BENEATH THE SKIN

Emulating human physiology using a novel bitmap-based “voxel” 3D-printing workflow.

Ana Morris

2020

—

Cover:

Figure 1. Close-up of bitmap-based 3D-printed neonatal limb (leg).

BENEATH THE SKIN

by

A N A M O R R I S

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

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*School of Design Innovation
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DEDICATION

To my Nana, Mary Morris

Left:

Figure 2. A bitmap-based 3D-printed foot. A close-up of the toe flexing.

—

Abstract

Novel technologies that produce medical models which are synthetic equivalents to human tissue may forever change the way human anatomy and medicine are explored. Medical modelling using a bitmap-based additive manufacturing workflow offers exciting opportunities for medical education, informed consent practices, skills acquisition, pre-operative planning and surgical simulation. Moving medical data from the 2D-world to tactile, highly detailed 3D-printed anatomical models may significantly change how we comprehend the body; revamping everything – from medical education to clinical practice.

Research Problem

The existing workflow for producing patient-specific anatomical models from biomedical imaging data involves image thresholding and iso-surface extraction techniques that result in surface meshes (also known as objects or parts). This process restricts shape specification to one colour and density, limiting material blending and resulting in anatomically inequivalent medical models. So, how can the use of 3D-printing go beyond static anatomical replication? Imagine pulling back the layers of tissue to reveal the complexity of a procedure, allowing a family to understand and discuss their diagnosis. Overcoming the disadvantages of static medical models could be a breakthrough in the areas of medical communication and simulation. Currently, patient specific models are either rigid or mesh-based and, therefore, are not equivalents of physiology.

Research Aim

The aim of this research is to create tangible and visually compelling patient-specific prototypes of human anatomy, offering an insight into the capabilities of new bitmap-based 3D-printing technology. It proposes that full colour, multi-property, voxel-based 3D-printing can emulate physiology, creating a new format of visual and physical medical communication.

Data Collection and Procedure

The work explored and in this research portfolio is the first of its kind, entering into a 3D-printing territory that has never been published before. For this study, biomedical imaging data was converted into multi-property 3D-printed synthetic anatomy by bypassing the conversion steps of traditional segmentation. Bitmap-based 3D-printing allows for the precise control over every 14-micron material droplet or “voxel”. Control over each voxel involves a process of sending bitmap images to a high-resolution and multi-property 3D-printer. Bitmap-based 3D-printed synthetic medical models – which mimicked the colour and density of human anatomy – were successfully produced.

Findings

This research presented a novel and streamlined bitmap-based medical modelling workflow with the potential to save manufacturing time and labour cost. Moreover, this workflow produced highly accurate models with graduated densities, translucency, colour and flexion – overcoming complexities that arise due to our body’s opaqueness. The presented workflow may serve as an incentive for others to investigate bitmap-based 3D-printing workflows for different manufacturing applications.

This *designed definition* may serve as an incentive for others to go beneath the skin and touch upon the essence of existence.

Figure 3. Image of bitmap-based 3D-printed neonatal toes.

P r e f a c e

“With kindred presumptions of benefice, the doctor studies the body to improve its fate; the artist to improve its spirit.

Above all, these students start with the same genre of book: the illustrated anatomy. Here the body is laid bare inside and out in pictures that work in several realms.

They are science in subject, illustration in usefulness, but art in their potential emotional impact”

(Rifkin et al., 2006, p. 7).

Personal Motivation

Throughout my Industrial Design Undergraduate Degree at the School of Design Innovation at Victoria University of Wellington, I had the privilege of being able to work on many multi-property 3D-printing projects. This undergraduate research led on to a Summer Scholarship research opportunity developing 3D-printed test and calibration phantoms for X-ray CT imaging in collaboration with the Department of Radiation Therapy, University of Otago Wellington and MARS Bioimaging, New Zealand (MBI). As a result, the summer research project taught me about the principles of biomedical imaging. This research portfolio presents a creative exploration that lies in the intersection between medical imaging principles, new technology and design.

Figure 4. Unboxing 3D-prints sent from Stratasys in Shanghai, China.

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This research portfolio would not have been possible without all the people who have helped me throughout the way, and because of this, I will be forever grateful.

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TABLE OF CONTENTS

.....

01

Dedication / IV
Abstract / VI
Preface / VIII
Personal Motivation / IX
Acknowledgements / XI

INTRODUCTION

- 1.1 Chapter Content Descriptions / 2
- 1.2 Terminology
 - 1.2.1 Digital Fabrication Terminology / 4
 - 1.1.1 Medical Terminology / 6
- 1.3 Introduction to the Research / 11
- 1.4 Research Direction / 14
 - 1.4.1 Purpose Statement
 - 1.4.2 Research Question

02

METHODOLOGY

- 2.1 Research Aims and Objectives / 18
- 2.2 Research Methodologies / 21
 - 2.2.1 Research Structure / 23
 - 2.2.2 Practical Action Research / 24
- 2.3 Research Methods / 24
- 2.4 Software, Hardware and Data / 28
 - 2.4.1 3D-Printers / 30
 - 2.4.2 Programmes / 32
 - 2.4.3 Data & Ethics / 33

03

BACKGROUND RESEARCH

- 3.1 Historical Overview / 39
- 3.2 Literature Review / 43
 - 3.2.1 Biomedical Imaging / 44
 - 3.2.2 Physical Modelling in Medicine / 47
 - 3.2.3 Multi-Material 3D-Printing / 62
 - 3.2.4 Project Scope / 68

Note: All *Figures* are the author’s own images or diagrams, apart from *Figure. 18.*, which is an artwork in the public domain.

04

PRACTICAL ACTION RESEARCH

4.2 Case Study 1 / 76

- 4.1.1 Overview / 79
- 4.1.2 Criteria / 80
- 4.1.3 File Preparation / 81
- 4.1.4 Design Experimentation / 85
- 4.1.5 Final Design / 99
- 4.1.6 Reflection / 114

4.3 Case Study 2 / 119

- 4.2.1 Overview / 121
- 4.2.2 Criteria / 122
- 4.2.3 File Preparation / 123
- 4.2.4 Design Experimentation / 127
- 4.2.5 Design Refinement / 149
- 4.2.6 Final Design / 165
- 4.2.7 Reflection / 179

4.4 Case Study 3 / 183

- 4.3.1 Overview / 184
- 4.3.2 Criteria / 185
- 4.3.3 Material Exploration / 189
- 4.3.4 Design Experimentation / 199
- 4.3.5 Reflection / 201
- 4.3.6 DAP Voxel Software Concept / 213

05

DISCUSSION

5.1 Key Findings / 219

5.2 Interpretations / 222

- 5.2.1 Case Study 1 / 222
- 5.2.2 Case Study 2 / 224
- 5.2.3 Case Study 3 / 227

5.3 Implications

- 5.3.1 Bitmap-based vs. Mesh-based 3D-Printing / 229
- 5.3.2 3D-Printing Theory and Practice / 234
- 5.3.3 Cultural Implications / 235

5.4 Limitations / 236

5.5 Recommendations / 237

06

CONCLUSION

6.1 Concluding Statement / 241

6.2 Reference List / 242

6.3 Appendix A / 250

6.4 Appendix B / 256

01

INTRODUCTION

Figure 5. Bitmap-based 3D-printed neonatal foot (left).

1.1 CHAPTER CONTENT DESCRIPTIONS

01

INTRODUCTION

A brief introduction outlining the project and the issue under investigation (introducing the reader to the topic).

02

METHODOLOGY

This section outlines how the research was undertaken using the Research *through* Design methodology and a criteria-based approach. This chapter describes the research procedures, structure, software, hardware, aims, objectives and methods.

03

BACKGROUND RESEARCH

The Background Research section sets the scene and contextualises the research. A Historical Overview and a review of literature will support the research by analysing past studies and identifying gaps in the knowledge to help shape the research. Themes explored in this chapter include the history of anatomical studies, the value of 3D-printing in medicine and current 3D-printing workflows.

04

PRACTICAL ACTION RESEARCH

This chapter focusses on developing primary research through a creative and iterative design research process.

A Case Study approach was used in this section to show three avenues of design exploration. The three case studies are outlined in chronological order and become more refined based on feedback from expert opinions and qualitative analysis of design experiments.

05

DISCUSSION

Included within the Discussion section is a critical analysis of the results, including the underlying meaning of the research, possible implications, improvements, limitations of the study, and whether the results successfully address the research criteria

06

CONCLUSION

The concluding section of this research summarises the key points in the research and highlights the research value by reiterating the main points, the research problem, results, findings, and future avenues for exploration.

*1.2.1***Digital Fabrication Terminology****3 D - P R I N T I N G**

a type of additive manufacturing (AM) that builds a physical object out of a digital blueprint by depositing sequential two-dimensional (2D) layers of material in order to create a three-dimensional (3D) form (Bastawrous et al., 2018, p. 2809).

B I T M A P

a type of image (e.g. PNG or JPEG file formats) that is made up of squares, or ‘pixels’, that form a grid making up a full image. The smaller the squares that make up an image, the higher the quality (resolution) of the image. Each pixel holds colour data.

