd et al. 2012, 76). However, co-design in healthcare is still largely in its infancy. Sanders and Stappers 2008, 9-10) suggest this is due to the competitive and hierarchical nature of large long-established organisations such as hospitals. "Existing power structures" are hesitant to relinquish "control", while participatory research is viewed as a "big and expensive step into the unknown" (Sander and Stappers 2008, 10).

In the context of this research, it's important to note that the focus of co-design in healthcare has largely been on improving the quality of service through experience-based co-design, and not on product design (Friere and Sangiorgi 2010, 3). Bate and Robert discuss how participatory design efforts in healthcare have focused predominantly on "healthcare processes" (2006, 307). This trend can also be observed in results from searches done using Google's online scholarly database (scholar.google.com 2016). Using the search terms 'co-design healthcare service', 'co-design healthcare experience' and 'co-design healthcare product', results from the year 2000 onwards show substantially more service and experience-based design listings (6140 and 8370 respectively) versus a considerably smaller number of product-based design listings (4950).

The emerging co-design approach advocates for collaboration between the designer and end-user throughout a design project to generate more relevant design solutions. However, research demonstrates a number of different co-design interpretations, all of which imply varying roles and levels of involvement from both designers and users (Sanders and Stappers 2008, 4). Co-design's collaborative interactions range from isolated exchanges of knowledge, treating participants as 'passive users', to ongoing design relationships where co-design participants are given the opportunity to be involved as 'active contributors'. The role of designers in co-design is also brought into question. Traditionally, the craft-based skills of product designers, such as the ability to use 3D printers and associated digital technologies, have been kept separate from end-users. However, as an anti-hierarchical approach, co-design advocates for a sharing of design-related activities. Considering the complexity of technologies like 3D printing, its difficult to envisage a suitable level of participatory involvement.

Friere and Sangiorgi (2010, 8-9) argue that co-design, although inclusive, still requires engaging the right people at the right time. Non-designers are involved, but not all the time. Researchers Bate and Robert (2006, 307) also suggest there are times when designers need to exercise their expertise independently in order to effectively develop a design. Learnt design skills or tools, such as those of an industrial designer, might include the likes of sketching, modeling, proficiency in CAD or even the use of 3D printing. It is these 'expert skills' that allow

DHW Lab design studio *– DHW Lab. "DHW Lab." http://www.dhwlab.com/about/. 2015.*

Helix Centre design studio *– Helix Centre. "About." http://www.helixcentre.com/. 2015.*

designers to turn mental concepts into tangible design solutions. Etienne Wenger (1998, 58) describes this process as "producing objects that congeal this experience into thingness". Friere and Sangiorgi's view proposes the use of technologies like 3D printing be kept principally for designers. The print itself may be used as a visual aid or a means of testing before final use, but they suggest the action of physical or digital creation remains independent from largely 'passive' co-design participants.

Design researcher Yanki Lee (2008, 32-33) describes this type of participatory design as "tokenistic", where users are "treated as subjects". Participants' knowledge or experience may be used by designers to help inform design decisions. For example, a patient's experience of radiation treatment may help inform the design of radiation equipment, but the participants themselves are not working with designers to develop the design solution. Lee argues that "designers designing in their own expert world" (2008, 39) contradicts the very nature of co-design. In order for true collaboration to exist, Lee believes that participants need to be treated as 'active', given a significant level of engagement – for example, assisting in tangible two-dimensional and three-dimensional model construction.

However, in recognising the complexity of active participant engagement, Lee also points out that more involved forms of creative engagement would need to be simplified. Her text describes a number of examples where co-design participants were given basic materials like card and tape in order to construct "quick and dirty" models representing spatial workspace configurations (2008, 39). Facilitating participants in this way gave them the opportunity to better articulate themselves through physical objects. These objects also taught them about the design process and how design tools are used. Tangible construction feeds back into participant understanding and generates new ways of thinking outside their own discipline (Lee 2008, 39-40). Although Lee gives a number of practical co-design examples, her research fails to address how more complex design technologies like 3D printing could be simplified or made accessible to users.

Design groups such as Helix Centre, DHW Lab and others have endeavoured to make design more accessible by physically locating themselves closer to the hospitals they are designing with. Helix is a design studio inside St Mary's Hospital in London, while the DHW Lab is embedded within Auckland City Hospital itself. Both studios strongly emphasise the combined power of co-design and locality. The Helix website at helixcenter.com states "together we can respond quickly to healthcare issues, turning ideas into prototype products, processes and services" (2015). In a similar vein, regular face-to-face interaction allows the DHW Lab to build strong working relationships with patients and staff. The aim for these groups is to use locational proximity as a means of providing ongoing support and integrating the processes that designers use with those involved in healthcare.

Proximity also helps improve the transparency of co-design. This transparency acts as an openness that helps to balance users' knowledge with practitioners' knowledge (Reay et al. 2015, 4-5). In the DHW Lab context, designers have access to the clinical environment, and thus the ability to readily observe how patients and staff operate within it. Conversely, staff and patients are able to more easily access and engage in the design process, helping them to better understand the purpose and function of design practice. This includes being exposed to the tools and technologies that designers use, and that end-users are often unfamiliar with, such as 3D printing. However, there still remains the issue of helping end-users overcome the barrier of complexity. Participants may be exposed to 3D printing, but that does not mean they know how to use it effectively. Human-centred design aims to bring the worlds of researchers and users together, but, as Marc Steen (2011, 47) highlights, this needs to be done "constructively". Steen suggests that human-centred design practitioners need to "balance their own knowledge and ideas with users' knowledge and ideas" (2011, 47) in a way that maximises the proficiencies of each member.

In this research, for instance, more 'active' participant engagement might involve healthcare professionals being provided with the opportunity to edit or adapt their own digital 3D models, or given access to a 3D printer. Despite potential interest, however, full-time clinicians such as plastic surgeons or radiologists may not have the time or the expertise to operate these design tools. Sanders and Stappers (2008, 8) discuss how the success of increased participatory involvement largely depends on participant's "level of expertise, passion and creativity". The pair argue that although all people have the potential to be

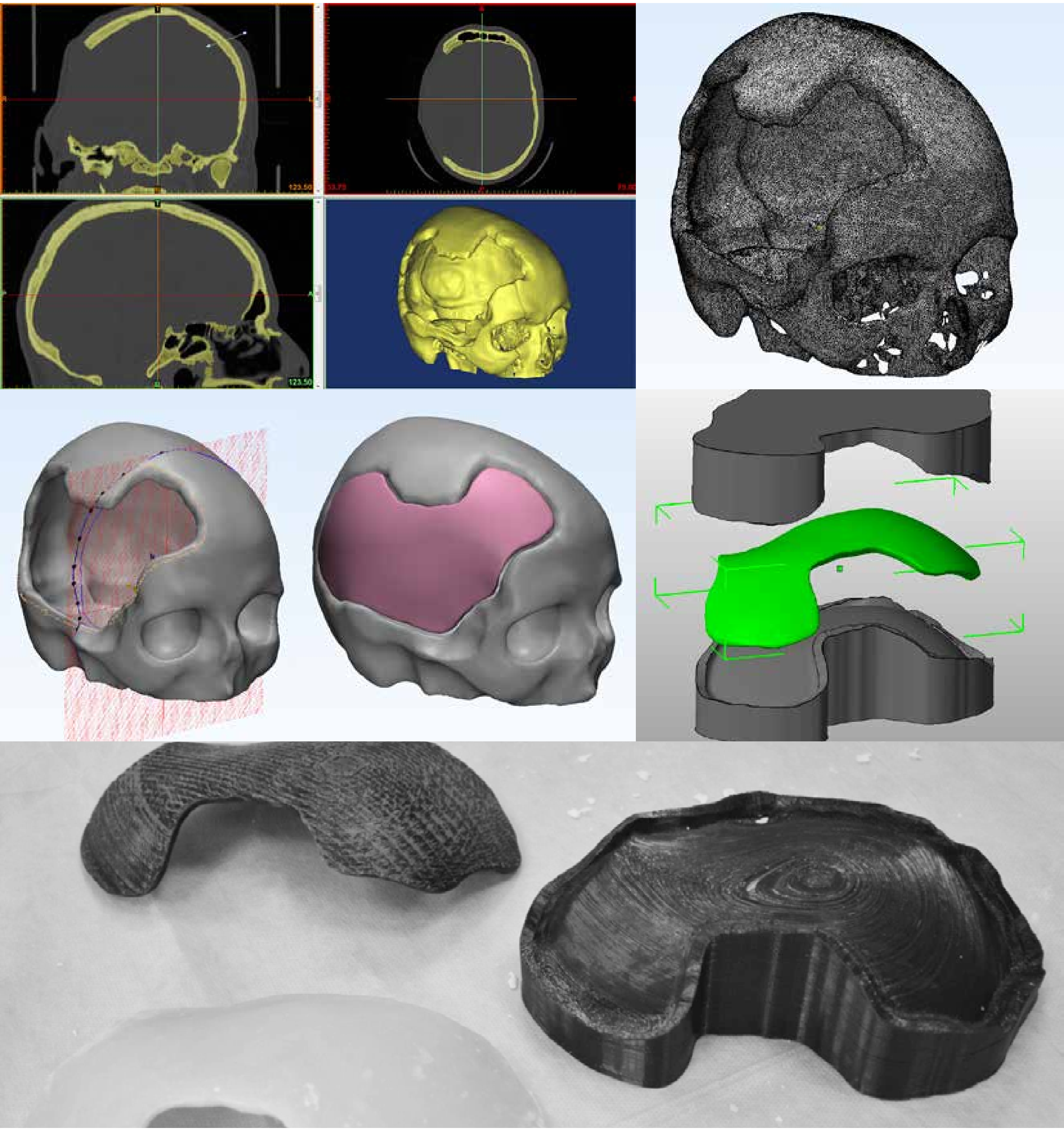
***'Quick and dirty' model making led by designers with clients** – Lee, Yanki. "Design Participation Tactics: The Challenges and New Roles for Designers in the Co-Design Process." Co-Design 4, no. 1 (2008): 31-50.*

creative, "not all people become designers" (2008, 8). Participants attempting to operate the software and hardware necessary for 3D printing would be faced with steep technological learning curves. Even if they were able to use the technology, as Sanders and Stappers emphasise, there is still the need for "creative thinking" in order to generate ideas and concepts. Simpler forms of modeling software, such as Google's SketchUp (www.sketchup.com 2016), have been developed to help reduce this learning curve, but even programs like these require considerable time and effort to not only operate, but use effectively. The misinformation created by the media may also have to be addressed before participants are able to use the technology effectively (Ventola 2014, 8).

Simpler digital platforms also often lack the capabilities of more extensive software preferred by designers. Features such as 'Scan to 3D' in SolidWorks (www.solidworks.com 2016) allow complex biometric data to be converted into digital models. Manipulating this type of data simply isn't possible in applications like SketchUp. In addition to software, participants would also require an understanding of 'design for manufacturing' – designing products to optimise the functions of a particular manufacturing method, such as 3D printing (Anderson 2014, 3). Functions such as design orientation, density and scale are crucial to the success of additive manufacturing. In an interview with Lipson and Kurman (2013, 78), a 3D printing technician explains how "if you get a design file that's poorly done, you end up wasting raw material". He goes on to argue that most design files require expert tweaking: "although people talk a lot about the quality of design software, what really matters is the skill of the human who made the design file" (Lipson and Kurman 2013, 78). Considering the knowledge and experience required for effective 3D printing, the potential benefit of participant input may not justify a compromise in experience and functionality.

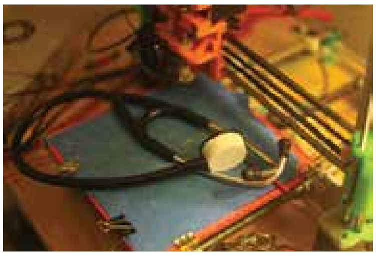
Design technologist William Buxton (2005, 52-53) describes this compromise as "diluting" the skills and expertise of both designers and participants. Buxton argues that higher levels of participant involvement fail to maximise the abilities of those involved in co-design – participants as experts in their own experiences and designers as experts in craft-based design tools like 3D printing. Even though they lack design experience, participants are given the opportunity to participate as designers. Designers, on the other hand, shift from the role of craft-based experts to act as design facilitators. Sanders and Stappers (2008, 7) discuss this emerging design practice as a shift from a 'product' perspective to a more expansive 'purpose' perspective. Within this development, concentrated design disciplines such as product or graphic design are superseded by broader, more experience-focused disciplines such as experience design or transformation design. These design practices focus more on the needs of people than conventional design tasks or technologies relating to a specific discipline (2008, 7). However, by focusing so closely on people and not production, designers may be moving away from the craft needed to expertly create 3D-printed design solutions.

Co-design aims to create more informed design solutions by involving end-users as part of the design process (Sanders and Stappers 2008, 8). Research suggests co-design participants are capable of communicating more effectively and contributing creatively if they are given the right design tools with which to express themselves and their ideas. However, due to the complexity of a technology like 3D printing, its difficult to determine whether 3D could serve as an effective co-design tool. Excluding participants from the technology gives designers more control, but the overall design is less informed (Sanders and Stappers 2008, 8). On there other hand, treating participants actively and facilitating their engagement allows them to contribute more creatively. But, this means simplifying the tools designers use and potentially limiting the capability of technologies like 3D printing. A third possibility is a compromised result from both sides. In this scenario, designers set up a situation in which participants are expected to act as designers. However, for various reasons, such as availability or a lack of willingness from participants, this ideal level of involvement may never be reached. Whether technologies like 3D printing can serve as a suitable co-design tool remains largely unexplored. Rather than pure theory, this research set out to explore 3D printing as a design tool and uncover an optimal strategy through a series of practice-based co-design projects.



Russian neurosurgeons use 3D printing to create skull implant for trauma patient *– Cosimo, Simon. "Russian Neurosurgeons Use 3d Printing to Create Skull Implant for Trauma Patient." http://www.3ders.org/articles/20150501-russian-neurosurgeons-use-3d-printing-to-create-skull-implant-for-trauma-patient.html.*

matrix analysis_


Stethoscope


Ear Reconstruction Simulation


Brain Simulation Model

LOW-COST (approx <$50)


Anaesthetic Bottle Clip


Total Body Irradiation Blocks

Ear Reconstruction Simulation: Langston, Jennifer. 2015. " 3D Printing Techniques Help Surgeons Carve New Ears | UW Today ". Washington.Edu.
Brain Simulation Model: Matisons, Michelle. 2015. "Stratasys Introduces New Medical Solutions Group To Meet Growing Demands". 3Dprint.Com.
Socliosis Back Brace: UNYQ,. 2015. "Treating Scoliosis With 3D Printing & Style".
Hemi Pelvis Implant: Ossis.com,. 2016. "Custom Hemi Pelvis – Ossis, Custom Orthopaedic Solutions".
Stethoscope: Wired UK,. 2016. "Meet The Doctor Bringing Cheap, 3D-Printed Medical Devices To Gaza (Wired UK)".

BROADLY APPLICABLE (MASS MARKET)

HIGH-COST (approx >$1000)

Scoliosis Back Brace

Hemi Pelvis Implant

Prosthetic Nose

Exo Prosthetic Leg

WETA Film Props

Escapism Dress

NARROWLY APPLICABLE (NICHE MARKET)

WETA Film Props: Idealog,. 2015. "Absolutely, Positively 3D Printing: The Future, Here Now In Wellington".
EXO Prosthetic Leg: Behance.net,. 2016. "Exo Prosthetic Leg".
Escapism Dress: Van Herpen, Iris. 2011. Escapism by Petrovski & Ramone. Image.
Prosthetic Nose: Idealog,. 2015. "Absolutely, Positively 3D Printing: The Future, Here Now In Wellington".
Anaesthetic Bottle Clip & TBI Blocks: Josh Munn

CHAPTER 02

methodology_

methodology_

Co-Design

Co-design is a human-centred design methodology used to help facilitate the participation of end-users in the design process. Conventional co-design methods include interviews, focus groups and surveys. These methods allow designers to gain a deeper understanding of the people they are designing for therefore making more informed design decisions (Sanders and Stappers 2008, 6).

A visual interpretation of the current landscape of human-centred design research, as practised in the design and development of products and services, is represented by Figure 02 (2008, 2) on page 27. According to Sanders and Stappers, it's important for designers to situate their research within this landscape in order to know who should be involved as part of the collaboration, when and in what role. This project, for instance, was conducted using a design-led research approach, where healthcare professionals were facilitated as a partners throughout the co-design process. However, due to the developing nature of the research question and the number of collaborative partnerships established, participant involvement tended to vary. Healthcare professionals, individuals embedded a clinical environment, were engaged in the hopes that their clinical understanding would help to more effectively identify and select appropriate design opportunities. Appropriate is defined here as 3D-printed design solutions that address a clinical problem and maximise the benefits of additive manufacturing. The expertise of healthcare professionals also helped to ensure that design solutions were clinically accurate and suitable in modern clinical environments.

During the project, co-design relationships were largely established and maintained via semi-formal expert interviews, discussions and feedback sessions. These were to be conducted repeatedly throughout the design process. However, under action research, the way in which these relationships were managed evolved. Again, in reference to the research question, one of the objectives was to explore and potentially develop more effective ways of using 3D printing as a co-design tool.

Action Research

Author Jean McNiff defines action research as a form of reflective inquiry that aims to improve practice and create new knowledge about practice (2016, 12). Action research sets itself apart from more traditional research approaches by not only attempting to generate new knowledge, but also putting this knowledge into action. Cycles of planning, actioning and analysis are deliberately repeated (see Figure 03, page 28) in an effort to validate "knowledge claims" and improve future practice (McNiff 2016, 16). Design researchers Coughlan and Coghlan (2002, 222) describe the cyclical nature of action research as "research in action rather than research about action". In this research project, transformative cycles were used to develop the way in which 3D printing was utilised as a tool for co-design. This included how design opportunities were identified and selected, how working co-design relationships were facilitated and how the chosen technology was utilised.

Action research is commonly used in conjunction with collaborative research approaches such as co-design. End-users, as part of the system being studied, are invited to actively participate in action research's cyclical process instead of being treated as "objects of study" (Coughlan and Coghlan 2002, 223). Developing and improving the experiences of end-users requires a level of what Coughlan and Coghlan term "interactivity" – a cooperation between researchers and end-users that enables knowledge to be put into action (2002, 225). Instead of new knowledge remaining as theory, it can be applied and tested in the next recurring action research cycle.

Action research is deemed appropriate when the research question relates to a series of actions in a given group and an understanding of how a member might be able to change or improve that system. There also needs to be an understanding of what this process looks like in order to test and learn from it (Coughlan and Coghlan 2002, 227). In the context of this research, the series of actions were a set of co-design partnerships, the organisation was a local hospital and the process for change was the use of 3D printing as a tool to help facilitate this collaboration.

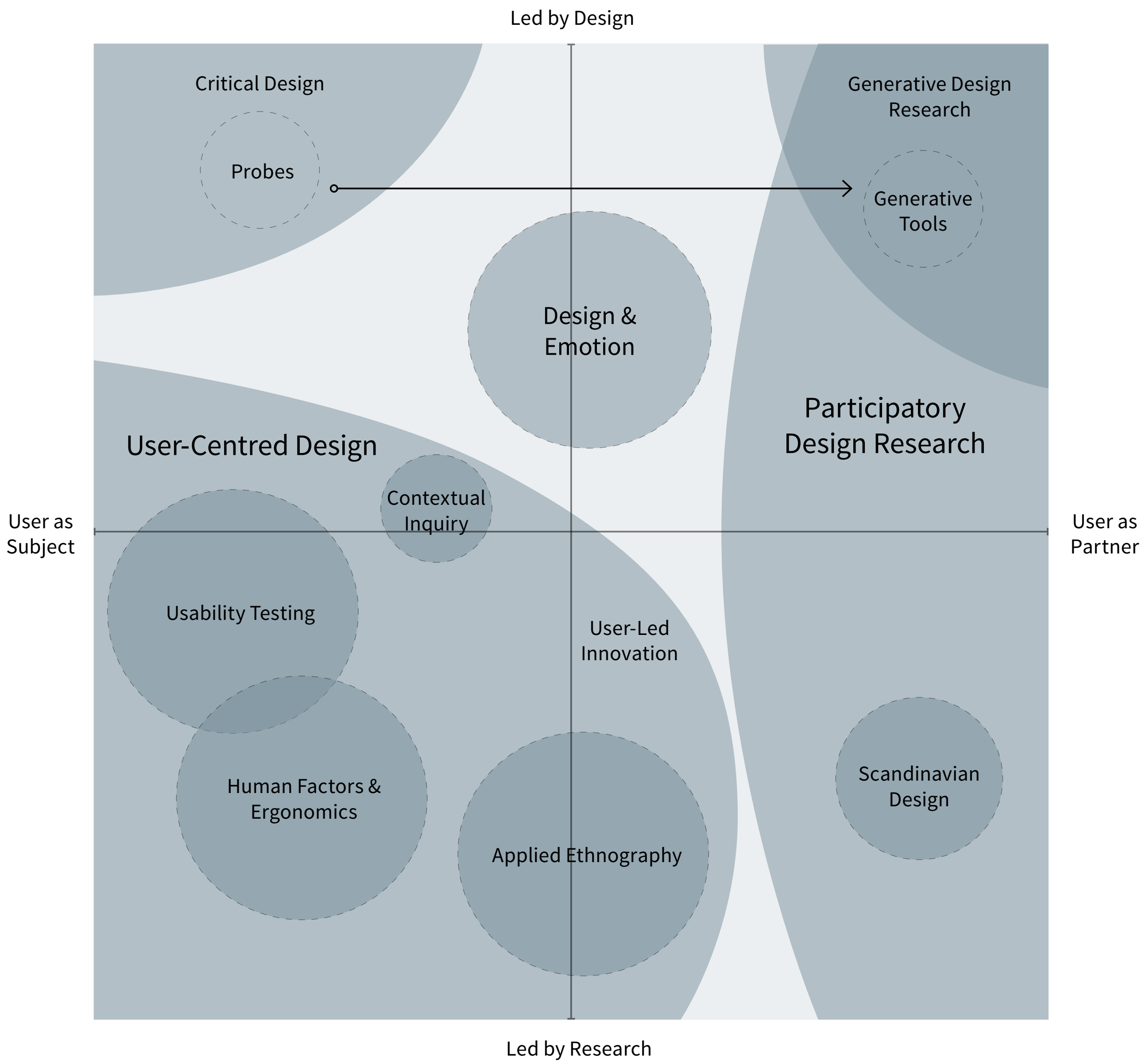


Figure 02. Current Landscape of Human-Centred Design – Sanders and Stappers 2008, 2

It's important to note that action research's cycles of self-improvement can theoretically continue indefinitely (Campbell et al. 2007). Within the scope of this research project, there was only one year to complete my inquiry. A clear sense of purpose and time management were maintained in order to come to a satisfactory degree of resolution, particularly in relation to physical 3D-printed design solutions. Precautions such as assessing the research scope of each opportunity and informing participants of these research constraints helped to prevent me from running out of time.

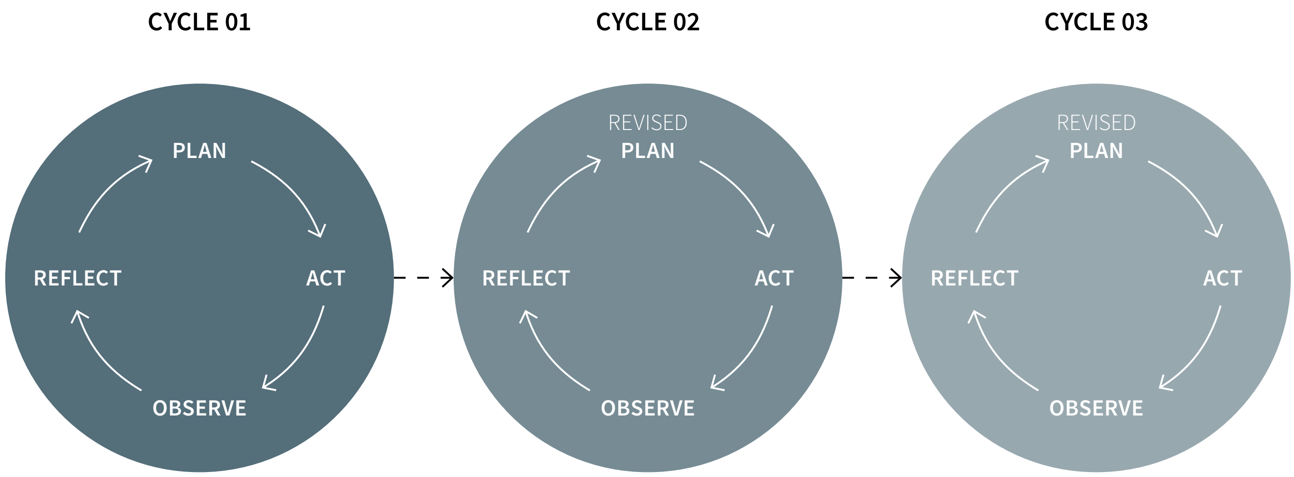


Figure 03. Action Research Cycles – Wilfred and Kemmis 2003

theoretical frameworks_

Actor Theory Network

Actor Theory Network (ANT) is a framework used to help examine and disassemble the factors that surround and form social networks (Latour 2005, 10-11). These "actors" as Latour terms them, both human and non-human, are assigned equal amounts of agency within networks such as co-design (Storni 2015, 169). Human elements include stakeholders – those affected by a particular design, while non-human elements may include objects, services or technologies (Latour 2005, 10-11). Interaction design lecturer Cristiano Storni suggests that principles of ANT should be part of a participatory design approach in order to understand how both human and non-human elements connect to a design and in some way inform the design process. ANT is most commonly used to explain how networks are constructed or deconstructed, rather then why they exist (Latour 2005, 10-11). This framework, or lens, was used to help interpret and understand how a technology like 3D printing and the artefacts it produces inform my research.

Strong parallels can be seen between Sanders and Stappers' exploration of design probes (2014, 7), agents that help to construct a shared understanding, and Storni's design of "things" (2014, 149). Storni discusses how ANT requires a shift from designing objects to designing things – designs that keep focus open-ended and help define or redefine a problem. An artefact may not necessarily represent a resolved product for a particular purpose, but rather an embodiment of an idea or collection of ideas that relate to a particular issue, opportunity or need (Storni 2014, 150). Storni calls this a "de-centred" design process, the aim of which is to observe how other systemic research agents, both human and non-human, respond to these things. In my research, these things embodied the intersections of 3D printing, healthcare and the knowledge of co-design members.

Human-Centred Design

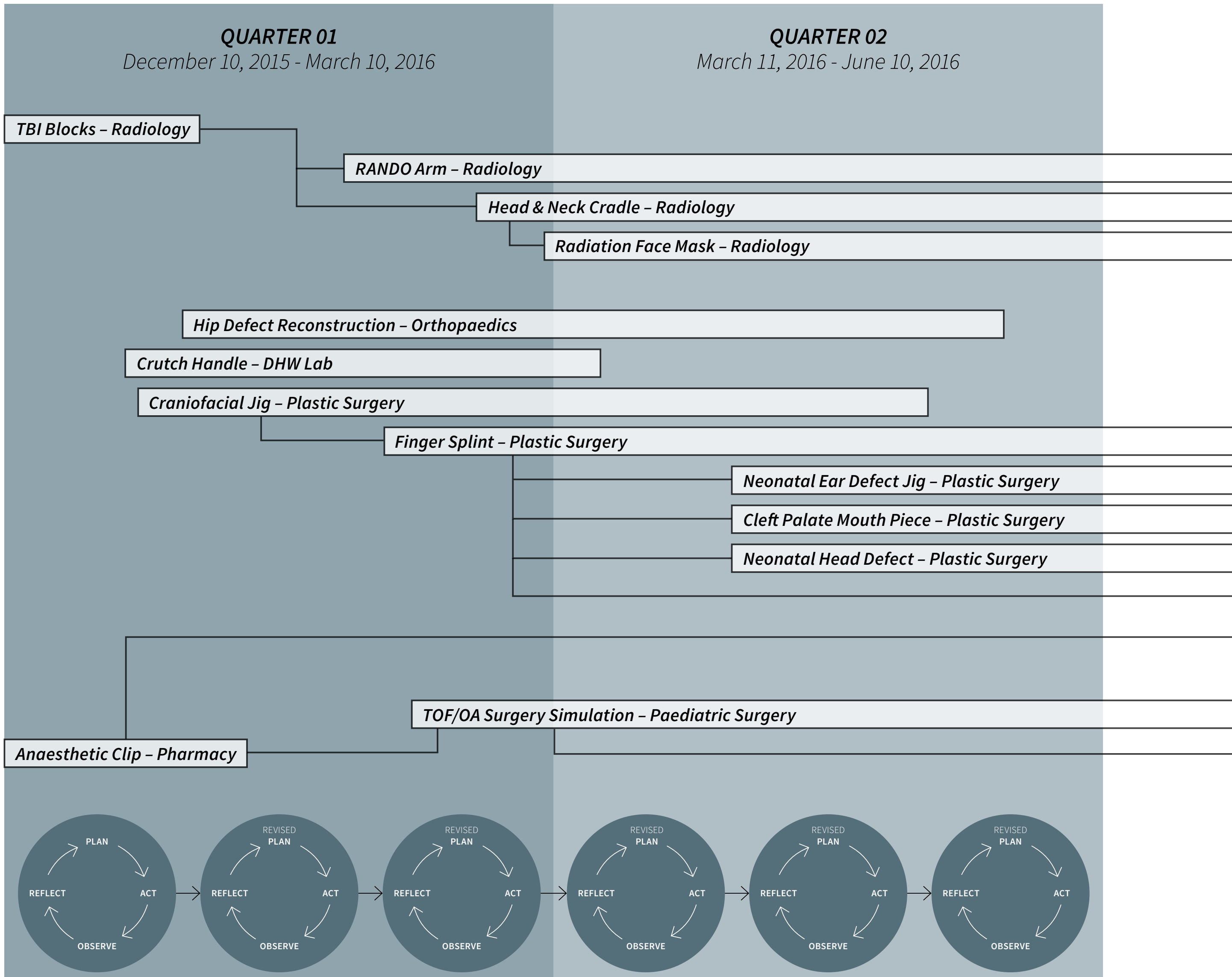
Joseph Giacomin (2014, 608-609) divides modern day design into three main design paradigms – technology-driven design, human centred design (HCD) and environmentally sustainable design. HCD is unique in that it is driven by the needs, desires and experiences of people. The outcome, therefore, often remains undetermined. Within a human-centred design approach, designers' activity instead concentrates on the overarching purpose before identifying the means or medium of implementation. Similar to the premise of co-design, the aim of HCD is to obtain a deeper understanding of people in order to inform the creation of more intuitive products, systems and services. Ethnographic interviews, questionnaires, role-playing and focus groups are commonly used HCD methods to explore and analyse this information. Giacomin suggests that HCD informs the way in which idealogical design opportunities are selected for development (2014, 610). Establishing a better understanding of participants is used not only in development, but also in identifying design problems. Design is used to "stimulate" and "communicate" with the people involved (Giacomin 2014, 610). Giacomin also suggests the push from manufacturers to adopt new technologies does not always align with the needs or desires of users (2014, 611).

Design researcher Marc Steen (2011, 45) discusses two tensions in human-centred design. The first tension originates from the difficulty experienced in connecting the worlds of designers with the worlds of users (Steen 2011, 48). Designers, as facilitators of HCD, must decide on a strategy for bringing these worlds together constructively, either by helping designers to move towards users, or by helping users to move towards designers. Within the context of this research, for example, the strategy for collaboration began as a expert interviews. Verbal dialogue, however, proved limited in this regards. Thus 3D-printed design probes were therefore introduced as a way to integrate end-users into the process of design, the thinking of the designer and the capabilities of the technology.

The second tension relates to the "juggling act between collecting and analysing data versus the role of initiating and sustaining significant change" (Steen 2011, 48). He refers to this as the ongoing concern for "what is" versus "what could be". This second tension coincided with the question of how 3D printing or products of 3D printing were best utilised as a tool for co-design.

research timeline_

Projects



Each co-design project acts as an action research cycle. Learnings from one cycle are used to inform and improve the next and validate knowledge claims.

Practice

Previous Contextual Projects around 3D printing
The re-design of total body irradiation blocks with Clinical Engineering and the design of a safety cap for isoflurane bottles alongside Pharmacy

Mobile 3D Scanning
Learning to use a mobile 3D scanner associated digital technologies

Establishing Co-Design Collaboration
with Clinical Engineer

Establishing Co-Design Collaboration
with Plastic Surgeon

Establishing Co-Design Collaboration
with Mould Room Technician

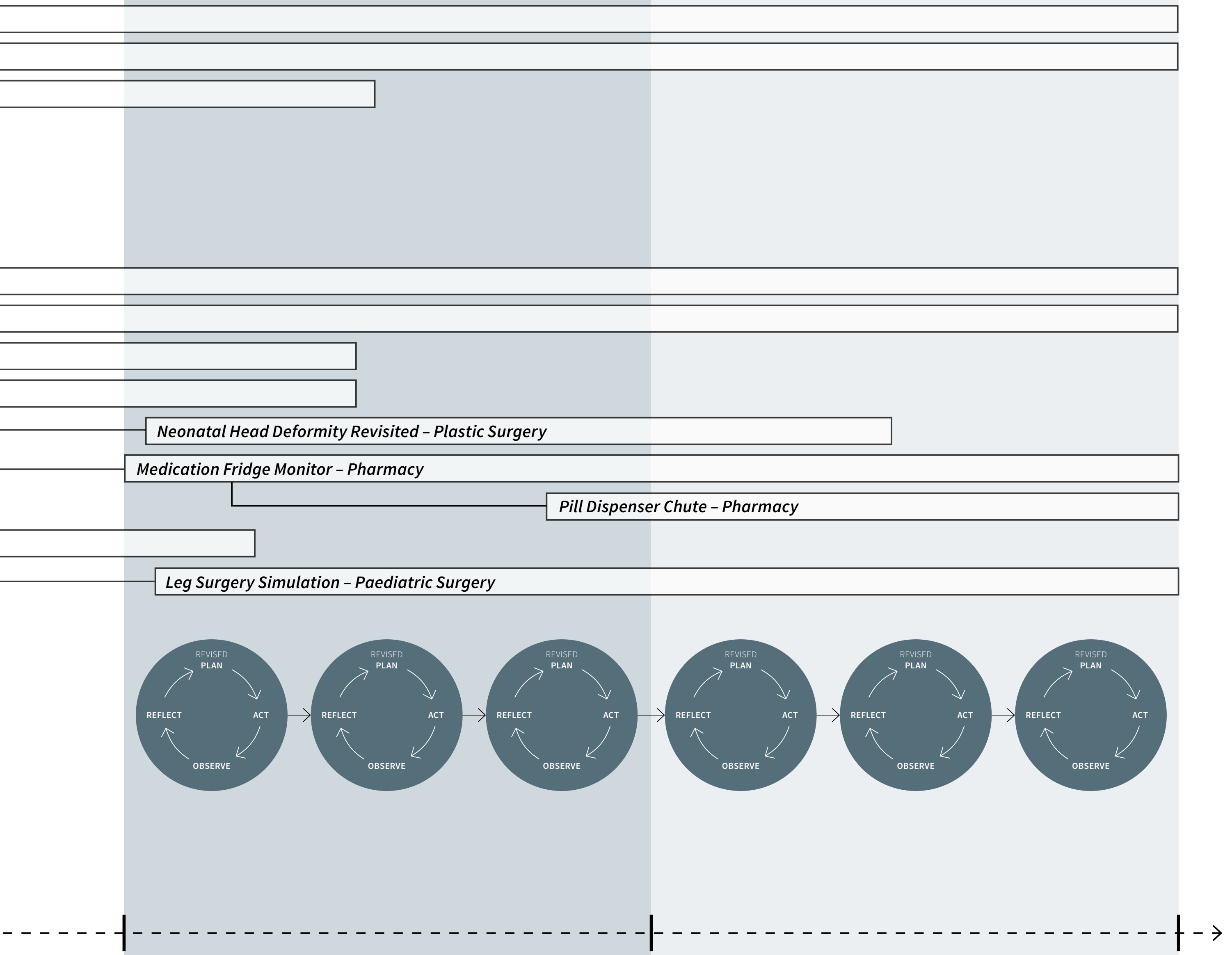
Establishing Co-Design Collaboration
with Oncology Physicist

Establishing Co-Design Collaboration
with Plastic Surgeon

Establishing Co-Design Collaboration
with Orthopaedic Surgeon

Experimentation with 3D Scanner
Scanning and manipulating body parts relating to suggested design opportunities

QUARTER 03	**QUARTER 04**
June 10, 2016 - September 10, 2016	*September 11, 2015 - December 10, 2016*



3D Print Final Prototypes
for testing and validation

Test & Validate Prototypes
where possible with healthcare professionals

Schedule 3D Prints
unsuitable for DHW Lab 3D printer

Establishing Co-Design Collaboration
with Medication Safety Technician

Establishing Co-Design Collaboration
with Paediatric Surgeon

Final Co-Design Project
with Medication Safety Technician

Final 3D Printed Prototypes
Due mid to late October

3D Printing Co-Design into Healthcare Best Practice
Due mid to late October

project selection_

Before beginning to search for suitable co-design participants, a set of criteria was created to evaluate the 'appropriateness' of each opportunity. Research scope, design benefit and participation were chosen, based on what was discussed in the contextual review and considering the constraints of research in terms of academic scope and resources. It's important to note that these were subjective assessments, based on my initial interpretation of the clinical problem and my understanding of 3D printing technologies. These criteria were evaluated at the beginning and end of each project to compare my initial assumptions with what actually eventuated during research. Each evaluation was documented as a reflective written analysis and shown visually using a radar chart. In line with action research this reflective information was used to inform and validate potential improvements to co-design practice.

Research Scope

Cost: The cost of development and other design-related expenses needed to be realistic within the constraints of both the DHW Lab's and my own personal budgets.

Time: The project/projects selected needed to be achievable within the time constraints of an academic year (nine months).

Regulations: Opportunities where the design was likely to have high-risk regulatory requirements were avoided due to cost and time.

Scale: There was a pragmatic consideration for the expected size and number of 3D printed objects for each selected design opportunity.

Market Analysis: An analysis was undertaken of whether a particular design already existed. If it did, there needed to be an idea of what benefit could be added by further research.

Design Benefit

Applicability: Ideally, selected designs needed to apply to as many people as possible. A highly niche design may not be viable under strict hospital budgets (cost versus value).

Reduced Cost and Time: When possible, the design aimed to reduce the current cost and time taken to produce a particular device, service or system.

Improved Health: The design should in some way aim to improve the quality of healthcare, whether it be accuracy, longevity or usability, particularly if cost or time is not reduced.

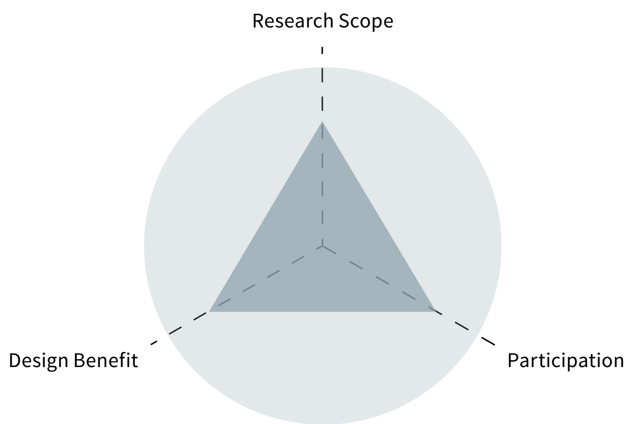
Low-Cost 3D Printing: Preferably the elected design should be able to be manufactured using a low to medium-cost 3D printer with low to medium-cost materials. However, this shouldn't be a limitation, especially considering the research focus is on the collaborative interaction.

Participation

Co-Design Involvement: It was important to gauge how willing participants were to be involved and how available they were to contribute over the course of a project. As part of the project information sheet, participants were made aware that they needed to be available at least once a month. Those that could not were excluded.

Problem Knowledge: When possible, healthcare professionals closest to problems associated with specific opportunities were recruited as co-design participants (e.g. hands-on experience or direct interaction with the patient).

Position of influence: When possible, participants in a key organisational positions were recruited in order to more easily gain access to, or be referred to, extended circles of experts.



research methods_

Literature Review

A literature review is a written contextual review that discusses key issues, thinking and tensions from published sources in a given field. The aim of a review is to draw connections and insight from converging information relevant to the focus of research (Hanington et al. 2012, 112). This discussion is referred to and reflected upon throughout the development of the research project and used to inform the purpose, aims and overall approach of research (Shuttleworth 2016). In this project, the fields explored were 3D-printed applications in healthcare and the implications of 3D printing technologies as part of the co-design process. Resources included books, journals and research papers from Google Scholar and AUT Library as well as online 3D printing and healthcare-related databases such as 3ders.org and Medsafe.com. Search terms used included: co-design, participatory design, co-design in healthcare, transformation design, co-creation, meta-design, participatory design in healthcare, user-involvement, innovation in healthcare, barriers to co-design, barriers to innovation, 3D printing, 3D printing in healthcare, 3D printing in hospitals, benefits of 3D printing, additive manufacturing, and additive manufacturing in healthcare.