B I T M A P - B A S E D “ V O X E L ” 3 D - P R I N T I N G

a method of AM that can translate information from various types of bitmap datasets into heterogeneous physical entities by converting on-screen pixels into multi-material droplets. These micro-droplets are also referred to as ‘voxels’ (Bader et al., 2018, p. 2).

V O X E L

a term used to describe a ‘3D-printed pixel’, a 14-micron material droplet.

T H E S T R A T A S Y S J 7 5 0 ™ 3 D P R I N T E R

a full-colour and multi-material Polyjet 3D-printer manufactured by Stratasys and supplied by the School of Design Innovation, Victoria University of Wellington.

A G I L U S 3 0 ™

a rubber-like PolyJet photopolymer material that can flex and bend.

V E R O ™

a rigid PolyJet photopolymer material available in many colours.

S H O R E H A R D N E S S S C A L E

a scale which measures the ‘hardness’ (density) of rubber and plastic materials.

Figure 6. Bitmap to voxel process.

1.2.2

Medical Terminology**BIOMEDICAL IMAGING TECHNIQUES**

are also known as “volumetric scanning technologies”, which include computed tomography (CT) and Magnetic Resonance Imaging (MRI) (Doubrovski et al., 2015, p. 9).

SEGMENTATION

the process of extracting elements of an image into different parts such as different tissue classes, organs, and structures.

MEDICAL MODELLING (also known as Bio-Fabrication)

a term that refers to the use of biomedical imaging datasets to produce computer-aided design (CAD) models, resulting in personalised medical devices or exact replicas of a patient’s anatomy (Allenby & Woodruff, 2019, p. 161).

Figure 7. Details of bitmap-based 3D-printed Visible Human®.

Figure 8. Anatomical directional terms.

Figure 9. Growth through 3D-printing.

CHAPTER 1

1.3 INTRODUCTION

FOR MILLENNIA, HOMO-SAPIENS HAVE BEEN FASCINATED BY WHAT LIES BENEATH THE SKIN. This curiosity has resulted in a constant evolution of technology and medical knowledge – providing for an ever-increasing understanding of the human body and its various intricacies.

Despite the wealth of knowledge available about the human body, it is still difficult to truly visualise what lies under the skin and how the body functions. To some degree, the human body has a mind of its own. Lungs instinctively fill with air; a baby will swallow without being told. Because of the body's automatic nature, there is immediate and justified cause for concern when the human body momentarily malfunctions. Clinicians question the cause of the malfunction, along with how it can be remedied.

Currently, clinicians rely on their use of tactile interaction with anatomy, feeling the range of textures and densities beneath the skin's surface. But, imagine if skin were transparent; if we could see underneath it, and watch a heart fuel our organs while they work away like little machines.

It is this possibility that spurred this research.

Topic

The purpose of this research is to 3D-print patient-specific and high-fidelity medical models on the Stratasys J750™ 3D-Printer using a bitmap-based 3D-printing workflow and biomedical imaging data. This will ultimately expose the potential of bitmap-based 3D-printing for the purpose of replicating anatomical density and colour in patient-specific medical models by engineering complex material combinations, controlling every 14-micron voxel. Harnessing novel medical modelling techniques may provoke a newfound way of imaging the human body – allowing for a whole new dimension of medial visualisation.

Research Problem

3D-printed medical models are currently used in the medical field in areas including surgical simulation, pre-operative planning and education. These models are created from biomedical imaging data to allow the production of exact replicas of patient-specific anatomy time and time again, without the need to access anatomically inequivalent cadavers. Current medical models are often low-fidelity and do not accurately reflect the intricacies of the human body to a high degree of realism.

A justification of, or the importance of, the problem as found in the past research and in practice.

At the beginning of 2019, the high-resolution Stratasys J750™ 3D-Printer became available to use at the School of Design Innovation at the Victoria University of Wellington. The opportunity to use this 3D-printing technology and its manufacturing capabilities drew interest. Notably, the capability to 3D-print in a bitmap-based format referred to by Stratasys as their “voxel printing” capability.

Bitmap-based 3D-printing is novel. Literature suggests that a bitmap-based medical modelling workflow has the potential to create medical models at a quicker rate and at a higher-resolution than traditional medical modelling workflows.

The deficiencies in our existing knowledge about the problem.

Since the 1980s, limited research has been conducted into developing 3D-printing workflows to suit the cellular make-up of the human body (which is organic in nature) (Bastawrous et al., 2018, p. 2809; Swetly et al., 2016, p. 145). Past bitmap-based 3D-printing studies have focused on the process of converting bioimaging medical data directly into 3D-printing files and physical models. However, past

research does not address the replication of accurate anatomical colour and densities using a bitmap-based 3D-printing workflow.

The audiences that will benefit from a study of the problem.

This study was conducted by way of a research through design methodology. This methodology allowed for a thorough design exploration of bitmap-based 3D-printing for medical modelling opportunities.

Bitmap-based medical modelling bares potential to be used as a replacement or adjunct to more traditional medical modelling workflows. This research may provide a general overview of novel high-end 3D-printing to the wider community, along with how to efficiently utilise the technology by emphasising the degree of detail that can be achieved by using a bitmap-based 3D-printing workflow to create high-fidelity medical models.

This research aims to encourage collaboration between designers and medical professionals to push for the capabilities of new technologies – creating a future focussed dialogue. Subsequently, this may help to improve healthcare and save lives by democratising important information about novel technologies and bitmap-based 3D-printing workflows. In turn, this may improve communication between clinicians, families and communities.

The value of this may may be quantified through future studies.

1.4 RESEARCH DIRECTION

1.4.1

PURPOSE STATEMENT

The purpose of this creative design exploration is to investigate the possibilities of bitmap-based 3D-printing using biomedical imaging data to 3D-print patient-specific and high-fidelity medical models that mimic anatomical colour and density using the Stratasys J750TM 3D-Printer, exposing the value of novel additive manufacturing methods for anatomical visualisation, communication and modelling.

1.4.2

RESEARCH QUESTION

What are the opportunities offered by high-resolution 3D-printing using a bitmap-based additive manufacturing workflow for highly realistic patient-specific medical modelling?

Figure 10. 3D-printed synthetic human skin.

...ment, the use of 3D printing in medicine is a promising technology that can be used to create custom-made medical devices and implants. This technology has the potential to revolutionize the way we think about medicine and healthcare. It can be used to create custom-made medical devices and implants that are tailored to the specific needs of individual patients. This can lead to improved patient outcomes and reduced costs. The use of 3D printing in medicine is a promising technology that can be used to create custom-made medical devices and implants. This technology has the potential to revolutionize the way we think about medicine and healthcare. It can be used to create custom-made medical devices and implants that are tailored to the specific needs of individual patients. This can lead to improved patient outcomes and reduced costs.

no - ep

INTO

Scanning to 3D Print While OCTA generates a 3D image, it is not possible to directly 3D print of the cell morphology. However, a number of methods can be used to convert the 3D data into a format that can be used for 3D printing. One method, such as Fixed Dissection, involves using a fixed dissection method to convert the 3D data into a format that can be used for 3D printing. Another method, such as Fixed Dissection, involves using a fixed dissection method to convert the 3D data into a format that can be used for 3D printing. [23].

Projection microstereolithography (PML) is a 3D printing process that employs a dynamic mask to project light onto a photoresist layer. The process is dependent on the pixel size of the mask.

Voxel-based Printing: Motivated by the need for 3D printing of biological structures, voxel-based printing represents the most commonly used method for 3D printing of discrete voxels as the resolution of the model is determined by the voxel size. The PML process, 3D printing, is a 3D printing process that is dependent on the pixel size of the mask. [2, 27]. Thus, a site

corresponding biomedical structures, or more importantly the high-throughput data, can be accomplished in a timely manner by modeling (FDM), selective laser sintering (SLS), or point-by-point scanning of the structure via synergistic integration of OTC and FDM. The use of a dynamic mask, which can reduce the number of unique capabilities, we report in this paper, can then may introduce unnecessary design and scanning process. Thus, conversion of a 3D model into a series of 2D masks can be used as the basis of a 2D mask-based process flow can be established to bypass the use of 3D CAD model. It can be used for the production of biomedical devices containing high resolution diagnostic imaging and/or the production of microscale-vasculature.

02

METHODOLOGY

Left:

Figure 11. Taking notes from a book and reviewing literature. The book photographed in the image is *Encyclopaedia Anatomica: A complete collection of anatomical waxes* (p.58), by M. Düring, M. Poggesi, G. Didi-Huberman, 1999, Germany: Taschen.

2.1 RESEARCH AIMS & OBJECTIVES

1

Aim 1

Situating the research within a body of knowledge of the discipline

Research medical modelling and bitmap-based additive manufacturing techniques to form the foundation of knowledge for future bitmap-based 3D-printing research.

Objectives

1a. Research the context of depicting human anatomy in order to understand the development of anatomical communication, creating an overview of important historical milestones and information (Historical Overview).

2b. Analyse literature regarding the current state of medical modelling and additive manufacturing technology, identifying the advantages and disadvantages of current practices, the value of 3D-printing medical models and the gaps in the current knowledge. (Literature Review)

2c. Develop initial design experiments to explore bitmap-based 3D-printing methods, establishing the foundation for a systematic enquiry (Parallel Prototyping).