Expert Interviews

Bogner and his fellow researchers (2009, 2) define expert interviews as structured or unstructured oral discussions framed around a particular topic, typically between two or more people during the exploratory phases of a research project. By talking to experts, the aim was to obtain an 'inside' understanding of a particular topic from someone who was experienced in that area (Dorussen et al. 2005, 317). Structured interviews tend to strictly follow a set of key questions, while unstructured interviews allow for more flexible discussions (Hanington et al. 2012, 102). However, in both structured and unstructured interviews, it is common for researchers to have a set of key topics to help guide the discussion (Hanington et al. 2012, 102). Using questions as a consistent structure also allows the researcher to interpret the data more efficiently and make more accurate comparisons between one interview and another (Hanington et al. 2012, 102). In this research, a series of unstructured interviews were conducted with healthcare professionals initially to help recruit co-design participants and identify suitable design opportunities. In preparation for these interviews a set of five open-ended questions was created to help facilitate broad discussion around key areas relating to my research question – 'How can 3D printing be used as a design tool to help facilitate co-design in healthcare?' –. The five interview questions, along with the anticipated areas of interest, were:

1. How much do you know about 3D printing in terms of both capabilities and application?
Exploring clinical application, tacit knowledge, previous experiences, skewed perceptions

2. Do you currently use 3D printing in any of the areas you are involved in? If so, in what way is it used? If not, why?
Exploring clinical areas of interest, existing application, barriers to adoption, benefits of 3D printing, potential design opportunities

3. Are you aware of any clinical problem or need where a potential solution may lend itself to 3D printing design opportunity?
Exploring perceived benefit of 3D printing, clinical areas of interest, clinical problems, preconceived design solutions, potential design opportunities

4. Why do you feel that 3D printing would be a suitable manufacturing method or design tool for this particular problem or need?
Exploring technological understanding, assumptions, problem solving ability and rationale

5. What would the value of design be if this opportunity was further developed?
Exploring understanding of design, the role of designers, understanding of the creative process

Strategies for arranging interviews included asking members of extended networks, such as the DHW Lab team and existing co-design partners, if they knew of any specific areas of healthcare or healthcare professionals that might offer suitable avenues for research, as well as contacting local healthcare professionals associated with clinical areas where 3D printing was more likely already being explored, such as plastics and orthopaedics. Additionally, four of the interviews originated as a result of one healthcare professional referring the researcher on to other experts, including interviews with craniofacial surgeon 1, plastic surgeon 2, orthopaedic surgeon 1 and paediatric surgeon 2. Bogner et al. describe this flow-on effect as an "added bonus" of interviewing experts in key organisational positions, giving the researcher access to "extended circles of experts" (2009, 2).

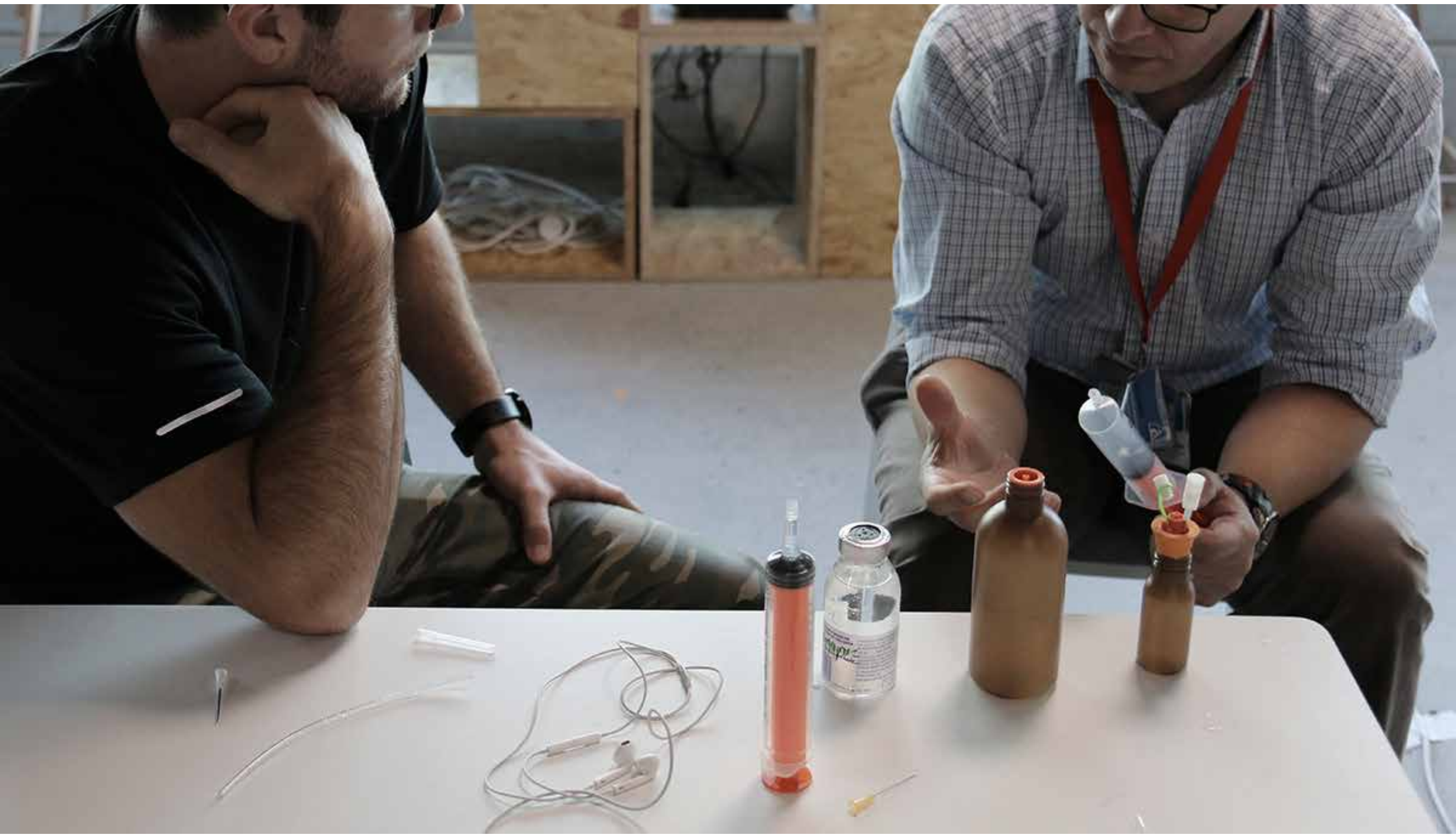
Interviews were organised at a time and place that best suited the selected interviewees, mainly in their offices, before or after their working shifts. Prior to the interviews, experts were sent an information sheet summarising the research (see Appendix 3, page 145). Each of the interviews was documented and analysed using the 'iceberg' approach (Norman and Stappers 2015, 90). Notes and photos were taken with the interviewee's permission during the interview to document what was observed and said at the time (surface level observation – tip of the iceberg). In order to unpack these interactions further, a set of reflections was written up following each meeting. Rather than audio or video recording, note taking was chosen as a more concentrated and selective method of documentation. The purpose of these reflections was to interpret what was discussed and observed, and how this was relevant to my research question. By doing so, the goal was to progressively improve the effectiveness of each meeting by consciously testing and validating my learnings from one session to the next.

In this research, expert interviews served two key purposes: First, as an exchange of knowledge. I shared information relating to the purpose of research and the role of design. Healthcare professionals shared information about their clinical role, their existing understanding of 3D printing and design, and whether they were aware of any design opportunities for 3D printing. Second, and perhaps more importantly, interviews served as a means of identifying and recruiting suitable co-design participants. Although initial interactions were conducted as expert interviews, the intention was for these interactions to evolve into co-design partnerships or, as Sanders and Stappers (2008, 9) describe this development, to transition from "subjects of research" to "partners in research". As soon as the social dynamic of a meeting was facilitated beyond an exchange of knowledge, these interactions would no longer be considered expert interviews. Instead, as part of a co-design approach, follow-up interactions were structured as co-design workshops. These interactions were largely between two people – the researcher and a healthcare professional. However, some interactions, such as the workshop with plastic surgeon 1, three other clinicians were invited by the surgeon to join the session. Thus the workshop ended up being between five people.

Co-Design Workshops

Common co-design tools include group sketching, prototyping, mind mapping, role-play and story telling (Sanders and Stappers 2008, 10-11). Although tools such as prototypes were used during research, as part of an exploratory practice-based approach, initially it was unclear whether specific tools would necessarily apply. For example, at the beginning of this research the co-design workshops were structured very similarly to interviews. Instead of questions, however, discussion was guided by a design opportunity in the form of a written or sketched idea. As research progressed, new strategies were implemented, such as the introduction of 3D-printed 'design probes' – artefacts that acted as a 'vehicle' for observation, reflection, interpretation, discussion and expression, rather than a forerunner of the future product (Sanders and Stappers 2014, 7-8). In conjunction with the 'cyclic' nature of action research, the introduction of probes was part of an aim to progressively develop the strategy for each workshop by consciously testing and validating my learnings from one session to the next.

Initially, co-design workshops were organised in the offices of each participant in order to make it more convenient for them to meet. Some of these workshops were located off-site, on other hospital campuses. However, in building upon the benefits observed during the use of probes, subsequent workshops were organised in the DHW Lab. This location gave participants the opportunity to observe a 3D printer in action, improving their understanding of the technology and triggering an increased level of excitement. It also provided them with direct access to a number of design tools such as pen, paper, clay, a 3D scanner and CAD. Plastic surgeon 1 and craniofacial surgeon 1, for example, both used these tools to express themselves more effectively. As with the interviews, each workshop was documented and analysed using notes and photography to record what was observed and said during the interaction and a set of reflections was written up afterwards. However, the purpose of these reflections was different to that of the interviews in that they were targeted towards developing the strategies for the ongoing co-design practice rather than interpretations and relevance to the research question.



Co-Design meeting with medication safety technician.

design methods_

Sketching & Prototyping

Prototyping refers to the "fleshing out" or embodiment of research in the form of a conceptual product, service or system (Maguire 2001, 611). These embodiments represent an idea, or group of ideas, in response to a design problem. In this research project, concepts often began as rough 2D sketches. A number of times these were done during the expert interviews or co-design workshops. The purpose of sketching was not to accurately or realistically portray a design solution, but rather to quickly and efficiently capture undeveloped ideas. Subsequently, these sketches would be developed into a CAD model that was 3D printed. In contrast with "rough" forms of prototyping such as paper modeling, additive manufacturing has the capability to rapidly produce "highly resolved" tangible 3D models (Hanington et al. 2012, 138). 3D-printed concepts were therefore able to be tested and evaluated by those involved in the design.

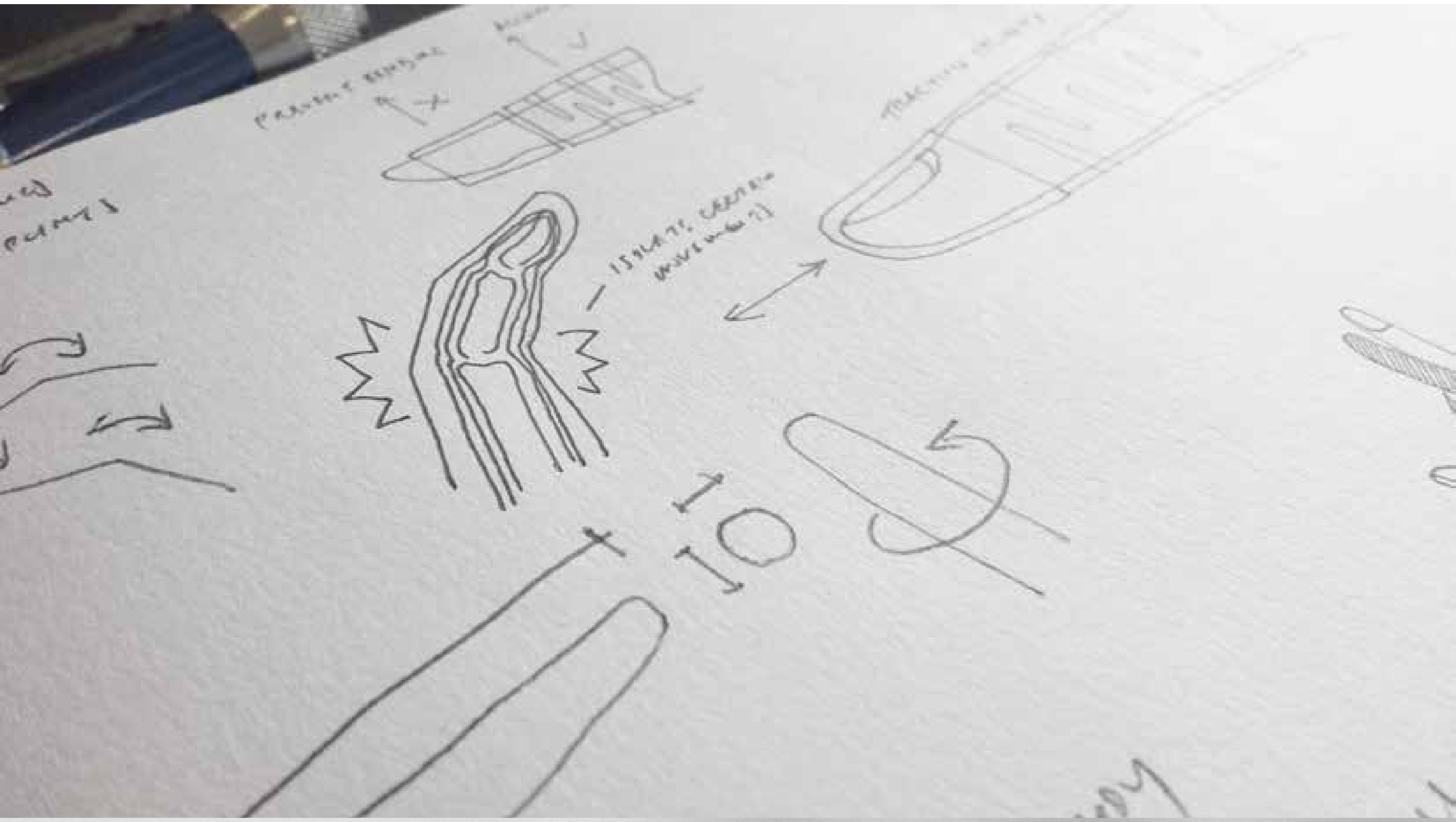
However, prototypes were not always intended to represent a potential design solution, particularly in the early phases of the design process (Hanington et al. 2012, 138). Some prototypes were created as design probes (Sanders and Stappers 2014, 7-8). These were artefacts used to demonstrate the capabilities of 3D printing, or to help map my own assumptions around a particular problem or topic (Hanington et al. 2012, 54). Deposition 3D printers, such as the one used in the DHW Lab, also have varying levels of resolution. Designs can be printed in lower or higher levels of detail based on the chosen layer thickness – 0.3mm, 0.2mm or 0.1mm. For earlier prototypes, or probes that did not necessarily require a high level of detail, thicker layers were chosen in order to reduce 3D printing time. The main 3D printers used to produce artefacts were Makerbot's Replicator 2 and Z18. However, the Formiga P100, a larger SLS printer, was also used for the simulation arm project to create a watertight structure (shapeways.com 2016).

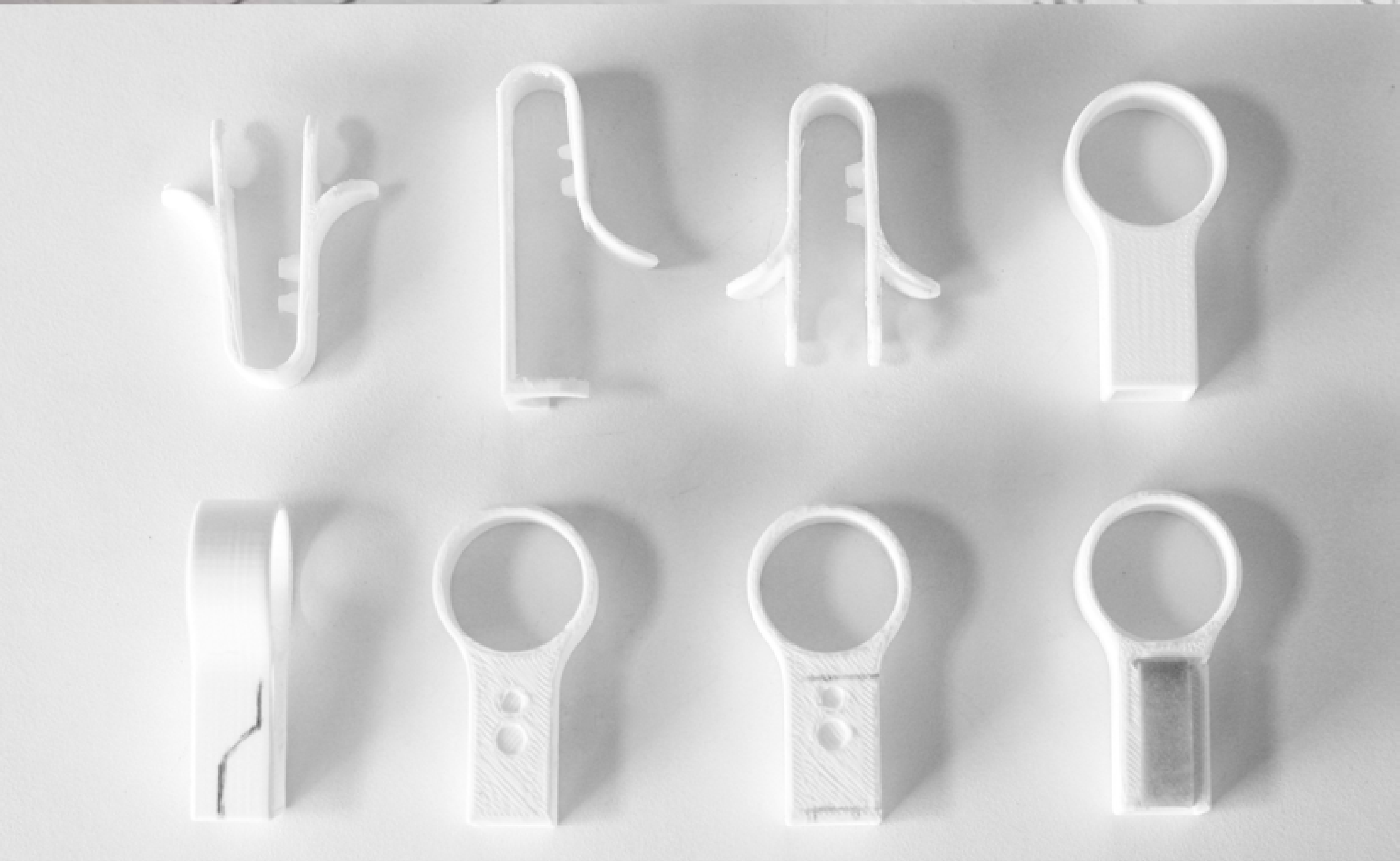
Computer-Aided Design (CAD)

Computer-aided design is digital software used to create technical drawings, two-dimensional (2D) and three dimensional (3D) models. Models produced using CAD were often based on rough sketches or existing design solutions. 3D models are particularly important in the context of this research project as they can be easily exported into a format suitable for 3D printing. This method was used throughout my research to explore design ideas, visualise concepts and simulate how they might perform in the real world (Autodesk 2016). Digital designs would often go through several iterations before they were 3D printed.

CAD was also used to process three-dimensional scan data from the Creaform Go!SCAN portable 3D scanner (creaform3d.com 2016). This digital information is often referred to as point clouds – a series of three-dimensional coordinates that form a digital object. A range of software packages including Solidworks, Netfabb, Meshmixer, Meshworks, Matlab and Blender were used to process and manipulate this point cloud data. However, due to the complexity of 3D scan models and the difficulty experienced editing them, I switched to using parametric CAD principles – digital files structured so that the overall geometry is defined by only a small number of adjustable dimensions (Camba et al. 2016, 18-19). Designs could be altered and reused simply by editing the values of certain interdependent parameters. Designs such as the finger splint could be modeled using a set of five key measurements – the heights and widths of the top and bottom parts of the finger and its overall length.

Sketches done during one of the expert interviews with plastic surgeon 1 discussing the idea of finger splints.





Prototype iterations for the anaesthetic bottle adapter clip.

Role-play

Role-play refers to taking on the physical or emotional characteristics of the people a design is intended for (Simsarian 2003, 1). The purpose of this method is to help designers gain a deeper understanding of users and develop empathy for how they experience a product, system or service. Simsarian explains how different types of role-play relate to different phases of the design process. These phases include understanding, observing, visualising, evaluating, refining and implementing (2003, 1). In this research, role-play was most often used during the refining phase as a form of a debugging. The objective of this refinement was to discover hidden nuances and work through details of possible scenarios before implementation (Simsarian 2003, 2). For example, during the ear splint project, although the design was intended for neonatals, a number of prototypes were tested on my own ear in order to test attributes such as cost, accuracy and usability.

Role-play was also selected as an alternative to patient testing for projects such as the finger splint, the ear splint and the radiation head and neck cradle. It's important to recognise that direct patient feedback was likely to have been more comprehensive and accurate (Hanington et al. 2012, 78). Simulating complex experiences such as radiation treatment or birth deformities simply wasn't possible to the extent that patients experienced them. However, due to being constrained by formal ethical review processes, actual user testing was not easily feasible within the allocated time frame. Although not as effective, role-play and expert feedback helped to validate 3D-printed concepts without the need for ethics approval and the potential risk for delaying or hindering my design practice.

It is also important to acknowledge that the focus of this research is more about exploring 3D printing as a co-design tool and less about successful design outputs. Many of the designs created during research are still in development. Following this research project I may look to secure ethics approval for patient testing in order to validate certain 3D-printed concepts further.

Expert Evaluation

An expert evaluation involves an expert of a particular field using his or her knowledge and experience to test, evaluate and give feedback on a particular product or system during development (Rubin and Chisnell 2008, 21). Rubin and Chisnell (2008, 21) describe this as evaluating "the degree to which a product meets specific usability criteria". The purpose of this feedback is to help designers identify potential problems with the design, recognise opportunities for improvement and better understand the needs of the end-user. In this research, experts were healthcare professionals who had been recruited as co-design participants. For example, the oncologist team leader was asked to give feedback on the radiation neck cradle because of her hands-on experience with radiation equipment and her regular interaction with patients undergoing radiation treatment. She not only acted as a source of information, but also as a way to access the experiences of patients.

Similar to role-play, expert evaluations served as an alternative to user testing due to ethical constraints. However, as Stephanie Rosenbaum (uxmatters.com 2009) states: "regardless of the evaluators' skill and experience, they remain surrogate users – expert evaluators who emulate users – and not typical users." Rosenbaum describes how users will often experience and interact with a product completely differently to experts. Expert evaluations are still useful as a form of secondary research, but offer less insight than direct user feedback.

However, there were a number of projects where healthcare professionals did participate as the end-user, at least for parts of the design interaction. For example, each of the head and neck cradles needed to be connected to the radiation bed before patients underwent treatment. This assembly process was carried out by the oncology team leader and her staff. Although the cradles were intended predominantly for patients, a large aspect of the design's functionality was driven by the clinicians. For other projects, such as the simulation arm and the medication fridge insulator, the healthcare professional was, in fact, the end-user.

methods map_

The British Design Council's (designcouncil.org.uk 2013) 'Double Diamond' design process diagram is used below to illustrate when research methods were used during co-design projects. Although each project unfolded in different ways, the use of methods to target specific phases of the design process remained fairly consistent.

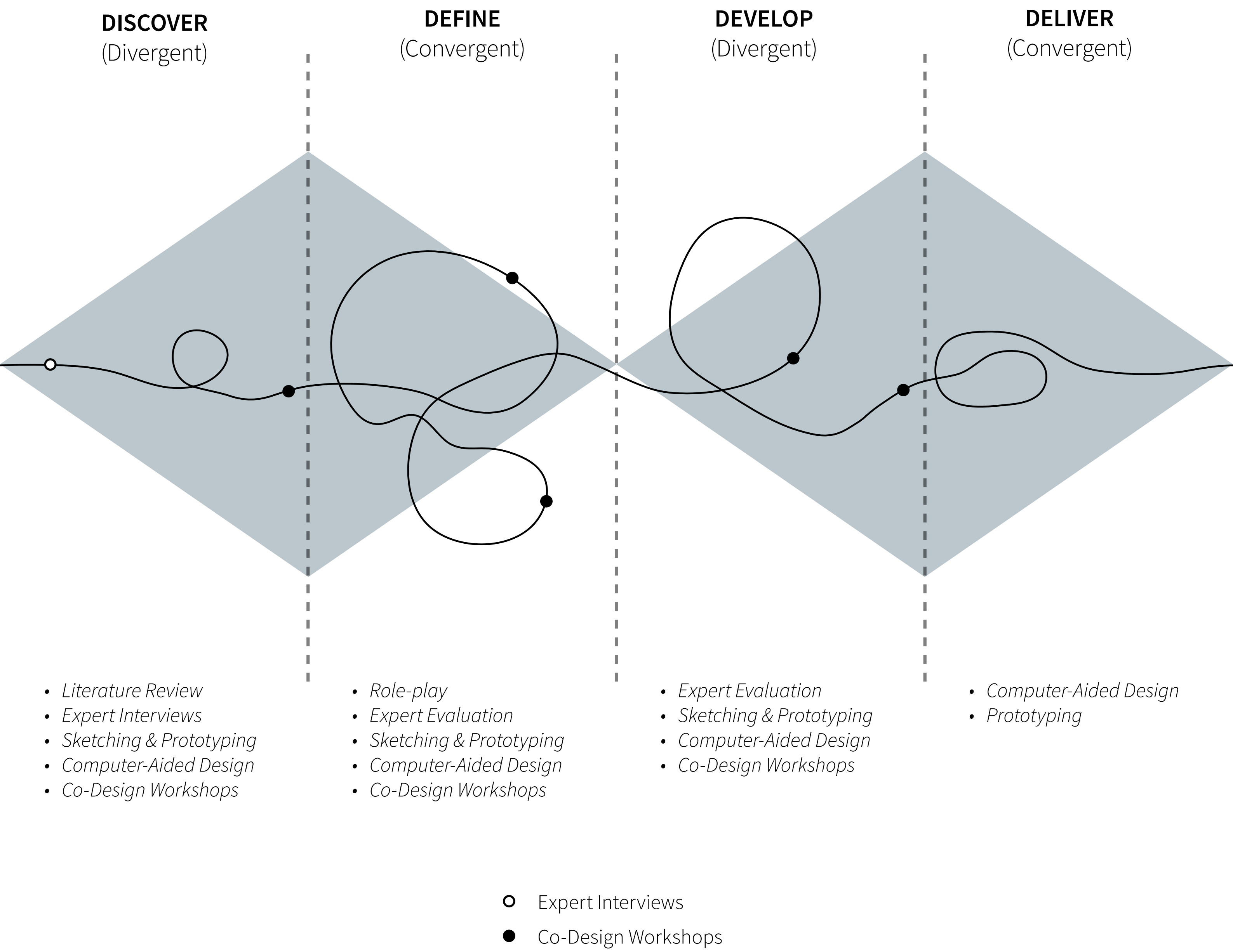


Figure 04. The Double Diamond Design Process Model – UK Design Council 2005

ethics_

At AUT university, all proposed research involving human participants requires a formal ethics review by Auckland University of Technology Ethics Committee (AUTEC). Ethics approval was applicable to this research due to the involvement of healthcare professionals. The ethics committee was consulted before any participant interactions took place in order to identify any issues with the proposed research approach. Fortunately, no issues were raised. Ethics application number 16/60-0703-2016 was approved by AUTEC as of March 11, 2016 for three years (see Appendix 5, page 146 for approval letter).

Peter Cave (2015, 32) defines ethics as the study of moral dilemmas in action. In this research we are concerned with 'normative ethics' – a set of guides that "determine the norms or values by which we should live" (Cave 2015, 33). Normative ethics are relevant as they provide a platform for the way ethics should be applied to practical situations, such as the way design research is conducted. AUTEC's guidelines for the ethical treatment of participants are based on three key principles: "partnership, protection and participation" (AUT University 2015, 98). In accordance with these principles, a number of precautionary measures were put in place before interacting with chosen participants.

In relation to partnership, mutual respect and participant autonomy were achieved by ensuring that all participants were acting of their own volition. Each participant was given the freedom to withdraw at any time during the research. Part of this measure involves informed consent – communicating the risks and benefits of the research to participants so they can make an informed decision on whether or not to participate (Hammond 2016, 1). Each healthcare professional was emailed a summary of the intended research and a consent form prior to initial interactions. These documents helped to ensure participants understood the purpose of the research and what was expected from them as co-design participants. Details such as the likelihood of subsequent interactions were included in the information sheet in order to minimise the risk of participants terminating interviews or co-design workshops. Consent was also necessary in order for me to use the information discussed and observed during collaborative interactions.

Participants were protected by ensuring privacy and confidentiality. The identities of healthcare professionals were kept anonymous at all stages of research in order to prevent the risk of sensitive information being associated with a specific participant (Petrova et al. 2016, 443). In research documentation, participants were represented by their profession or clinical role. If the same clinical role occurred more than once a number was added, for instance, 'plastic surgeon 1' and 'plastic surgeon 2'. Data that did contain identifiable details were only ever seen by the researcher (myself) and his supervisors.

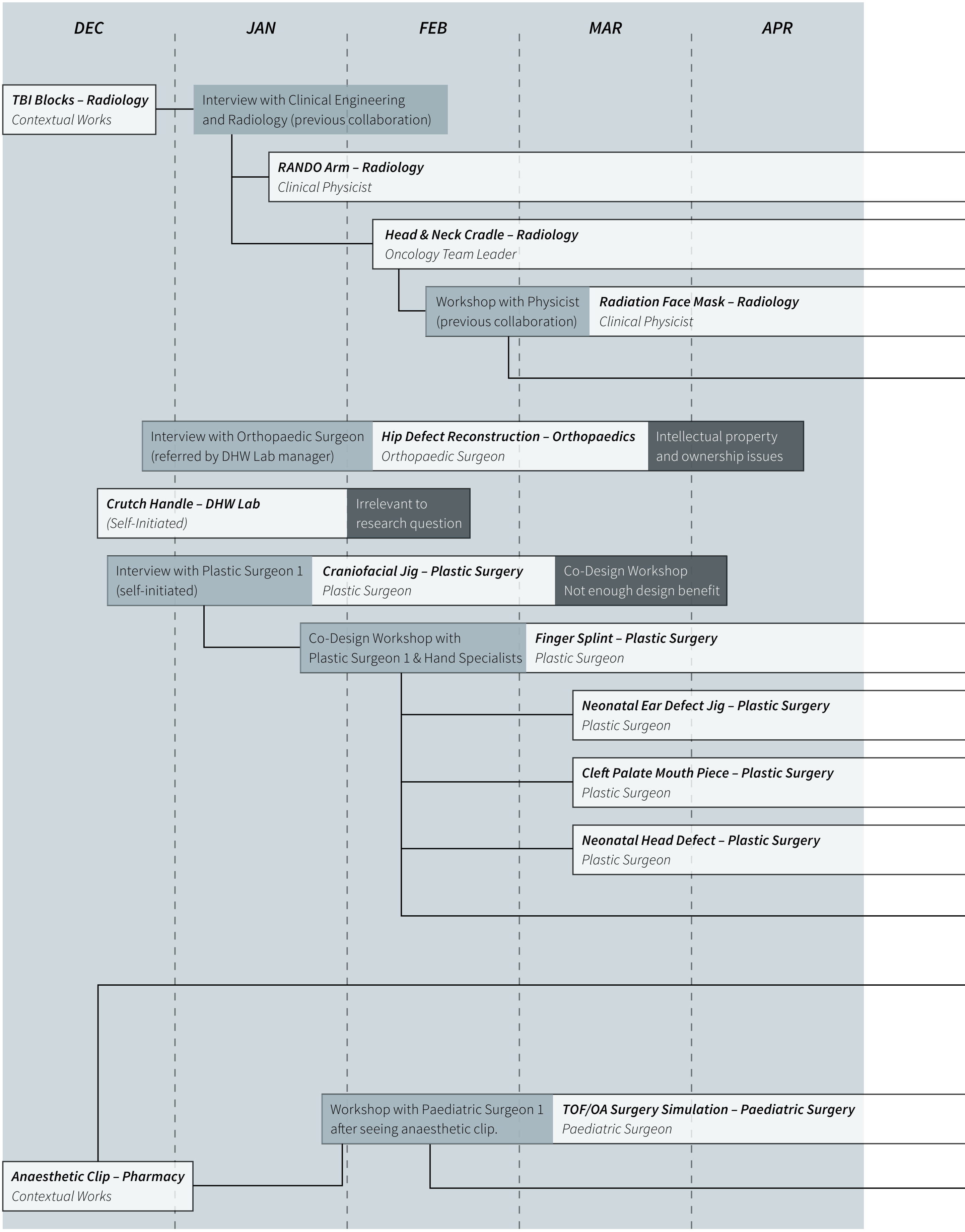
In regards to participation, the role of participants was primarily to help to inform the research outcomes by providing the researcher with insight into their own knowledge and experiences. Participants were not involved in conducting the research, but their responses and contributions during co-design workshops did help to influence the nature of the research. For example, unexpected insights such as the limitations of verbal communication resulted in changes to the way co-design workshops were facilitated.

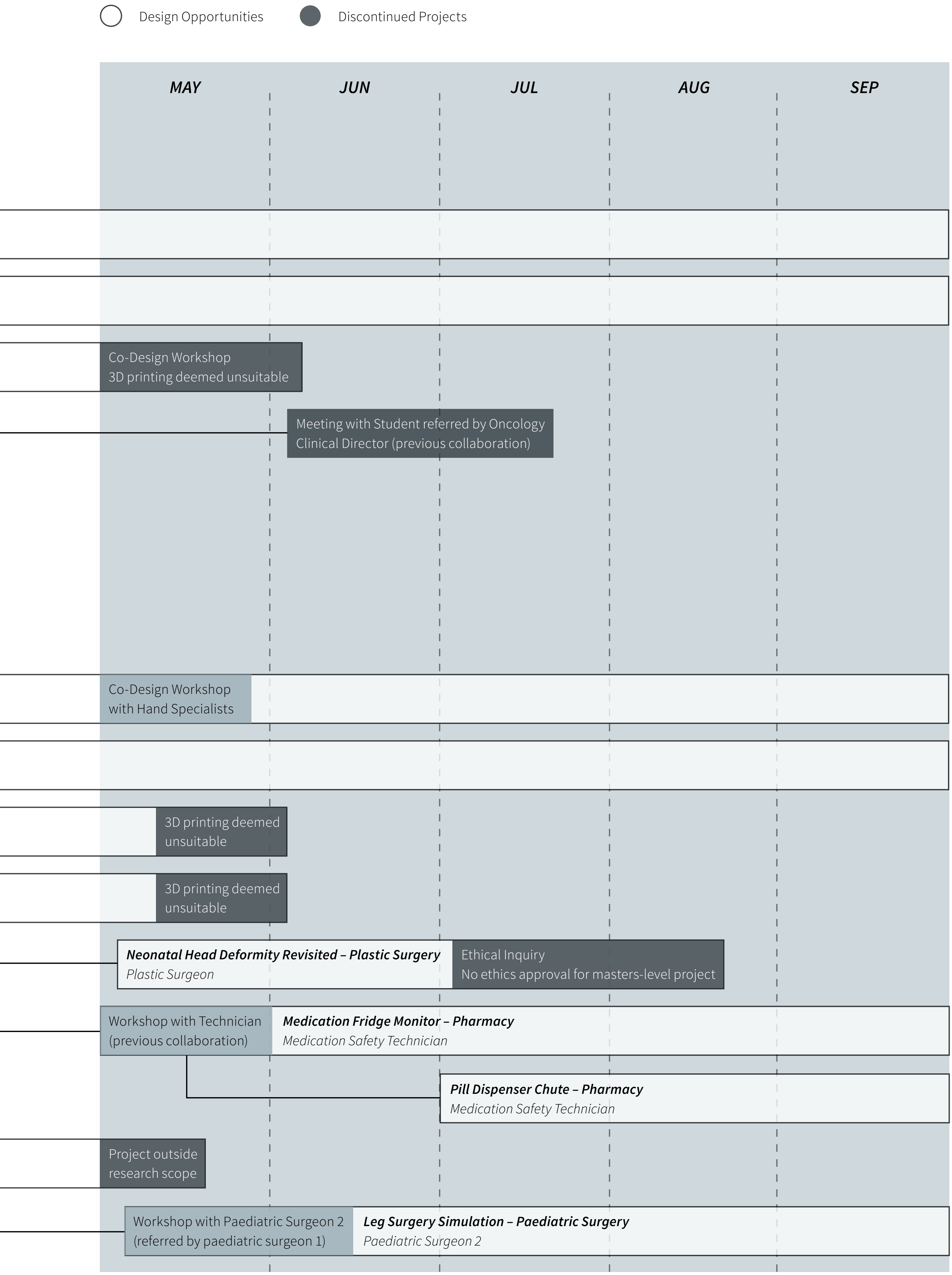
Due to the limited scope of the research and the nature of ethics, I only engaged with healthcare professionals, even though some of the designs were intended predominantly for patients. The focus of research also evolved to be more about exploring 3D printing as a way to engage healthcare professionals in co-design, rather than simply a form of manufacturing. In order to engage a number of participants, each project needed be developed in short rapid cycles. Seeking ethical approval for the ability to co-design with patients or work with sensitive patient data may have taken longer than these short research cycles would have allowed.

CHAPTER 03

research documentation_

co-design projects map_





Design Opportunities
Discontinued Projects
MAY
JUN
JUL
AUG
SEP
Co-Design Workshop
3D printing deemed unsuitable
Meeting with Student referred by Oncology
Clinical Director (previous collaboration)
Co-Design Workshop
with Hand Specialists
3D printing deemed
unsuitable
3D printing deemed
unsuitable
Neonatal Head Deformity Revisited – Plastic Surgery
Plastic Surgeon
Ethical Inquiry
No ethics approval for masters-level project
Workshop with Technician
(previous collaboration)
Medication Fridge Monitor – Pharmacy
Medication Safety Technician
Pill Dispenser Chute – Pharmacy
Medication Safety Technician
Project outside
research scope
Workshop with Paediatric Surgeon 2
(referred by paediatric surgeon 1)
Leg Surgery Simulation – Paediatric Surgery
Paediatric Surgeon 2

initial expert interviews_

Clinical Engineers

The first interviews were conducted with clinical engineers to get the ball rolling, as I had worked with them previously. Although I would not be establishing a new co-design relationship, I felt it important to gain some research momentum. I hoped an existing partnership would generate design opportunities. However, it was important for me to recognise these clinical engineers were not clinicians. Despite operating within a clinical environment and contributing to the physical services patients interact with, they did not directly interact with patients, nor did they operate in specific clinical spheres such as plastics or orthopaedics. It was probable, therefore, that the collaborative interactions with clinical engineers would differ considerably from those of clinicians, the type of healthcare professional I was likely to engage with more often during research. This is not to say the clinicians would not also differ from each other, but rather that the role and expertise of clinical engineers may have naturally resulted in a very different understanding of design and 3D printing.

At the beginning of the interview, the clinical engineering team were hesitant to speak and struggled to think of ideas suitable for my research, making statements like "I just can't think of anything off the top of my head" and "there might not be anything right now". I began discussing existing 3D printing projects in the hope this might help trigger ideas. Examples included a 3D-printed ear reconstruction model by the University of Washington, a 3D-printed stethoscope created by Tarek Loubani (motherboard.vice 2015) and two of my own designs: 3D-printed TBI blocks and a 3D-printed anaesthetic bottle clip. Although some of the engineers had been involved in the TBI block project, the majority appeared unfamiliar with the technologies. Therefore, I made sure to comment on the specific attributes 3D printing was enabling in each project, e.g. adaptable, complex, low-cost and personalised. After discussing these examples, the engineers began contributing more actively to the discussion. Statements such as "well, now you mention it, I can think of a few things" suggested that learning about some of the possibilities of 3D printing had helped trigger a new line of thinking. By the end of the interview they had come up with two potential design opportunities.

The first involved the design of a collision indicator for a large imaging machine – a safety tool used before imaging to test whether the extended arm cradle would hit the patient. The second opportunity was around the redesign of head and neck cradles used for patients during radiation treatment. Cradles purchased from an overseas manufacturer failed to meet the level of accuracy and consistency required by the radiology team. The design also lacked important features specific to the imaging machine, for example, vertical adjustability.

Of the two proposed opportunities, the cradles appeared to be more suitable, mostly because they were intended for individual patients, and therefore likely to require a degree of personalisation and tailorability. However, I explained to the engineers that without seeing the cradles first-hand and exploring the context of the problem myself, this was simply an assumption. Interestingly, in response, one of the engineers stated he had noticed how designers tend to try and "get a better understanding of the problem" before jumping to the final solution, whereas for them, "the hospital comes to us with fairly resolved ideas of what they want and we simply do our best to create it". Very seldom would they challenge the validity of design propositions made by the hospital. This wasn't to say that problems didn't exist or that proposed design solutions weren't appropriate, but it did raise the question of how they were deemed appropriate.

During the interview, I realised that verbal dialogue was considerably limited as a form of communication, especially in relation to design and technology. The engineers weren't able to observe or interact with any of the objects or technological features I described to them. Additionally, my verbal explanations took a considerable amount of time. Because more visual examples such as photos or objects may have helped me communicate more effectively, I made a note to bring 'visual aids' to subsequent interviews.

Following the interview I was taken to look at a radiation simulation device in oncology that one of the engineers believed to be reproducible using 3D printing. However, it quickly became apparent it wasn't. The device varied in density, used multiple materials and was too large. Although possible, Clinical engineering meeting notes showing photos of the imaging machine that required a collision arm and drawings of the radiation head and neck cradles.

Head and neck cradle vacuum form moulds for various patient head sizes.

the type of 3D printing required was likely to be substantially more expensive than the cost of the existing product. After discussing these barriers with the engineer, he agreed 3D printing was not an ideal solution.

Having worked with them previously, I had thought the engineers would be able to identify some of the more promising design opportunities. My interactions with them, however, suggested an inaccurate understanding of 3D printing technologies. They were also unclear as to the purpose of redesigning the existing products. When asked why a new radiation simulation device was required, one responded: "I'm not actually too sure, oncology just said that they needed another one." This made it even more difficult to determine whether there was an opportunity beyond an exact reproduction. The product needed to be reproduced, but it wasn't clear why, or if there were parts of the existing design that could be improved.
Although this could have simply been a lack of communication, the engineers may also have been too far removed from the clinical context to understand the problem in enough detail.

Plastic Surgeon 1

Based on my existing knowledge of 3D printing, one of the clinical areas I felt had potential for its application was plastic surgery. In 2015 I sustained a compound head fracture that required surgical reconstruction and a titanium plate. During this time, I discovered plastic surgeons do the majority of this procedure by eye. My thought was that a 3D-printed mould, based on the unaffected side of the face, could help form the implant more precisely. To validate this idea and potentially identify others, I set up an interview with a local plastic reconstructive surgeon.

Although the surgeon knew very little about 3D printing, the craniofacial department had already begun using it for more complex patient cases. Most of the examples were bone structures for preparative surgery, such as a patient's skull or hand. Patients' CT scans were sent to an overseas agency, which then processed that data and 3D-printed them. Despite its clinical benefit, 3D printing was rarely used due to the "exorbitant cost and time taken to receive the prints". A 3D-printed skull, for example, could cost anywhere between $500 and $1500 and take up to two weeks to be delivered. When I began to specify the relative time and costs of smaller desktop 3D printers, such as the Makerbot used in the DHW Lab, the surgeon became more animated and engaged in the conversation. From his reaction, I realised research participants may have not only a lack of technological understanding, but also an inaccurate understanding.

I felt it important to explain to the surgeon how the process for creating the type of models he was familiar with required very little 'design'. With recent advances in the technology, 3D printing bone structures for preparative surgery is much simpler, even for someone with limited experience. The digitisation process is essentially a solved problem. Knowing this helped the surgeon understand what I meant by the 'purpose of design', and the types of design opportunities I was looking for.

The rest of the interview was spent discussing specific ideas and other clinical areas with potential for 3D-printed applications. These included working with the hand physiotherapy team to create customised and potentially modular hand splints and the burn department to create external pressure casts for skin graft treatment, as well as working on the development of facial prosthetics for patients with damaged or missing facial structures. As we were finishing, the surgeon mentioned it "would have been nice to see some 3D-printed models". This was another reminder to try using tangible objects to help facilitate discussions, rather than just relying on questions or verbal discussion.

A photo showing the clinical engineer pointing at the radiation simulation machine in oncology. This was a device he thought might be replicable using 3D printing. However, due to its size and material requirement, it was deemed unsuitable.

Custom moulded face masks for a keeping patient's head still during radiation treatment. Although these mask effectively keep patients' head still during treatment, they cause considerable discomfort by covering the patients' faces.

Plastic Surgeon 2

In addition to the opportunities presented by the first plastic surgeon, he also referred me to one of his colleagues. This surgeon had a much better understanding of 3D printing technologies and capabilities due to a general interest in new technologies. He was also familiar with a number of existing clinical applications and areas in healthcare where 3D printing seemed to be evolving most rapidly. This existing knowledge meant there was level of common understanding already established. Instead of me spending a large part of the interview bringing the surgeon up to speed on the basics, we were able to have an in-depth discussion in relation to a number of design opportunities. His suggestions included custom hand splints to help patients keep their wrist at a specific angle, finger splints, antibacterial implants made of 3D-printed silicon, jigs for ear reconstruction, multi-pressure moulds for burn victims, custom splints for rhinoplasty and preparative bone structure models with pre-made surgical cuts.

From these suggestions, the most promising ideas appeared to be the jig for ear reconstruction and the finger splint. Again, though, this was an assumption based on my knowledge of 3D printing and the constraints of the research scope. Interestingly, the surgeon's understanding of 3D technology meant he also understood the importance of scope. For instance, as soon as he mentioned the antibacterial implants, he realised the design idea was probably too advanced, stating "actually it might be a bit too complex to attempt in such a short time".

Despite his considerable knowledge, plastic surgeon 2 had a skewed perception of cost. Similar to the first surgeon, he was surprised by the lower costs of smaller desktop 3D printers and their level of quality. Using my phone I showed him photos of 3D-printed examples I had previously made as part of my DHW Lab work. Although the photos helped as a visual aid, I was once more reminded of the need to bring physical examples to interviews.

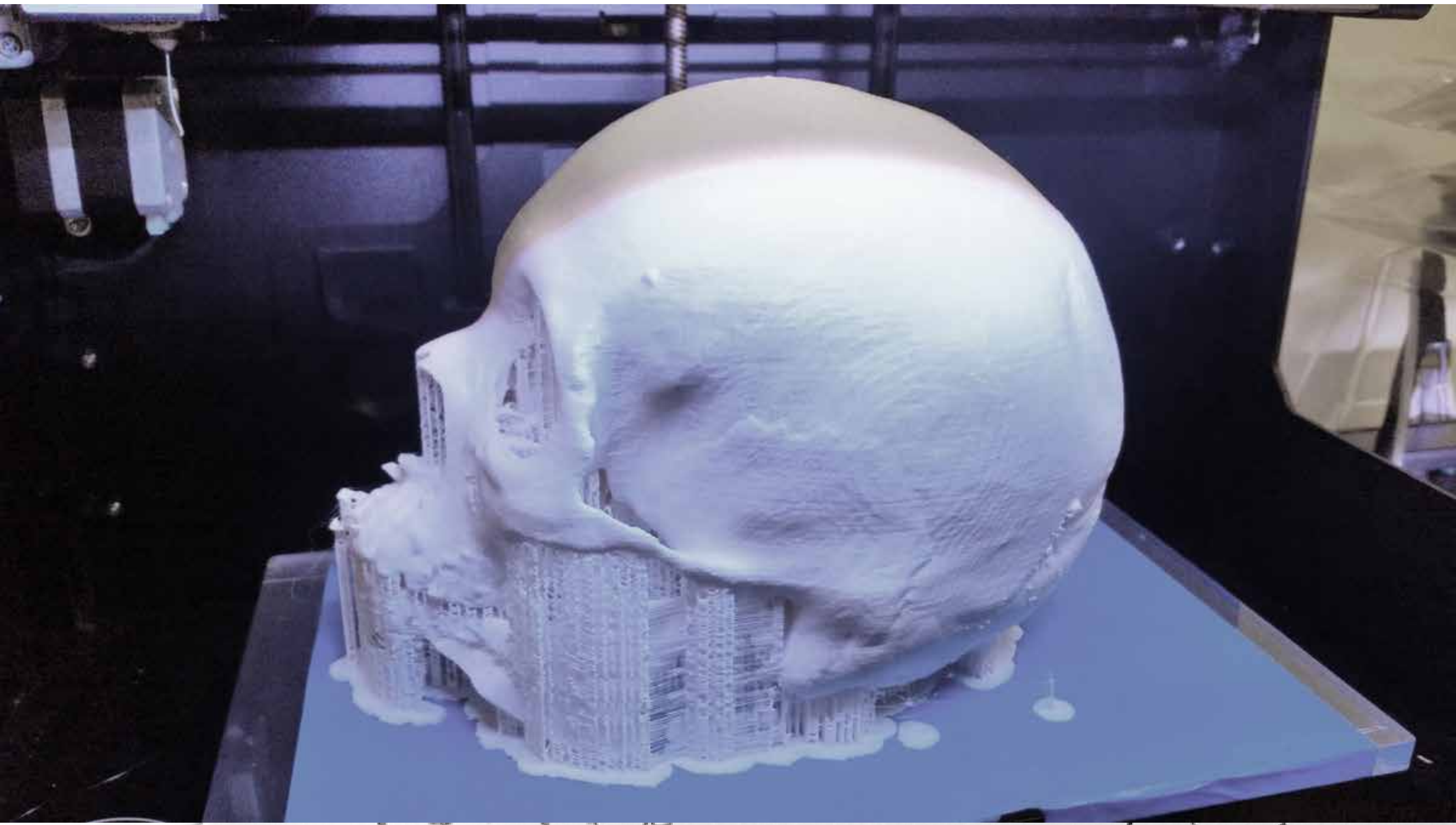
Oncology Physicist

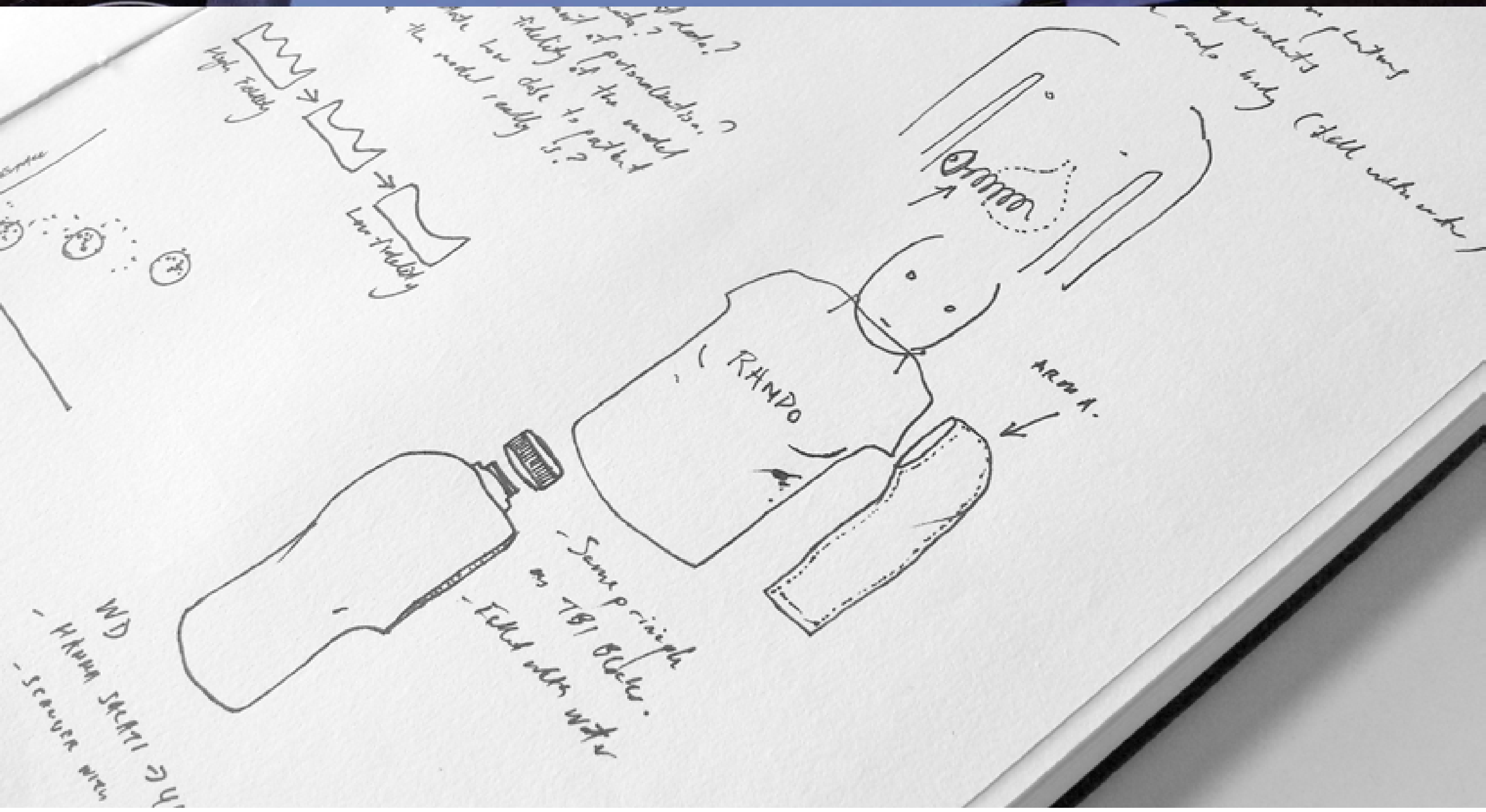
As with the engineer, an interview was organised with a physicist I had previously worked with, hoping to build on this partnership. Having already observed and been a part of two 3D-printed projects, including the total body irradiation blocks (see Appendix 1, page 140), the physicist had good prior knowledge. I also knew something about his role and the clinical area he worked in. When asked why he thought we worked well together, the physicist replied: "it's probably just because we have gotten to know each other and what each other can do." This common understanding provided a foundation whereby we could hit the ground running. Although the interaction was arranged as an expert interview, the structure very quickly developed into more of a collaborative workshop.

Like the TBI blocks, most of the physicist's ideas were based around radiation treatment and partial shielding. His suggestions included 3D printing: shields for spinal radiation treatment, additional parts for a radiation simulation model, and custom body segments for a radiation simulation mannequin (RANDO). Although most concepts seemed plausible, it was difficult to tell whether 3D printing would be the most suitable manufacturing method, especially as I was unable to see or interact with the existing designs. Just as sketches, photos or physical examples may have helped me to communicate, existing designs may have provided a way for the physicist to convey his ideas more effectively.

My immediate reservation with his suggested concepts was the large size. Large-scale designs increase both the cost and time taken for 3D printing. The most feasible of the physicist's suggestions appeared to be the opportunity around additional parts for a radiation simulation mannequin (see page 78). This assessment was based on the replacement parts being the smallest of the objects he discussed and the lowest risk, as they would be kept completely separate from patients.

CT scans of bones are already being 3D-printed at plastic surgeon 1's hospital. However, these prints are being outsourced. The example below was printed on a small low-end printer at the DHW Lab.





Illustrations and notes taken during the interview with the oncology physicist. These sketches show how the 3D-printed arms were going to be created in a similar way to the 3D-printed total body irradiation blocks – printed as a hollow shell and filled with water (tissue equivalent) as a form of radiation attenuation.

Orthopaedic Surgeon

The last candidate for my initial set of interviews was a local orthopaedic surgeon. In contrast with the other meetings, he initiated the interview after hearing about my research from another member of the DHW Lab.

Early on, I discovered the surgeon had an comprehensive and accurate understanding of 3D printing, in terms of both capability and cost. Most of his knowledge came from prior project experience, one of which involved his own surgical practice. Again, this meant the dynamic of the interaction evolved very quickly from an interview into a co-design workshop. The meeting was unique in that he came with a specific idea he'd already begun thinking about. Even when asked about other opportunities, he kept coming back to his own concept.

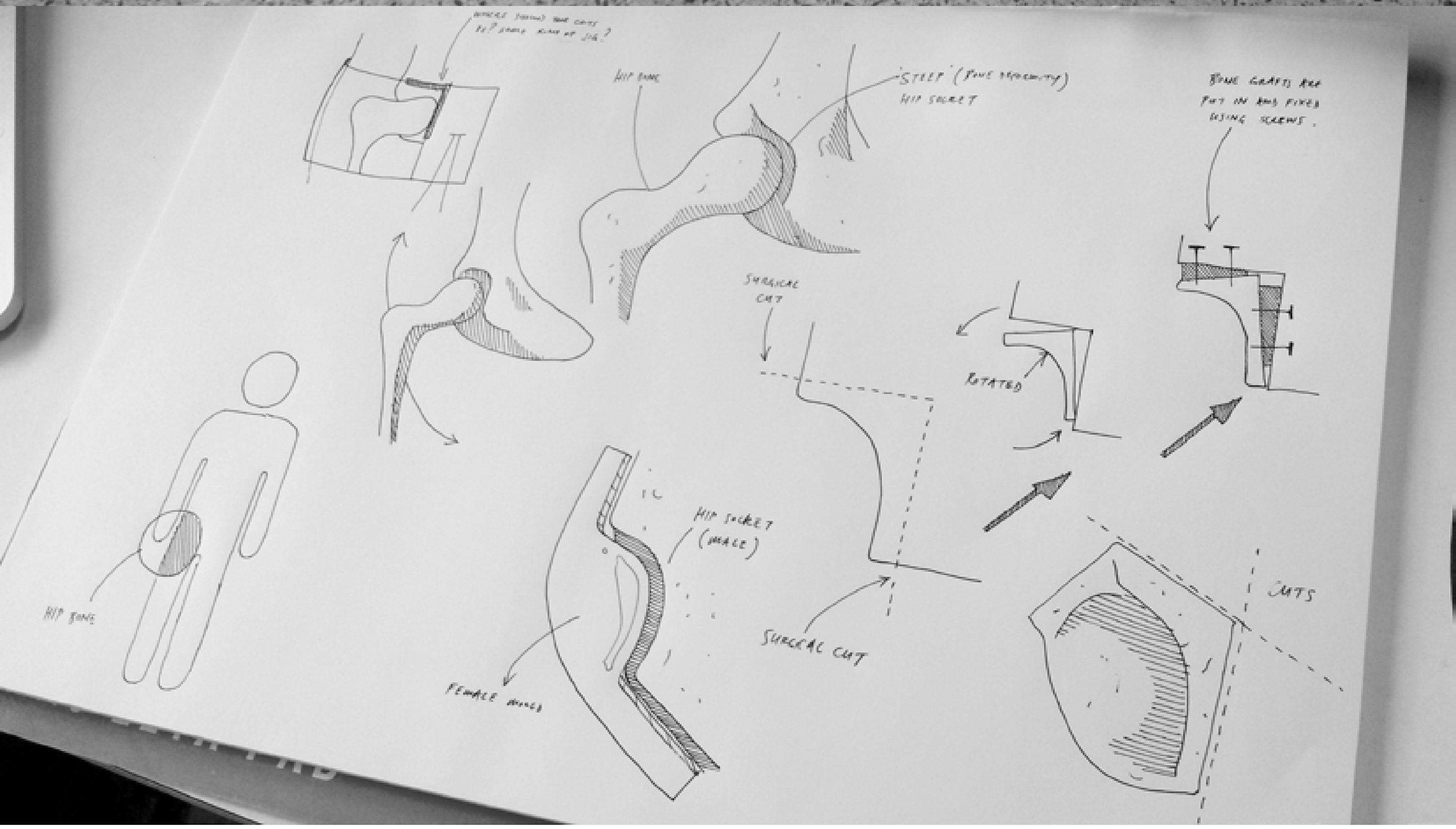
The surgeon's proposed design related to a rare pelvis defect where people are born with steeper than normal hip sockets, which can lead to early-onset arthritis and the need for a hip replacement. To correct this, surgeons perform a procedure where part of the hip socket is cut out and rotated to reduce the steepness, thus reducing the likelihood of ongoing health risks and long-term costs. 3D-printed models of the patient's pelvis were already being used to help prepare for the procedure, but the surgeon felt there was a greater potential for 3D printing.

His proposed solution involved planning the intended surgical cuts digitally using computer-aided software before the model was 3D printed. Displaying the cuts in a tangible form would provide surgeons with a much more accurate representation of the surgery itself. A number of vital nerves, arteries and other anatomical structures create what he termed a "surgical minefield" around the hip socket. A 3D-printed 'cutting jig' based on the external structure of the patient was suggested as a potential design solution to help increase accuracy and reduce risk.

Despite the need for a design intervention, I was unsure whether such a high-risk procedure was suitable. There was also doubt as to how well we would work together collaboratively. Although the meeting began with semi-formal questions, the bulk of discussion was dictated heavily by the surgeon. What felt like a fairly one-sided social dynamic seemed to conflict with the anti-hierarchical nature of co-design. As Yanki Lee argues, for co-design to be effective, participants cannot continue to be treated passively (2008, 32-33). Following my interaction with the surgeon I felt the other extreme was also true – co-design cannot operate effectively if the designer has no active 'say' or ability to contribute.

I decided not to develop the project any further. Despite significant interest in the project's development, his availability was extremely limited. Design decisions made without his input would risk being clinically inaccurate and unsafe. I learned later that there would have been issues with intellectual property and commercial sensitivity, as he had already conceived and begun this project. This situation identified how ownership complications are another possible barrier to effective collaboration within a healthcare environment.

3D-printed segment of a pelvis bone showing an example of a patients steep hip socket.



A drawing showing an overview of the hip socket defect and the surgical procedure.

reflections_

The initial set of meetings provided me with a number of design opportunities to work with, but the interactions also raised a number of potential obstacles to effective collaboration.

Almost all of the meetings were challenging to organise due to the busyness of those involved and the limited time they had available. I realised this was likely to be an ongoing concern, particularly under a co-design approach that advocates for participants to be engaged frequently over the course of a project. In order to counter these availability issues, I began scheduling interviews further in advance and communicating to participants my expectation for follow-up sessions.

Another challenge was determining how design opportunities were selected. Although the qualitative measurement system I developed helped to give a rough idea of an idea's potential, these measures of scope, design benefit and participation were largely based on assumption. In reality, one of the more promising design opportunities could end up entirely unfeasible further into development. This uncertainty placed pressure on my ability to develop a range of different design solutions. Given the scope constraints, I had to rethink my ability to do this.

The last consideration was the structuring of interactions. Verbal dialogue proved to be a limited form of communication for both parties. The roles of both designer and non-designer were still firmly in place. To collaborate more effectively and begin blurring these roles, the interactions needed to be facilitated as co-design workshops. This involved making better use of additional communication tools such as sketches, photos and 3D-printed objects. Despite setting out with a reasonably clear research direction, the focus of my inquiry shifted after the initial interviews. What began as a broad attempt to identify, develop and resolve a series of 3D-printed solutions with healthcare professionals, became a more focused exploration of 3D printing as a co-design tool and its agency in collaborative interactions (see Figure 05, page 53).

Key insights

- The busyness of healthcare professionals needed to be factored into future co-design interactions.
- A shared understanding helped participants to identify more suitable design opportunities.
- Not all of the opportunities considered 'suitable' would be successful as this potential was often based on undeveloped assumptions.
- Sketches, photos and 3D-printed artefacts may act as a complementary and effective form of communication.
- In order to properly facilitate collaboration, the dynamic of interactions needed to be facilitated more as co-design workshops.

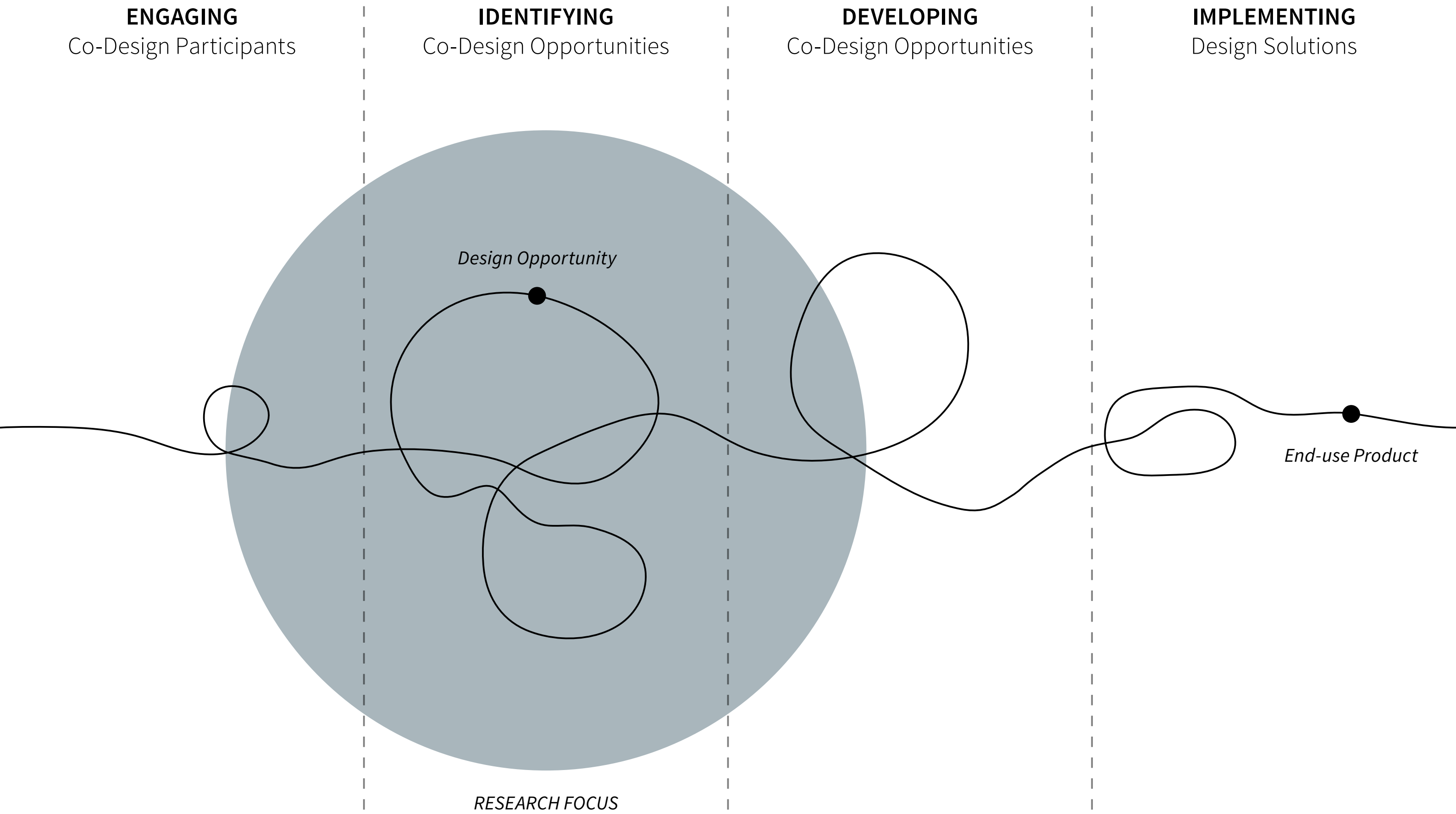


Figure 05. Shift in Research Focus – Josh Munn

finger splint_

Initial Problem

3D printing finger splints was suggested by plastic surgeon 1 based on his reservations around the accuracy and effectiveness of traditional splint-making techniques and the use of thermoplastics. These are plastics that become soft and manipulatable when heated (commonly done using hot water). Once heated the plastic is wrapped around the patient's finger to create the splint then left to cool. During the cooling process, however, there is often 'bounce-back', where the plastic distorts slightly due to the change in temperature. The splint therefore doesn't fit the patient accurately, which can affect recovery.

Initial Scope

The aim of this project was to improve the accuracy of finger splints using 3D printing, and explore whether there was an opportunity to create personalised splints based on patient data using associated digital technologies such as a 3D scanner.

Key Considerations

Different types of finger breakages exist, some far more complicated than others. It was important for me to consider whether I was going to create a solution that applied to a specific type of break, or a more versatile splint that applied to many.

Research Scope – High Feasibility

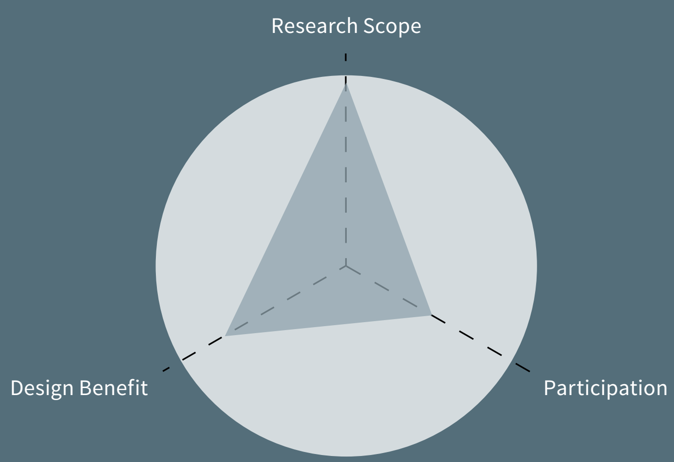
Cost: Low, due to scale and material
Time: Low, due to scale
Regulations: Low-risk
Scale: Small
Market Analysis: There are a few existing 3D-printed splint designs but none of them are personalised to the patient.

Projected Design Benefit – Fairly High

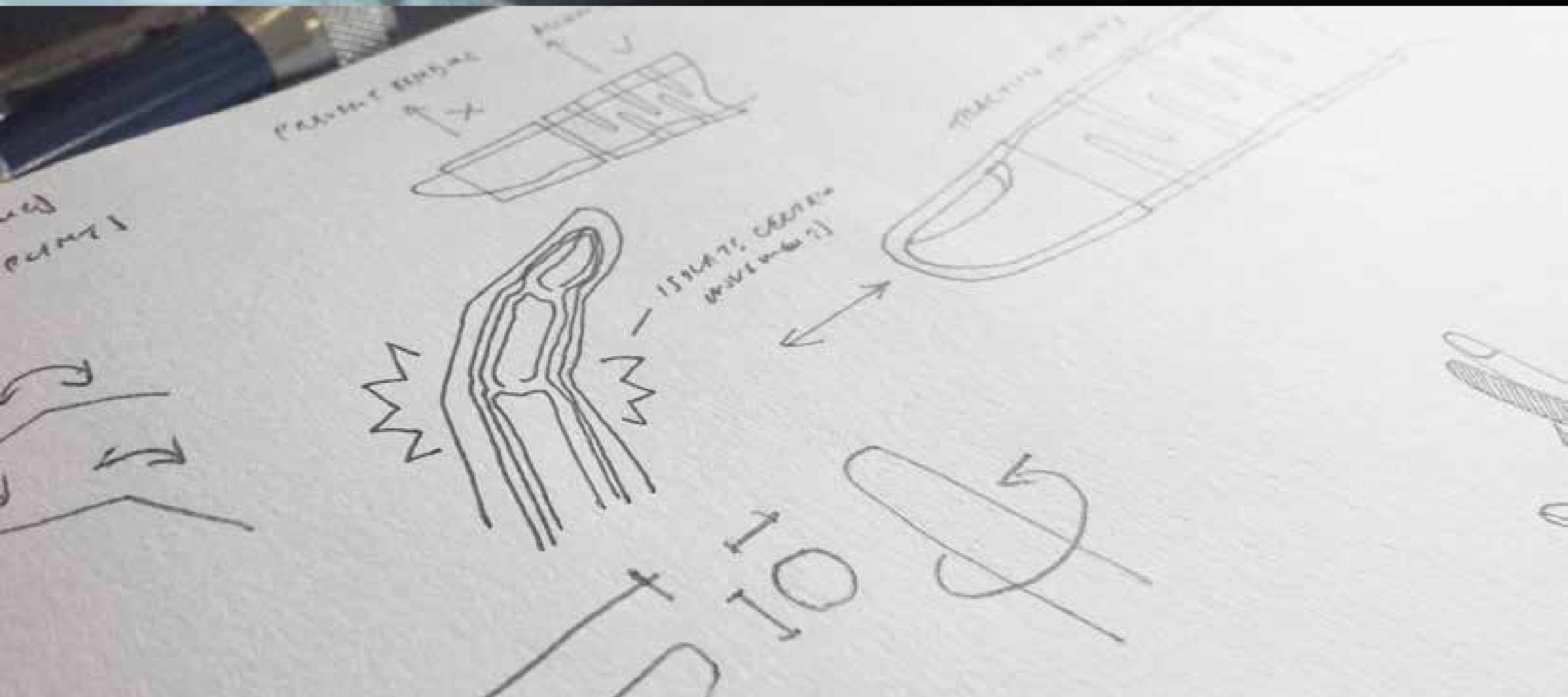
Applicability: High, due to common injury
Reduced Cost: Unsure
Reduced Time: Unsure
Improved Health: Yes, potentially
Low-Cost 3D Printing: Yes
Customised: Yes

Participation – Medium

Co-Design: Yes
Availability: Low
Level of Involvement: Medium



Broken Finger X-Ray – *Erickson, John. "Symptoms of a Broken Finger." http://www.johnericksonmd.com/news/symptoms-of-a-broken-finger/.*



Notes taking during second meeting with Plastic Surgeon 1, including a drawing highlighting the importance of focusing the splint's bending mechanism around the joints.

design process_

Co-Design Relationship

A broad problem was highlighted by plastic surgeon 1 relating to problems he had experienced with existing finger splints. He also expressed a wish that I had brought 3D-printed models to the initial interview.

Co-Design Practice

The co-design workshop was organised to be considerably less structured than the previous interview. Discussion was guided by objects rather and than a set of questions.

Probes increased the surgeon's level of excitement and participatory enthusiasm. He was noticeably more animated and verbal during the meeting. Later in the workshop he invited others to join the meeting as it was taking place (craniofacial surgeon 1 and hand specialists).

To test the concept of design 'probes', I began to create a wide range of 3D-printed objects that focused on technological capability and specific functional qualities such as flexion and customisation. For instance, using rubber created tension and a 3D scan was used to create a splint tailored specifically to my finger. In accordance with Madden and his research team's (2014, 14-15) interpretation of design probes, these objects were created with the aim to share knowledge and bring to light any assumptions.

Plastic surgeon 1 confirmed my assumption that restricting certain movements would help a large number of trauma patients, but the area of isolation needed to be a lot more concentrated. The assumption that customised splints would prove more effective was deemed "a bit far-fetched" as "most often the splints need to be ready within 24 to 48 hours". The hand specialists also emphasised the often acute nature of plastic surgery. There was also the cost and time of the scans to consider (CT scan or portable 3D scanner). As an alternative plastic surgeon 1 suggested using key measurements.

Splints were created that isolated more concentrated areas of the finger (e.g. upper-joint or lower-joint). I also explored the use of parametric CAD principles – digital files structured so that the overall geometry of a design is defined by a small number of adjustable dimensions (Camba et al. 2016, 18-19). Designs can be altered and reused simply by editing the values of certain interdependent parameters. The digital CAD file was modeled using a set of five key measurements – the heights and widths of the top and bottom parts of the finger and its overall length.

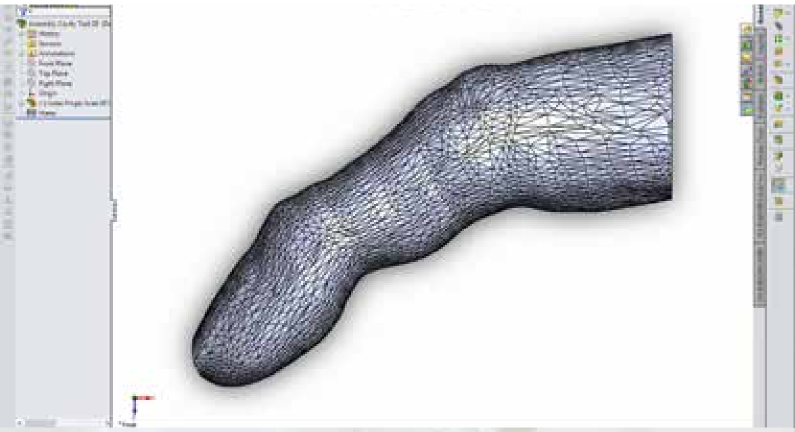
Previous experience with 3D printing had given craniofacial surgeon 1 a much better understanding of 3D printing and its capabilities. His suggestions for potential 3D printed design opportunities were more suitable than many other participants, and included an ear splint for neonatals born with ear defects and a mouth piece for neonatals born with cleft lips.

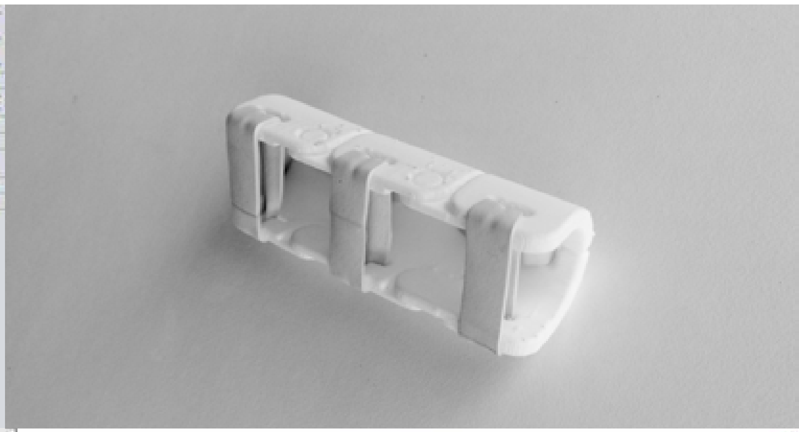
The idea that technological exposure increased technological knowledge led to an increased number of probes being introduced earlier in subsequent co-design workshops.

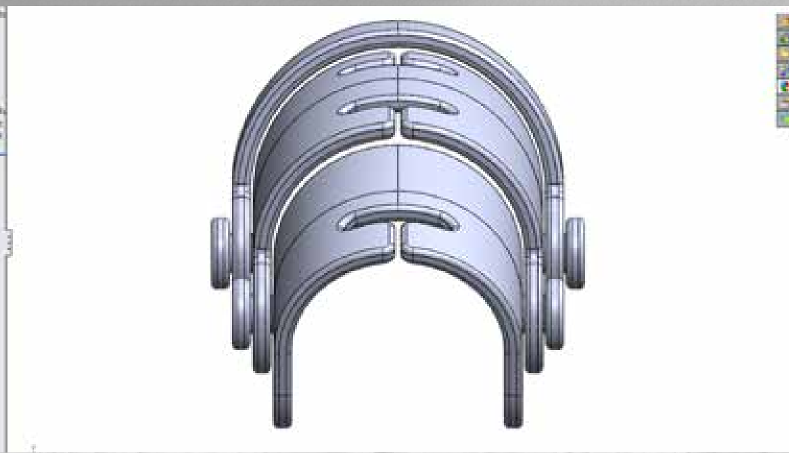
Due to the high cost of craniofacial surgeon 1's prior 3D printing project, he understood all additive manufacturing to be expensive. Whenever these "unrealistic" costs were mentioned, the level of participant interest and excitement decreased.

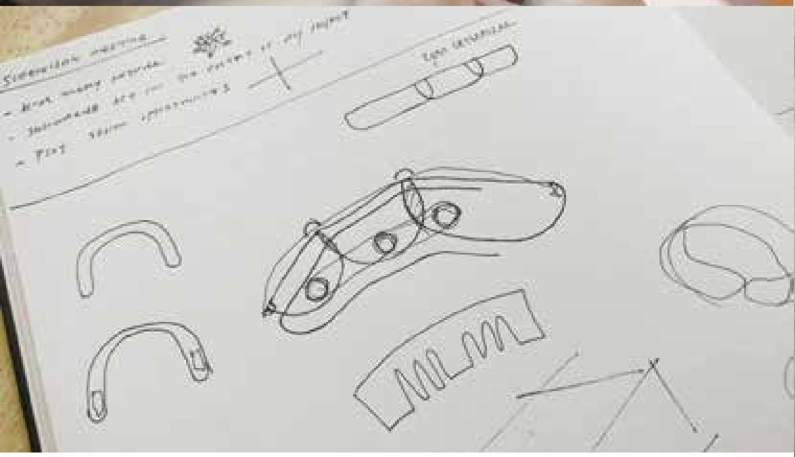
I made a note to discuss and clarify misconceptions of 3D printing-related costs in subsequent co-design workshops.

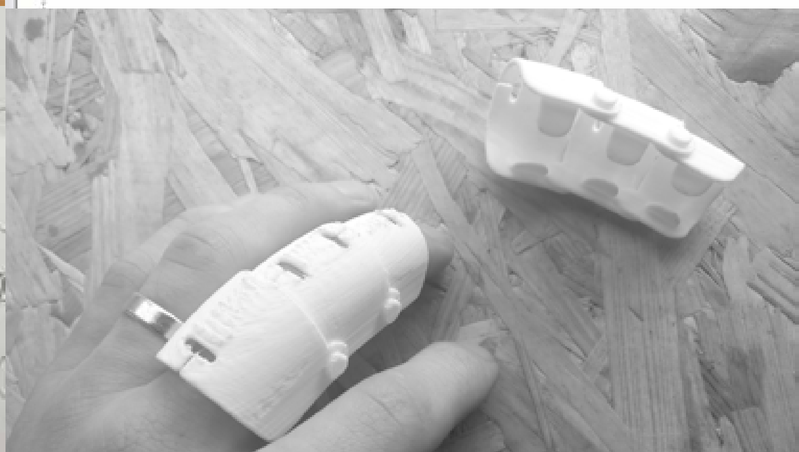
The first splint probes were designed using a 3D scan of my finger. However, following the surgeon's feedback, these quickly developed into simpler parametric-based designs. Flexion splints were created using 3D printing and rubber bands. This tension helped ensure patients' fingers would always spring back to an upright position during recovery.

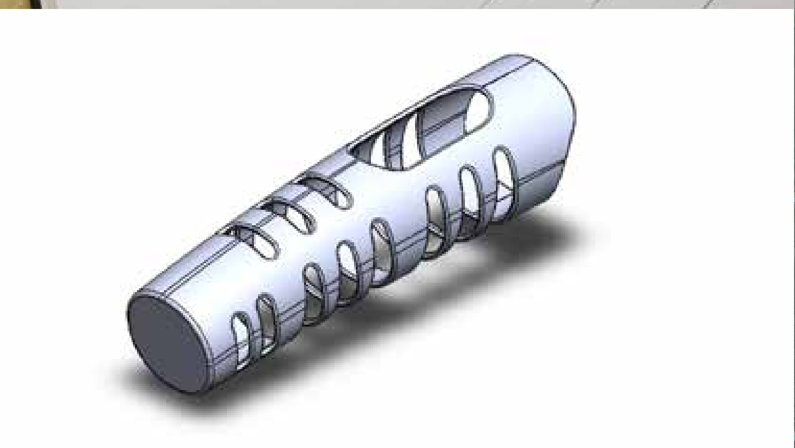












Instead of relying on rubber bands, I began to create flexion using the print itself. This started as hinge joints, but later developed into a slotted design. Although the slotted design was promising, according to plastic surgeon 1, it needed to be strengthened.