2

Aim 2

Designing a systematic enquiry

Through a creative design exploration, investigate the opportunities of bitmap-based 3D-printing for the purpose of replicating realistic anatomical colour and density using patient-specific medical imaging data (Case Studies, Practical Action Research, Documentation).

Objectives

2a. Technique Exploration (*developing a workflow*)

Develop a bitmap-based 3D-printing workflow by creating a series of design experiments using the full-colour Visible Human Project® Data with a focus on replicating realistic anatomical colour (Parallel Prototyping and Focussed Prototyping).

2b. Design Discovery (*material exploration*)

Iterate the bitmap-based 3D-Printing workflow so that that it can convert greyscale, patient-specific bioimaging datasets into dynamic and realistic medical models of anatomy with a focus of mimicking anatomical density and dynamics (Parallel Prototyping and Focussed Prototyping).

2c. Stratasys J750™ Digital Anatomy™ 3D-Printer Study (*exploring novel medical modelling materials*)

Produce material swatches and traditionally segmented anatomical models to test on the novel Stratasys J750™ Digital Anatomy™ 3D-Printer. Compare and contrast Stratasys J750™ Digital Anatomy™ 3D-printing materials with the Stratasys J750™ 3D-printing materials (Parallel Prototyping).

Figure 12. Removing support material.

2.2 RESEARCH METHODOLOGIES

Outlining a design methodology for design research environments is often challenging, and can be difficult to define based on the lack of a strict systematic enquiry. Many designers “struggle to situate their creative practice within a theoretical context” (Rodriguez Ramirez, 2017, p. 11). It is, therefore, important for design research to include focused creativity, whereby a designer has the freedom to explore a project within a set of criteria that guides their research. An iterative design process (referred to as “Practical Action Research”) is moulded by design experimentation, critical reflection and design adaptation helps to form design outcomes. Engaging in a creative and iterative design process in this manner must follow a structure. However, the design process, equally, cannot be subjected to strict research restrictions that hinder creativity. The overarching aim of this chapter is to clearly outline a research design methodology and methods that will systematically guide this research portfolio without forfeiting the creative element of design research.

The overarching methodologies that this research followed were Research *into* Design, Research *through* Design and Research *as* Design. More specifically, this research portfolio followed a Research *through* Design methodology with a criteria-based approach outlined by Rodriguez Ramirez (2017). This research framework was initially outlined by Christopher Frayling in 1933 (Frayling, 1993) and has since been adapted by many design researchers such as Rodriguez Ramirez (2017).

RESEARCH INTO DESIGN

involves situating the research within a body of existing knowledge. This research methodology includes investigating the traditional history, theory, criticism, as well as research into technical, material and structural aspects of the design field. Research *into* Design is the design activity which studies design including historical and theoretical research. It therefore helps to set a foundation for future design work based on past research (Frayling, 1993, p. 5).

RESEARCH THROUGH DESIGN

is the activity of creative exploration and reflection. Predominantly, Research *through* Design involves iterative models, material and colour tests, and feedback from experts. The iterative process was recorded and contextualised by communicating the design steps in detail through photography, text and physical prototypes (Frayling, 1993, p. 5). Research *through* Design was best suited to this research because the methodology is centred around the idea of studio-based, “hands-on” design conducted through practice-led research (Frayling, 1993, p. 5).

DESIGN AS RESEARCH

runs parallel to Research *through* Design and suggests that discoveries made through the material exploration of tangible models can constitute the production of new, innovative knowledge (Hanington & Martin, 2012, p. 146). This research methodology was selected because the design process focusses on material exploration and design technique (rather than finding information through interviewing or “human-centred” design practices).

Throughout this research, these three methodologies worked in combination with each other, focussing on responding, adapting and critically reflecting on designs to reach an “appropriate” design solution (Hanington & Martin, 2012, p. 146). It is important to note that design practice inherently involves risks, failures and successes. Therefore, the emphasis behind the methodologies selected is not about defending the designs – rather, the goal is to learn and adapt from “failures” to reach a valuable design conclusion. Accordingly, the end-design does not need to address all criteria to be treated as successful.

2.2.1

Research Structure

Figure 13. Outline of research structure.

Figure 14. Practical action research cycle.

2.2.2

Practical Action Research Cycle

(Crouch & Pearce, 2012, p. 138; Frayling, 1993, p. 5)

The Results Chapter of this research followed a Practical Action Research Cycle. This cycle involved observing, reflecting, planning and acting with the end results being the development of new practices and knowledge. Using Design Criteria as a starting point, the iterative Action Research Cycle emphasised reviewing and revisiting designs to reach a design conclusion.

1. OVERVIEW

This step involved planning the research, developing criteria and identifying the main concern that could be solved through design.

2. CRITERIA

This stage involved reflecting on possible 'solutions' to the main design problem. This began by setting initial design criteria that guided each *Case Study*.

3. FILE PREPARATION

This research step involved producing physical 3D-printed models. 3D-printed models are created through different file preparation workflows that differ depending on the desired outcome.

4. 3D-PRINTING

This research stage involved 3D-printing and cleaning the 3D-prints. Any adjustments to the model (dyeing, cutting, soaking, etc.) happens during this stage.

5. DOCUMENTATION & PHOTOGRAPHY

This research stage was concerned with observing, tactile interaction and monitoring design outcomes by documenting the 3D-printed models through photography, film and notes.

6. EVALUATE AND REFLECT

This research step focussed on evaluating the designs by highlighting the disadvantages and advantages of the design technique. The design analysis helped to identify new design opportunities, including particular elements of the design process that had potential for readjustment and improvement. This stage was conducted through self-reflection, material observation, conversations with experts and analysis from Bernard Guy, the primary research supervisor.

7. MODIFY

Design modification during this research step was used to identify ways to move forward, adopting suggested ideas for the development of refined designs.

8. MOVE IN NEW DIRECTIONS OR RETURN TO A PREVIOUS RESEARCH STEP

This research step involved shifting the area of focus and forming a new set of criteria or returning to previous research steps and tweaking designs.

Figure 15. Outline of research methods.

2.3 RESEARCH METHODS

SECONDARY RESEARCH

Information from existing data, including journal articles, books, reports and other similar documents.

PRIMARY RESEARCH

Information collected primarily as 3D-printed prototypes and subsequent analysis as well as information collected through current medical modelling company studies and discussions with experts.

DESIGN CRITERIA

A criteria-based research approach allows creative design practice to become a systematic form of enquiry (Rodriguez Ramirez, 2017, p. 12). Design criteria was outlined at the start of each *Case Study*, guiding and serving as a starting point for design experimentation, development and refinement (Rodriguez Ramirez, 2017, p. 13). Results developed during each *Case Study* were evaluated against the outlined criteria in the Discussion (ch.5).

BRAINSTORM GRAPHIC ORGANISERS (BGO)

A graphic representation of new knowledge that includes brainstorm webs, tree diagrams, flow diagrams to help with organising information and organizational thinking in 'networks' creating research frameworks and fluency of thinking. (Hanington & Martin, 2012, p. 22).

DOCUMENTATION

The entire research process was documented to communicate, synthesize and record design results. This was achieved through photography, videography, material analysis and note taking (Hanington & Martin, 2012, p. 146).

EXPERT OPINIONS

The MADE Drill stream has a current ethics approval for 'Gaining an Expert Opinion' from Industry (Application ID: 0000024294). Expert reviews and opinions were given by specialists in the areas explored. The specialists consulted with included (but were not limited to) biomedical engineers, the team at Stratasys, neurologists, anaesthetists and neonatal anatomy specialists. The project supervisor can account as an expert reviewer or opinion if the feedback is given objectively (Rodriguez Ramirez, 2017, p. 24).

HISTORICAL OVERVIEW

An outline of the history behind understanding within the human body and how anatomical knowledge developed to where it is today. This was conducted by gathering historical sources and collating information (Frayling, 1993, p. 5).

LITERATURE REVIEW

A review of the relevant literature was conducted to gain knowledge of relevant disciplines. It was guided by the initial research question and project aims and objectives. The Literature Review focussed on the value of medical modelling and its associated problems as well as gaps in current research (Rodriguez Ramirez, 2017, p. 25).

The Literature Review captures the essence of previous research and aims to answer the following questions (Rodriguez Ramirez, 2017, p. 25).

- *What do we know about the topic in the discipline?*
- *What is the debate?*
- *What future research has been suggested?*

CASE STUDIES

A *case study* research strategy was applied during the primary research element of this project presented in the Practical Action Research Chapter.

The purpose of including three research *case studies* was to highlight different medical modelling workflows, with a primary focus of achieving the research aims and objectives (specifically research aims 2a., 2b., and 2c.).

Each case study discussed in this research had a different set of criteria that were guided by a specific research objective. Throughout the research, the *case studies* are presented in chronological order based on the time of completion. This process involved selecting a specific situation with a corresponding medical dataset; once the dataset was selected, 3D-prints were produced based on the outlined criteria.

The Practical Action Research chapter is separated into three *case studies*:

1. Technique Exploration

Developing a bitmap-printing workflow with a focus on colour.

2. Design Discovery

Material exploration with a focus of mimicking attenuation (H.U) properties in bitmap-based 3D-prints.