Co-Design Relationship

The introduction of probes helped plastic surgeon 1 develop a better understanding of both 3D printing and design. When explaining to the hand specialists how he understood the aims of my research, he told them: "Don't limit yourselves by trying to come up with a perfect solution or thinking about what is done currently. You come up with the problem and Josh will use his understanding to explore whether 3D printing can help solve that problem."

In the workshop with hand specialist consultant 1, he also became more excited when probes were introduced during meeting.

Similar to plastic surgeon 1, the hand specialist consultant invited his colleagues to join the workshop. Both the surgeon and his colleagues initially had a very limited understanding of 3D printing and a skewed perception of cost.

The hand specialists raised a number of issues around the use of thermoplastics in casts for burn injuries to larger parts of the body including the arm or neck. I explained that although 3D printing would have increased accuracy, large-scale 3D printing would take longer and cost more. Once again, discussing ideas that were likely to be too expensive within a hospital budget lowered the level of excitement and engagement.

Both the surgeon and the hand specialists advised that the splints needed to be stronger and more comfortable.

Co-Design Practice

The idea that probes helped to develop a level of shared understanding between the healthcare professionals and myself also led to an increased number of probes being introduced earlier in subsequent co-design workshops.

A workshop with hand specialist 1 was arranged based on plastic surgeon 1's referral, with the aim of exploring further design opportunities and receive feedback on the finger splint design. Due to their evident success, probes were used again in the workshop with hand specialist 1.

Excitement created by probes not only led to a shared understanding between myself and participants, they showed potential for participants to share amongst themselves. I made a note to try and give participants a 3D-printed probe to keep in the hope they might refer me to another potential co-design participant.

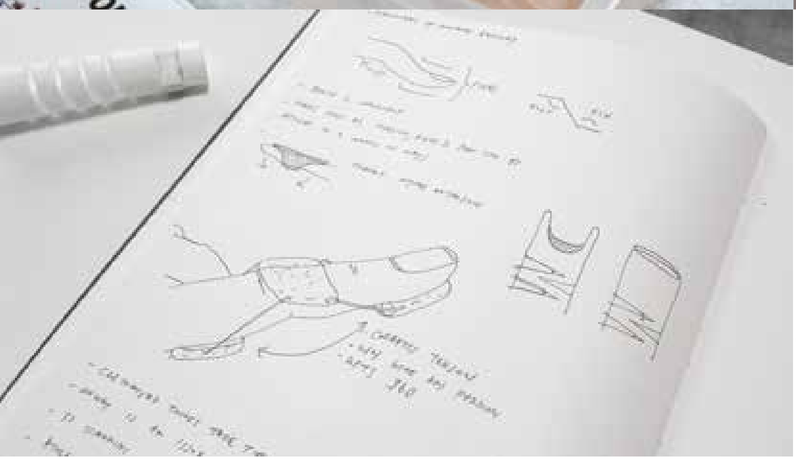
Feasibility was a concern for healthcare professionals. In subsequent workshops, when possible, I tried to focus on smaller, low-cost design opportunities, while explaining why.

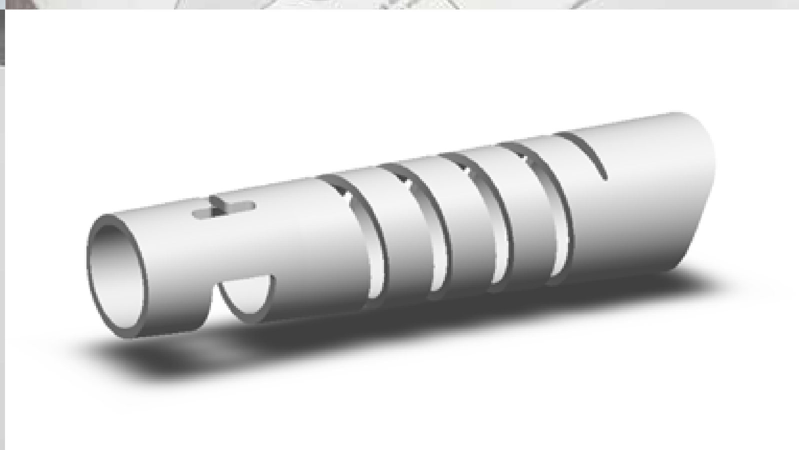
Strength and comfort were improved by experimenting with a '3D slicer' – the computer software used to convert the digital model into a series of two-dimensional slices in preparation for 3D printing. Splints printed horizontally proved to be considerably stronger and required less support material, producing a smoother overall finish and thus a more comfortable fit. Silicon coating was also explored to improve comfort, but did not prove effective enough to justify the added cost and time.

Examples of 3D-printed objects or 'probes' taken to meetings, to illustrate some of the advantages of 3D printing.

Slotted splint design demonstrating flexion and craniofacial surgeon 1 showing a 3D-printed jig for jaw reconstruction surgery that was used for a patient he treated.

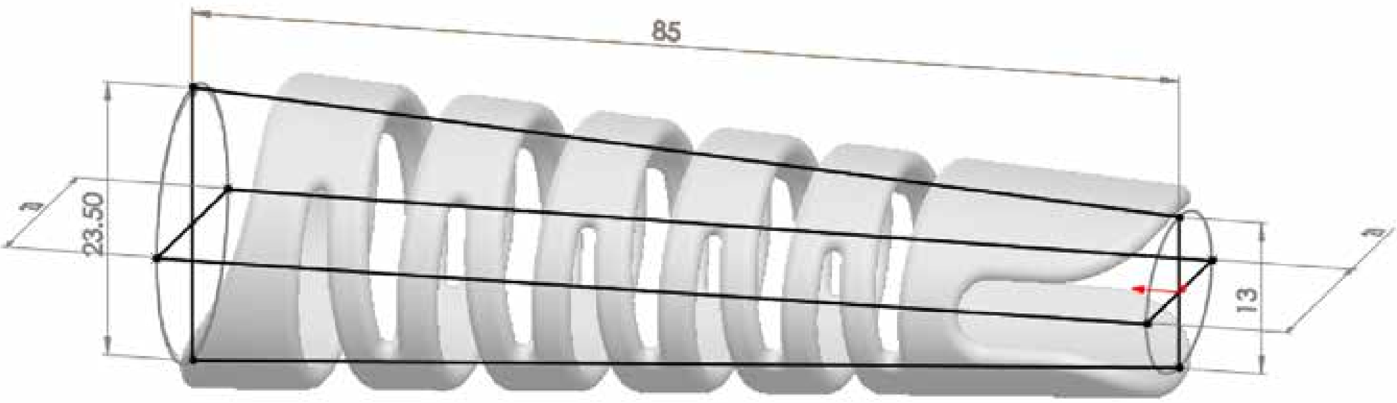
Following a suggestion from plastic surgeon 1, I arranged a co-design workshop at a local hand clinic. I was shown a number of samples to help develop my understanding of existing splinting techniques. These samples included a wide range of pre-made and custom items, as well as guidebooks on how to make them.

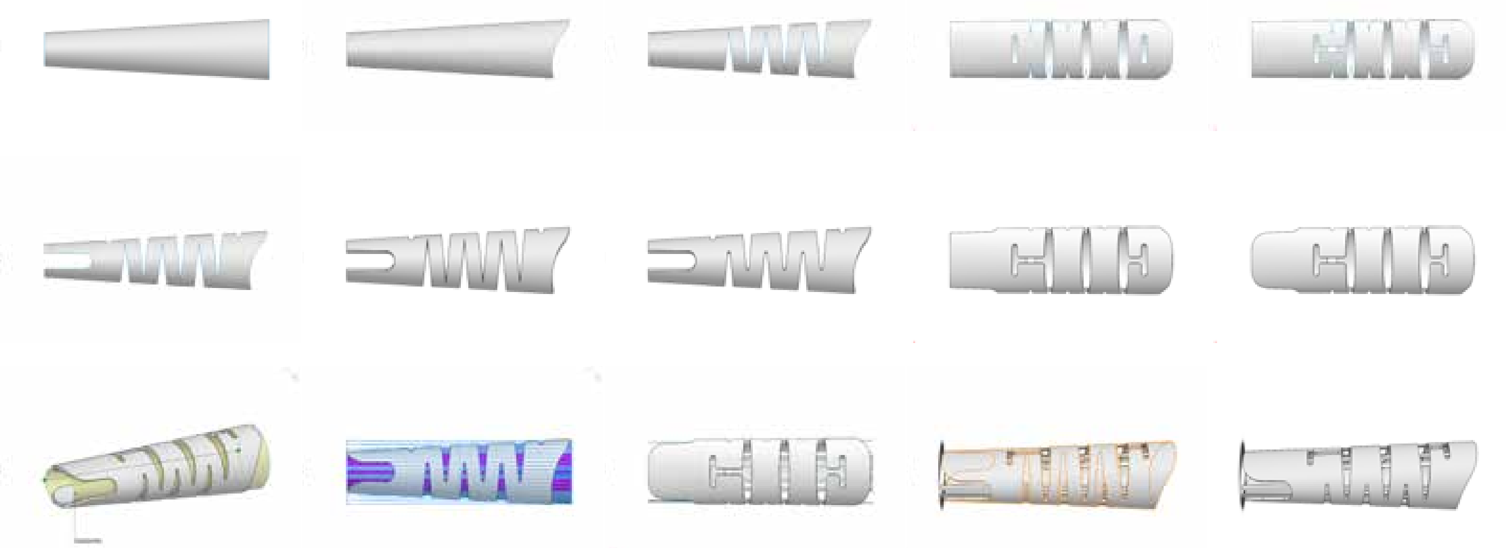




Visiting the clinic also gave me an idea for a 'mallet' splint design, where the top of the finger is pulled upwards during recovery. However, 3D-printed material proved to be too weak for this type of splint.

A number of experiments were done with silicon coating to improve comfort, and a perforated splint design was created to reduce weight.





A screenshot showing the splint's parametric-based design and a series of photos demonstrating the finger splint CAD creation process.

reflections_

The finger splints were found to be even more feasible than I originally foreseen. I was able to develop designs quickly and efficiently on a small desktop 3D printer due to the small size of the splints. This efficiency also allowed me to generate and trial probes early in the design process to help facilitate co-design sessions with those involved.

From my initial set of interviews and co-design workshops I learnt the way in which I engaged participants for the first time was more crucial than I had first anticipated. Without at least a basic understanding of 3D printing and each other's expertise, participants found it difficult to identify suitable design opportunities. It seemed that working towards a common goal required a common understanding. During the earlier phases of the project I had assumed this common understanding could be achieved verbally. Although discussion had worked to an extent, oral dialogue proved to be inadequate as a communication tool for key aspects of 3D-printed design. Only once I began experimenting with probes did I recognise the power of giving 'form' to information, especially when trying to cover a wide range of systemic elements within a short space of time. 3D printing enabled me to produce highly resolved one-off designs quickly and efficiently

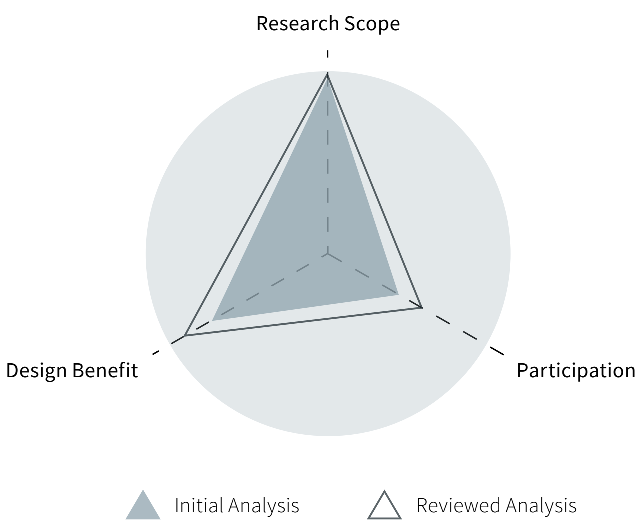
Discovering the need for the use of probes early in the design process also highlighted an important evolution in my research. I realised the focus of my investigation had become less about resolving design solutions, and much more about developing effective strategies for using 3D printing within collaborative interactions. This was not to say the physical 3D-printed outputs were no longer important, but rather that their success was more dependent on the co-design partnership than I had realised. As Storni (2014, 149-150) states in his text on ANT, the underlying purpose of probes is much more about their "social impact" than it is a resolved design. Early in co-design partnerships, when the interaction is more about bringing participants up to speed with research and creating a shared understanding, this social impact is arguably more important. The interactions I observed with participants and 3D-printed objects spoke more and provided greater insight than the interactions between participants and myself.

Reducing the complexity of the customisation process also increased the likelihood of someone unfamiliar with computer-aided design being able to make the necessary changes for each patient. As Lee argues, in order for true collaboration to exist, participants need to be treated as "active", and given the opportunity to be involved in design-related tasks, such as three-dimensional model construction (2008, 39).

Although the 3D-printed finger splint design appeared to be fairly resolved, in order to accurately validate its safety and effectiveness, the design would need to be tested against existing splint designs with real trauma patients.

Key Insights

- Small 3D-printed designs made it efficient to print and iterate designs during development.
- 3D-printed probes help to communicate assumptions and technological capability more effectively than verbal discussion.
- Small 3D-printed objects also make it easier to create models earlier on in the co-design process.
- Probes embody a wide range of information that conveys itself in a short space of time.
- Parametric CAD design may be a way to facilitate further participatory involvement.



3D-printed splints tailored specifically to the size of each finger using the same template.

3D splints demonstrating different concentrated areas of isolation and rubber coating versus raw printed material.

radiation face mask_

Initial Problem

Face masks used during radiation treatment are currently produced using thermoplastics – a material that becomes highly malleable when heated. Each mask is placed in hot water, moulded over the patient and left to set for up to 25 minutes. For a number of patients this process makes them feel highly uncomfortable, some refusing to take part altogether. 3D printing was proposed as an alternative method of manufacturing.

Initial Scope

The purpose of using 3D printing was to avoid the discomfort caused by thermoplastics and potentially improve the accuracy of the masks. The scope involved a full-scale 3D-printed mask at a resolution sufficient enough for proof-of-concept. The print would have to undergo radiation testing, but this would not require a patient.

Key Considerations

PLA, the material commonly used in desktop 3D printers, may not have withstood radiation over an extended period of time. This would need to be tested if the project was developed further.

Research Scope – Low Feasibility

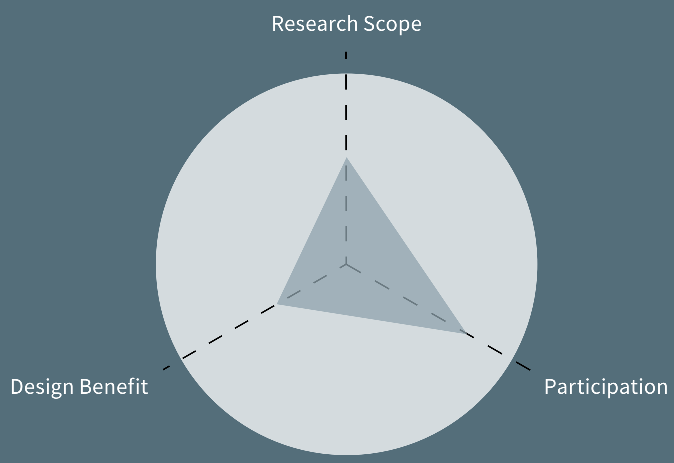
Cost: High, due to scale and material
Time: High, due to scale
Regulations: Medium to low-risk
Scale: Large
Market Analysis: 3D-printed face masks for radiation treatment are already being used in other hospitals around the world.

Projected Design Benefit – Fairly Low

Applicability: Fairly high, due to number of cancer patients treated each year around the head and neck areas.
Reduced Cost: No
Reduced Time: No
Improved Health: Unlikely
Low-Cost 3D Printing: No
Customised: Yes

Participation – Medium

Co-Design: Yes
Availability: Medium
Level of Involvement: Medium



Thermoplastic face mask for keeping patients in a fixed position during head and neck radiation treatment.

design process_

Co-Design Relationship

3D printing was suggested as a alternative way to manufacture radiation masks by clinical engineering. Due to the curing process of thermoplastics, patients experienced significant discomfort.

Co-Design Practice

Due to the large scale of the masks, 3D printing them was considerably more expensive and time consuming. Existing thermoplastic could be formed in a matter of minutes, without the need for additional 3D scans or computer-aided design.

To begin with, the physicist confirmed he too thought 3D printing was a suitable alternative. However, his initial assessment shifted as I began explaining my reservations around the cost and time taken for large-scale 3D prints.

To resolve potential issues of cost and time, a workshop was organised with the oncology physicist. The aim was to discuss the suitability of 3D printing the masks and to get a better understanding of the issue patients were experiencing. One of the existing masks and a concept sketch was used to help facilitate the session.

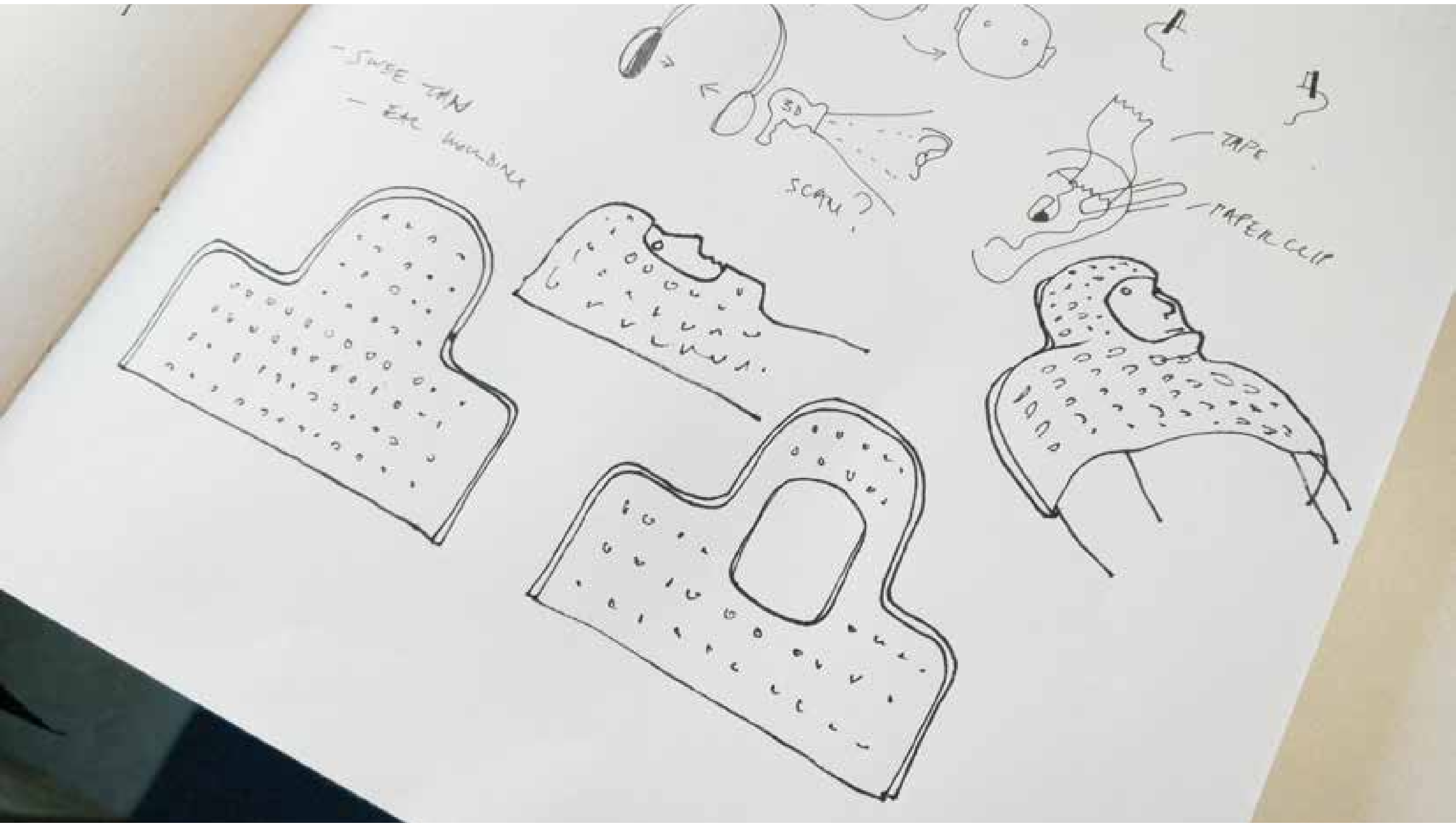
From the drawing the physicist realised that 3D printing the masks failed to address the issue of discomfort during treatment. Patients who described feeling "trapped" during the curing process were likely to feel similar discomforts while wearing the masks during treatment. The root of the problem was not the method of manufacturing, but rather the design itself.

As 3D printing did not solve the issues of discomfort, the masks were not developed any further.

Because the clinical engineers and mould technician were not involved in radiation treatment directly, their understanding of the masks and the experiences of patients was limited.

In preparation for subsequent co-design opportunities, when possible, I endeavoured to engage only those directly involved with the clinical problem.

Sketches showing the existing thermoplastic mask templates and concepts for how the design could be improved.



reflections_

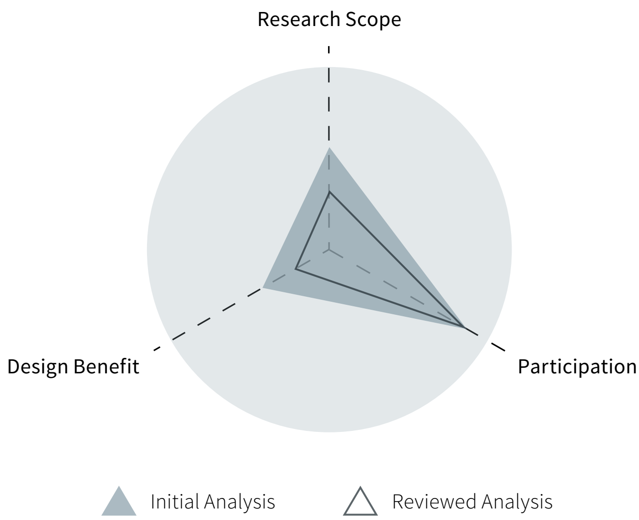
Although the mask project was discontinued, there were still a number of interesting observations. For example, the engineers may have been too far removed from the clinical practice and the chosen technology to be suggesting 3D printing as a suitable alternative. They were aware of the problem but had not fully understood it in the context of the treatment process. The physicist was also doubtful of whether they were familiar with the issues being experienced by patients and staff first-hand, commenting that "they probably just saw something 3D printed that looked similar and decided that it might work for the masks too". This remark was significant because the physicist was recognising the importance of having an accurate, common understanding. Design researcher Antonio Raciti terms the idea of sharing information as "collective knowledge", a concept he believes is crucial throughout the participatory design process (2016, 14-15). In his research, Raciti describes how decisions became isolated without transparency of information and effective communication. Uninformed decisions also fail to maximise the knowledge and expertise of those involved.

I also learned that one of the physicists working in Radiology had been a part of a research team that had already explored 3D printing as an alternative means of producing the masks. They too had come to the conclusion that the benefits weren't enough to justify the added time and cost. Those who had initiated the new mask project, however, were unaware of this previous work. If this knowledge had been shared the faculty may have been able to identify a more appropriate design solution sooner, again reiterating the importance of transparency and effective communication.

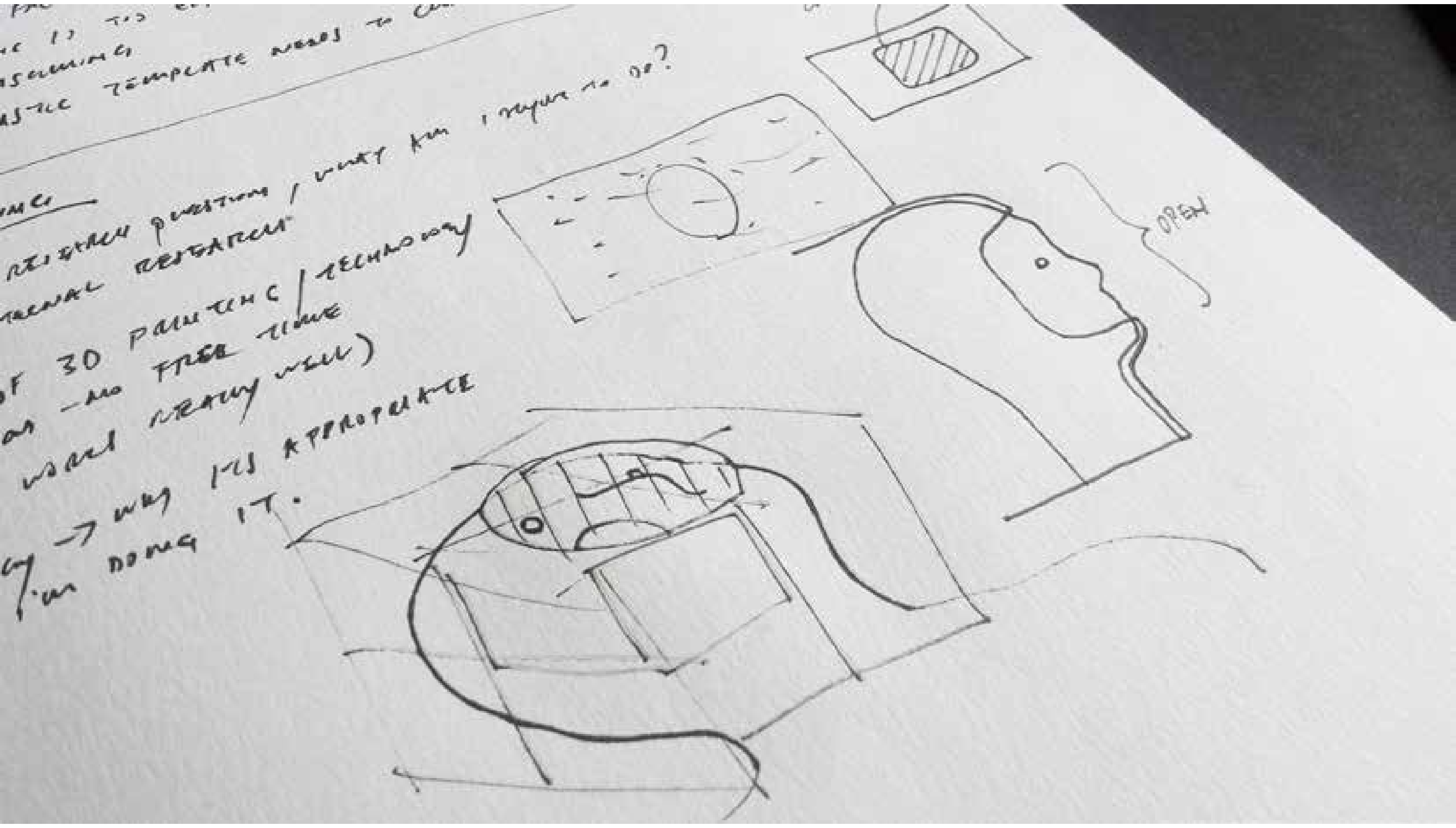
Interestingly, the concept resurfaced again much later in the research via an engineering student who was also attempting to 3D print the masks as part of her postgraduate research. As with me, the idea had been proposed to her by a healthcare professional markedly far removed from the clinical environment in which the masks were being used. What appeared to be yet another assumptive decision suggested it may have been more effective to collaborate with only those closest to the design problem.

Key Insights

- Technologies like 3D printing need to be fully understood before electing them as a design solutions.
- The cause of the problem needs to be fully understood before proposing a design solution.
- When engaging suitable participants as part of co-design, those working closest to the identified problem are likely to have the most accurate understanding.
- In order to maximise the expertise of those involved in co-design, transparency and communication are crucial (collective knowledge).



Notes taken during the meeting with the physicist who had already been part of a research team that explored 3D printing the masks. The sketches below represent my suggested changes to the existing mask designs. Instead of using 3D printing to create the masks, a small hole in the existing thermoplastic masks may have helped to solve patients' issues of discomfort.



head & neck cradle_

Initial Problem

Radiation head and neck cradles are used to keep patients' heads still during radiation treatment. In order to maintain an accurate dose of radiation the patient needs to be fixed in the same position for each treatment. However, the vacuum forming process used to create the cradles produced varied results, therefore making it difficult to provide accurate treatment. Some of the clinical engineers thought 3D printing might act as a more precise form of manufacturing.

Initial Scope

The purpose of using 3D printing was to eliminate inaccuracies that occurred with vacuum forming and manual drilling. This required a full-scale head and neck cradle to be 3D printed at a resolution sufficient enough for proof-of-concept. The print may have to undergo radiation testing, but this would not require or involve a patient.

Key Considerations

PLA, the material commonly used in desktop 3D printers, may not have withstood radiation over an extended period of time. This would need to be tested if the project was developed further.

Research Scope – High Feasibility

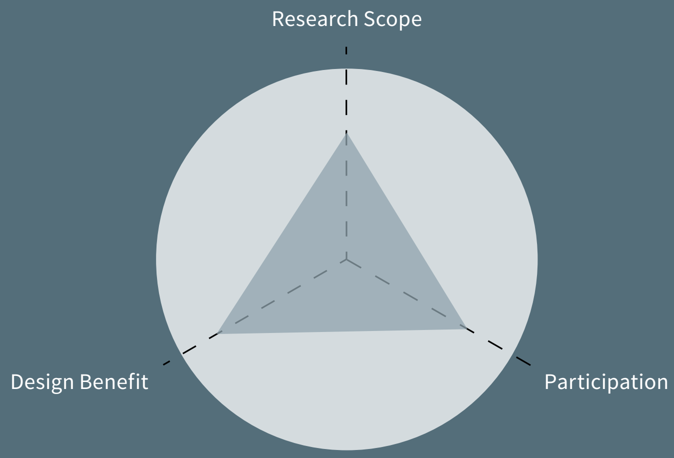
Cost: Fairly low, due to scale and material
Time: Fairly low, due to scale
Regulations: Medium to low-risk
Scale: Medium
Market Analysis: 3D-printed head and neck cradles for radiation treatment do not exist as a standalone product as far as I'm aware.

Projected Design Benefit – Fairly High

Applicability: Fairly high, due to the number of cancer patients treated each year around the head and neck areas.
Reduced Cost: Unsure
Reduced Time: Unsure
Improved Health: Yes
Low-Cost 3D Printing: Yes
Customised: Yes

Participation – Medium

Co-Design: Yes
Availability: Medium
Level of Involvement: Medium



A photo of the moulds used for the existing head and neck cradles, in 3 different sizes.

A photo of an early 3D-printed head and neck cradle probe (left) next to an existing vacuum formed cradle (right).

design process_

Co-Design Relationship

The oncology team leader had a much more accurate understanding of radiation treatment and the issues being experienced with the existing cradles than the clinical engineers.

In response to the 3D-printed cradle, the team leader demonstrated a very limited understanding of 3D printing. She was also distracted by the bright orange colour, which she felt would deteriorate, and the absence of a perforated base for adjustability. She was unaware that the base was intentionally left out to fit the design onto a smaller low-end 3D printer, or that the colour of the filament could easily be changed.

Even after explaining the concept of 'probes' and admitting that the model was largely based on assumption, she still seemed distracted.

Initially the team leader had no intention of changing the design. 3D printing was only suggested as a an alternative form of manufacturing in order to increase the level of accuracy. After being shown a range of design probes, she realised that there were a number of other potential design improvements, such as comfort and size reduction.

In discussing the potential for improved comfort, the team leader suggested a number of form adjustments, including increasing the depth of cut-out for the head, increasing the width of the cut-out for the neck and softening the area around the neck.

Co-Design Practice

A workshop was organised with the team leader of oncology to discuss a potential opportunity around radiation head and neck cradles. In contrast with the clinical engineers, she was directly involved with radiation treatment on a regular basis.

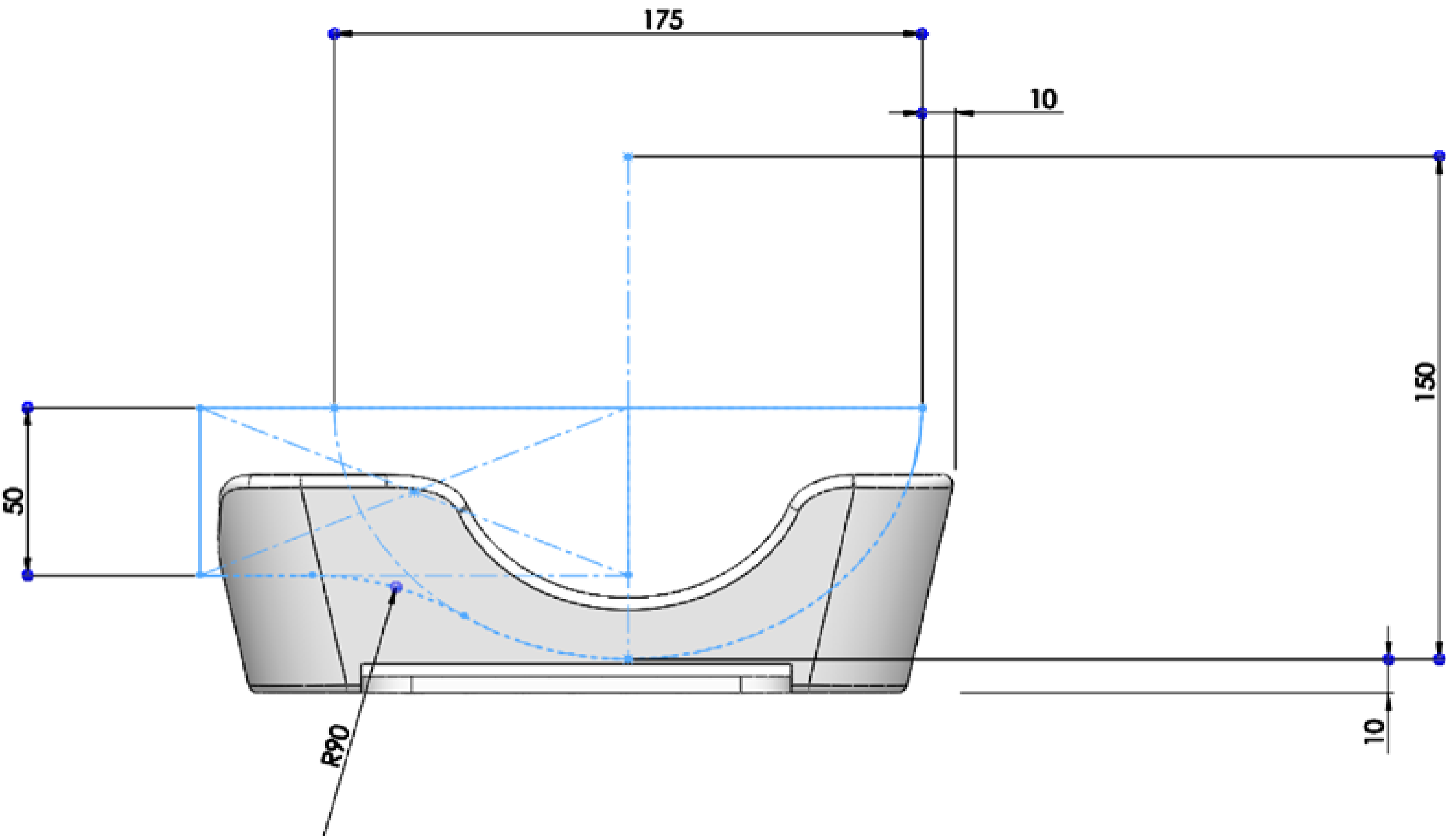
In preparation for the workshop with the team leader I produced a 3D-printed cradle almost identical to the existing design. Again, the main purpose of the this model was to act as a design probe, rather than a design solution.

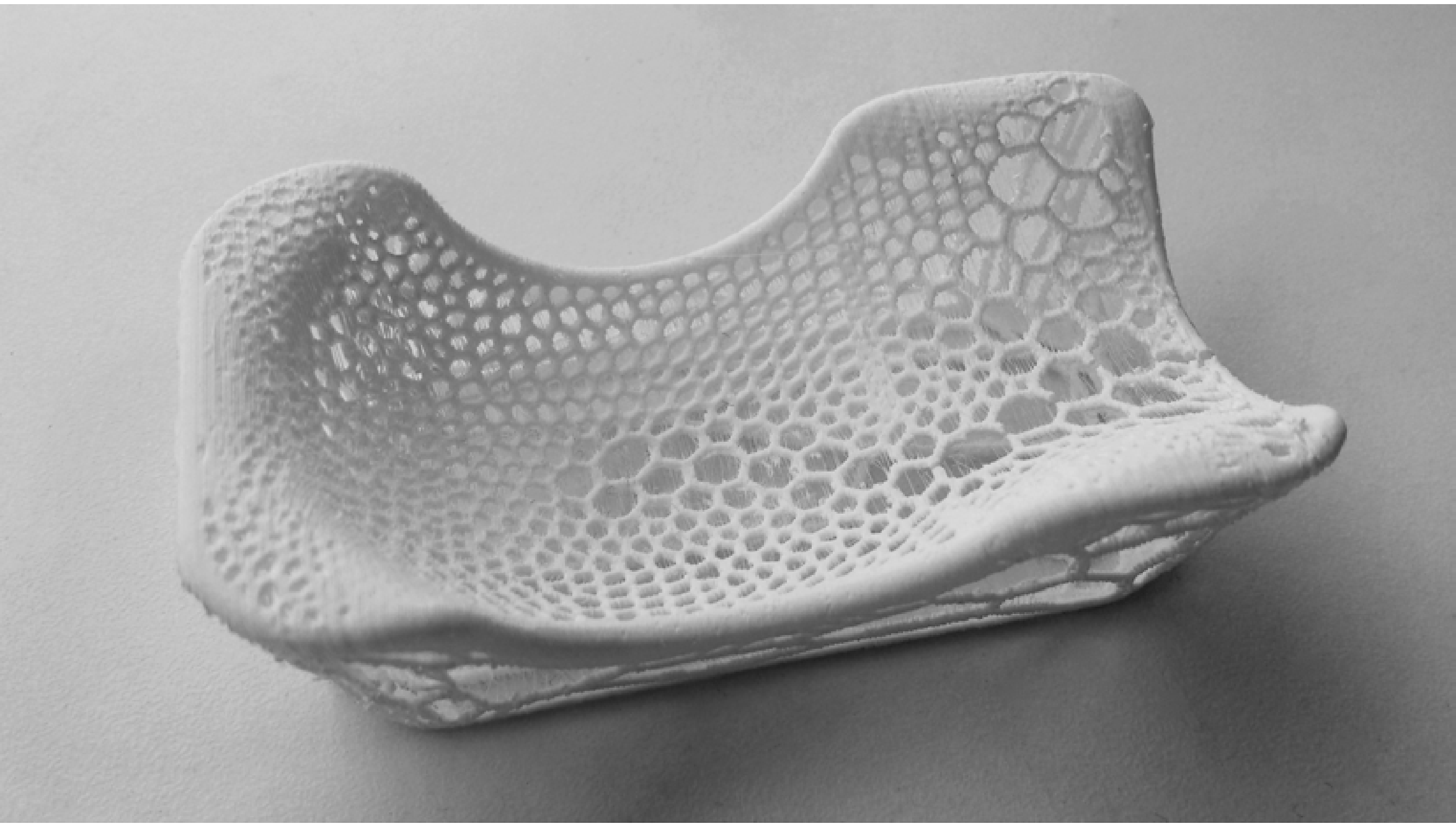
Although the details of the probe seemed minor to me, I made a note to err on the side of caution in future meetings. Choosing a more neutral colour and scaling the model down to print a complete unit may have allowed the session to be more productive.

In conjunction with the cradle, other 3D-printed artefacts were used to demonstrate 3D printing capability and design benefit.

Comfort was improved by creating subsequent cradles using a parametric-based design. This type of design allowed digital models to be easily adjusted according to the patient using a small number of key measurements. The comfort of each cradle was tested using roleplay – resting my own head on the cradle for five and ten minutes in order to pinpoint areas of discomfort.

Screenshot showing the parametric-based design used to customise the second iteration of head and neck cradles.





One of the cradles was created using the 'Voronoi' patterning formula to reduce material and produce a lighter structure. However, due to the fragility and complexity of the structure, this design was too weak and the print time was considerably longer.

Co-Design Relationship

Co-Design Practice

In preparation for the second workshop with the oncology team leader, cradles were modeled using a 'Voronoi' pattern, a mathematical formula used to generate organic structures from 3D models through software such as MeshMixer (autodesk.com 2016). The patterned structure used less material and greater breathability.

Although the patterning created an interesting aesthetic, none of these improvements, however, could justify the added complexity. The intricate design meant the print took considerably longer and produced a finished structure that was both lower-quality and weaker than previous models.

Separating the cradle design from the base was also explored in order to reduce the overall print time and improve clinicians' ability to replace broken or worn units.

The team leader felt that separating the unit created unnecessary complexity by increasing the difficulty and time taken to assemble each cradle. A potentially more sustainable solution also didn't justify the risk of staff assembling the parts incorrectly.