3. Stratasys J750™ Digital Anatomy™
3D-Printer Study

Exploring novel medical modelling materials.

PARALLEL PROTOTYPING

Parallel Prototyping was used during Research Stage Two whilst conducting free design exploration (Crouch & Pearce, 2012, p. 138; Frayling, 1993, p. 5). Parallel prototyping is the action of simultaneously exploring multiple design opportunities. Material exploration was conducted using parallel prototyping methods. The process included producing multiple 3D-printed design experiments at once and comparing the outcomes to refine the direction of research and the preferred bitmap-based 3D-printing technique.

FOCUSSED PROTOTYPING

High-Fidelity prototyping was used to develop and focus refined final 3D-printed models at later stages during the *case study* investigations (Hangington & Martin, 2012, p. 138). The translation of hypothesised ideas into refined tangible objects helped to realise the research and provide a means for analysis against the outlined design criteria.

FINAL EVALUATION

A final evaluation helped to determine the disadvantages and advantages of the bitmap-based 3D-printed medical models. Avenues for further exploration were identified based on the information and new knowledge discovered throughout this research (Rodriguez Ramirez, 2017, p. 14).

2.4.1

3D-Printers

Table 1. THE STRATASYS J750™ 3D-PRINTER SPECIFICATIONS

MODEL MATERIALS	Vero™ family of opaque materials (VeroMagenta-V™, VeroYellow-V™, Vero-Cyan-V™, VeroPureWhite™, VeroBlackPlus™) Agilus30™ VeroClear™
BUILD MODEL	High Mix: up to 6 base resins, 27-micron resolution
SUPPORT MATERIALS	SUP706™ (waterjet removable)
BUILD SIZE	490 x 390 x 200 mm
LAYER THICKNESS	Horizontal build layers down to 14 microns
SOFTWARE	PolyJet Studio™ 3D printing software GrabCAD Print compatibility, including the optional add-on GrabCAD Voxel Print

Table 2. THE STRATASYS J750™ DIGITAL ANATOMY™ 3D-PRINTER SPECIFICATIONS

MODEL MATERIALS	VeroYellow-V™, VeroPureWhite™, VeroMagenta-V™ Agilus30™ TissueMatrix™ BoneMatrix™ <i>J750™ materials also available</i>
BUILD MODEL	High Mix: up to 6 base resins, 27-micron resolution
SUPPORT MATERIALS	SUP705™ (waterjet removable) GelMatrix™ (waterjet removable)
BUILD SIZE	490 x 390 x 200 mm
LAYER THICKNESS	Horizontal build layers down to 14 microns
SOFTWARE	PolyJet Studio™ 3D printing software GrabCAD Print compatibility, excluding the optional add-on GrabCAD Voxel Print

3D SLICER

3D Slicer is an open source software platform for medical image informatics and image processing. 3D Slicer was used to segment parts of CT scans and to produce volumetric visualisations of medical data.

AUTODESK FUSION 360

Autodesk Fusion 360 is a 3D CA tool that was used to edit segmented meshes (STL files). Autodesk Fusion 360 was also used to produce any material swatch files.

RHINOCEROS 3D

Rhinoceros3D (dubbed ‘Rhino’) is a commercial 3D computer graphics and computer-aided design (CAD) application software. In this project, Rhino was used for the production of more complicated meshes of body parts.

AUTODESK MESHMIXER

Autodesk Meshmixer is a free 3D sculpting-based CAD programme created by Autodesk as part of their “123D” software line. The Meshmixer software was used in this project to repair any problems in the mesh as well as to slice and scale mesh files.

AUTODESK NETFABB

‘repair script’ on Autodesk Netfabb was utilised to fix any details in models to prepare them for 3D-printing. The Autodesk Netfabb ‘Boolean’ function allows users to cut a 3D part away from another 3D part.

FIJI - IMAGE J

ImageJ (also known as Fiji) is a Java based, open source image processing program, bundling a wide series of plugins that facilitate scientific image analysis. Fiji is the “batteries-included” distribution of ImageJ and was used to analyse medical data. The software was used to re-slice medical data image stacks.

ADOBE ILLUSTRATOR

Adobe Illustrator is graphic-driven software used primarily for creating vector graphics. Adobe Illustrator was used in this project for graphic design purposes including infographics.

ADOBE PHOTOSHOP

Adobe Photoshop is a raster graphics editor developed and published by Adobe Inc. Adobe Photoshop was used to automatically process bitmap-based 3D-Printing files.

GRABCAD PRINT

GrabCAD Print is a programme that streamlines the 3D-printing workflow by setting up the printer tray, material colour and density selection specific to the Stratasys Polyjet 3D-printing system.

GRABCAD VOXEL PRINT UTILITY

The GrabCAD Voxel Print Utility is a software add-on for GrabCAD Print which widens the capabilities of the kind of parts you can print on a Stratasys J750™ 3D-Printer and is used to process bitmap files into 3D models and .GCVF files.

2.4.2

Data & Ethics

CASE STUDY 1

Visible Human Project® Data Courtesy of the U.S. National Library of Medicine.

As of July 2019, the NLM Data License has been replaced by Terms and Conditions. No registration is required to access data available from NLM's FTP servers (The National Library of Medicines Visible Human Project, n.d.).

Images used were full color: The original cryosectional images at 0.33mm XY resolution, formatted in a lossless, directly readable .png format.

CASE STUDY 2

Ethics approval was granted through Dr. Ali Mirjalili at the (Senior Lecturer at the University of Auckland, New Zealand).

PROTOCOL REFERENCE # 32679

Research protocol entitled, "Clinical anatomy of the infant: Correlation with clinical landmarks using imaging, digitization and 3D modelling".

ETHICS APPROVAL

Original Approval Date: March 1, 2016

CASE STUDY 3

Same as Case Study Two.

—

AIM	OBJECTIVES	Ch.	METHODS	RESEARCH STAGE	CRITERIA
			Secondary Research, Primary Research, Design Criteria, BGO, Documentation, Expert Opinions (throughout research)		
		1			What designers want to express from a personal perspective.
		2			*Each method is chosen to address specific criteria. Each objective is matched to a method.
AIM 1	a.	3	Historical Overview	Background Research	*Criteria based on the findings from the literature review. • What should the design address? *Criteria based on comparisons with other existing designs. • How can the design improve or move away from existing designs? Use the criteria to set up a design research question and design hypothesis.
	b.		Literature Review		
	c.				
AIM 2	a.	4	Case Study 1 Parallel Prototyping Focussed Prototyping Practical Action Research	Design Experimentation Final Design	
	b.		Case Study 2 Parallel Prototyping Focussed Prototyping Practical Action Research	Design Experimentation Design Resolution Final Design	*Initial experiments should be assessed based on criteria developed in the background chapter. New and more specific criteria should be constructed. *Present the final design/s and how it addresses criteria.
	c.		Case Study 3 Parallel Prototyping Practical Action Research	Material Exploration Design Experimentation	
		5	Final Evaluation		*Compare design to criteria and use the criteria as a way to define explicit knowledge produced by the project.
		6			

○ Written Criteria * Criteria Description ● Research Question

Figure 16. Methodology chapter summary.

03

BACKGROUND RESEARCH

Left:

Figure 17. The Stratasys J750™ 3D-Printer 3D-printing neonatal feet and a 1:1 scale neonatal leg (75% completed).

3.1 HISTORICAL OVERVIEW

The History of Understanding Human Anatomy

Researchers from many fields have laid the foundation for contemporary anatomical knowledge. Scientists, physicians, artists, engineers, criminals, and martyrs were all instrumental in the progression of anatomical imaging – from ancient Egyptian papyri to the use of magnetic resonance imaging (MRI) (Owen, 2016).

The controversies associated with the study of human anatomy must also be acknowledged. Medical history is, tragically, riddled with many discomfiting insights and atrocities, along with the exploitation of minorities and the vulnerable (Ghosh, 2015).

Figure 19. provides a brief outline of the historical development of understanding human anatomy. It seeks to illustrate that reproducing human anatomy at a high-fidelity has been central to medical progression.

Left:

Figure 18. Dr. Nicolaes Tulp demonstrating an educational dissection session explaining the physiology of the arm and exposing anatomy that lies beneath the skin. From *The Anatomy Lesson of Dr. Nicolaes Tulp*, by R. V., Rijn, 1632 CE, reproduced from the public domain.

Figure 19. The history of understanding human anatomy (western history).

Uterus gravidus, Fetus

View of a fetus
inside the uterus
Darstellung eines
Föten in der Gebä-
rutter
Fœtus dans l'uté-
rus ouvert

Uterus gravidus, Fetus

View of a fetus
inside the uterus
Darstellung eines
Föten in der Gebä-
rutter
Fœtus dans l'uté-
rus ouvert

BACKGROUND RESEARCH

3.2 LITERATURE REVIEW

The *Literature Review* will outline:

- Basic biomedical imaging principles.
- The value of physical modelling in comparison to virtual models.
- General 3D-printing.
- The value of physical medical modelling using high-resolution 3D-printing workflows.