The clinicians' reaction to the model suggested there may be a point in a design's development where propositions for design improvements become disadvantageous.

Although probes proved effective at early divergent phases of the design process, they may not have been effective in helping to further define and converge on a single design solution (see Figure 06, page 74).

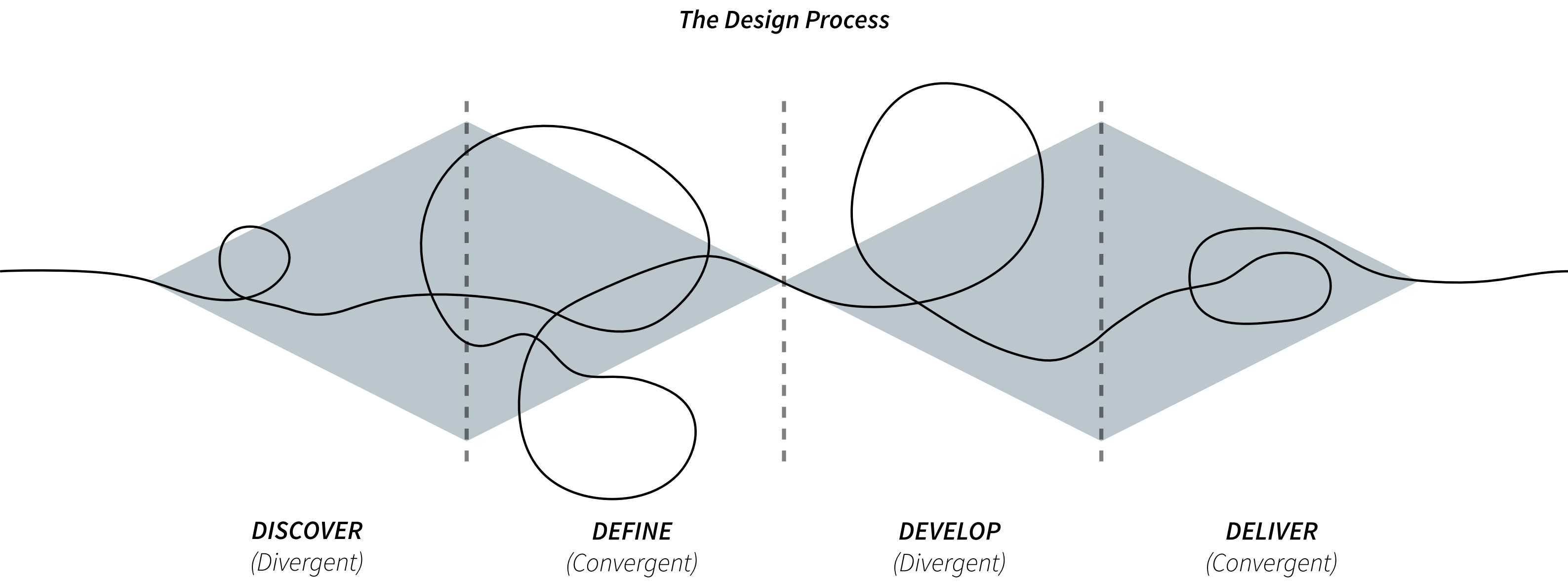
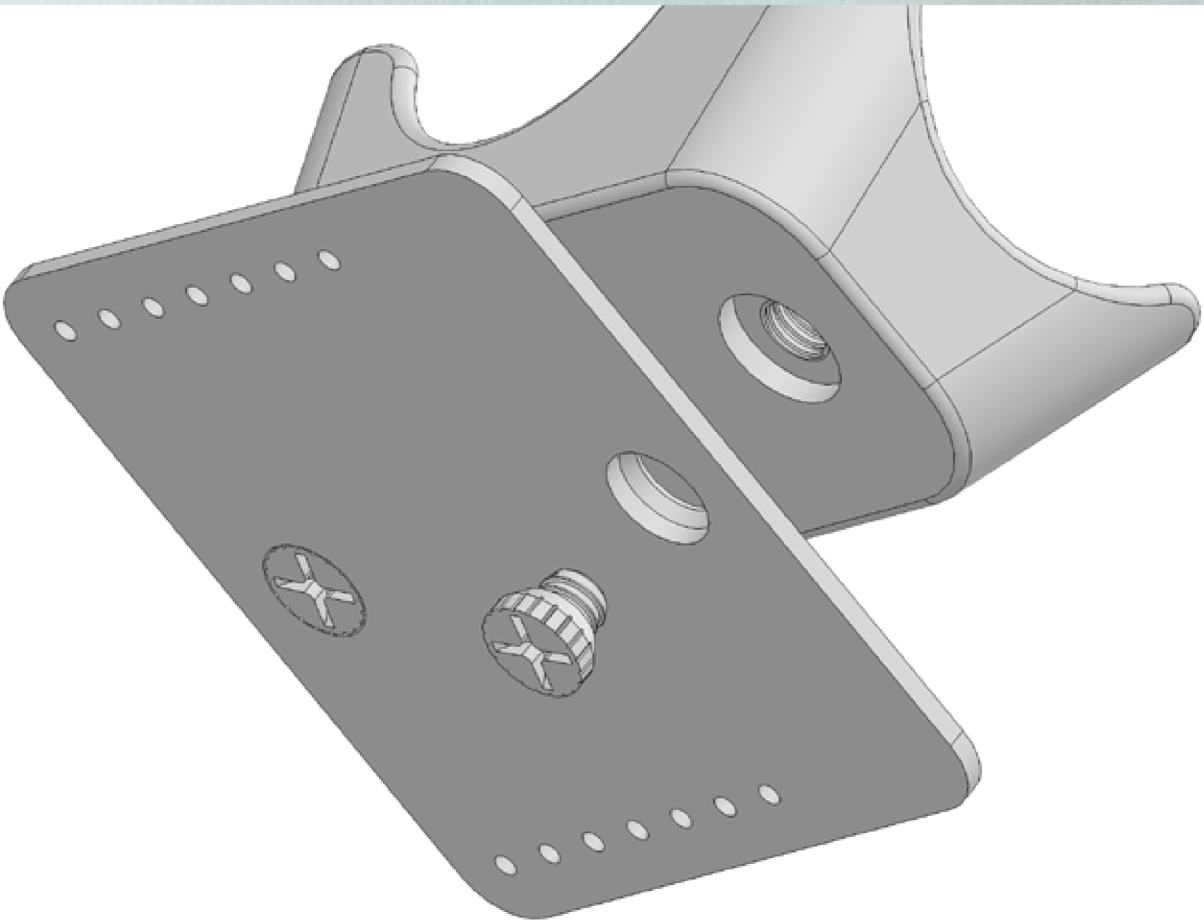


Figure 06. Double Diamond Design Process Model – UK Design Council 2005.

Test prints of the fastenings used to secure the base of the cradles to the cradle itself. Although these fastenings enabled the cradles to be replaced at a lower cost, they also increased the complexity of the assembly process. As such, this concept was not progressed.



CAD model demonstrating the idea of separating the base from the cradle using 3D-printed fastenings.

reflections_

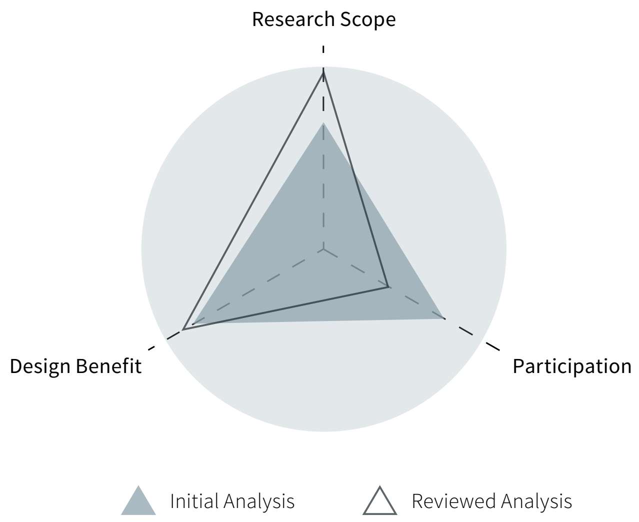
Despite having very restricted opportunities to meet with the radiologist, our time was productive and overall, the head and neck cradle ended up being a far more promising opportunity than I had first anticipated. The most notable reflection from the cradle project was the radiologist's surprisingly positive reaction to design probes and the proposition for further design improvements. Attributes such as comfort and customisation weren't requested in the initial scope of the brief. However, by exposing her to more radical design solutions, she was able to begin thinking beyond her existing mindset.

Still, the question had to be asked: "why didn't this expansion of scope occur to begin with? Deborah Dougherty, in her text '*Interpretive Barriers to Successful Product Innovation*', describes this difficulty as the challenge of escaping one's own "thought world" (1992, 182). These worlds represent the products, processes and systems that are used, discussed and reflected upon within an individual's working environment. Dougherty explains how people often find it "difficult to relate" to things that exist or operate outside of their own thought worlds.

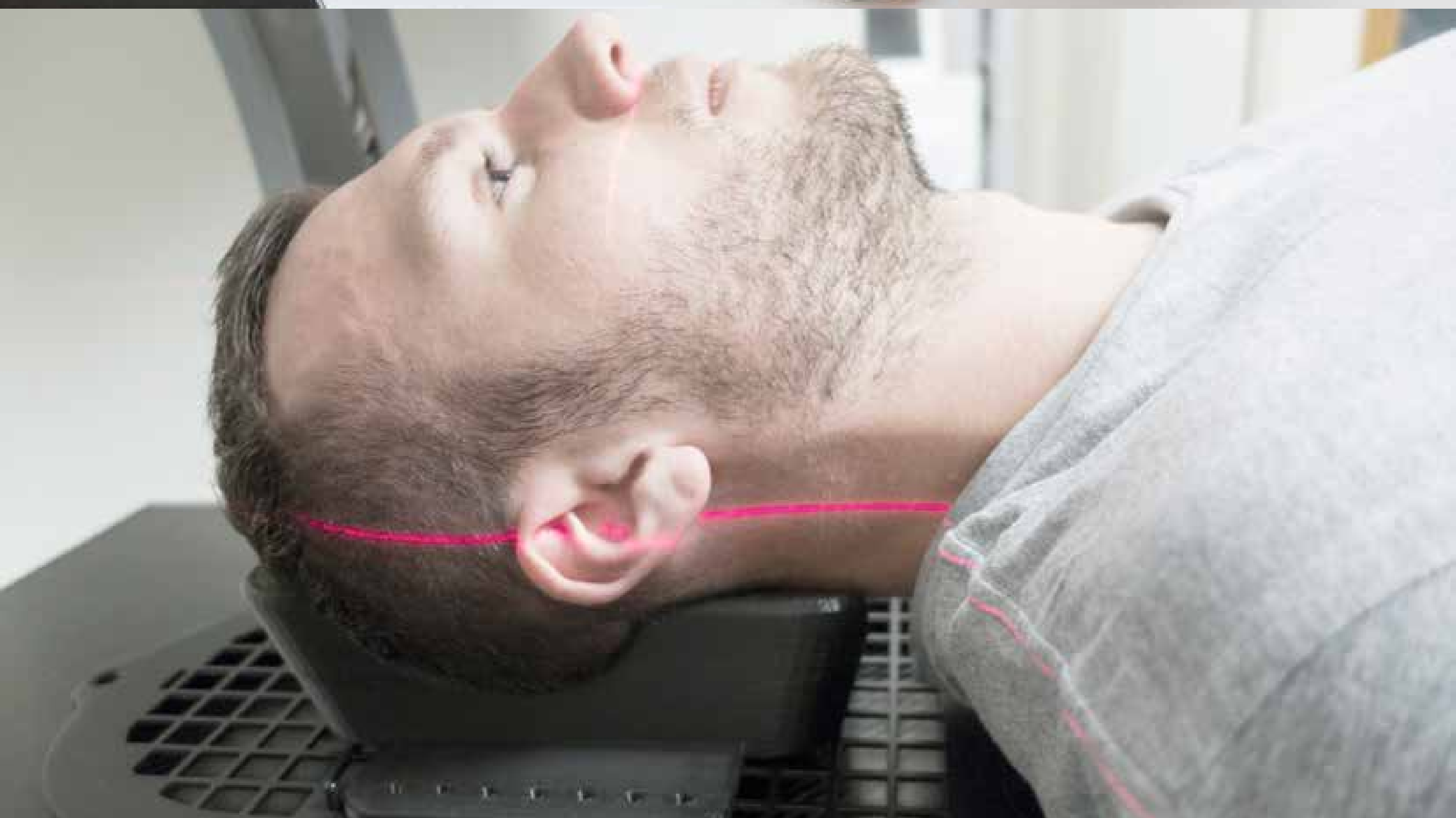
The text goes on to discuss how innovation can only occur when thought worlds are "linked" (Dougherty 1992, 191-192). Dougherty's method of linking involves individuals acting as the facilitator between worlds. These people act as the common language that allows each world to develop a shared understanding. In the context of my research, I was acting as the facilitator, linking non-designers with design and 3D printing technology. It could be argued that the most ideal form of this linking would be a person who was deeply embedded in the thought worlds of both design and health. Yet, in reality this ideal most likely doesn't exist. The knowledge and skills of a 'cross-world' individual are also likely to be less effective than those only concentrated in one – 'jack of all trades, master of none'. However, it's important to note that all of these 'links' are limited to human agents. In reflection of my research up to this point, the questions had to be asked of whether worlds could be bridged using non-human agents, such as design probes. Could the agency of objects act as the common language between thought worlds?

Key Insights

- Probes can be used to help identify design improvements for a specific opportunity.
- Exposing participants to more radical design solutions provokes thought beyond what they are used to, i.e. existing design solutions.
- The benefits of probes lend themselves to divergent phases of the design process.
- However, there comes a point when the design needs to converge on a single idea, for which probes may not be productive or an efficient use of co-design.
- Probes may act as a common language between thought worlds, helping to create a shared understanding.



3D-printed head and neck cradle prototype used for testing and validation.



A photo showing the final in-situ evaluation with the oncology team leader on the radiation treatment bed (me role-playing as patient). Although the cradle design appeared to function well, the hospital's infection control team needed to assess whether 3D-printed material was safe and cleanable before the cradles were implemented.

rando simulation arm_

Initial Problem
Initially the idea was to design and produce arms for Radiology's human simulation model (RANDO), using the mobile 3D scanner to scan my own arm and 3D printing the digital output.

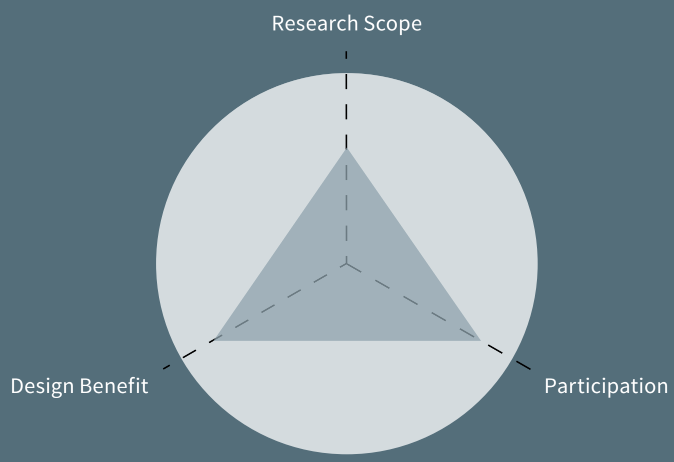
Initial Scope
In order to more accurately test and validate ongoing radiation treatment, the simulation model required arms. The structure of each arm needed to be modeled for the specific simulation model I was working on, and made from a material that attenuates radiation in a similar way to the human body, such as water. The intended construction process was almost identical to the 3D-printed total body irradiation blocks (see page 140).

Key Considerations
The model was too large to be easily made on a small 3D printer, therefore potentially requiring a larger, more expensive type of 3D printing. Access to these types of 3D printers needed to be organised and booked in advance.

Research Scope – Medium Feasibility
Cost: Fairly high, due to scale and material
Time: Fairly high, due to scale
Regulations: Low-risk
Scale: Large
Market Analysis: Complete simulation models exist but they are incredibly expensive. Printing arms for the model at hand was potentially more cost effective.

Projected Design Benefit – Fairly High
Applicability: Fairly high, due to the number of cancer patients treated each year and the number of simulations required for these treatments.
Reduced Cost: Yes
Reduced Time: Not applicable
Improved Health: Potentially, yes
Low-Cost 3D Printing: No
Customised: Yes

Participation – Medium
Co-Design: Yes
Availability: High
Level of Involvement: Medium



RANDO simulation models for radiation treatment testing – *de Selding, Peter B. "Rando Phantom." http://spacenews.com/42294dummy-astronaut-shows-iss-crew-better-protected-from-radiation-than/.*

Rando simulation models or 'phantoms' are mannequins moulded using tissue-equivalent material to mimic the human body. Probes embedded throughout these phantoms provide clinicians with a detailed map of dose distribution that is essential for evaluating and calibrating radiotherapy treatment plans.

design process_

Co-Design Relationship

Because the oncology physicist and I had previously worked together, he had a fair understanding of 3D printing and the design process. In contrast to the broad clinical problems raised by other participants, his suggestion for a 3D-printed design opportunity was very specific. His idea was also partly validated through its similarities to the TBI blocks – using a 3D scan to model a hollow shell and filling it with water to mimic the density of the human body.

Co-Design Practice

A portable 3D scanner was used to scan my arm and the existing simulation model as a reference for joining the two parts together. Scan data was then converted into 3D models using CAD software. However, this process took a considerable amount of time. The complexity of the scan data also meant that it was difficult to and time consuming to make changes to the digital model.

While using the 3D scanner, the physicist was notably more excited and engaged. During the process he commented "it seems a lot simpler when you're actually using it". He had assumed the scanning technology would be complicated and difficult to use. Using the scanner helped him to gain a more accurate understanding of the digitisation process and how it could potentially be applied to other clinical areas he was involved in.

The physicist was invited to participate in the scanning process. Similar to probes, the aim was to develop his technological understanding and provoke thought beyond his own "thought world" (Dougherty 1992, 182), as there may have been further opportunity to use the scanner within oncology.

After observing the 3D-printed arm in conjunction with the simulation model, the physicist felt it extended too far out from the torso and the transition from one to the other was not smooth enough. There was also no way for the arm to fasten to the simulation model.

In preparation for the next workshop, the arm was modeled and printed using CAD software and a larger Makerbot Z18 3D printer.

The physicist explained that the arm didn't necessarily need to be a realistic representation of a human arm. He had simply suggested scanning because it looked "fairly straightforward" based on his observations of the TBI blocks.

Due to the complexity of the scan data, editing and manipulating the CAD model was both difficult and time consuming. As part of subsequent workshop with the physicist, I brought my laptop to demonstrate these challenges.

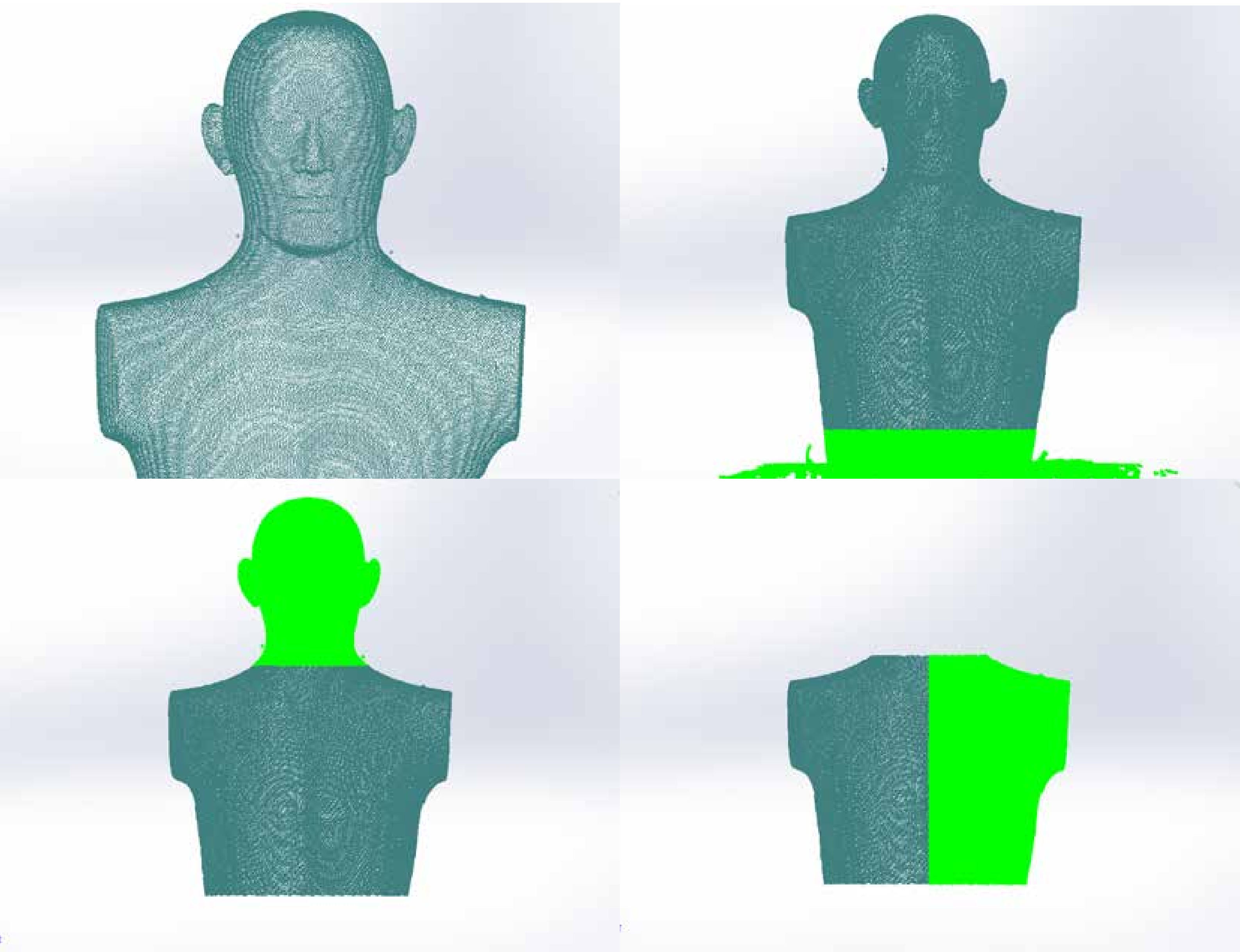
Although it may not have been as accurate, the physicist advised that the arm's design could afford to be simplified for the purpose of radiation testing.

Instead of using scan data, the CAD model was driven by manually entered measurements and a superimposed image of the existing simulation model.

Reducing development cycles allowed me to meet with the physicist more regularly. This was significant because out of all the participants I worked with, he was the most available and willing to be involved.

Simplifying the design also allowed me to make changes more readily, reducing the length of each development cycle. The time taken to CAD and 3D print an arm went from close to a month to less than a week.

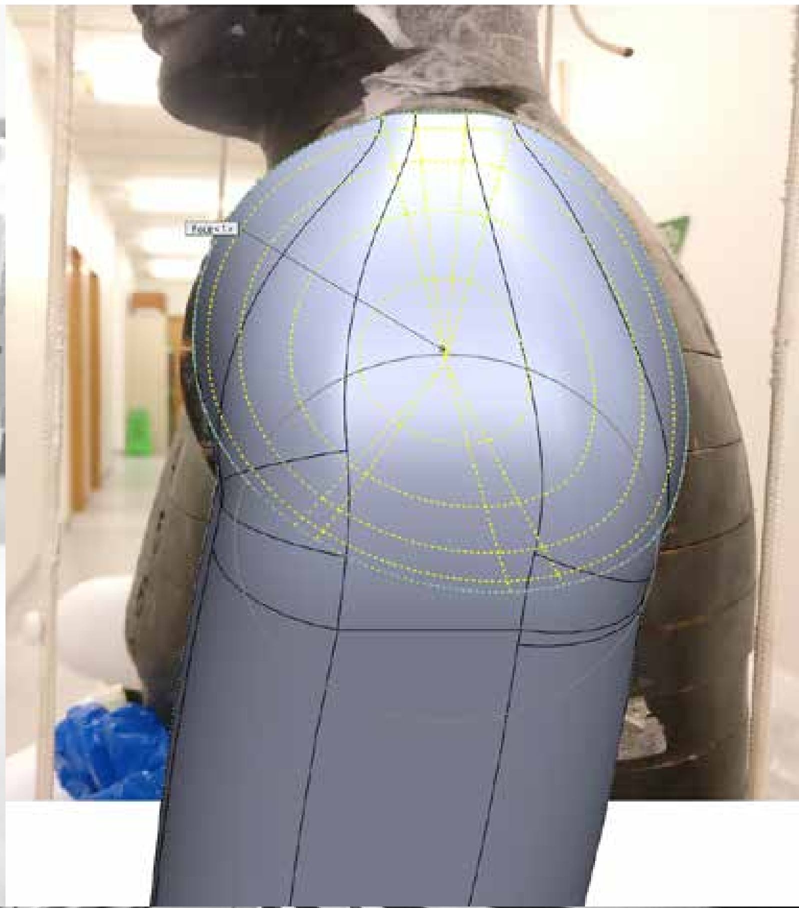
Images showing the process of taking a digital scan 'point cloud' and using CAD to turn it into a digitally manipulatable model.



Images showing the process of taking a digital scan of my body and using it to model the simulation arm. Scans of both my arm and RANDO were done in order to be able to simulate their connection in CAD before 3D printing them.

The first prototype being held up against the simulation model by the physicist. Although the 3D-printed model connected accurately with RANDO, it extended too far from the torso. The physicist also realised that in order to fulfil its purpose the arm did not need to be life-like.

Image showing the various ways in which I attempted to obtain the measurements necessary for modeling the arm without scan data. These included manually measuring RANDO with a ruler and overlaying an image on the digital 3D model to trace the outline of the connection.



A photo showing water being poured into the 3D-printed arm shell. Because water is similar in density to the human body, it acts as a suitable human tissue-equivalent material for radiation attenuation testing.

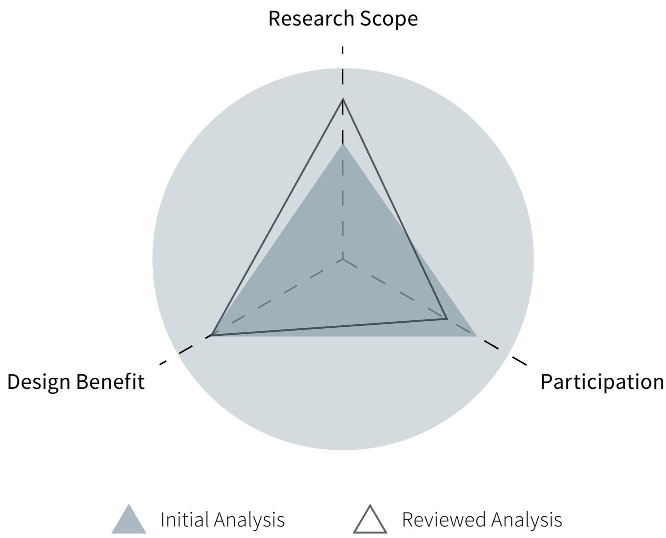
reflections_

3D printing the simulation arm opportunity ended up being considerably more feasible than first anticipated, mostly due to the shift away from 3D scanning. When this research concluded, two full-scale simulation arms were being tested by the physicist for validation. However, even when the design was simplified, the time taken to print such large-scale models meant I still wasn't able to maximise the availability of the physicist involved. Simpler, smaller-scale designs such as the finger splint design, allowed me to quickly and efficiently print models. Some iterations were within hours of each other. The speed of this process also allowed me to produce and utilise probes early in the design process. Developing probes for the arm project, on the other hand, would have been costly and inefficient, particularly if I had continued to use the portable scanner. This was not to say that complex or larger-scale projects shouldn't be attempted, but rather that smaller, simpler design opportunities seem to take better advantage of 3D printing as a co-design tool, particularly for participants like the physicist who were willing to be more involved.

Another significant insight was discovering the reasoning behind the physicist's suggestion for 3D scanning. Comparable with the 'false expectations' created by the media around the capabilities of 3D printing (Ventola 2014, 8), there was always the risk that participants would translate what they had observed inaccurately. Even though recent advances in 3D printing have made the 'scan-to-print' process a lot easier, adapting scan data has remained an intricate process. The physicist had identified a clear problem, but his suggestion for a design solution was based on an inaccurate understanding of scanning technologies. Perhaps one of the signs of an effective co-design partnership is when this no longer occurs. In this ideal scenario, the designer and the participant would have developed a shared understanding. Participants would therefore be trusted to make considered suggestions for design solutions.

Key Insights

- A better technological understanding allows participants to establish more accurate links between problems and potential design solutions.
- One of the aims or signs of an effective co-design partnership could be that non-designers are trusted to define the problem accurately and identify a potential design solution.
- The complexity of the scan data makes the process of manipulating and altering the digital model difficult and slow.
- Smaller, simpler projects seem to take better advantage of 3D printing and design capabilities than larger, complex projects, particularly in relation to the feasibility of co-design tools such as probes.
- Slow cycles of development may prevent participants from being heavily involved, even if they are willing.



A simplified 3D-printed representation of the human arm, constructed without the need for three-dimensional scan data being tested with the simulation model. Although the 3D-printed arm fitted, the transition between the two objects was not fluid enough for accurate testing. Smaller portions of the overall model could be used to test against the simulation model and reduce the time for each development cycle.

A photo showing the final 3D-printed arms being testing on the simulation model to make sure they fit correctly.

neonatal ear correction_

Initial Problem

Ear defects such as 'floppy ear' or 'bat ear', where the top of the ear is folded over or sticks out prominently from the head, are both common birth defects. However, because neonatal ear cartilage is still in very early stages of development, these defects can be corrected by simply fixing the ears in a desired position for a few weeks. Existing methods, such as pulling the ear back with adhesive tape or wire, often result in undesirable characteristics - asymmetry and tight folds at the top of the ear. The original idea was that a customised 3D printed device may produce a better outcome than what currently exists for correcting neonatal ear defects.

Initial Scope

The initial aim was to design a patient-specific object that applied equal pressure to a neonatal's ear cartilage whilst keeping the ear in a desired position. Due to limitations associated with ethical considerations and the challenges of using baby ear, my own ear was to be used as proof for concept design process.

Key Considerations

Ears in general have a very complex form. Similar to the simulation arm, if 3D scanning was used, I needed to consider how I was going to efficiently manipulate complex scan data.

Research Scope – High Feasibility

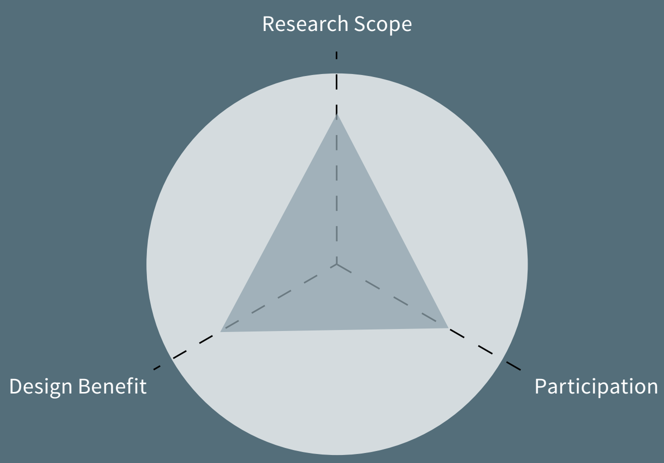
Cost: Fairly high, due to scale and material
Time: Fairly high, due to scale
Regulations: Low-risk
Scale: Small
Market Analysis: Current ear splints are made from a combination of adhesive tape and wire.

Projected Design Benefit – Fairly High

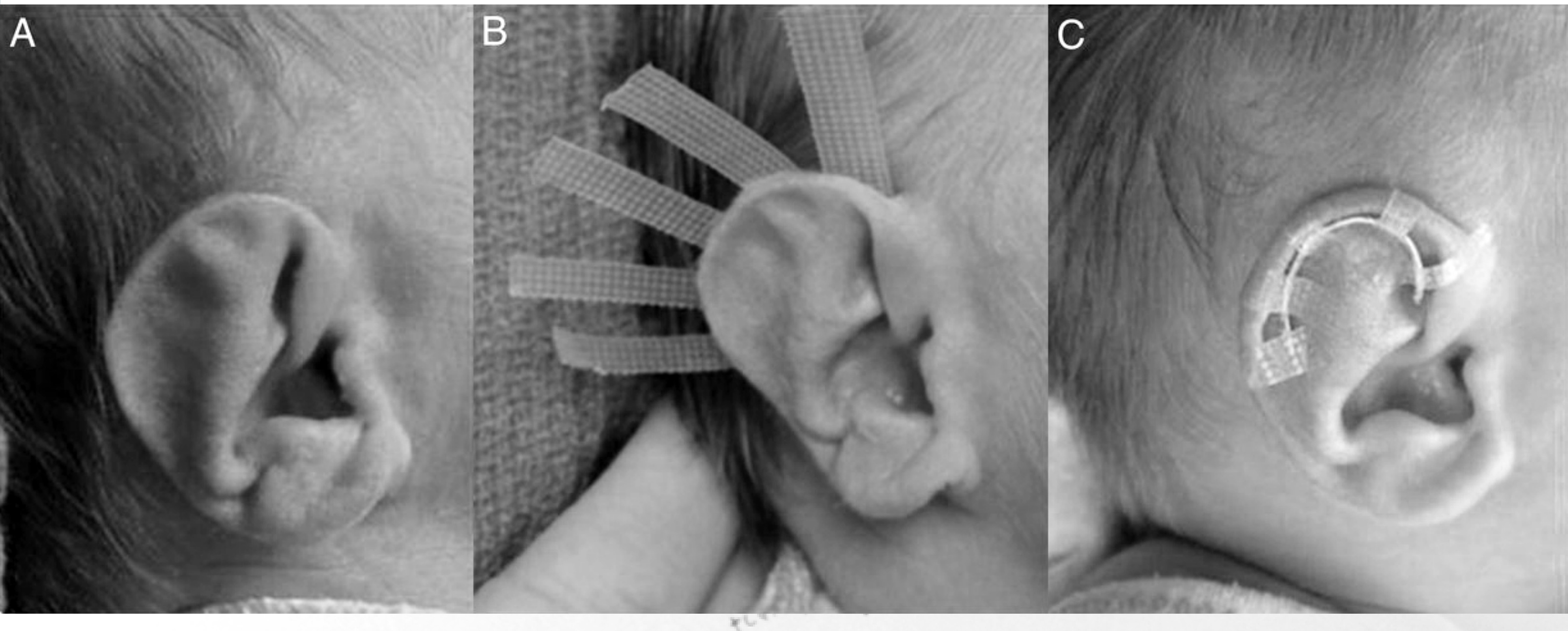
Applicability: Very high, due to the number of babies born with ear defects every year.
Reduced Cost: Unsure
Reduced Time: Unsure
Improved Health: Potentially, yes
Low-Cost 3D Printing: Yes
Customised: Yes

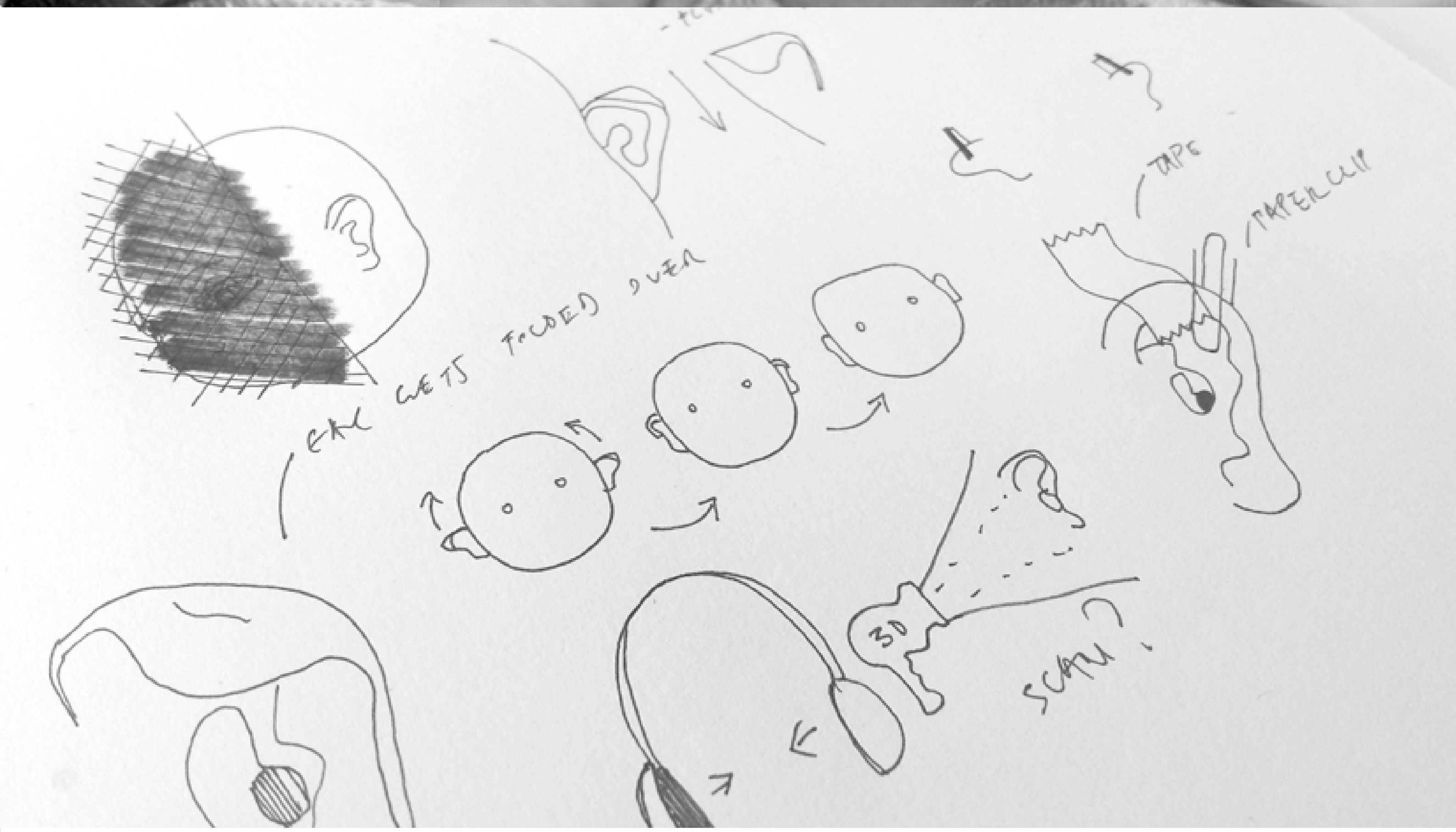
Participation – Medium

Co-Design: Yes
Availability: Medium
Level of Involvement: Medium



__Ear Deformity Before & After –__ Anstadt, Erin Elizabeth, Barbu Gociman, Dana Nicole Johns, Alvin Chi-Ming Kwok, and Faizi Siddiqi. "Neonatal Ear Molding: Timing and Technique." In Pediatrics, 2016.





Sketches made during my initial workshop with the craniofacial surgeon illustrating the existing correction method for neonatal ear defects. The key issue was accuracy and consistency. Crude correction methods often led to varied and undesirable results. The combination of 3D scanning and 3D printing were suggested early on due to their high level of personalisation and accuracy.

design process_

Co-Design Relationship

There were a number of concerns about the functionality of the first probe. For instance, the surgeon felt the shape and contours of the scanned ear were more complex than they needed to be (see images on page 89). Using an exact scan of my ear resulted in a number of undercuts and overhangs – attributes that made it difficult to fit onto the ear.

The surgeon noted that the first method partially solved the problem by softening the undercuts and overhangs but still would have been difficult to fit onto the ear, particularly for neonatals with irritable skin. The clay mould created a simpler, approximated surface. It also provided a way for the ear to be pressed into a more desirable position, instead of the defective position. However, the surgeon explained how both designs were too cumbersome and failed to target the correct area (helix and anti-helix).

Craniofacial surgeon 1 sensed that I hadn't fully understood the purpose of the correction process. Interestingly, he asked for paper and pen so he could draw the defect in more detail. His request was significant because it was the first instance of a participant using an alternative form of communication. Instead of a 3D-printed splint covering the entire ear, his drawings proposed a lightweight structure that wrapped around the back of the ear and prevented it from being pressed too hard against the baby's head.

The thing that excited the surgeon most was seeing the Lab's 3D printer in operation. There appeared to be something unique about the surgeon experiencing 3D printing first-hand.

Co-Design Practice

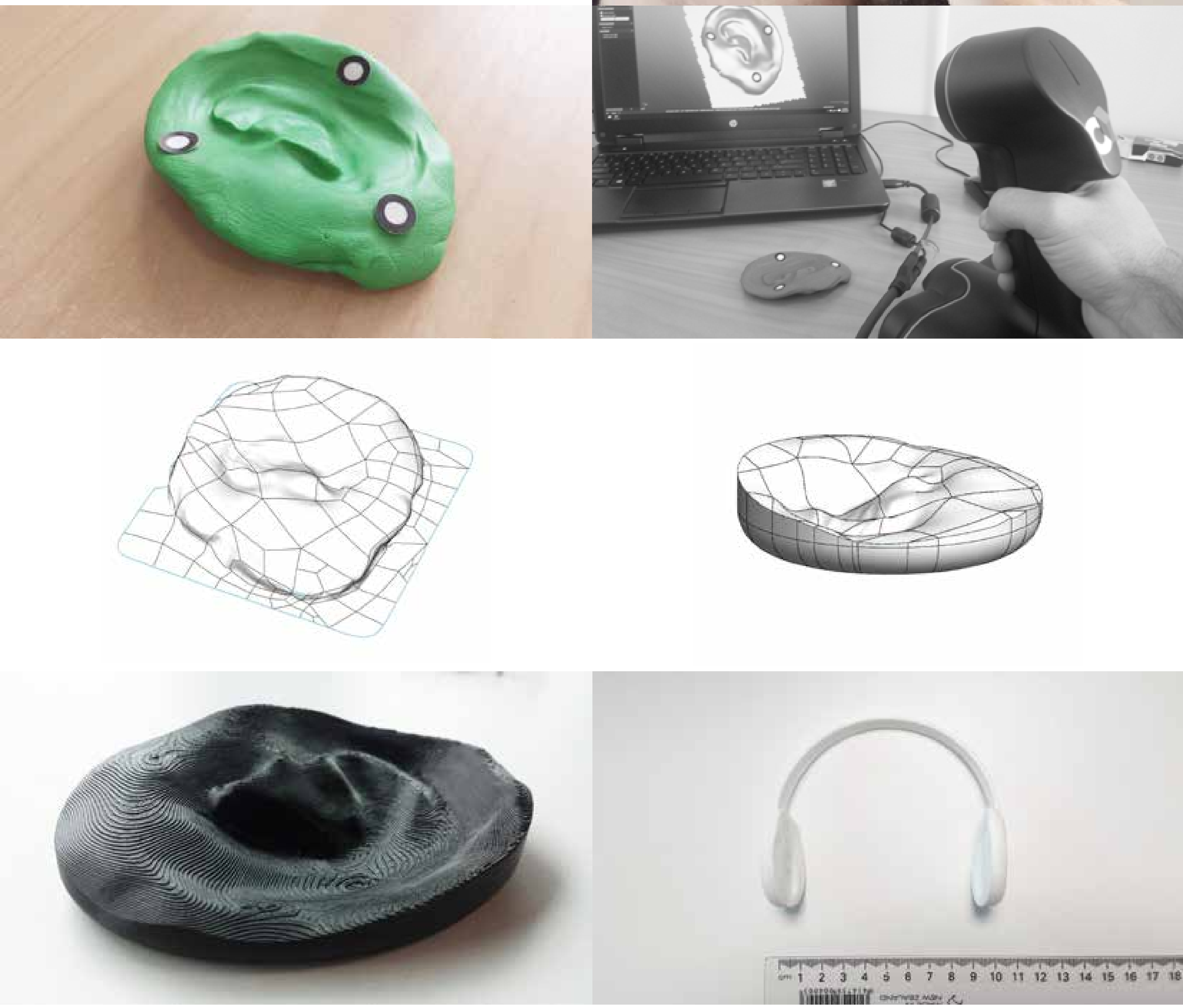
I prepared for a co-design workshop with craniofacial surgeon 1 by creating a series of design probes based on his broad suggestion of the problem and what was important to solve. My understanding of ear deformities was limited, but again, these objects were created with the aim to share knowledge and capture my assumptions. In the first probe design a scan of my ear was used to form the surface of an over-ear splint design.

Because I was already aware of the issues relating to complexity, for the second probe I explored two different simplification methods. The first was to take the original scan and decrease the number of data points, thus averaging the point cloud and softening the form. The second method involved pressing my ear into soft clay to create a mould. Rather than the ear itself, the clay mould was scanned.

Having the surgeon draw whilst I made suggestions felt like the roles of the designer and the non-design had been reversed. Sanders and Stappers refer to this 'blurring' of roles as one of the objectives of co-design (2008, 8-9). Having organised the workshop in the DHW Lab design studio, I realised that having the resources and tools available for creative participation was critical, regardless of the meeting's intended format.

Meeting in the DHW Lab meant I was able to show him a number of the projects I had worked on as part of the DHW Lab, including those that had utilised 3D printing such as the TBI blocks and the anaesthetic bottle clip adapter.

Using a portable 3D scanner, I took a three-dimensional scan of my own ear. This scan was used as a negative cut-out to create a an over-ear splint design. However, due to the complex shape of the scan, the splint did not fit over the ear easily.



A clay mould of my ear was scanned in order to capture a simplified version of my ear. These scans were then used to create an over-ear splint design. The left and right ear splints were held together using a head band.

Co-Design Relationship

Reducing the time of development cycles meant I could collaborate with the craniofacial surgeon more regularly and frequently.

Plastic surgeon 1 thought the thin scaffold structure was better, but still raised a number of issues concerning the design. The part that slid behind the ear was too long while the extrusion inside the ear was too short. Interestingly, parametric-based CAD allowed him to make some of these suggested changes himself using the software available.

Like the craniofacial surgeon, plastic surgeon 1 felt that I had not fully understood the nature of the defect. He too requested a paper and pen to help demonstrate what he was describing, but after a short time he still felt as though he wasn't adequately capturing his thoughts. He then asked for modeling clay, which was used to model an ear and demonstrate the correction process (see page 92 for images).

Plastic surgeon 1 was also highly interested in the 3D printer, commenting: "it's great to finally see how it actually works. I just had no idea. Its so simple yet so amazing." Outsourcing the 3D printing done in his hospital had led to a disconnect between his world and the world of manufacturers (Dougherty 1992, 182). Failing to link these worlds may have prevented both parties from being able to recognise potential applications for 3D printing.

Towards the end of the session the surgeon even stated: "I've been thinking for some time now, we really need to have one of these [3D printers] in the hospital. There are just so many other things we could have been using it for."

Co-Design Practice

The next iteration of ear splints used a much thinner scaffold structure. Although it took several attempts to arrive at the right shape, the process was fairly rapid due to the small size of the prints.

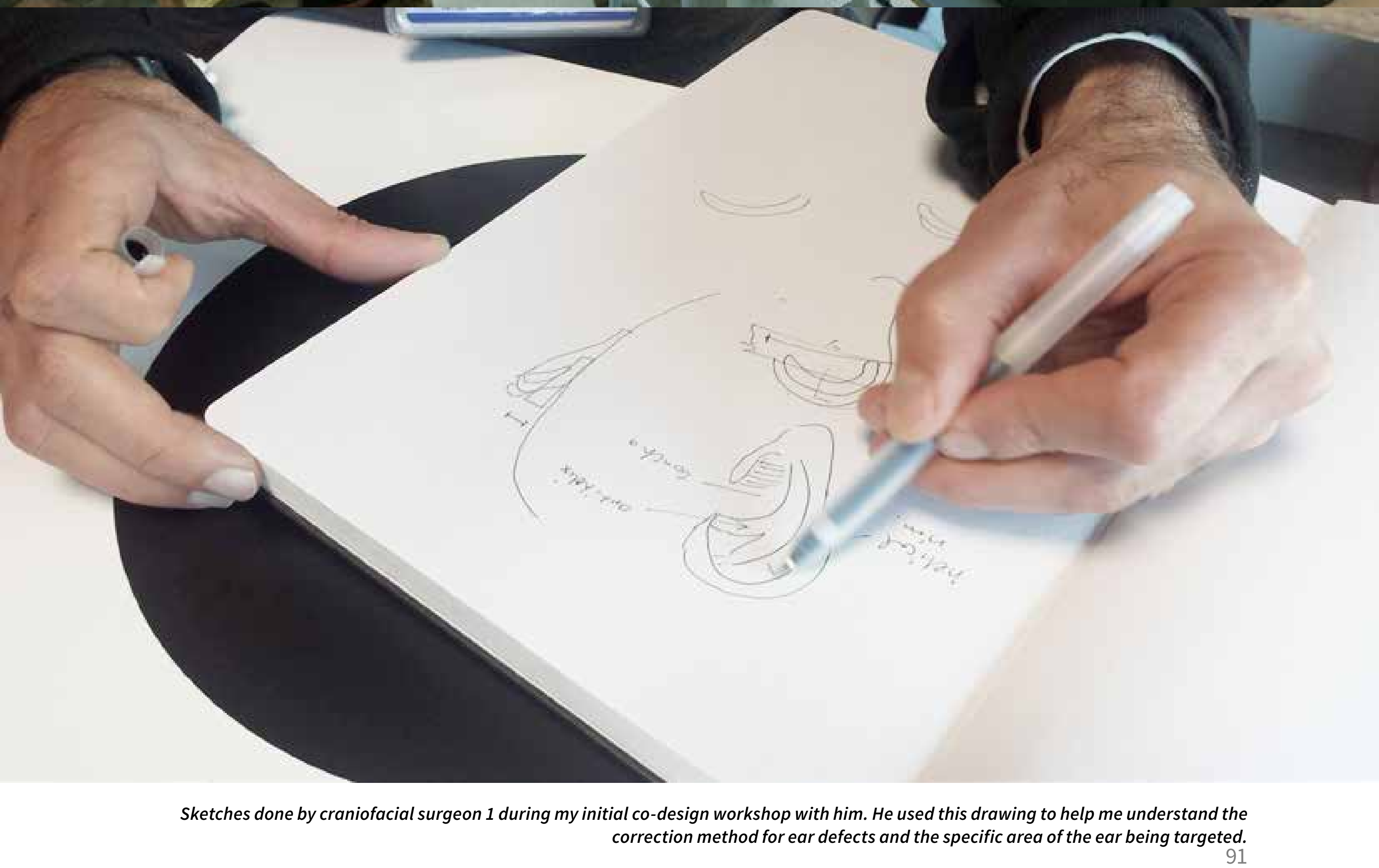
Similar to the finger splint, the ear splint design was changed to parametric-based CAD as a form of customisation as the design developed (see page 93 for image). A co-design evaluation was organised with plastic surgeon 1 to receive secondary feedback and explore whether there were any further design improvements.

Co-design participants can be more useful in the design process if they are given the appropriate tools with which to express themselves (Sanders 2000, 4-5). Visual and verbal tools such as paper, pens or clay help to create a common language that reveals meaning and understanding. In subsequent workshops a conscious effort was made to have tools such as paper, pen and clay available.

Because the previous workshop with the craniofacial surgeon had gone so well, the workshop with plastic surgeon 1 was also conducted in the DHW Lab (see page 91 for image of workspace).

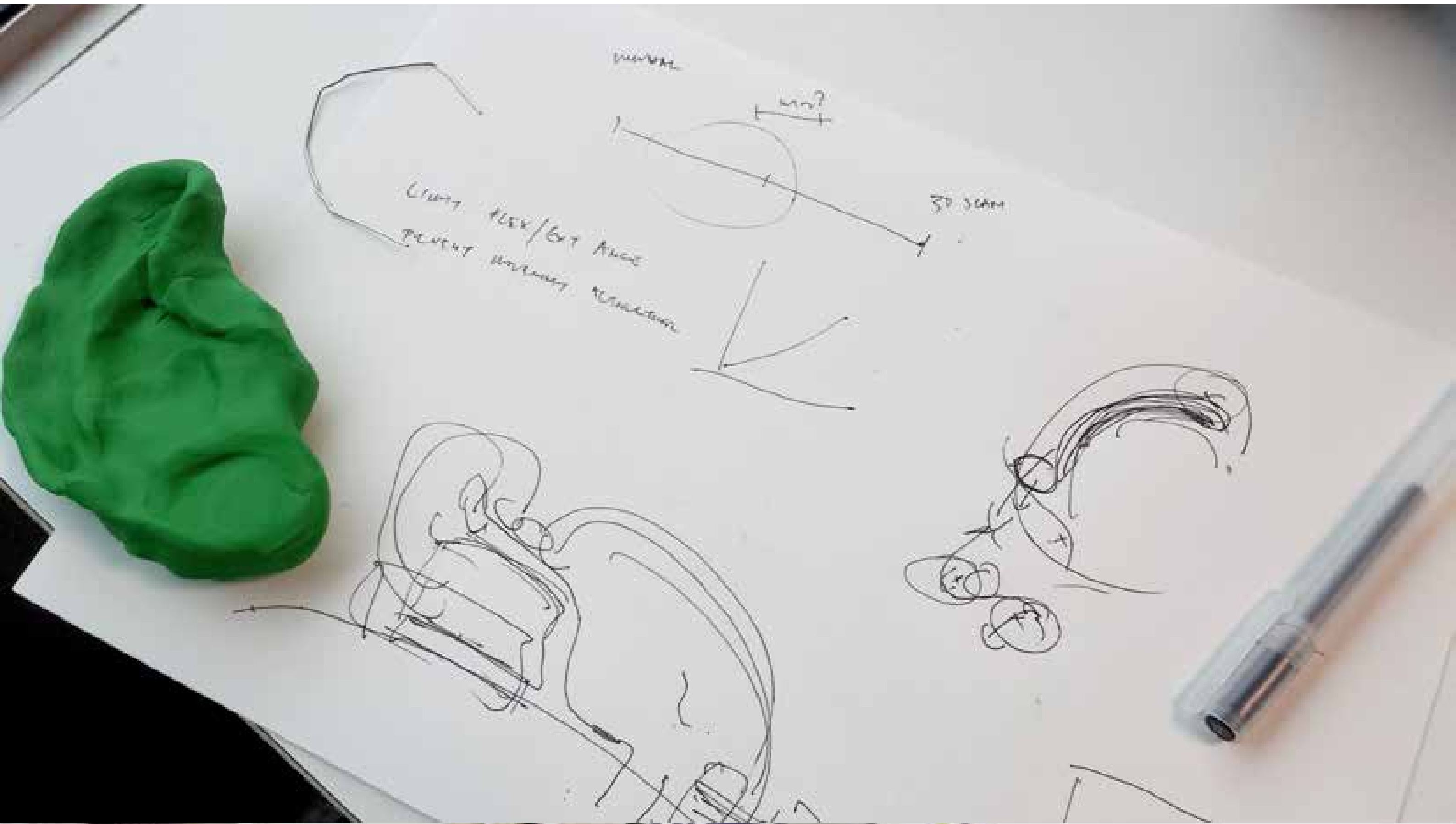
Giving participants the opportunity to observe the technology in person may have helped them to develop a more accurate understanding of it. Almost all subsequent workshops were therefore conducted in the DHW Lab design studio.

To help develop participants' shared understanding I began to organise co-design workshops in the DHW Lab design studio, a workspace that contains a number of design tools including a small desktop 3D printer. This gave participants the opportunity to gain a better understanding of the design process and design tools such as 3D printing.



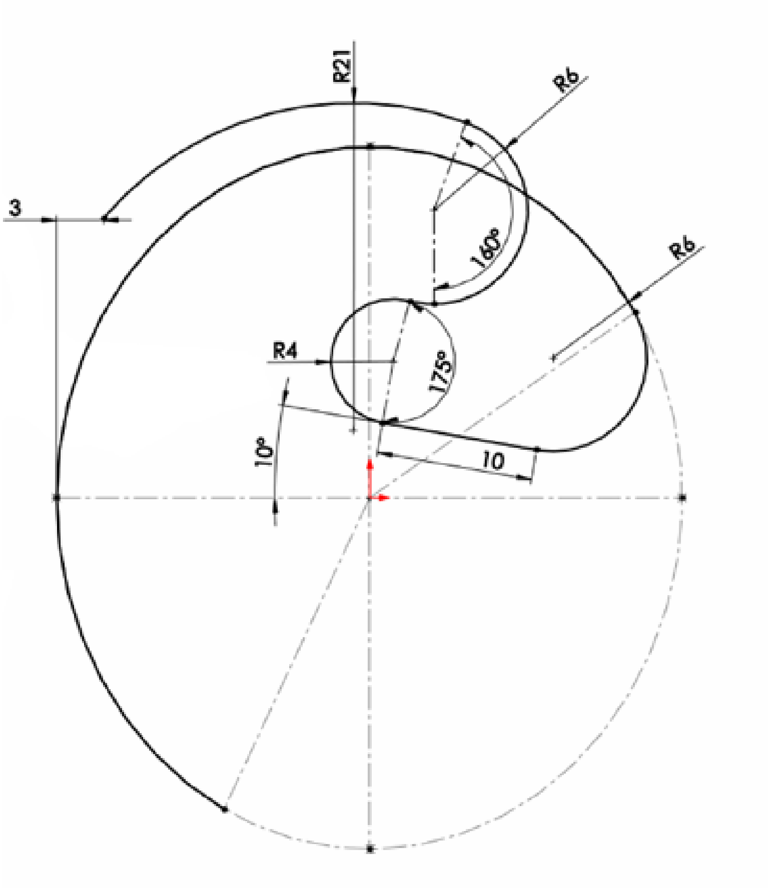
Sketches done by craniofacial surgeon 1 during my initial co-design workshop with him. He used this drawing to help me understand the correction method for ear defects and the specific area of the ear being targeted.

Image showing the initial drawings done by plastic surgeon 1 during a co-design workshop before using the clay. He was trying to communicate to me how the correction process worked and what part of the ear was being targeted.



Plastic surgeon 1 using clay to create a human ear to help demonstrate the correction process. Existing techniques often involve the use of wire to form the channel running along the top of the ear (know as the helix and anti-helix).

The left image is a CAD drawing demonstrating the use of parametric design – a form dictated by a small number of key dimension. The right image shows one of the splint concept designs being fitted and tested.



A photo showing the splints being tested. Although the splint fitted accurately, it was uncomfortable due to the edges and texture of the 3D print. This test also made me realise that there may have been design opportunities beyond splinting, such as custom earbuds or headphones

reflections_

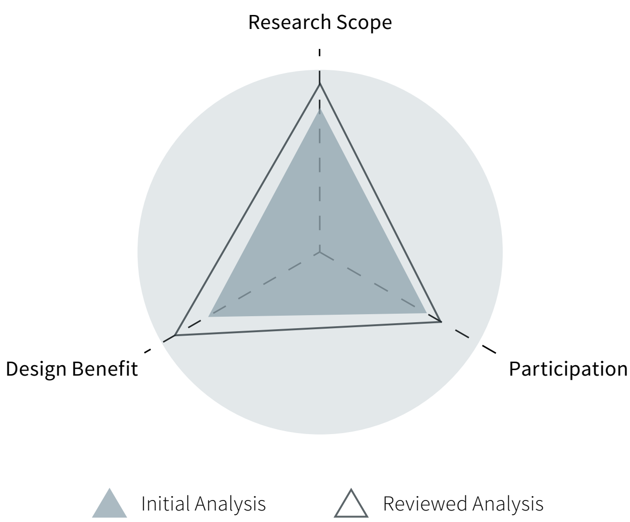
Due to the reduction in size and complexity, the ear splints ended up being more feasible then first anticipated. Shifting to simpler parametric CAD also meant that the design was easier to adapt, and therefore faster to produce. Similar to the finger splint, the ear splint was another example of a smaller-scale design that appeared to make better use of 3D printing's advantages, particularly in combination with parametrics. The sooner participants were exposed to 3D-printed design, the sooner a common understanding could be established. This speed was not just significant in terms of product development, but also in the development of the co-design partnership.

From what I had experienced during the collaborative design process, it took some time before the co-design became productive or effective. Early in the design process, participant's input was restricted due to their lack of technological and design understanding. Until they had at least a basic comprehension of 3D printing, how it worked and what is was capable of, their suggestions for design opportunities or design improvements were often unsuitable. The same was also true for the purpose of design. Until participants began thinking outside of what they were used to, their suggestions remained heavily constrained by existing design solutions and inaccurate perceptions of the technology, such as cost.

Another insight from the ear splint project was how excited participants became when seeing a 3D printer in operation. It was the same type of response I had witnessed when introducing 3D-printed design probes. There appeared to be something special about allowing participants to experience 3D printing first-hand. Education researchers Kyle Peck and Denise Dorricott argue that this excitement occurs because technology acts as a "Trojan horse", engaging and inspiring people to be more focused, harder working and further involved (1994, 3-4). Modern technologies like 3D printing stimulate people in a way that existing, or more traditional, manufacturing methods do not. This was yet another potential advantage for exposing participants to 3D printing earlier in the design process.

Key Insights

- Design probes can be used to capture and communicate the knowledge, beliefs and assumptions of the designer.
- 3D scans take considerable time and generate data that is difficult to manipulate or adapt.
- Making design tools available such as pen, paper or clay is critical to being able to communicate effectively during co-design workshops.
- Designers can use 3D-printed objects to express their ideas, but for non-designers, sketching or making simple models may be a more suitable way to communicate.
- Because of its advanced capabilities and high degree of resolution, 3D printing appeared to excite people in a way that other, more traditional, methods do not.
- There may still be benefits (e.g. technological understanding, design understanding, building trust etc.) in being part of co-design opportunities that are deemed unsuitable.
- Developing effective co-design may act as a sustainable model for identifying and developing design solutions in the future.



The top photo shows the evolution of the ear splint's design, in terms of both shape and finish. Experiments with rubber coating were done towards the end of the project to try and improve the splints' comfort. However, the rubber dipping process was very inconsistent. In order to improve consistency, I may have needed to try a spray rubber instead.

paediatric leg surgery simulation_

Initial Problem

During paediatric surgery, one of the fastest ways to introduce medication into the patient's system is to inject the fluid straight into the leg bone. This procedure involves a high level of precision and therefore requires training. Surgeons currently practice on a simulation bone made by an external manufacturer. After a period of use, the bones have too many perforations and are therefore replaced. 3D printing was suggested as an alternative method for creating the bones due to the high cost and considerable time taken to produce the existing replacement product.

Initial Scope

The initial scope involved using the 3D scanner to scan the existing leg bone model then 3D printing it for proof of concept.

Key Considerations

The only concern was whether or not the 3D-printed material would be suitable for the simulation process.

Research Scope – High Feasibility

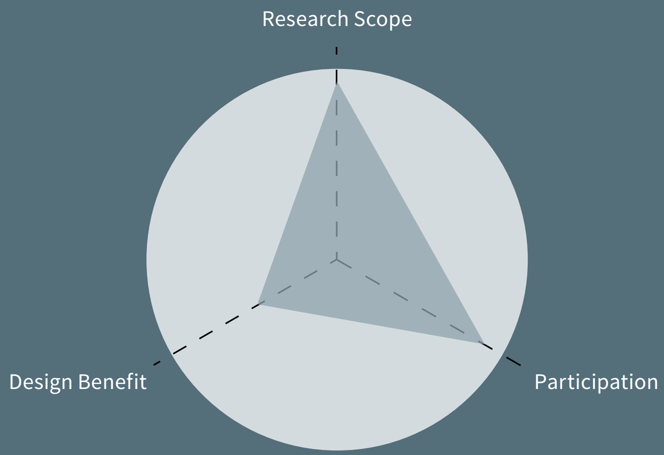
Cost: Low, due to scale and material
Time: Low, due to scale
Regulations: Low-risk
Scale: Small
Market Analysis: It is becoming a more common practice globally to 3D print bone structures for surgical simulation and preparation.

Projected Design Benefit – Fairly Low

Applicability: High, due to the number of simulations done each year.
Reduced Cost: Yes
Reduced Time: Yes
Improved Health: Not applicable
Low-Cost 3D Printing: Yes
Customised: No, as there will be no changes to the scan data before the leg is 3D printed.

Participation – High

Co-Design: Yes
Availability: High
Level of Involvement: Medium



A photo showing an existing leg bone model inside a paediatric simulation leg.
Although the existing models worked well, they were easily damaged and expensive to replace.

design process_

Co-Design Relationship

Paediatric surgeon 1 spoke with one of his colleagues (paediatric surgeon 2) about my research.

By sharing his new-found knowledge with a fellow colleague, paediatric surgeon 1 fulfilled one of my roles as a facilitator of co-design. Not only had he helped initiate a co-design partnership, he also acted as a link between the worlds of design and health.

During the workshop I was surprised to learn that paediatric surgeon 2's main purpose for the meeting was not to discuss a potential design opportunity, but rather to develop a better understanding of 3D printing. The session was therefore spent showing him a range of 3D-printed objects, demonstrating how the 3D printer worked and discussing technological constraints.

Paediatric surgeon 2 explained how it was important for him to understand the capabilities and limitations of the technology before trying to identify areas where it may prove useful.

Only towards the very end of the meeting did paediatric surgeon 2 feel comfortable proposing any design opportunities, the most promising of which was the reproduction of leg bones for surgical simulation.

Observing the different densities as physical examples allowed paediatric surgeon 2 to immediately understand the concept of 'infill'. Based on his understanding of the procedure, he selected a lower density infill.

Co-Design Practice

After hearing about some of my research projects, paediatric surgeon 2 contacted me in regards to an idea he had for simulation surgery. A workshop was subsequently organised in the DHW Lab.

Non-design participants can be used to share technological and design understanding with other non-designers, instead of solely relying on the designer.

As with previous workshops, the session with paediatric surgeon 2 was organised with the aim to identify potential design opportunities and clinical areas of interest.

I realised it would have been useful to ask paediatric surgeon 2 what he wanted to get out of co-design workshops. In accordance with co-design's aim to blur to the roles of designers and participants, healthcare professionals could be part of coordinating collaborative interactions.

I attempted to scan an existing leg model as proposed. Due to the coating on the surface of the leg, however, the scanner couldn't collect an accurate three dimensional image. As an alternative I used a leg scan found on NIH 3D Print Exchange, a free online database of anonymous anatomical models created by the US Department of Health and Human Services (3dprint.nih.gov 2016).

The internal density, or 'infill', of the print was increased in order to simulate needle injection correctly. Instead of trying to explain the concept of infill density to the paediatric surgeon, I simply gave him a selection of tangible examples to choose from.

Tibia and fibula bone scan screen-shot from 3D modeling application showing the scanned object as a digital model.

In my attempts to 3D scan the existing leg bone, small spots were drawn on to the model to help the scanner's sensor pick up the model. However due to the coating on the surface of the model, the 3D scanning did not work. Instead, digital paediatric leg models were downloaded from a free online database.

reflections_

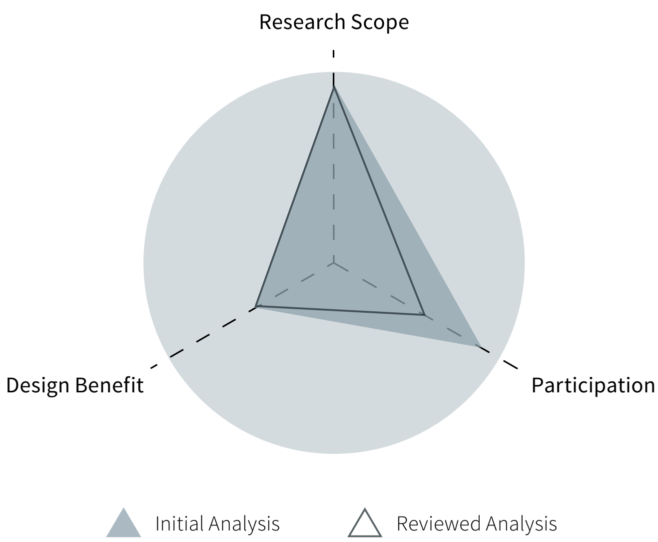
Overall, the project's development eventuated very closely to what I had anticipated. The design remained highly feasible and fulfilled its purpose, but did not provide substantial design benefit. With recent advances in 3D printing technologies, the scan-to-print process is now considerably easier and more accessible. Other than reduced cost and time, the 3D-printed leg held no other advantage over the existing design. Interestingly, the fairly simplistic nature of the project also meant that there was no real need for ongoing design input or collaboration. Like the oncology physicist, the surgeon's willingness to be involved went underutilised.

Although the output wasn't overly beneficial, there was a lot to learn from the co-design interactions. For instance, it was the first time I had observed a participant pursue a 'shared understanding'. Paediatric surgeon 2 recognised that in order to link 3D printing with a suitable clinical problem he needed to learn more about the technology. Although some of the clinicians had shown a prior interest in 3D printing, very few of them had pro-actively invested any time researching it. This was true even for those that came to me with a specific design solution (such as the oncology physicist). Arguably this could have been due to a lack of time, but it may have also suggested that most of the participants didn't recognise the benefit in developing a shared understanding.

It was also interesting to learn how the "prospect of 3D printing" for one of his own projects had led paediatric surgeon 2 to contact me. Again, there seemed to be something especially provocative and inspirational about a modern technology like 3D printing. In this instance, however, it was a fellow healthcare professionals who had exposed the participant to the technology (participant-to-participant sharing), instead of me and the participant (designer-to-participant sharing). The idea of participant-to-participant sharing was particularly significant when considering my role as a facilitator of co-design. By passing on shared knowledge between themselves, participants would be acting as another form of 'link' between the worlds of design and health.

Key Insights

- 3D-printing technologies can instill a sense of excitement in participants that leads them to share their new-found knowledge and experiences with others non-designers.
- Participants that recognise the benefit in developing a shared understanding are likely to learn and engage more during collaborative interactions.
- Conservative design solutions that don't require a high level of creative input fail to maximise the capabilities of design tools like 3D printing and limit the potential benefits of participatory input.
- Conservative projects also limit what participants are able to experience and learn about design and design tools like 3D printing.



3D-printed design probes showing a range of 'infill' densities were introduced during a co-design workshop with paediatric surgeon 2 to demonstrate how the same model could be printed at different densities and different strengths according to what was needed.

The 3D-printed tibia and fibula models were tested inside the simulation models to ensure that they fitted correctly.

medication fridge insulator_

Initial Problem

In a clinical environment a large number of the refrigerated medications require a consistent temperature in order for them to remain safe and effective for patients. Fridges are therefore fitted with a monitoring system that sends temperature readings periodically to an intranet database within the hospital. A reading lower or higher than the required temperature triggers an alarm that warns clinicians of the potential safety risk. The monitor itself, however, is currently too sensitive. For instance, an open fridge door dramatically affects the monitor's temperature reading, even if it is only left open for a short time. This is problematic as there is no way for clinicians to tell the difference between an open fridge door and a real fault unless they physically go and check.

Initial Scope

In order to delay the change in temperature, the ends, or 'slugs', of the monitor needed to be covered with an insulating material without hindering the existing functionality. The initial scope required a custom 3D-printed cap that was to be tested by the clinical engineering team to ensure the 3D-printed material provided sufficient insulation.

Key Considerations

Not applicable

Research Scope – High Feasibility

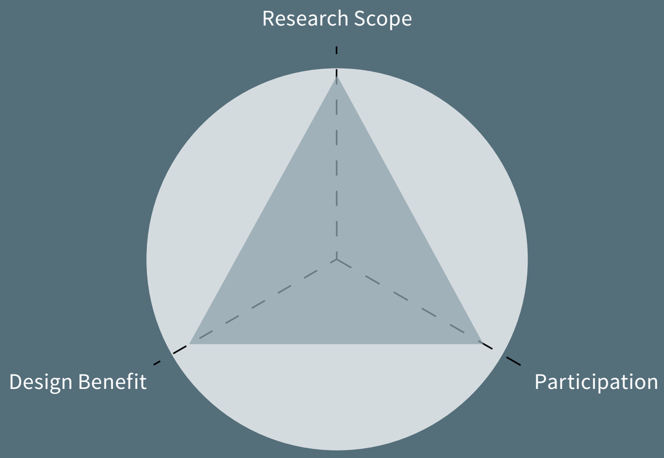
Cost: High, due to scale and material
Time: High, due to scale
Regulations: Low-risk
Scale: Small
Market Analysis: Not applicable

Projected Design Benefit – High

Applicability: Very high, due to the number of medication fridges in hospitals.
Reduced Cost: Yes
Reduced Time: Yes
Improved Health: Potentially yes
Low-Cost 3D Printing: Yes
Customised: Yes

Participation – High

Co-Design: Yes
Availability: Medium
Level of Involvement: Medium



A close-up of the slugs put inside hospital fridges as part of the existing monitoring system.

design process_

Co-Design Relationship

During the first workshop, the medication safety technician was not able to think of any suitable opportunities or problems that might lend themselves to 3D printing. He explained that he would "go away and think about it" and "keep an eye out" for potential opportunities.

Several weeks later the technician came back with a problem around medication fridge monitors that he thought might be solved with 3D printing. Because the design problem was specific and his direction was clear, the entire workshop took less than ten minutes.

The technician also used to sketching to help communicate his thoughts. Not only did it help him to describe the problem, he also used drawing to demonstrate how a design solution might work.

In a subsequent workshop, the technician approved the design and the T-shaped hook, commenting "I hadn't even thought about how it would go inside the fridge". He reminded me that he needed to test the model's level of insulation before progressing any further.

Although the first prototype was able to be developed in a short period of time, the tests needed to measure the level of insulation necessary took considerably longer. This delay was mainly due to the safety technician's schedule, as he was only free for short periods of time throughout the day.

Having a range of sizes available provided a way for the technician to test a number of units at once instead of one at a time. Once completed, the tests revealed that the 6mm model provided sufficient insulation.

Co-Design Practice

Because the medication safety technician and I had previously worked together on a 3D printing project, there was no need to explain the technology during the first workshop. Therefore no design probes were needed. The purpose of the session was to identify suitable design opportunities for 3D printing.

Rather than expecting participants to be able to identify suitable opportunities straight away, it may have been more effective to give them time to think beforehand, particularly for those new to co-design and a complex technology like 3D printing.

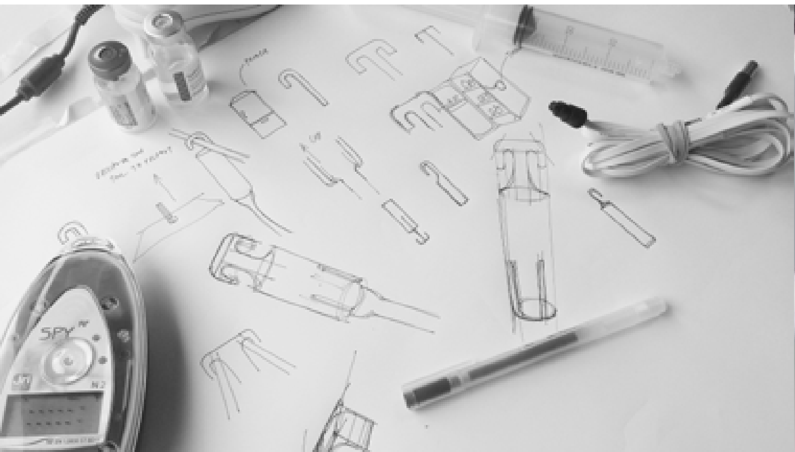
Sketching was again used in conjunction with discussion. I began sketching while the technician was demonstrating how the existing thermometers worked and why insulation was needed.

The overall design was very basic, consisting of a small cylindrical extrusion that fitted over the metal thermometer slug. Although the technician had not discussed any design features other than the need for insulation, I designed a T-shaped hook that slotted onto the rails of the fridge without the need for tape or adhesive.

In order to optimise my interactions with the medication safety technician, I chose to 3D print the cap design in a range of thicknesses.

The number of models printed was over and above what was necessary to determine a suitable thickness.

The photo on the left shows drawings of early ideas done by the technician and me during the initial co-design workshop. On the right is one of the earlier 3D-printed insulator models being tested inside a medication fridge.



Examples of the insulator caps 3D-printed in multiple sizes in order to test the level of insulation.

reflections_

Overall, the medication fridge project developed as expected, in terms of both feasibility and design benefit. Testing took considerably longer than anticipated, but after I became more proactive with model production, the process was a lot more efficient.

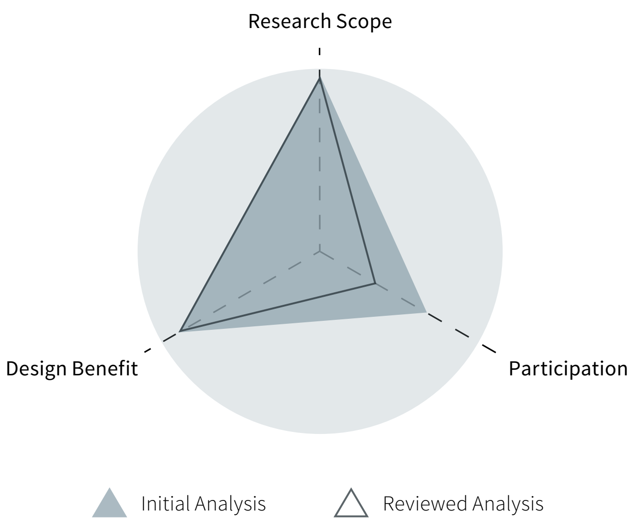
Another key takeaway from my interactions with the medication safety technician was once again recognising the effectiveness of more mature co-design partnerships. After working together on a number of projects, the technician and I had developed a deeper understanding of each other's capability and expertise. Other, newly developed, partnerships simply didn't have this shared understanding. As Madden and his fellow researchers highlight, involving participants does not necessarily guarantee innovation (2014, 14-15). The first time collaborating with a participant might be unsuccessful because the relationship has not matured.

During the project, it was also surprising to see how beneficial it was for the technician to go away and think before being able to suggest a suitable design opportunity. Often there was a considerable amount of information to take in during workshops. For some participants, it was the first time they had observed a 3D printer or 3D-printed object. Giving participants time to properly absorb this information may have taken longer, but perhaps it would have been a more effective way for me to discover suitable co-design opportunities.

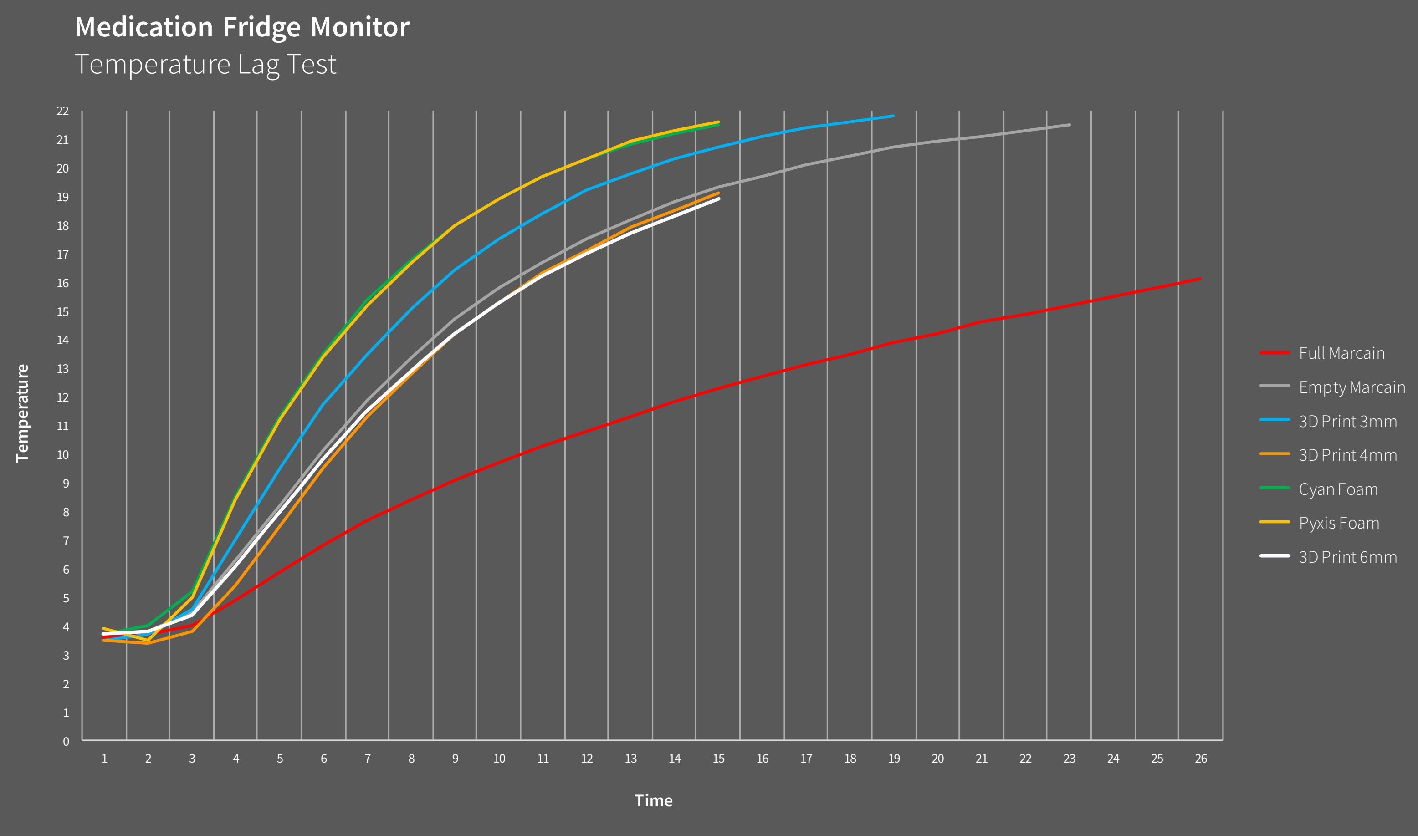
The technician's lack of availability during testing again highlighted the challenges of practicing co-design in active working environments such as a hospitals, even with professionals who were willing to participate. Therefore, I needed to consider how to get the most out of every co-design session. For new participants, the focus of workshops might be to create a shared understanding as quickly as possible. However, in existing co-design partnerships, the workshops need to maximise the skills of participants and cater for the level of involvement they are comfortable with. In a workshop with plastic surgeon 1, simply by having pen, paper and clay available he was able to communicate with me more effectively. Without access to these tools the session may not have been nearly as productive.

Key Insights

- Giving participants time to absorb and reflect on new information seems to allow them to identify more suitable design opportunities.
- Establishing a shared understanding can increase the efficiency and productivity of collaborative interactions.
- The busyness of healthcare professionals demands more efficient co-design strategies.
- Erring on the side of caution during workshop preparation – creating enough model variations or providing the design tools necessary for higher levels of involvement – is better than limiting productivity.
- As with any learned skill, it may take a number of projects and considerable time before a co-design relationship becomes effective.