Left:

Figure 20. Reading a book about anatomy. The book photographed in the image is from *Encyclopaedia Anatomica: A complete collection of anatomical waxes* (p. 674-675), by M. Düring, M. Poggesi, G. Didi-Huberman, 1999, Germany: Taschen.

Figure 21. CT imaging process (from data acquisition to virtual reconstruction).

3.2.1

Biomedical Imaging

Since the 1980s, visualising human anatomy through multiplanar reformations, maximum intensity projections, volume renderings, and cinematic renderings for the purpose of understanding physiology has been an area of extensive exploration (Fellner, 2016, p. 170). Cross-sectional images through the human body can generate 3D reconstructions of anatomy. Specialists capture anatomical images using scanning modalities, including computed tomography (CT) and magnetic resonance imaging (MRI) (Bibb et al., 2015, p. 7). The appropriate scanning modality is selected based on the objective of the scan, the area of anatomy and the desired image quality.

COMPUTED TOMOGRAPHY (CT)

CT imaging entered the world of medicine due to the advancement of computers and allowed the capture of multiple tomographic images (slices) of the body (Bradley, 2008, p. 351).

Measuring Density

CT works by measuring the amount of energy absorbed by the body as an X-ray tube rotates around a patient. Various detectors pick up the X-rays that are not absorbed, reflected, or refracted (Bibb et al., 2015, p. 8; Bradley, 2008, p. 351). When CT data is captured, the resulting images are divided into greyscale pixel matrixes (Bibb et al., 2015, p. 9). Each pixel is a shade of grey that relates to the density of tissue at that location and the density is quantified using the Hounsfield unit (H.U.) scale (Bibb et al., 2015, p. 8).

In a CT image, air has a value of -1000 (black on the greyscale) and bone has a value of +700 to +3000 (white on the greyscale) (Bibb et al., 2015, p. 8). Soft tissues and organs are often harder to identify and range anywhere between -1000 to +700 (appear in different shades of grey) (Bradley, 2008, p. 8). One pixel can only have one threshold or H.U. value, and therefore its value is determined based on which tissue type fills the majority of the pixel (Bibb et al., 2015, pp. 9–10).

The Volumetric Pixel

If the distance between axial images (slice thickness) is known, software can allow for interpolation between cross-sectional tomographic images to create volume reconstructions with smooth surfaces (McGurk et al., 1997, p. 170). Voxels are formed by interpolating one image to the next, creating a voxel representation of the human body (Bibb et al., 2015, p. 9). These voxel datasets can then be resliced on the different axes to generate cross-sectional views of the data (Bibb et al., 2015, p. 9).

MAGNETIC RESONANCE IMAGING (MRI)

MRI works similarly to CT imaging. However, instead of measuring density, MRI measures the amount of water in the body. MRI scanning targets the hydrogen nuclei present in water molecules and; therefore, areas of the body with less water content show up lighter, and areas with more water show up darker (Bibb et al., 2015, p. 21). For example, air and dense bone will appear black, whereas fat will appear white (Bibb et al., 2015, p. 21). MRI images also have significantly larger pixel sizes than CT images.

Chung and Park (2007) argue that virtual reconstructions of anatomy with virtual reality environments could compensate for the limited availability of cadavers due to time, place and cultural limitations of cadaver dissection. Pommeret et al. (2001) also suggest that computer-based representations of biomedical imaging datasets are superior to traditional methods of medical communication where anatomy is presented in books and atlases.

Wu et al. (2012) challenged this idea by stating that thin-sectional images of human cadavers (cryosectioning) can be used to construct realistic 3D models of anatomy without any loss of information and in true colour (which is beyond the reconstruction capabilities using greyscale biomedical imaging datasets). Chung & Park (2019) validate the proposed value of cryosectioning through their highly realistic virtual reconstruction created by using the Visible Korean Human (VKH) dataset. However, cryosectioning cannot be conducted on live patients. Biomedical imaging modalities, on the other hand, can produce cross-sectional images of live patients, allowing the reconstruction of patient-specific anatomy in living patients.

Physical Modelling in Medicine

VIRTUAL REALITY VS. PHYSICAL MODELLING

Physical or virtual medical modelling is almost always used to provide a complementary educational experience to cadaveric dissection. Whether medical models are created for surgical simulation, pre-operative planning, patient-surgeon communication, product testing, didactic instruction, prosthetics or biomechanical research purposes, the end goal is almost always to improve and accelerate the quality of medical treatment and experiences (Palter & Grantcharov, 2010, p. 1195).

Many academics and clinicians question whether there is value in physical modelling considering Virtual Reality (V.R.) environments can also incorporate the use of realistic haptic feedback (Lioufas et al., 2016; Panait et al., 2009). Physical medical modelling could be made redundant once V.R. technologies develop, presenting a justified concern about the future of physical modelling. V.R. models can now incorporate tactile and kinaesthetic receptors to allow surgeons to feel force feedback while using surgical instruments (Lioufas et al., 2016; Panait et al., 2009). A medical student or professional that immerses themselves in this kind of sophisticated V.R. environment, can see a rendered visualisation of bone and tissue and can feel virtual contact forces while interacting with different anatomy (Hochman et al., 2015, p. 264).

However, a drawback of most haptic V.R. models is that the “stiffness” of the bone and tissue is not as realistic as most physical models (Hochman et al., 2015, p. 263). Additionally, tools such as robotic drills cannot be tested on V.R. models meaning medical procedures cannot be conducted in their entirety (Hochman et al., 2015, p. 264). Authors have criticised current V.R. models because of the high initial cost of system acquisition, limited force feedback with the use of surgical instruments, and the lack of realism in graphics (Bader et al., 2018; Breimer et al., 2017; Palter & Grantcharov, 2010).

The available literature concludes that the technology chosen for anatomical modelling should be selected based on specific learning objectives and training goals (Breimer et al., 2017, p. 93). For example, evidence shows that high-fidelity physical simulator models are more useful for practising complex procedures, whereas V.R. simulators work well for teaching fundamental technical skills (Palter & Grantcharov, 2010, p. 1194). A consensus gathered from literature was that “depending in the perceived educational requirements, it is possible that one system [V.R.] or the other [3D-printing] may provide the most useful platform” (Hochman et al., 2015, p. 264).

Breimer et al. (2017) compared physical and V.R. neurological simulators. Their study concluded that a physical simulator is a better tool for applications such as familiarising trainees with different instruments and techniques, helping with teamwork, communication and different bleeding scenarios. The V.R. model was better suited for learning anatomy in three-dimensions. The results of the study indicated that 50% of participants stated that the physical model was superior, 12% of participants indicated that the V.R. model was superior, 19% of participants indicated that the V.R. model was better for learning anatomy and the physical model was better for learning instrument handling techniques and the final 19% of participants were undecided.

Figure 22. Virtual Reality vs. Physical Model
(Neurosurgical Resident Preference)

Figure 23. Person experiencing V.R. environment.

Scerbo et al. (2006) compared the effectiveness of a V.R. simulator in comparison to a traditional plastic limb for training phlebotomy (drawing blood). Improper performance of this procedure can lead to some complications, including injuries and inaccurate test results (Scerbo et al., 2006). In their study, medical students were trained under one of the two methods.

Overall, results showed that students performed better on a physical model rather than in a V.R. environment. Authors concluded that ultimately the central factor of success for a simulation device is the realism and fidelity of the training task. Procedures such as cutting organs, checking a patient's pulse and using medical instruments sometimes rely solely on a medical professional's sense of touch. Therefore, having realistic haptic feedback is imperative to a useful simulation device. Scerbo et al. (2006) concluded that currently there is more evidence to suggest that a physical simulator is a more effective method of teaching.

There are a limited amount of studies that have quantified the effectiveness of physical modelling in comparison to V.R. models for medical simulation and educational purposes. Existing studies conclude that, overall, a higher percentage of surgical trainees and surgeons preferred learning on a physical model. Currently, literature shows that both modalities have strengths and weaknesses and that establishing the long-term effectiveness and superior modelling method of V.R. in comparison to physical modelling will take time and an extensive body of research (Breimer et al., 2017; Cromeens et al., 2017; Hochman et al., 2015).

3D-printed medical models are useful tools for resident education and pre-operative surgical rehearsal when compared to a V.R. model with haptic feedback. In a study conducted by Hochman et al. (2015), a haptic voxel-based virtual model and a physical 3D-printed temporal bone model were developed from CT data. Resident surgeons were asked to rate their experience on both simulators based on a range of different parameters. Most resident surgeons agreed that both models were productive adjuncts to traditional educational resources and could help in improving surgical skill acquisition. However, the 3D-printed model was perceived to be more productive and was the preferred training tool across most domains due to the lack of realism of the haptic feedback of the virtual model.

3D-PRINTING OVERVIEW

Three-dimensional (3D) printing technologies offer great opportunities for physical anatomical modelling. 3D-printing is a manufacturing technology that can create physical forms from computer-aided design (CAD) models. Originating in the early 1980s, 3D-printing was first introduced to produce prototypes in a quick and automated manner and found great success in areas such as aerospace, automotive, military and architecture (Bastawrous et al., 2018, p. 2809; Swetly et al., 2016, p. 145). Unlike traditional subtractive manufacturing methods, 3D-printing works by depositing material, layer-by-layer, to create a physical model. Machines can now efficiently produce objects with less material waste and associated costs (Watson & Taminger, 2018, p. 1317).