A close-up of the insulator caps design showing how the cap fits over the end of the thermometer.



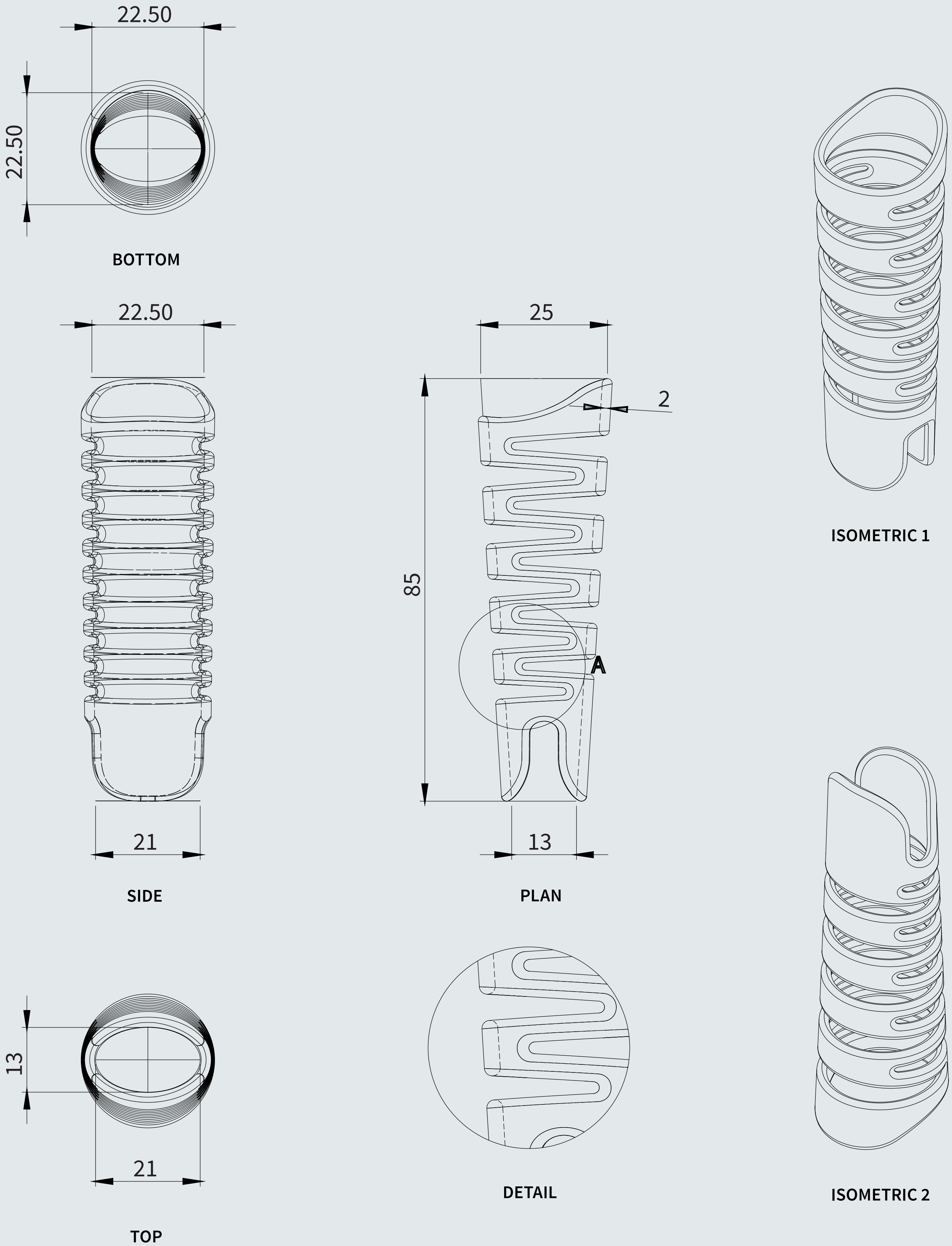
A graph showing a range of different methods used to insulate the cap based on a test done by the medication safety technician. The most effective 3D-printed model is represented by the white line (6mm). A number of these 6mm models were printed for further testing.

thinking progression_

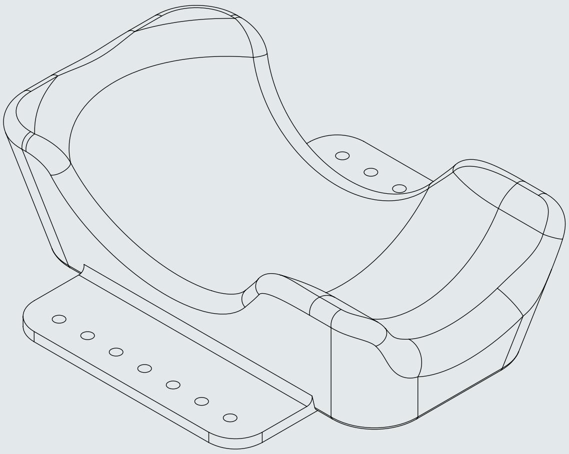
	PRIOR TO RESEARCH	*EARLY IN RESEARCH*
Technology 3D Printing	3D printing lends itself very well to a wide range of clinical problems. Scanning and manipulating complex data such as patient biometrics is fairly easy with today's software. 3D printing is most commonly used for high-end/high-cost applications in healthcare. 3D scanning with a portable 3D scanner is a simple process and will be a useful tool during my projects.	3D printing lends its major capabilities, customisation and personalisation to only a limited range of clinical areas such as plastic surgery, orthopaedics and oncology. Scanning complex data such as patient biometrics and bringing it into modeling software is easy but manipulating and editing it is difficult. Although 3D printing is most commonly used for high-end/ high-cost application in healthcare, this partly due to the price of outsourcing. 3D scanning with a portable 3D scanner is a fairly laboured process in order to get usable three-dimensional data.
Experts/Users Healthcare Professionals	Designers have a better understanding of additive technologies than other stakeholders, e.g. healthcare professionals. Clinicians' understanding and experience in healthcare allows them to identify problems/needs. Once healthcare professionals are given context and a better understanding of 3D printing capability, they will better be able to match up clinical problems/needs to 3D printing solutions. Stakeholders, or those involved as part of a network around an elected area of design research, are only human. Healthcare professionals' perception of 3D printing is skewed regarding its capabilities, complexity, cost and how long it takes.	Designers and non-designers need to have a common understanding of 3D printing in order to effectively identify design opportunities. Healthcare professionals' understanding and experience in healthcare allows them to identify common clinical problems. Even if healthcare professionals have a basic understanding of 3D printing, they won't necessarily be able to appropriately link clinical problems to 3D printing. The treatment of objects as part of social networks is a necessary consideration. My research involves the collaboration and participation of elements both human and non-human (Storni 2015, 169). Generally, healthcare professionals' understanding of 3D printing is skewed. These inaccuracies include capability, complexity, cost and production speed.
Environment Hospital	Proximity is the key to participatory design within a healthcare organisation (of collaborators and equipment). Transparency of the design process within an organisation such as the hospital allows healthcare professionals to gain a better understanding of the value of design. Proximity is also key in relation to design response, particularly for a technology like 3D printing.	Proximity, willingness and availability are the keys to participatory design within a healthcare organisation as well as for more effectively identifying design opportunities. Proximity is also the key to better outcomes in relation to design response for 3D printing, particularly in acute patient cases (24 to 48 hours). Giving participants the opportunity to experience parts of the design process helps them gain a better understanding of the purpose and capability of design. Availability (primarily of time for meetings, but also of equipment and materials for workshop sessions) is an ongoing barrier to collaboration in healthcare due to the fast-paced, non-stop nature of hospitals.

LATER IN RESEARCH	*FOLLOWING RESEARCH*
3D scanning lends itself more to bespoke, one-off products and less to designs with high applicability and therefore higher output. 3D-printed objects that are producible at high quality on low-cost 3D printers, using a low-cost material, vastly increases the likelihood of implementation. High-end 3D printers not only make it difficult to justify the upfront cost of the printer and ongoing service costs, but production time is also longer, leading to long, inefficient development cycles.	Without at least a basic understanding of both 3D printing and design, participants struggle to make suitable links between the technology and problems within their working environments. Small, low-end 3D printers combined with simple parametric-based CAD design may serve as a more effective and sustainable model for the integration of 3D printers into healthcare environments. Although it limits the capability of 3D printing technologies, there may need to be a balance between complex high-end 3D printing and simpler low-end 3D printing in order to develop effective co-design relationships and identify suitable design opportunities.
Probes speak a language far more powerful and convincing than any conversation between a designer and a non-designer. Probes create excitement among 'thought worlds' that normally aren't exposed to new ways of thinking, such as design or a technology like 3D printing. The early use of probes, combined with discussion, is the best way to quickly and effectively communicate thoughts and assumptions from both the designer and the non-designer. Developing the co-design relationship is just as, if not more, important than developing a successful design output. A successful product is simply the by-product of successful co-design.	3D-printed design probes acted as a common language between the researcher (myself) and participants (healthcare professionals). Probes helped to communicate both the capability and potential of 3D printing technologies to participants more effectively than only verbal dialogue, helping to create a shared understanding. Probes helped to capture my assumptions, knowledge and beliefs more effectively than verbal dialogue on its own, helping to create a shared understanding. Small-scale objects combined with simple parametric-based CAD design may serve as more effective and efficient probes in relation to collaboration and participant availability. Probes served as catalysts that helped participants to think beyond existing design solutions and identify opportunities for further design improvement.
Healthcare professionals are often limited by what they know. This affects their ability to identify potential design opportunities and additional areas of improvement. Transparency and communication helps to build shared knowledge among non-designers, a group who are limited in their ability to create and utilise probes. The excitement created by probes can help facilitate this communication between participants in a large organisation. The healthcare environment is a fast-paced, constantly changing landscape. Those involved are very susceptible to these changes, which makes it difficult to maintain excitement or an invested interest in a specific project.	In large public organisations such as hospitals design research is seen as a luxury. A way to help ensure successful design solutions may be to develop more effective co-design relationships instead of one-off exchanges of knowledge. It may take a considerable time and a number of projects before co-design relationships become consistently effective, particularly in healthcare where availability is an issue. Small-scale parametric-based designs, paired with convenience and transparency of a design studio located inside the hospital, may serve as a most effective and efficient way of developing successful co-design relationships.

3D-Printed Finger Splint
Technical Drawing Scale 1:1
Josh Munn



Radiation Head & Neck Cradle
Technical Drawing Scale 1:3
Josh Munn



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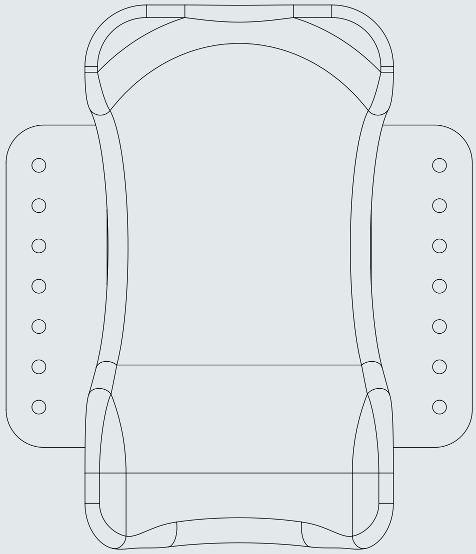

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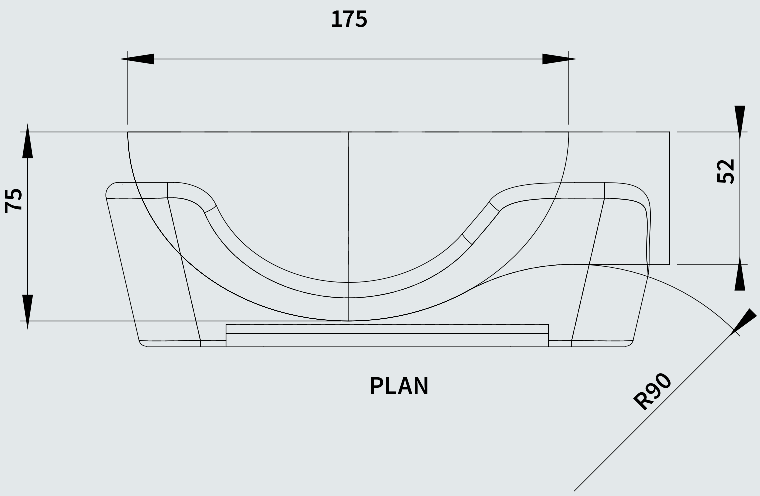

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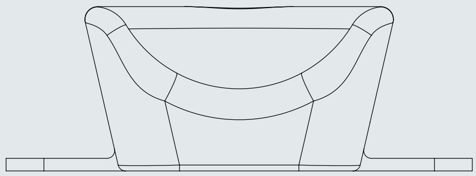

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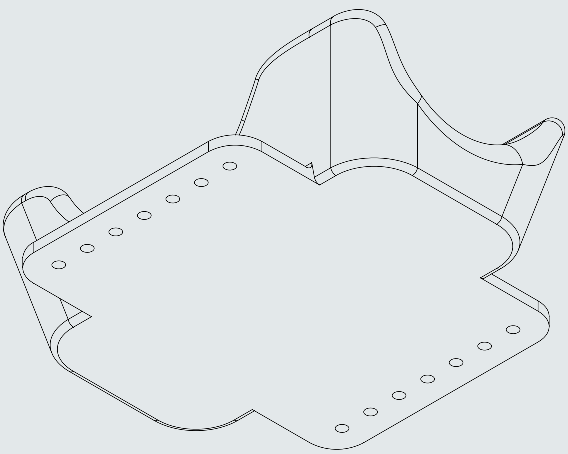

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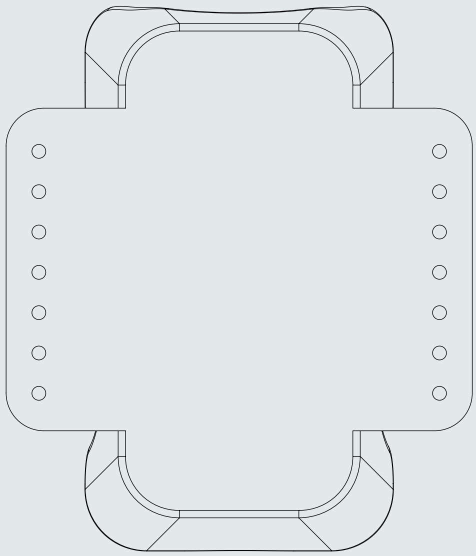

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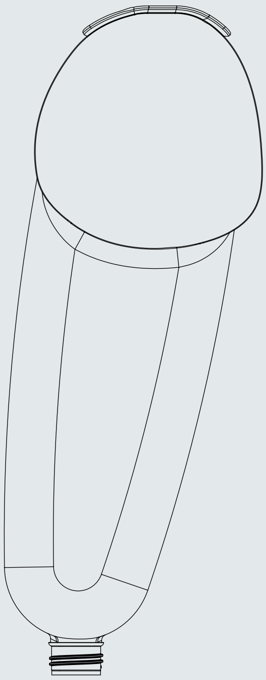
HR B MV6

Radiation Simulation Arm
Technical Drawing Scale 1:5
Josh Munn



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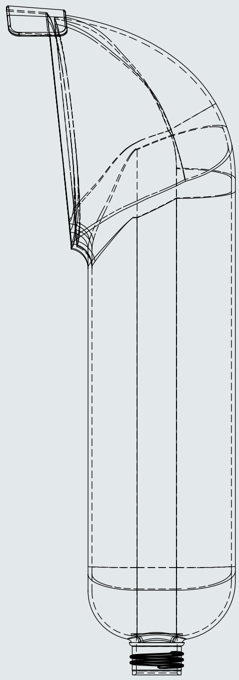

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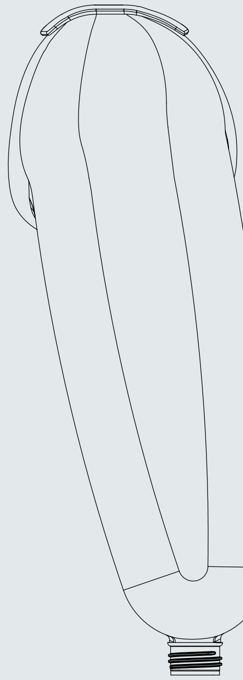

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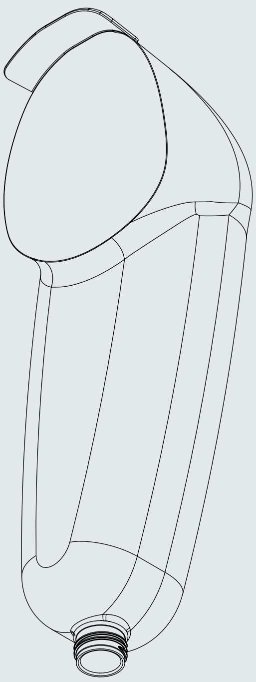

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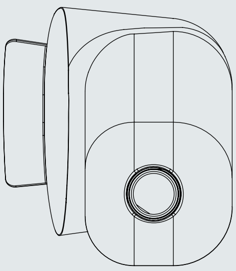

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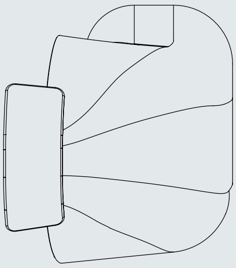

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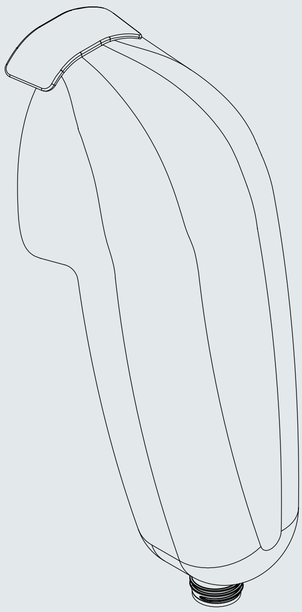
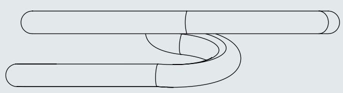


ISOMETRIC 2

Neonatal Ear Splint
Technical Drawing Scale 2:1
Josh Munn



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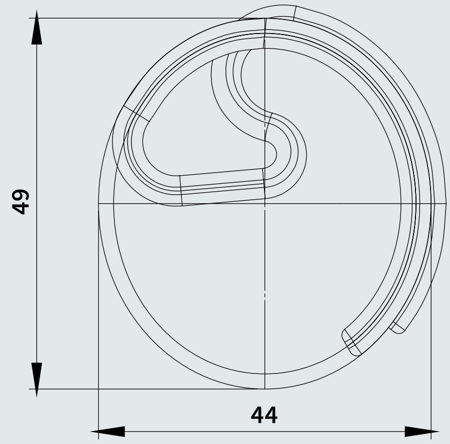

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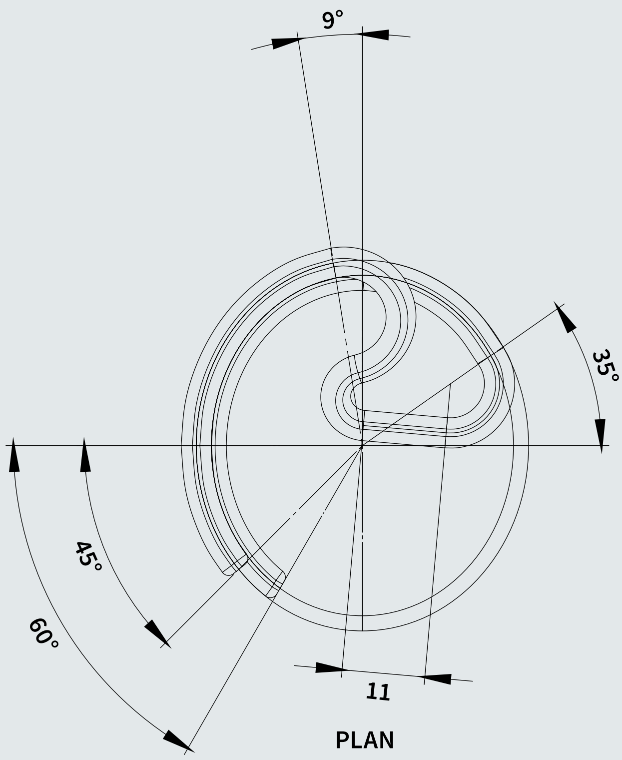

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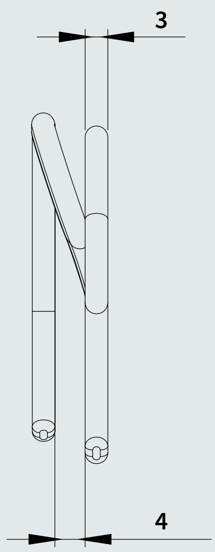

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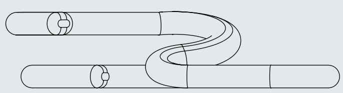

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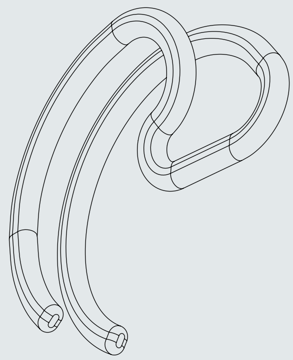

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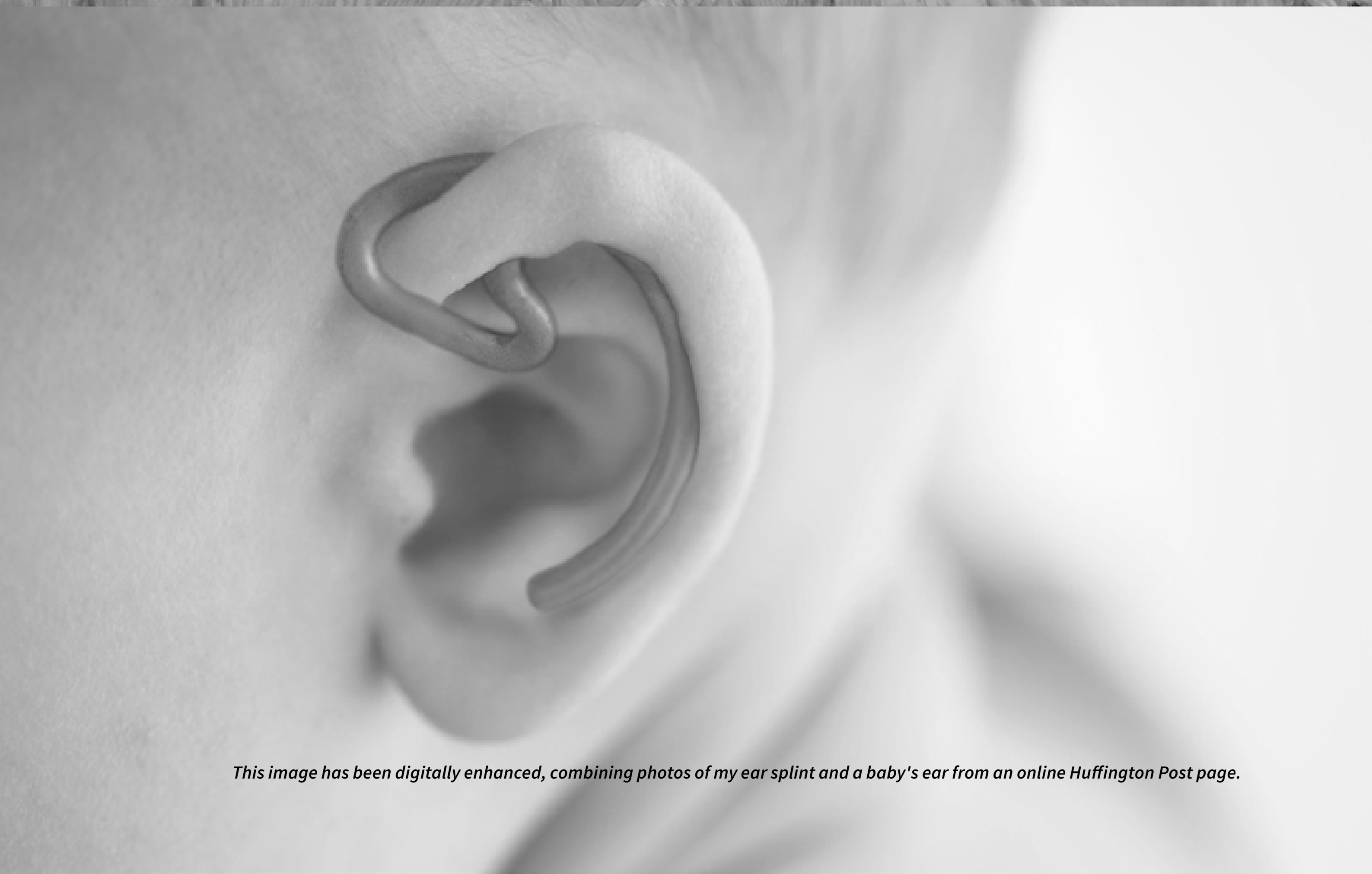
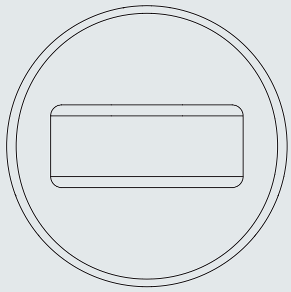


This image has been digitally enhanced, combining photos of my ear splint and a baby's ear from an online Huffington Post page.

Medication Fridge Insulator
Technical Drawing Scale 2:1
Josh Munn



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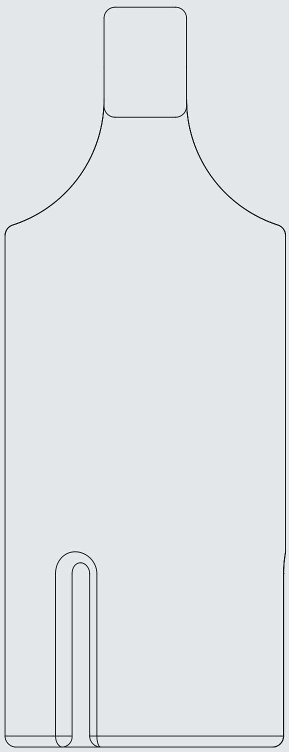

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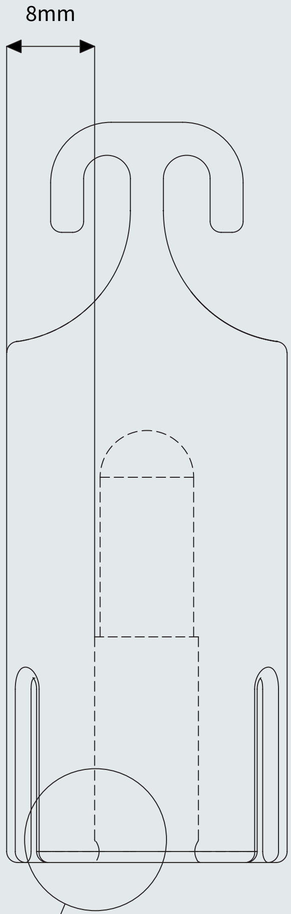

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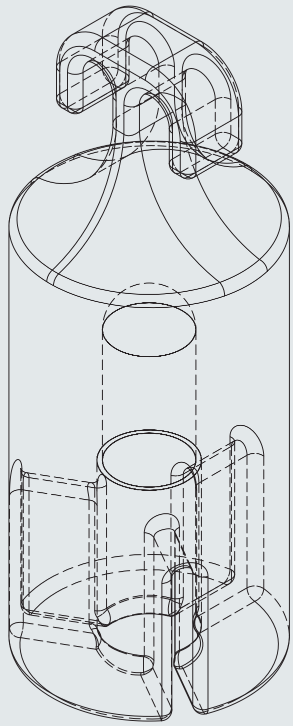

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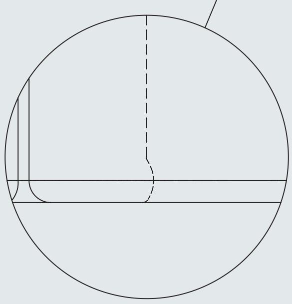
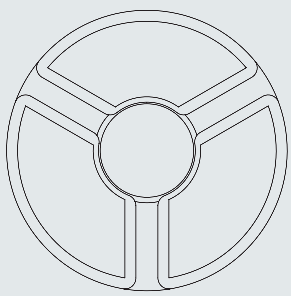


DETAIL



BOTTOM


PHT491
Vaxigrip
PHG267a
Hepatitis B Vaccine Paed
5mcg/0.5mL
Injection (0.5mL)
(HBvaxPro)
2401959
Neisseria
vaccine
Injection
2383047
Pneumococcal

CHAPTER 04

discussion_

discussion_

Despite setting out with a reasonably clear research direction, the purpose of my inquiry only became clear through the analysis of my initial interactions with healthcare professionals. What began as a broad attempt to identify, develop and resolve a series of 3D-printed solutions with healthcare professionals became a more focused exploration of 3D printing as a co-design tool and its agency in collaborative interaction.

Shared Understanding

The healthcare professionals involved during this research generally had a very limited understanding of 3D printing. Those with some knowledge often showed an inaccurate understanding of factors such as cost and production time. Participants also largely failed to demonstrate a good understanding of the design process, such as the importance of defining the problem first and then using design to resolve it. The clinical engineering team, for instance, proposed 3D printing head and neck cradles for radiation treatment based on their knowledge that the additive manufacturing was more accurate. However, because they were not familiar with the level of discomfort patients were experiencing, they did not realise that increased accuracy only partially solved the problem. Norman and Stappers (2015, 91) discuss how design seeks to discover the underlying causes of a problem before jumping to design solutions like the engineers did. This inquiry is done in order to "illuminate" issues and opportunities that may not have been apparent initially.

Due to this lack of "shared understanding" (Sanders and Stappers 2008, 13), participants also found it difficult to identify or consider design opportunities beyond existing design solutions. Deborah Dougherty (1992, 182) describes this difficulty as the challenge of escaping one's own "thought world". These 'worlds' represent the products, processes and systems that are used, discussed and reflected upon within an individual's working environment. People often find it difficult to relate to things that exist or operate outside of their own thought worlds. Dougherty (1992, 191-192) argues that the only way to "innovate" with technologies like 3D printing is by linking the thought worlds of industry members with end-users. Dougherty describes the need for a person to create this link. This person, or facilitator, acts as a common language between worlds, helping those involved to develop a shared understanding.

Early in this research, my strategy for establishing this shared understanding was solely through expert interviews discussion. Verbal dialogue, however, proved limited as a form of design communication. Participants were not able to observe or interact with any of the objects or technological features I attempted to describe to them. Some participants were notably disappointed when they realised I had not brought any 3D-printed examples with me. Additionally, my verbal explanations took a considerable amount of time. For healthcare professionals with limited time availability, this lack of efficiency was a significant concern, especially considering co-design's advocacy for participant engagement throughout the design process. Also absent was a collaborative approach – what Sanders and Stappers (2008, 13) call the "blurring of roles". Participants were invited not only to exchange their knowledge and experiences, but to participate in design-related tasks (Sanders and Stappers 2008, 8). Within expert interviews, however, the roles of designer and non-designer were both still firmly in place.

Based on these limitations, the question was asked of whether these worlds could be bridged using alternative approaches such as "design probes" (Sanders and Stappers 2014, 7). It was this question that saw the strategy for collaboration develop from person-to-person interviews into facilitating co-design workshops focused more on object-to-person interactions.

Probes

Traditionally, designers begin 'making' after a design opportunity has already been identified. However, Sanders and Stappers (2014, 3) suggest making is an exploratory tool necessary in all stages of the design process. Making is broken down by Sanders and Stappers into three different approaches – probes, toolkits and prototypes. Considering the need to develop a shared understanding, the most notable of these approaches in the context of this research was probes. Sanders and Stappers (2014, 9) define probes as materials designed to "provoke or illicit a response" from participants in order for designers to "find inspiration in users' reactions to their suggestions". Instead of designers using 'making' to shape the solution, 'making' becomes a way for designers to better make sense of the problem (Sanders and Stappers 2014, 7-8). These 'materials' include objects such as storyboards, workbooks or physical artefacts. Here, the 'thing' being made is not a forerunner of the future product, but rather a 'vehicle' for observation, reflection, interpretation, discussion and expression (Storni 2015, 169). Storni describes this as a "de-centred" design process.

Jayne Wallace and fellow researchers (2013, 3) discuss how probes are not just an "arbitrary set of objects", but rather the embodiment of a question or an idea in three-dimensional form. Therefore, probes are designed in a way to help participants to accurately understand a question or idea and facilitate their creative ability accordingly (Wallace et al. 2013, 3). In this way probes assist in preparing participants for co-design (Sanders and Stappers 2014, 11). In this research it was found that probes combined with discussion were the most effective way to communicate and share ideas and understand differing views. For example, without plastic surgeon 2's vocal response to probes used during the ear splint project, I would not have realised that my understanding of ear defects was significantly inaccurate. This example is consistent with the suggestion from Krippendorff and Klaus (2005, 49), who purport the way probes are understood by participants is largely informed by what is said about them.

Common Language

Probes were first introduced into this research as a way to capture and demonstrate the capabilities of 3D printing. For example, during the finger splint project, an array of probes was created to help demonstrate a range of technological capabilities to one of the plastic surgeons. Unique attributes such as flexibility, strength and customisation were embodied in a range of 3D-printed objects, some which looked like fingers splints, others that did not. The goal was not to create potential design solutions, but rather to help participants understand the possibilities and limitations of 3D printing. Providing the surgeon with the opportunity to observe and interact with physical examples proved to be a far more effective strategy for translating complex information than verbal dialogue alone. The capability to produce small one-off objects without the need for expensive tooling associated with traditional manufacturing meant that these probes came at very little cost. Design samples could also be tailored according to a specific project or participant depending on their level of understanding.

The same advantages were observed when communicating my understanding of the clinical environment. During the research there were a number of instances where participants proposed very broad design opportunities for the use of 3D-printed objects as design solutions. For example, in an interview with craniofacial surgeon 1, issues relating to neonatal ear defects were raised as a potential opportunity for 3D printing. The idea seemed promising, but I knew very little about the condition. Instead of trying to communicate my understanding solely through verbal explanation, three different splint designs were created to demonstrate my interpretation of the problem. By observing and interacting with these objects, the surgeon was immediately able to recognise the assumptions I made about the defect and how I planned to correct it.

In this way, probes served as a way to break down communication barriers between designer and participant. The objects provided healthcare professionals with a way to access the knowledge, beliefs and assumptions associated with my understanding of a specific clinical issue (Madden et al. 2014, 14-15). Although some of the design's functional elements were realised in the final product, the main goal initially was to help create a shared understanding. 3D-printed objects served as a more effective language, speaking more about the problem than I would have been able to express purely through discussion (Wallace et al. 2013, 2).

This idea of objects being used as a common language strongly coincides with Latour's (2005, 10-11) actor network theory – a framework used to help examine and disassemble the factors that surround and form social networks. 'Actors', as Latour terms them, both human and non-human, are assigned equal amounts of agency within networks such as co-design (Storni 2015, 169). Human elements include those affected by a particular design, while non-human elements may include objects, services or technologies (Latour 2005, 10-11). Participants' observed response to 3D-printed probes was consistent with Latour's theory in that object-to-human interactions had just as much, if not more, agency than purely human-to-human interactions.

Collaboration

Probes made it possible to communicate a wide range of information and receive valuable feedback in a short space of time. Considering healthcare professionals' limited availability, this efficiency was highly significant. Some of the participants were available to meet fairly regularly, but others were only able to meet approximately once a month. Therefore, each co-design workshop needed to maximise the effectiveness of collaboration.

Benefits of time efficiency were most evident in projects with smaller designs, such as the finger splint and the medication fridge insulator. Small-scale models used less material and therefore took less time to 3D print, most prints only taking between 20 and 30 minutes. Reducing the length of development cycles meant that it was easier to produce larger quantities of probes. The sooner probes could be used to help participants develop a shared understanding, the more productive and effective co-design workshops became. In contrast, larger designs such as the radiation simulation arm often took between 10-20 hours to produce. There was also an additional lead-time of two to three weeks due to the designs being printed on larger high-end 3D printers not located in the DHW Lab. Slower cycles of development associated with larger, more complex designs may have prevented healthcare professionals from being heavily involved, even if they were available and willing.

Parametrics were also a key factor in time efficiency. Projects such as the finger splint and the ear splint began by using a portable 3D scanner to customise the form of each design. The complexity of the scan data, however, meant that manipulating the digital model was difficult and slow. By switching to simpler parametric-based CAD designs, editing the models became considerably easier. Instead of using scans of patients' fingers, the design could be adapted by changing five key measurements. Digital models that had taken hours to produce were tailored according to the needs of the patient within minutes. Parametrics also allowed a blurring of roles to occur, by providing a way for participants with limited modeling experience to make changes to the design. For example, during the ear splint project the design also shifted from using 3D scan data to parametric CAD design. Reducing the complexity of the digital model allowed a craniofacial surgeon to alter the design by changing key dimensions in one of the CAD file sketches.

As Sanders and Stappers (2008, 8) describe, the ideal co-design approach is where participants are involved throughout the design process. The simple, yet efficient nature of smaller parametric-based designs appeared to better maximise the opportunities of 3D printing in relation to developing shared understanding and building co-design relationships.

In discussing the extent of what probes represented, it's important to note that workshops often left participants with new information to digest. For example, during the initial workshop with the medication safety technician, he was not able to identify any design opportunities straight away and asked for "time to go away and think about it". A few weeks later he came back with the idea for 3D-printed fridge insulators. Returning to his clinical environment and day-to-day routine with a deeper understanding of technology and design helped him to see and approach problems differently. Despite not knowing exactly what the 3D-printed solution would look like or how it would work, he knew that the technology paired with my trained skills as a designer could produce a customised object. Therefore, instead of expecting participants to generate ideas immediately, it may have been more effective to allocate participants time to reflect on new information. Although, again, in the pressure of time availability, this may not have been possible for every participant.

Catalysts

In addition to helping develop a shared understanding, probes also proved to be effective as design catalysts. Participants often found it difficult to imagine alternative solutions outside of what they were used to or, as Dougherty describes it, outside of their own "thought worlds" (1992, 182). Opportunities that involved the redesign of a particular product were often proposed without considering how to maximise the potential of the chosen technology. For example, the oncology team leader suggested

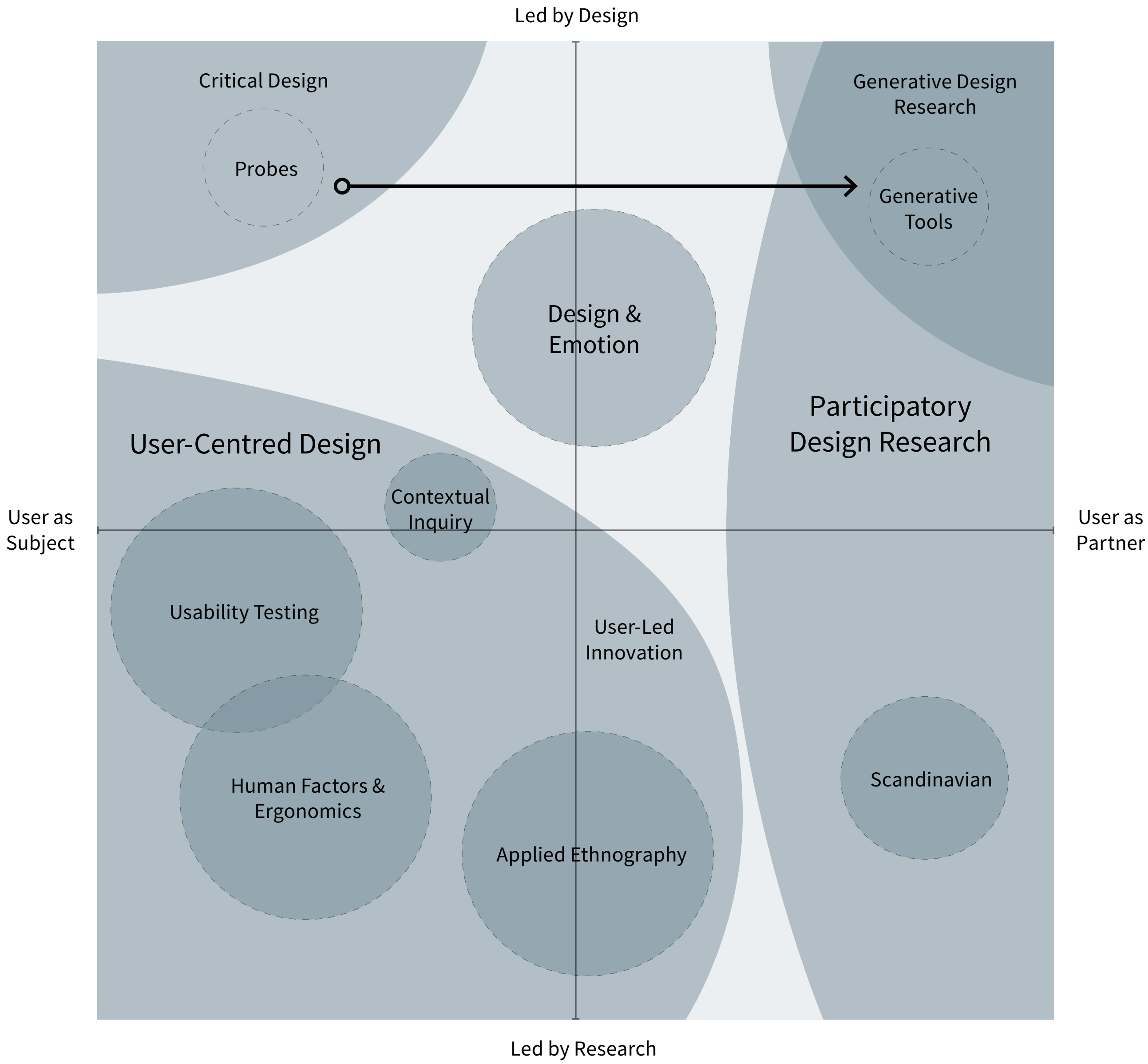


Figure 07. Current Landscapes of Human-Centred Design – Sanders and Stappers 2008

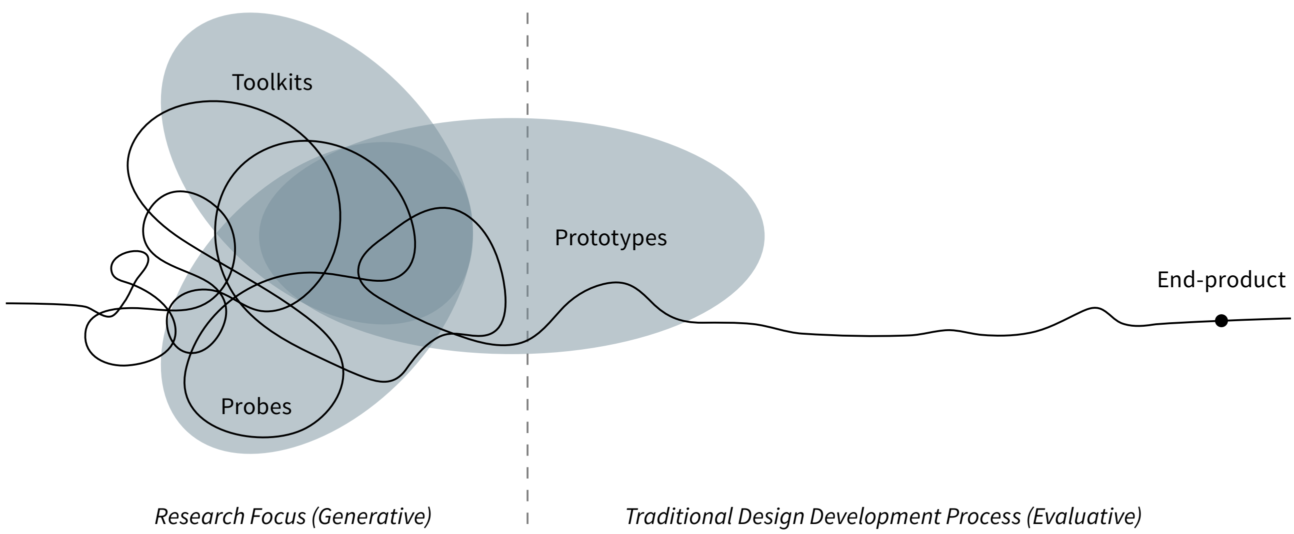


Figure 08. Three approaches to 'making' are located along a timeline of the design process – Sanders and Stappers 2008.

3D printing the head and neck cradles largely based on her understanding that it was more accurate than vacuum forming. She had no intention of changing the overall form or function of the cradles. However, as a designer, I felt that this was a good opportunity to re-frame the problem. Although 3D printing was indeed more accurate, it also possessed a number of other technological advantages. Not only could designs be heavily customised, because 3D printing did not require a mould, the scale of the design could also be considerably reduced. Therefore, instead of reproducing the existing design, a series of different cradle designs were created to demonstrate these advantages. By exposing the oncologist to unconventional interpretations of the cradle's design, she was able to recognise other areas of design improvement, such as comfort and usability, that better optimised the chosen technology.

3D-printed design probes also appeared to trigger increased levels of excitement in participants. Wallace et al. (2013, 2) refer to this as the "provocative" and "enticing" nature of probes. Every time an artefact was introduced during co-design workshops, participants would become noticeably more animated and engaged in collaboration. This response was most apparent when workshops were facilitated at the DHW Lab's design studio. Not only were participants able to observe and interact with 3D-printed design probes, they also had the opportunity to observe a 3D printer in operation. There was something special about allowing participants to experience 3D printing first-hand. Education researchers Peck and Dorricott (1994, 3-4) argue that this excitement occurs because technology acts as a "Trojan horse", engaging and inspiring people to be more focused, harder working and further involved. Modern technologies like 3D printing stimulate people in a way that more traditional manufacturing methods may not. The inspiring nature of 3D printing may be a consequence of how well resolved the outputs are. More crude forms of probes such as storyboards or paper models may not have had as great an effect.

Another unanticipated byproduct of this excitement was that participants shared their experiences with other non-designers. In the earlier phases of research, it was difficult to identify and recruit suitable co-design participants. However, after several workshops, participants began to refer me to others, starting a snowballing recruitment effect. For example, the leg surgery simulation project originated from a conversation between two paediatric surgeons. The idea of participant-to-participant sharing was particularly significant when considering my role as a facilitator of co-design. In addition to the agency of the designer and design probes, participants were acting as a 'link' between the worlds of design and health (Dougherty 1992, 191-192). By passing this knowledge on, they helped to create a shared understanding for other healthcare professionals.

Importantly, however, there came a point in the design process where the creation of probes was not a productive or efficient use of collaboration time. Probes were useful during phases of divergent research and ideation, but convergence was ultimately needed in order to assess ideas and "decide which is best" (Brown 2009, 3). Sanders and Stappers (2014, 9) discuss this as a transition from generative approaches to evaluative (see Figure 08). Designers decide when made objects shift from designs of provocation (probes) to manifestations that aim to resemble the end result (prototypes).

Sanders and Stappers (2008, 2) consider probes a design-led approach, where the user is treated more as a subject. However, within this research, probes were explored as a 'generative tool' to establish the 'user as partner' (see Figure 07). By acting as a common language between the designer and the participant, probes helped to establish a shared understanding. This shared understanding provided a stronger foundation for the collaborative identification and development of optimal design opportunities. In this way, 3D-printed probes helped co-design interactions evolve from passive exchanges of knowledge to active relationships. Ranging from small flexible splints to large patterned cradles, each object was created with a specific purpose.

Limitations

In addition to the insights observed during this research, a number of limitations became apparent in relation to the way it was carried out and how it applies to the wider body of human-centred design research.

The first limitation concerns the research sample size. This research, involving a total of 12 participants across two different hospitals, is considered a small-scale study (Hackshaw 2008, 1141). As Hackshaw discusses, small sample sizes limit the accuracy of results and risk over-estimating the "magnitude of an association" (2008, 1142). The data collected from collaborating with participants involved in this research may not accurately represent the wider body of healthcare professionals. For instance, selected participants may have had certain characteristics or personality traits. Those more curious about technology or design could have shown greater interest than those that did not. Some participants also weren't selected due to a lack of availability. Healthcare professionals with less time may have behaved differently to those that did. However, due to the time allocated within the scope of research, facilitating additional collaborations was not easily feasible. There is also the possibility that a larger sample size may experience the same discrepancies. The themes and insights that did emerge during research appeared to be fairly consistent across all of the co-design projects.

Another aspect of research limited by time was the way co-design workshops were scheduled. In attempting to work around the limited availability of different healthcare professionals, workshops were often sporadic and unpredictable. Fewer projects and more regular meeting times would have provided participants with the opportunity to meet more often. Organising workshops in a more controlled manner would also have allowed me to make more accurate comparisons between different co-design relationships and their development. Nevertheless, contact was predominantly restricted by participants and not myself. Oftentimes I was forced to wait due to the healthcare professionals' busy schedule.

There were also limitations as we tried to avoid projects that required formal ethical review – those that specifically required patients or the use of patient data. Despite this, using a co-design approach, this research aimed for designs to be driven by the needs, desires and experiences of end-users (Giacomin 2014, 608). Many of the designs were specifically for patients as end-users. However, due to the limited scope of research and the nature of ethics, I chose to engage only with healthcare professionals. Seeking ethics approval for each new project would not have been easily feasible within the constraints of masters research, particularly considering the agile nature of projects and opportunities. Despite this decision appearing to conflict with co-design, a number of strategies were used to get around this. Although not as accurate or informative, methods such as role-play and expert evaluations were used as an alternative way to access users' experiences and develop a sense of empathy for those the design was intended for.

However, this ethical issue became less of a problem as the focus of the research shifted. The focus moved away from end-users and end-products, and towards exploring 3D printing as a tool to help develop co-design relationships. Most of the designs generated during research are still under development, requiring additional resolution, safety testing and user validation. While a number of the designs created during research held promise, I needed to secure ethics approval for patient testing in order to validate certain 3D-printed concepts further. This is not to say that developing the design to the end-product stage was not important. As Sless (1997, 6) highlights, tightly budgeted organisations such as hospitals are often very interested in 'successful' design outcomes that reach this final end stage.

Benefits of Co-Design Relationships

By helping to develop shared understanding, 3D-printed probes enabled co-design interactions to evolve from passive exchanges of knowledge to active relationships (Rizzo 2011, 128). The benefits of these relationships were particularly evident with long-term co-design partners such as the oncology physicist and the medication safety technician. After collaborating on a number of projects, some of which took place prior to this research, we had developed a deep level of shared understanding and a strong sense of trust in each other's expertise. In contrast to the initial interactions with other research participants, communication with these particular participants was purposeful and efficient from the beginning. Rather than suggesting a broad problem area, both participants were able to effectively link specific clinical issues with an appropriate 3D-printed design solution. The physicist, for example, proposed the 3D-printed simulation arm based on his existing understanding and his experience with the 3D printing technologies used to produce TBI blocks. Similarly, the safety technician proposed 3D-printed insulators based on his experience from a prior project involving 3D-printed anaesthetic bottle clips. Because there was no need to educate the technician on technological capability or design purpose, the entire workshop took less than 15 minutes.

These kind of long-term relationships are thus incredibly effective and time efficient and may increase the likelihood of successful design outcomes. As Norman and Stappers (2015, 87-88) describe, designers often have to operate within constraints such as "regulatory agencies, laws, economic and business issues and safety concerns". In large complex organisations such as hospitals these constraints extend even further. Professor Leonardo D'Avolio (informationweek.com 2015) argues that "most of the healthcare industry views designers as a luxury". Collaborative design research may prove effective, but public service organisations operating under strict 'cost versus benefit' systems often see it as too high-risk (Sless 1997, 6). Sless argues that large organisations desiring to maintain "optimum usage" are most "interested in successful outcomes, and it is the responsibility of any profession to stand by its work and offer some guarantee of outcome and quality" (1997, 6). Yet, as Madden and his fellow researchers highlight, involving participants does not necessarily guarantee innovation (2014, 14-15).

For example, some of the design opportunities initially considered to be promising were later found to be unsuitable. Although collaborators did their best to identify suitable applications for 3D printing, the potential of chosen opportunities was based on undeveloped assumptions. Each collaborative venture therefore came with level of uncertainty and the risk of wasting time or resources. Although more matured co-design relationships did not guarantee collaborative success, they may have helped to reduce this risk. As with any relationship, it may take a number of projects and considerable time before co-design relationships become effective. Deana Pennington (2008, 3) suggests that learning to interact and collaborate well with members of different disciplines "takes time" and requires a "building of trust". With the help of design tools such as probes, co-design relationships may mature to a point where they act as a more reliable and efficient model for identifying and developing suitable design opportunities in the future.

Photos showing a collection of probes and prototypes created during this research.

conclusion_

3D printing is a unique form of manufacturing used for a number of high-end healthcare applications. Yet issues such as cost and applicability suggest these designs are being driven by an industry that may not have an in-depth understanding of the clinical environment. In order for designers to create more informed solutions, researchers advocate co-design – a human-centred design approach that invites users to not only exchange their knowledge and experiences, but also to actively participate in design-related tasks such as drawing and model making. In this research, healthcare professionals were engaged as users – clinical and patient experts – I worked with in order to identify suitable applications for 3D printing in a hospital context.

However, due to the complexity of 3D printing technologies, involving participants in the design process was not straightforward. Healthcare professionals' understanding of 3D printing capability and design potential was often limited or inaccurate. The same limitations applied to the designer's understanding of the clinical environment. Without shared understanding, co-design participants struggled to identify suitable opportunities. In order to establish this connection, research suggested a common language was needed to bridge disparate worlds of design and health. My strategy for developing shared understanding began as expert interviews. Verbal dialogue, however, was quickly found to be a limited form of communication.

As a result, probes were introduced – 3D printed objects designed to capture the knowledge and assumptions of the designer and demonstrate specific technological properties. These objects made it possible to communicate a wide range of information in the short space of time allocated to co-design workshops. The designs being produced were not representatives of the final product, but rather vehicles for expression, discussion and reflection. Combined with small-scale parametric-based CAD, the unique properties of 3D printing allowed me to efficiently produce highly resolved probes at very little expense. Digital models were easier to edit and faster to 3D print following participant feedback. This efficiency was especially significant considering healthcare professionals' limited availability. The earlier probes could be used to help participants develop a shared understanding, the more productive and effective co-design workshops became. Collaborative interactions evolved from passive exchanges of knowledge to active co-design relationships where participants were able to make informed design suggestions based on their new knowledge.

Probes also proved to be effective as design catalysts, particularly when workshops were conducted within a design environment. Participants were given the opportunity to observe 3D printing technologies in-person and interact with highly resolved 3D printed models first-hand. Exposing participants to more unconventional interpretations of design solutions helped them to identify further areas of design improvement. This excitement even led some participants to share their co-design experiences with other non-designers via word of mouth, helping them to also develop a shared understanding.

However, probes have a number of limitations. Probes embody a dense amount of information. Participants may need to be given additional time to reflect on this. Probes are most useful in the exploratory phrase. There comes a point in the design process where probes are no longer a productive use of collaboration time. Probes were applied at a small scale. It is difficult to assess whether other healthcare professionals or patients, if they had been included, would have responded differently to probes.

Despite these limitations, probes consistently demonstrated that object-to-human interactions had just as much, if not more, agency than purely human-to-human interactions. By helping to develop shared understandings, these objects provided a stronger foundation for the collaborative identification and development of optimal design opportunities. In an environment such as hospitals, where time and money is often limited, these more effective co-design relationships appear to provide a more reliable model for successful design outcomes.

recommendations_

Throughout this research, projects were constrained by issues of time, participant availability and ethics approval for involving patients. To further investigate the usefulness of 3D-printing design in a healthcare context, and return to the original intentions of the research question, there is certainly a place for following up on the collaborative insights and physical outcomes arising from this inquiry. Based on these key learnings, my recommendations are as follows:

Ethics approval and safety testing are needed to fully resolve some concepts. In order to develop and validate 3D-printed concepts to a point where they are suitable for patients as end-users, ethics approval for patient testing needs to be secured (page 38). Concepts requiring additional resolution, safety testing and user validation could be part of another research project, but at the least, can use findings from this research to enhance outcomes (page 127).

Additional material testing is required. A separate research project testing 3D-printing materials for usefulness in the healthcare context is needed (page 64). PLA plastic, the material commonly used in desktop 3D printers, may not be suitable in some clinical environments. Processes such as sanitation and radiation treatment might put too much stress on the material. For safety and suitability purposes, this conditioning would need to be tested in future research.

Strategic selection of co-design participants. To make more accurate comparisons between a range of co-design participants, designers need to be consistent with who they collaborate with. For instance, instead of involving both new and existing co-design partnerships, only new partnerships should be explored. Additionally, ideal participants understand both the problem and their department as a whole (page 68).

Further validate the unique value of 3D-printed probes (versus other construction processes). Future research might investigate the specific qualities of these objects (page 94). This might include comparing 3D printing probes with those made with cruder methods such as clay or paper mock-ups, or the use of similarly advanced technologies such as virtual reality. The aim would be to observe whether alternative methods have the same level of capability and influence as 3D printing.

Further validate the importance of physical location in co-design. The DHW Lab's location inside Auckland City Hospital is used as a means of providing ongoing support and integrating the processes that designers use with those involved in healthcare (page 18). To measure the collaborative benefits of this proximity, future research might compare the effectiveness of on-site co-design projects with projects that were managed off-site.

CHAPTER 05

bibliography_

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CHAPTER 06

appendices_

appendix 1: prior contextual work 1_

Total Body Irradiation Blocks

During my time at the DHW Lab, prior to this research, I worked on two projects that utilised 3D printing. The first project involved working with clinical engineers and the radiology department to redesign total body irradiation blocks (TBI). TBI blocks are solid acrylic extrusions used to attenuate radiation during treatment. The thickness of each block varies based on the area of the patient it is attenuating, so the patient receives a consistent dose throughout the body. In front of the lung area the block is particularly complex due to the air inside the lung. Due to the labour-intensive construction process, producing these complex lung blocks was both costly and time consuming. Clinical Engineering approached the DHW Lab hoping that our design expertise would help them identify a more efficient form of manufacturing.

Despite the engineering team only wanting me to explore an alternative form of manufacturing, I chose to examine the entire process from start to finish in case there was further opportunity to improve the design beyond manufacturing. Design researchers Norman and Stappers (2015, 87) describe this investigative process as the discovery of the underlying causes, and highlight how this is the only way for designers to properly solve the entire problem. My examination involved learning about the many stages of production and speaking to each person who was involved.

During this inquiry I discovered two key insights. The first was that the block's simple 'box like' appearance was a direct result of the chosen manufacturing method. The measurements from the patient CT scan data were too complex three-dimensionally for the engineers to recreate accurately using cut acyclic sheets. To make it easier for engineers, the data was therefore simplified. However, this simplification meant the blocks weren't as accurate and thus potentially as effective as they could have been.

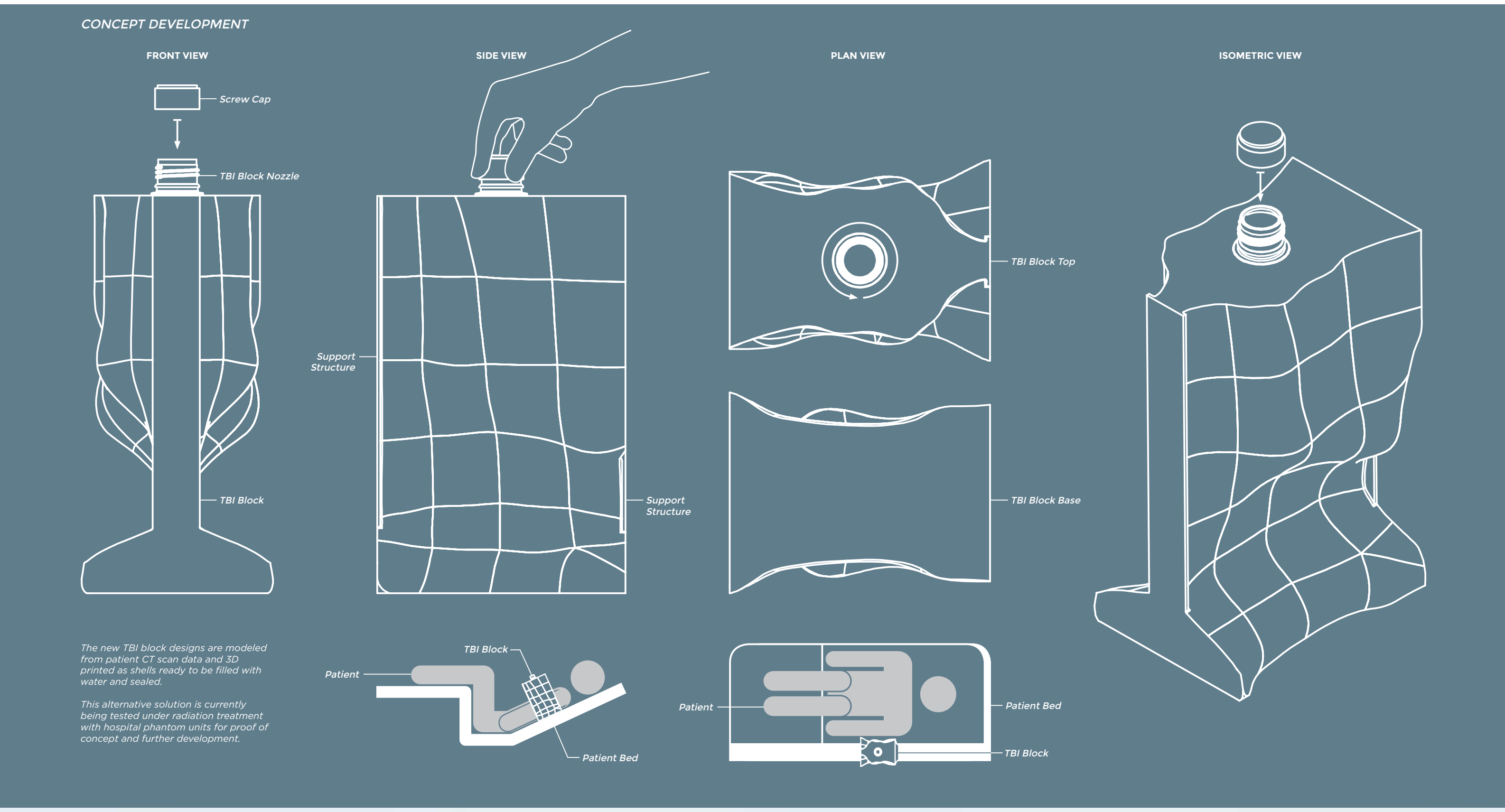
The second insight was the siloed nature of the production process. Each stage of production involved a number of different people, technologies and processes. Lack of effective communication between members of this complex system led to a number of misconceptions. For instance, the engineering team weren't aware the resolution of the scan data they used had been compromised to simplify construction. The meticulous and precise nature with which they created the blocks was therefore superfluous. On the other hand, the radiology team were unaware of both the considerable time it took for engineers to produce the blocks and the manually intensive manufacturing processes that were used (two to three days).

Identifying these communication issues allowed me to develop a solution beyond the scope initially suggested by the engineers. The proposed use of 3D printing not only reduced the number of manual steps needed in production (initial brief), it also enabled the production of more accurate blocks, and therefore potentially more effective treatment.

The development of the TBI blocks also raised a number of important questions in relation to design:

- *What did the decision to widen the scope of the project say about the role of designers and non-designers in design projects?*
- *What is the most effective way to link problems experienced in healthcare with suitable design solutions?*
- *How can technologies such as 3D printing help designers to facilitate this?*

Images illustrating how the 3D-printed TBI blocks work, and a photo of an existing block next to a 3D-printed model.



appendix 2: prior contextual work 2_

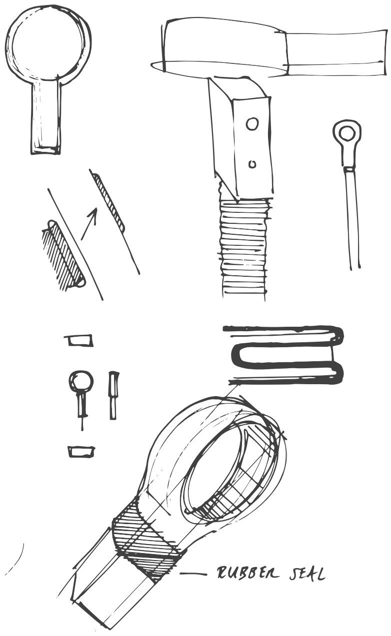
Anaesthetic Bottle Adapter Clip

The second contextual example involved working alongside a medication safety technician to solve a safety issue with medicine bottles holding inhalation anaesthetic liquid. These particular bottles required an adaptor piece (replacing the original bottle cap) in order to connect with the mechanism that injected the anaesthetic into the patient. When the bottle wasn't in use, however, openings at the top of the adaptor exposed staff to inhalation fumes and created a potential safety hazard if the bottle was knocked over. The technician tried contacting the original manufacturers of the adaptor but they declined to help. Only after hearing about the DHW Lab through a colleague did the technician then approach the Lab's design team.

Initially the goal of the project was to create an object that covered the opening that exposed staff to the liquid. The construction method, however, was undetermined. Due to the relatively small size of the adaptor, and the need for a customised design, 3D printing was selected as the logical choice for low-quantity manufacturing. 3D printing allowed me to quickly and iteratively develop physical prototypes that I could then test, analyse and further develop. I spent time finding out as much as I could about the process of using the bottles and the people involved. Similar to the TBI block project, this was done in case there were any issues that the technician had failed to identify.

Following a number of discussions with the pharmacy team I discovered that the adaptors were repeatedly being interchanged with the original cap because of the known safety issues. However, this made it difficult for staff to know when a bottle was already 'in use' – assigned to a specific patient or procedure, with dosed amounts already withdrawn. The final design solution consisted of a small 3D-printed clip paired with a silicon band to create a seal over the adaptor. This seal prevented fumes or liquid from escaping the bottle and removed the need for staff to switch back to the existing cap. The clip could also be slotted sideways onto the bottle to indicate when a bottle was being used.

My interactions during this contextual work also raised a number of interesting questions in relation to design. For example, how can designers help to ensure that issues absent from the initial problem, analysis are exposed and factored into the design solution? Without addressing the entirety of the problem are designers really maximising the opportunity to add design value? Sauder and Jin's (2016, 21) research on collaborative design thinking points out that collaboration does not necessarily guarantee the solution to a design problem. Co-design is not a magic formula or a silver bullet. That said, co-design can offer designers crucial insights into participants' understandings of their own problems. As Sauder and Jin affirm, this can increase the likelihood of arriving at well-informed design solutions. If this is true, are there ways to establish more effective design relationships? Are there parts of the design process where designers should be focused on relationships, and others focused more heavily on solutions?



Anaesthetic bottle adapter clip overview.

appendix 3: expert interviews_

Indicative interview questions are a set of questions that provide a consistent structure for each of the interviews conducted.

Structure

1. Introduce myself e.g. name, university, background, occupation etc.
2. Allow time for interviewee to introduce him or herself.
3. Allow time to go over consent form and information sheet.
4. Brief contextual summary of research aims and research thus far (designer).
5. Facilitate discussion using five indicative interview questions.

Question One

How much do you know about 3D printing in terms of both capabilities and application?

Question Two

Do you currently use 3D printing in any of the areas you are involved in? If so, in what way is it used? If not, why?

Question Three

Are you aware of any clinical problem or need where a potential solution may lend itself to 3D printing design opportunity?

Question Four

Why do you feel that 3D printing would be a suitable manufacturing method or design tool for this particular problem or need?

Question Five

What would the value of design be if this opportunity was further developed?

appendix 4: information sheet_

Project Title
3D Printing and Co-design into Healthcare

An Invitation
Hello, my name is Josh Munn. I am currently a Masters student studying Art and Design at Auckland University of Technology (AUT). I would like to ask for your help with my research, which aims to find out how 3D printing can add value to a co-design practice within a hospital context.

What is the purpose of this research?
With your help a series of 3D-printed design opportunities will be explored in response to real-world healthcare problems, investigating both the capabilities and limitations of 3D printing as a design tool in a hospital context. Using a practice-based model, these insights will feed into a written analysis, with the aim to propose how 3D printing can be used to advance clinicians' understanding and value of design, and conversely designers' understanding of the healthcare experience.

How was I identified and why am I being invited to participate in this research?
You have been approached because your area of work or expertise may lend itself to 3D printing or a potential design opportunity relating to my research. You may also have knowledge in an area that will help inform the development of a design concept.

What will happen in this research?
If you would like to participate in this research, then I will ask you some simple questions about your experiences in relation to your clinical area of expertise. For instance, I may ask you about any problems or needs you may have encountered that could potentially be of interest to my research. This will include your thoughts on some of the physical equipment or objects that you interact with as well as non-physical aspects of the experience, details about the processes that take place within your area of work, and any interesting observations you may have in relation to these topics. The aim of the questions is for me to understand your experience and perspective; there are no wrong answers and I am grateful for any thoughts you would like to share with me. You can ask me any questions that you have about my research, or choose to end the conversation during an interview. You may also withdraw any time before October 1st 2016 if you change your mind about participating or aren't available to continue participating. Written notes made during the interview will made available for you to review if at your request.

What are the benefits?
I benefit from this research by using the results to complete my qualification. I also get to practice my skills and gain experience running a project like this. In return I hope that you will benefit from the opportunity to share your thoughts and experiences. You will also have the chance to contribute towards a potential improvement of to the healthcare experience for patients or staff.

How will my privacy be protected?
For my thesis no information that might be used to identify you will be included. Any information that I collect about you in the form of written notes from our interviews will be kept for a minimum of six years and then destroyed. I will not be recording interviews via audiotape.

What are the costs of participating in this research?
There is no cost to you for participating in this research except for a time contribution. There is no mandatory time contribution, however it is expected that any interview session will take approximately thirty minutes and no more than an hour. You may be contacted at a later date for follow up interviews if your expertise is needed again in relation to the research. However, you will be under no obligation to participate in these further interviews and the duration of any interview sessions will be made flexible according to your availability.

How do I agree to participate in this research?
If you have considered this invitation and would like to participate in my research, you will need to let either myself (or the person who has supplied you with this information sheet) know. We will discuss the research with you including any questions you may have. If you are interested, you will be asked to complete a written consent form. You have the right to withdraw from this research at any point, no questions asked. Any data you have given will be destroyed. You also have the right to walk out of a session for any reason or to choose not to answer any questions that you are unhappy or uncomfortable with.

appendix 5: ethics approval_

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

11 March 2016

Stephen Reay
Faculty of Design and Creative Technologies

Dear Stephen

Re Ethics Application: **16/60 Layer by Layer - 3D printing co-design into healthcare**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 11 March 2019.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 11 March 2019;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 11 March 2019 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

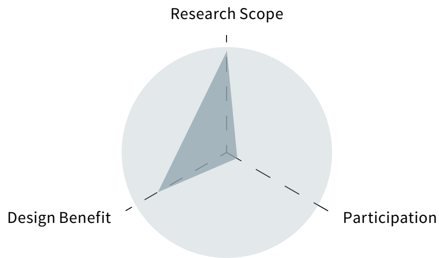
Cc: Josh Munn joshmunn.nz@gmail.com, David White

appendix 6: discontinued projects_

During research a number of additional opportunities were started but discontinued because, for various reasons they were unsuitable for research.

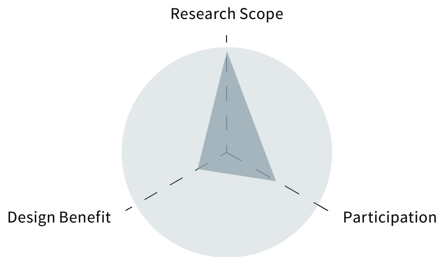
1. Crutch Handle

To try and gain some momentum early in research, I began developing a customised 3D-printed crutch handle concept. The project, however, missed the point of my research question and the opportunity to establish new co-design relationships.



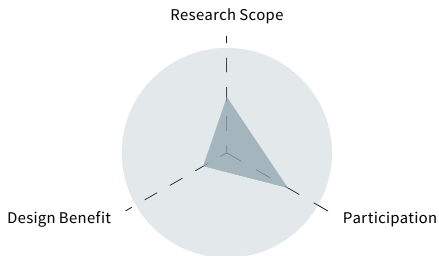
2. Craniofacial Reconstruction Jig

This concept involved printing bone structures to help with personalised moulds during facial reconstruction. However, similar to the crutch handle, this concept was self-generated, and therefore missed the point of my research. It was also deemed unsuitable by plastic surgeon 1 during a co-design workshop.



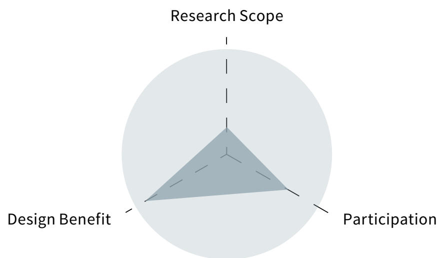
3. Cleft Palate Mouthpiece

Existing mould-making techniques for cleft palate mouthpieces held several advantages over 3D printing. Moulds took less time and didn't require a 3D scan of the patient. The materials used for mould making were also lower-cost, easier to manipulate and better suited for babies' mouths. 3D printing was therefore deemed unsuitable.



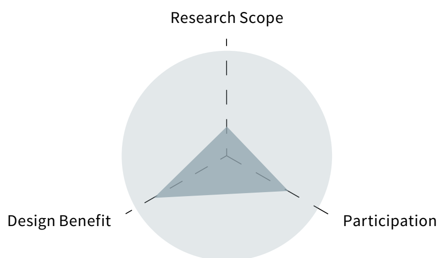
4. TOF/OA Surgery Simulation

OA is a defect where babies are born with a pouch at the top of their oesophagus which prevents food from reaching the stomach. TOF is a defect where the bottom end of a baby's oesophagus is joined to its trachea (windpipe). Without surgical intervention air can pass from the windpipe to the food-pipe and stomach. The concept was to create a 'baby-like' simulation model to practice this intervention. However, the scope and complexity of this project was also deemed too great.

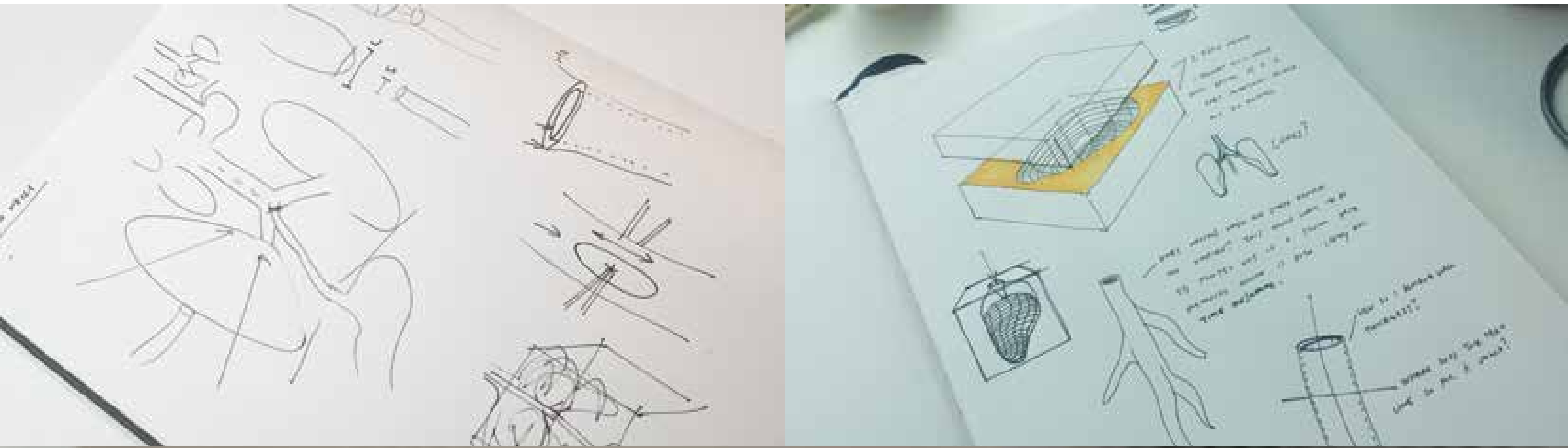


5. Neonatal Head Defect Helmet

Near the end of research the craniofacial surgeon contacted me in regards to a baby born with a head deformity. His idea was to 3D print a custom helmet that would help correct the deformity. However, due to a lack of ethics approval the project was deemed unsuitable. The scope of the project was also too great for the amount of time I had left, even for a proof of concept.



Sketches done during a workshop with paediatric surgeon while discussing the potential for a TOF/OA simulation model.



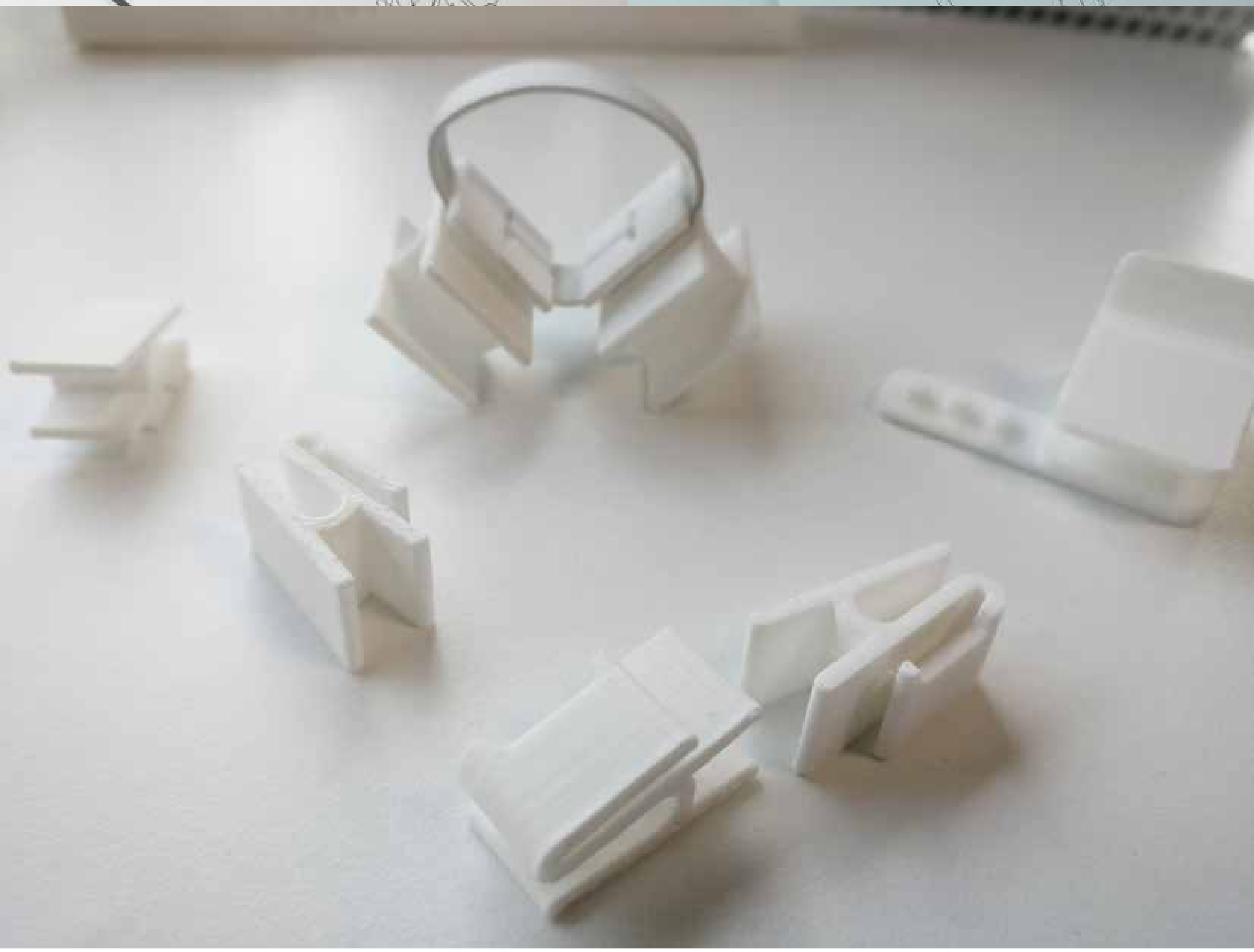
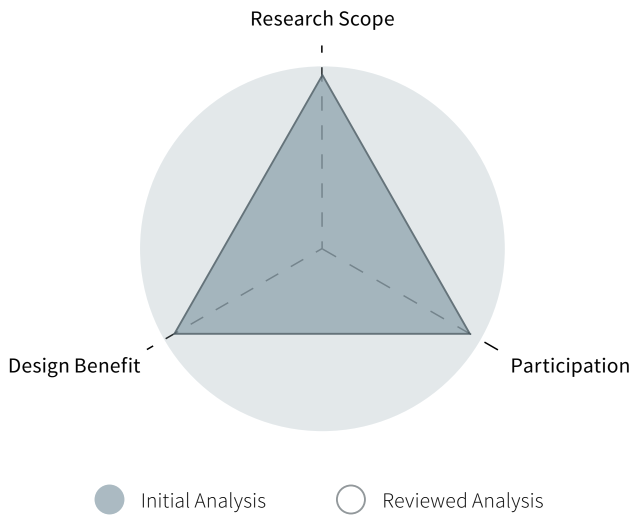


Photo showing a series of cleft palate mouthpiece design probes.

appendix 7: additional project_

During research an additional project was done with the medication safety technician around a pill dispensary machine. Although the project produced a successful end-use product, the collaboration did not help to answer the research question any further than medication fridge insulator already had.



Pill Dispensary Chute

The design problem was in relation to the overly large quantities of prescription medication in wards. A considerable portion of these medications would often expire. The medication safety technician believed that smaller containers with lower quantities may help to prevent this problem. Doing this manually, however, would have been far too time consuming for staff, and potentially inaccurate. Medication machines that automated this process were available, but they were deemed too expensive by the hospital. A smaller low-cost machine was purchased that automated the measuring process, but still required staff to individually handle each container. Although the machine could output smaller quantities, the metal chute at the bottom of the device was too wide for smaller containers. The technician proposed that I design a customised 3D-printed object that helped to rectify this functionality issue.

Based on the existing measurements of the machine and functionality required, 3D-printed attachments were developed and printed for two dispensing machines. The attachment narrowed the space the pills traveled through, allowing staff to accurately and consistently transfer medication into a range of smaller container sizes. A small vinyl sticker was also created to help staff know where to place the containers before carrying out the transfer process.

Photos showing the development of a customised 3D-printed chute for a pill dispensing unit.