The seven main 3D-printing categories include Binder-jetting, Vat photopolymerisation, Material Extrusion, Material jetting, Powder bed Fusion, Directed Energy Deposition and Sheet Lamination (Bastawrous et al., 2018, p. 2811). Each AM technology has its advantages and disadvantages and therefore deciding on which 3D-printing technique to use is dependent on cost, production time, material qualities, colour, intended use and detail requirements (Bastawrous et al., 2018; Swetly et al., 2016).

As the efficiency of 3D-printing manufacturing processes has improved, the 3D-printing market has grown drastically (Swetly et al., 2016, p. 145). The ambit of 3D-printing has expanded to include many different fabrication methods and 3D-printer types, ranging from relatively cheap to highly sophisticated machines. 3D-printing can produce complex geometries, internal structures and models in a range of different materials. AM is also now used for the end-production of products - rather than prototyping, which accounts for a “growing portion of the total revenue of the global AM market” (Doubrovski et al., 2015, p. 4). The use of 3D-printing has a growing importance in the medical industry - from 3D-printing Personal Protection Equipment to anatomical models of patient-specific anatomy (Stratasys Responds to COVID-19 Pandemic, 2020).

Figure 24. Origins of 3D-printing.

Bader et al. (2018), Hosny et al. (2018) and Yang et al. (2018) suggest using medical modelling to produce physical anatomical models allowing medical physicians, students and patients to interact with tangible patient-specific medical data. AM methods can build medical models that are impossible to make through other subtractive manufacturing processes such as silicone moulding. The hierarchical, functional and material complexities that can be attained through AM produce an unparalleled level of detail in physical objects that may begin to emulate the fidelities of human anatomy to the highest degree of realism (Sossou et al., 2019).

Usually, 3D-printed anatomical models are produced from patient-specific biomedical imaging data through a process called segmentation and the subsequent isosurface extraction. This method is known as “medical modelling” (Bibb et al., 2015, p. 1). Medical modelling can replicate exact patient-specific anatomical geometries quickly and in large quantities. There is a plethora of evidence to suggest that medical modelling is beneficial for the study of human anatomy, patient-surgeon communication, pre-operative planning, surgical simulation and medical research (Rengier et al., 2010; Young et al., 2019).

An example of useful medical modelling has presented itself recently as a response to the impact and effects of the COVID-19 pandemic. This pandemic has placed an immense amount of pressure on healthcare institutions. AM has provided some relief in many areas. Fusetec, an Australian-based medical modelling company, has responded to the COVID-19 pandemic by providing high-fidelity models of human nasal sinuses (FusetecSinus Trainer) to hospitals around Australia. The FusetecSinus Trainer has been distributed to hospitals to help ensure that front-line healthcare workers are appropriately trained in nasal swab collection techniques to test individuals properly, minimising the transmission of COVID-19 (Fusetec 3D Headquarters, 2020).

CURRENT MEDICAL MODELLING WORKFLOW

Most 3D-printed anatomical models currently produced are created following a workflow involving image thresholding and isosurface extraction techniques, resulting in the aforementioned surface meshes (STL files) (Hosny et al., 2018; Huotilainen et al., 2014). This process is commonly referred to as segmentation. Research is currently being conducted into adapting traditional mesh-based 3D-printing workflows to processes that are better suited to mimicking the fidelities of human anatomy, which is organic and cell-based in structure (Bader et al., 2018; Doubrovski et al., 2015; Hosny et al., 2018; Stute et al., 2018).

Current CAD programmes accommodate traditional segmentation manufacturing workflows. For example, *Materialise Mimics* is an image-processing tool that converts biomedical imaging data into traditional mesh-based models ready for 3D-printing (Materialise 3D Printing Innovators, 2020). Currently, Materialise Mimics have a significant influence over the segmentation and medical modelling industry. Interestingly, however, literature describes medical modelling using traditional mesh-based workflows to be time-consuming, resulting in anatomically inaccurate 3D-prints caused by data loss, segmentation artefacts and multiple post-processing steps using different software packages (Bader et al., 2018; Bibb & Winder, 2010; Hosny et al., 2018; Huotilainen et al., 2014).

Literature suggests that current workflows are limited, as shape specification is inherently linked with one colour and density – limiting the production of material gradients (Bader et al., 2018; Doubrovski et al., 2015; Stute et al., 2018). Mesh-based 3D-printing methods are inapt for 3D-printing complex material topologies (such as human tissue) and that production methods currently overlook the design potential of heterogeneous material distributions (Bader et al., 2016).

1

Image Acquisition

STEP ONE

Acquiring patient-specific data through different image modalities (in this case, CT imaging).

2

CT Data (Slices)

STEP TWO

The patient-data is stored as cross-sectional image slices through the body (or area of interest). Digital Imaging and Communications in Medicine (DICOM) files are the international standard to communicate and display medical imaging data.

Images can be interpolated (spaces between slices can be 'filled in') to create in between values or 'cuboids' and a 'voxelized' volumetric reconstruction of anatomy.

STEP THREE

Creating a volumetric reconstruction of the scanned patient on appropriate medical imaging software.

Segmentation involves selecting specific parts of anatomy to be extracted from scan data. For example, the skeleton (bone).

STEP FOUR

Exporting segmentation correctly and checking for any errors before sending the file to a 3D-Printer (such as the Stratasys J750™ 3D-Printer) to create a medical model.

Figure 25. Current medical modelling workflow.

MEDICAL MODELLING APPLICATIONS

Doctor-Patient Communication and Giving Informed Consent

3D-printed medical models have shown to be useful tools for diagnosis, doctor-patient communication and informed consent practices. Recently, 3D-printed patient-specific medical models were used as tools in pre-operative patient consultation (Kim et al., 2019; Yang et al., 2018; Yoon et al., 2019). The models were compared with conventional communication methods such as verbal methods of communication and 2D CT images based on patients' understanding of their medical procedure (Kim et al., 2019; Yang et al., 2018; Yoon et al., 2019).

The 3D-printed models were used to communicate anatomy and physiology, illness characteristics, the surgical procedure and surgical risks. In all cases, the use of 3D-printed models was associated with better patient comprehension for informed decision making during the consultation process before surgery (Kim et al., 2019; Yang et al., 2018; Yoon et al., 2019). Using 3D-printed models during the pre-operative consultation process was associated with higher patient satisfaction, involvement and reassurance - contributing to the body of evidence that 3D-printed models could be useful in the routine clinical process aiding doctor-patient communication (Kim et al., 2019).

Figure 26. Doctor-patient consultation with 3D-printed model.

Medical Education and Research

Cadaver vs. 3D-Print

Studies have shown that medical students respond positively to 3D-printed anatomical models for educational purposes, such as anatomical teaching (Kim et al., 2019; Young et al., 2019). Historically, anatomy has been taught through cadaver dissection and anatomy textbooks. Although extremely important, there are restrictions surrounding using these educational tools in isolation. Cadavers have been criticised for their cost, limited availability, lack of portability, lack of patient-specific anatomy, health risks (such as disease transmission), and because of cultural and ethical concerns (Aziz & McKenzie, 1999; Lim et al., 2016; Palter & Grantcharov, 2010; Young et al., 2019; Zhang et al., 2008). A patient-specific synthetic model offers much of the same experience and knowledge, without the ethical and practical concerns.

Studies have shown that learning anatomy with 3D-printed anatomical models does not disadvantage students (Lim et al., 2016; Lioufas et al., 2016; Young et al., 2019). A study conducted by Lim et al. (2016) concluded that students who learnt anatomy on 3D-printed models retained higher amounts of correct information about anatomy compared to students who learnt anatomy on cadaveric material. Interestingly, this study concluded that 3D-prints might be an appropriate supplement to cadaver-based education, even providing some benefits over cadaveric materials.

Figure 27. Cadaver vs. 3D-print.

Embryology Education

Medical bioimaging data is currently being used as a tool for teaching anatomy. This is because cadavers often do not show different ages, anomalies, normal anatomy and variations needed to understand anatomy completely (Rengier et al., 2010, p. 340). Preserved human embryonic and foetal specimens are not commonly available to most medical students due to legislative restrictions and the inherent sensitivity surrounding premature neonates and presenting foetal specimens as teaching materials (Young et al., 2019).

3D-printed embryonic, neonatal and paediatric anatomy can be produced from bioimaging datasets and used as teaching tools. Young et al. (2019) CT imaged and 3D-printed an archived series of preserved human embryonic and foetal specimens for the purpose of medical education. The virtual reconstructions and subsequent 3D-printed models allowed embryology students to have access to foetal anatomical specimens. The ability to interact with these 3D models without worrying about having an adverse reaction or damaging original the specimens has drastically improved this area of embryology education (Young et al., 2019, p. 90).

Figure 28. Foetal development.

Device Testing, Surgical Tool Development, Implants and Prosthesis

3D-printed medical models are suited to the testing of medical devices that are worn both outside and inside the body. Developing technologies and medical devices involves an iterative design process. Testing devices and tools on medical models means that device limitations, failures and successes can be identified and solved before clinical trials begin, decreasing overall expenses and safety threats for patients (Ionita et al., 2014, p. 1).

3D-printing can tailor to the full anatomic variation of the human body and individual patient circumstances. The production of patient-specific biomedical devices, including implants and prosthetics, can be custom-made for each patient. Custom-made implants come in extremely useful for patients that lie outside the “standard” range concerning implant size and individual anatomical needs (Rengier et al., 2010). For example, medical modelling can be particularly useful in the area of auricular prosthesis for people with ear deformities. By acquiring medical data from the “normal” ear, a replica ear can be 3D-printed to help create a patient-specific ear prosthetic that is an exact match to the existing ear (Lin et al., 2018).

Medical modelling can help to prepare for invasive procedures that are always unique to each patient and can create custom-made implants to fit defective areas during the surgical reconstruction process. Many factors, including injury, disease and tumours, can cause anatomical deformities (Jardini et al., 2014). Different facial features and skull geometries can make craniomaxillofacial reconstructive surgery extremely challenging. 3D-printed models have helped with pre-operative planning and have enabled the simulation of osteotomies (Mavili et al., 2007). For example, a patient suffered from severe facial deformities after a cycling accident and 3D-printing using direct metal laser sintering (DMLS) techniques created a patient-specific cranial implant to reconstruct the patient’s skull (Jardini et al., 2014).

Pre-Operative Planning & Intra-Operative Guidance

Medical modelling is used for teaching technical medical skills (Palter & Grantcharov, 2010). Traditionally, the act of learning and practising new skills such as suturing, phlebotomy and intubation have occurred on patients – largely due to a lack of alternative teaching tools (Reznek et al., 2002; Severseike et al., 2019). This process affords medical students limited opportunities to practice procedures and learn from their mistakes, resulting in decreased patient safety and increased procedure risk (Reznek et al., 2002, p. 79).

3D-printed models can increase the understanding of complex patient pathologies and improving technical skill competency (Rengier et al., 2010). Studies validate the notion that 3D-printed anatomical models contribute to personalised medicine, surgical planning and education across medical specialties and are rapidly changing the landscape of clinical practice (Jardini et al., 2014; Rengier et al., 2010; Yoo et al., 2016).

Planning procedures pre-operatively includes steps such as surgical incision, approach, hardware sizing and placement. Pre-operative planning can be helpful for complex maxillofacial and laparoscopic surgery (Kumara, 2012; Rengier et al., 2010). Operating strategy can be determined before the surgery, and subsequently, surgeons can enter procedures with more confidence (Rengier et al., 2010). 3D-printed models of patient anatomy can be valuable for complex patient cases where relationships between anatomical structures are hard to visualise through virtual mediums.

Cromeens et al. (2017) compared paediatric surgeons' understanding of complex connections between pygopagus conjoined twins when using a virtual reconstruction and a 3D-printed model. The authors concluded that the 3D-printed model was significantly more helpful for understanding spatial relationships between structures, along with scale, shape and identifying the correct anatomical features when compared to a virtual anatomical reconstruction. The authors concluded that not only was more knowledge acquired and retained, but visuospatial information was learnt faster when using a 3D-printed model.

Surgical Simulation

Simulation has come to the foreground as a method of teaching technical skills to surgical trainees. Practising and preparing for surgical procedures is possible with high-fidelity surgical simulators. Simulation-based training can immerse a trainee into a realistic and hands-on training situation (Cavaleiro et al., 2008). Surgical simulators offer the opportunity for surgical trainees to practice in a safe environment, receive valuable feedback without risking the safety of a patient, and can reduce the overall operating time (Barber et al., 2018; McGurk et al., 1997; Scerbo et al., 2006). 3D-Printed simulators have shown to be useful for communication, leadership and teamwork – skills which are an integral part of operative success (Palter & Grantcharov, 2010, p. 1191).

Neonatal & Paediatric Simulation

Studies have indicated that paediatric and perinatal acute care could benefit from simulators, especially in neonatal resuscitation and contributing to the success of a procedure (Barsness et al., 2013; Meurs et al., 2003; Rovamo et al., 2011). Preserving the realism of a surgical procedure by using the appropriate medical tools can help with incision placement, the identification of anatomy and the dissection of relevant tissues (Thielen et al., 2019). Unfortunately, paediatric and neonatal surgery are fields with limited access to high-fidelity simulation tools that accurately reflect individual neonatal and paediatric anatomy (Barsness et al., 2013). However, there is a growing amount of evidence to suggest that 3D-printed models are useful for the planning of paediatric and neonatal procedures and practices including the management of paediatric airway obstruction (Cavaleiro et al., 2008).

Approximately 10% of all neonates are admitted to Neonatal Intensive Care Units (NICU) every year with problems relating to the airway, breathing and circulation (Rovamo et al., 2011; Thielen et al., 2019). In many cases, medical simulative models are used to practice these essential procedures. However, models presently available are of low-fidelity, unrealistic and the materials do not reflect the complexities of neonatal and paediatric anatomy – potentially confusing even experienced surgeons and clinicians (Rovamo et al., 2011;

Thielen et al., 2019).

For example, high-resolution 3D-prints may also help to replicate intricate parts of neonatal anatomy such as the heart system including heart chambers and valves (Thielen et al., 2019). However, there are limitations in the current 3D-printing process, including the small number of flexible materials that can respond in a similar way to human myocardium or vessels (Yoo et al., 2016).

Neonatal simulators with higher levels of realism and physical fidelity have been shown to help advanced learners, such as clinicians and surgeons, develop technical skills (Barsness et al., 2013). Training neonatal skills with simulators with functional fidelity can optimise skill transfer by suspending disbelief, helping with remaining focussed and improving cognitive and psychomotor aspects of skill acquisition (Cavaleiro et al., 2008; Thielen et al., 2019).

Figure 29. Medical students practicing a neonatal intubation procedure.

Multi-Material 3D-Printing

Overall, evidence suggests that multi-material 3D-printing produces smoother model surfaces at higher resolutions, allowing for more control over both internal and external structures (Brunton et al., 2015, p. 1). Multi-material 3D-printing also has the potential to mitigate some of the frustrations caused by mono-material, low-resolution 3D-printers. This is because multi-material 3D-printing with photopolymeric materials can produce full colour and multi-density models in a single print (Kolb, 2017, p. 46).

Multi-material 3D-printing enables the fabrication of objects with heterogeneous material compositions allowing designers to “programme” detailed object functionality including anisotropic, colour and density property gradients (Doubrovski et al., 2015). Studies have shown that the multi-material Stratasys J750™ 3D-printer range exhibit great promise for high-resolution anatomical medical modelling because of the machine precision and ability to mimic human tissue and bone (Hosny et al., 2018; Lioufas et al., 2016; Severseike et al., 2019). The Stratasys J750™ 3D-Printer is a full-colour and multi-material PolyJet 3D-printer that works by simultaneously and sequentially depositing tiny droplets (voxels) of different ultraviolet (U.V.) cured resins in 14-micron layers producing 3D-models with varied translucency, density and colour qualities (Bader et al., 2018, p. 2; Doubrovski et al., 2015).

Multi-material 3D-printers can process 3D-prints with “nested” mesh-based (STL) file assemblies (where each STL is assigned with a different material quality). However, Hosny et al. (2018) highlight that creating “nested” STL file assemblies can be complicated and costly – exhausting computer processing power.

Figure 30. Multi-material 3D-printing on the Stratasys J750™ 3D-Printer.

Literature suggests exploring the potential of using a bitmap-based additive manufacturing workflow for medical modelling purposes. Many studies challenge traditional 3D-printing workflows and have documented a need for data-driven material modelling (Bader et al., 2016, 2018; Brunton et al., 2015; Doubrovski et al., 2015; Stute et al., 2018). Data-driven bitmap-based additive manufacturing - also referred to in the literature as “voxel printing” (Bader et al., 2018), “bitmap printing” (Doubrovski et al., 2015; Hosny et al., 2018), or “error-diffusion halftoning” (Brunton et al., 2015) - can translate information from various datasets into heterogeneous physical entities by converting on-screen pixels into voxels (Kolb, 2017) or 3D-pixels (Hiller & Lipson, 2009). Each voxel is a homogenous and isotropic material (Sossou et al., 2019).

How does bitmap-based 3D-Printing work?

A bitmap-based 3D-printing workflow allows image files to be sent directly to some multi-material 3D-printers, such as the Stratasys J750™ 3D-Printer for the production of physical forms. The Stratasys J750™ 3D-Printer can 3D-print one image on top of another, producing 14-micron resolution voxel matrices. When images are deposited sequentially on top of each other, the 3D-printer can construct a tangible 3D model.

Bitmap-based 3D-printing works by generating a set of layers (multiple isosurfaces) in a bitmap file format which is the same resolution as the native 3D-printer z resolution (Bader et al., 2018; Brunton et al., 2015). Each image sent to the 3D-printer contains a pixel matrix inspired by error-diffusion algorithms from 2D-printing (Brunton et al., 2015). Due to the limited amount of 3D-printer primary colours, additively manufactured shades and gradients can only be produced through 2D-printing Halftoning principles (Bader et al., 2016, 2018;

Brunton et al., 2015; Doubrovski et al., 2015; Stute et al., 2018). So, just like a printed photograph which is comprised of many pixels, a 3D-print made up of many voxels can be observed as a homogenous area with blended materials even though each pixel is assigned with a primary 3D-Printing material such as VeroCyan-V™, VeroMagenta-V™, VeroYellow-V™, VeroClear™, VeroBlackPlus™ and VeroPureWhite™ (Kolb, 2017). Each pixel within the matrix defines the material and placement specification of a 3D-printed voxel allowing for the generation heterogeneous material composites (Bader et al., 2016, 2018). Heterogeneous compositions mean that bitmap-based 3D-prints can be composed of multiple materials that are fused together, differing in their chemical and physical properties (Doubrovski et al., 2015, p. 4). The variations in materials, including the creation of gradients in colour and density, allow for exploration opportunities, especially in the fields of biomimicry and medical modelling. A bitmap-based 3D-printing workflow has potential to completely bypass traditional mesh-based segmentation methods.

There have been a limited amount of studies that explore the capabilities of bitmap-based 3D-printing techniques for purposes of medical modelling (Bader et al., 2018; Hosny et al., 2018). Huutilainen et al. (2014) suggest that there should be research conducted in the area of medical modelling, looking at the most accurate and feasible way of converting voxel-based DICOM data into 3D-printed medical models.

Overall, studies acknowledge that the strength of bitmap-based 3D-printing lies its accuracy, limitless manufacturing possibilities and the production of complex material combi-

nations at a microscale. In saying this, voxel-based 3D-printing also comes with colour and material reproduction challenges based on the need to control the material of every voxel to create accurate material combinations without appropriate software tools available (Brunton et al., 2015; Stute et al., 2018).

Figure 31. Converting on-screen pixels into 14-micron multi-material droplets (voxels).

1

Data Acquisition

2

Primarily Automated Digital Workflow

STEP THREE

Processing the images to create a bitmap-based 3D-printing file (defining 3D-print parameters and materials). This step may replace traditional segmentation processes.

Interpolation can happen at different stages in the process. These stages are highlighted in blue.

3

3D-Printing

Figure 32. Bitmap-based 3D-printing workflow.

THE GAP IN CURRENT KNOWLEDGE, THE PROPOSED RESEARCH &
ITS ANTICIPATED VALUE

A plethora of literature suggests that 3D-printing technologies are advancing at a fast pace and provide ample benefits in the areas of medical education, giving informed consent, surgical simulation and pre-operative planning - serving as a possible valuable tool for clinicians, families and communities.

However, the cost efficiency and the degree of realism of current medical modelling workflows have an immense impact on the overall quality of a medical model and the ability to produce “fit for purpose” models efficiently. Limiting factors of current medical models include the lack of soft tissue realism, low-fidelity detail due to traditional segmentation techniques and the processing time involved in traditional mesh-based segmentation methods (Huotilainen et al., 2014; Mavili et al., 2007; Yoo et al., 2016).

A Bitmap-based 3D-printing Workflow

Some authors hypothesise that surgical training using high-fidelity medical models will eventually be an “essential component” in surgical training programmes and a “prerequisite requirement for performing the procedure on the patients” (Yoo et al., 2016, p. 10). Therefore, there is value in exploring a more sustainable, streamlined medical modelling workflow that can create patient-specific medical models to a higher degree of anatomical realism.

Novel bitmap-based 3D-printing workflows may offer interesting opportunities for medical modelling at a high-fidelity, with potential to mitigate some of the disadvantages of current medical modelling workflows using traditional mesh-based segmentation techniques. Current 3D-printed medical models are predominantly created to replicate mono-material bony body structures (Huotilainen et al., 2014, p. e260). However, material properties created through bitmap-based 3D-printing have potential to emulate bioinspired material qualities inherent in human anatomies such as both bone density, soft tissue and skin elasticity (which is almost impossible to mimic using any other 3D-printing technique) (Doubrovski et al., 2015; Oxman, 2017).

A Streamlined Workflow

A streamlined medical modelling workflow has the potential to save time, money and produce highly accurate models with graduated densities, colour and flexion. An automated bitmap-based 3D-printing medical modelling workflow may produce a higher amount of patient-specific and high-resolution medical models at a lower cost by bypassing the need for current mesh-based segmentation methods and expensive CAD software. Therefore, there is immense value in establishing and exploring a bitmap-based medical modelling workflow and novel 3D-Printing technologies.

Parallels drawn between bitmap-based 3D-printing and bioimaging methods means that the conversion of bioimaging datasets to bitmap-based 3D-prints could be a promising direction for future research.

This research will build off knowledge from previous studies that suggest “generated stacks of binary bitmap files can be considered analogous to files produced in volumetric scanning technologies” (Doubrovski et al., 2015, p. 9). Both bitmap-based 3D-printing and biomedical imaging datasets are comprised of cross-sectional image stacks that create volumetric 3D forms. A CT scan can generate a voxel representation of the human body if axial slices are interpolated from one image to the next, forming volumetric pixels, also referred to as voxels (Bibb et al., 2015). Volumetric datasets composed of image stacks obtained from biomedical imaging can be used as direct 3D-printer inputs. A streamlined bitmap-based 3D-printing workflow may bypass the conversion steps of traditional segmentation, resulting in the preservation of anatomical detail and a completely automated manufacturing process – without the need for mesh-based file preparation.

Gap in Knowledge

Studies have demonstrated that biomedical imaging data can be utilised for the fabrication of medical models with graduated colour using a bitmap-based 3D-printing workflow (Bader et al., 2018; Doubrovski et al., 2015; Hosny et al., 2018; Kolb, 2017). However, bitmap-based 3D-printing is still novel, and its potential for medical applications has not yet been explored in depth, leaving considerable gaps in knowledge about the capabilities of bitmap-based 3D-printing for medical modelling.

Whether or not anatomically accurate and patient-specific colour or biomechanics can be mimicked through a bitmap-based 3D-printing medical modelling workflow is relatively unknown. Current bitmap-based 3D-printing research has produced 3D-printed models that successfully graduate material colour and opacities (Vero™) but limited exploration has been conducted into the gradation of 3D-printed material densities or ‘stiffness’ (Agilus30™) and the reproduction accurate anatomical colours (Bader et al., 2018; Hosny et al., 2018).

Bitmap-based 3D-printing has the potential to produce bespoke pathological models which vary in both chemical and physical properties (Doubrovski et al., 2015). Research should be conducted into streamlining the mesh-based traditional segmentation workflow by exploring the possibilities of bitmap-based 3D-printing for high-fidelity medical modelling. Further research could properly quantify the value of a bitmap-based medical workflow to the healthcare sector.

The Proposed Research

This research portfolio will creatively explore how bitmap-based 3D-printing can produce medical models from biomedical imaging datasets with graduated stiffness that mimic anatomical densities as well as anatomically accurate colours. Manufacturing on medical models at a 14-micron voxel resolution may provide another way of viewing and understanding the human anatomy, adding to existing knowledge about human physiology.

This research will introduce a bitmap-based additive manufacturing file preparation workflow that has potential to convert biomedical imaging data into multi-property and full colour 3D-printed synthetic anatomy in minutes. The hope is that this research will act as an introduction to bitmap-based 3D-printing techniques for medical applications and serve as a foundation for future studies that quantify the value of bitmap-based 3D-printing for medical applications. This research will bring to light the advantages and disadvantages of bitmap-based 3D-printing workflows for different medical applications.

Figure 33. Parallels between biomedical imaging techniques and bitmap-based 3D-printing.

04

PRACTICAL ACTION RESEARCH

Left:

Figure 34. Bitmap-based 3D-printed neonatal hip.

PRACTICAL ACTION RESEARCH KEY

MATERIAL COLOURS (RGB)

VeroPureWhite™
VeroCyan-V™
VeroMagenta-V™
VeroYellow-V™
VeroBlackPlus™
VeroClear™
Agilus30™
SUP706™

DIGITAL HALFTONING (DITHERING)

Figure 35. Practical action research cycle key (material colours and digital halftoning).

PRACTICAL ACTION RESEARCH

4.1 CASE STUDY 1

3D-Printing a Full-Colour Voxel Human using the Visible Female Dataset (Visible Human Project®) and a Bitmap-based Additive Manufacturing Workflow.

Left:

Figure 36. Digitally halftoned image of the Visible Female dataset from the Visible Human Project®.

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4.1.1

Overview

Case Study 1 focused on developing a streamlined bitmap-based additive manufacturing workflow to produce an anatomically accurate, high-fidelity, and full colour model of the Visible Female®. The 3D-printed model of the Visible Female® was produced by using serially sectioned cryosection images of a female cadaver produced by researchers working on the Visible Human Project® (VHP). The original cryosectional images at 0.33mm XY resolution generated cross-sectional images of anatomy, at the Stratasys J750™ 3D-Printer native z (axial) resolution, meant that three-dimensional forms could be additively manufactured from bitmap images.

Initial parallel prototyping in *Case Study 1* was conducted in another School of Design Innovation course at the Victoria University of Wellington, titled CCDN444. The final design workflow was developed based on the information gathered from the CCDN444 project. The developed workflow presented in this research produced a high-fidelity bitmap-based 3D-print of the Visible Female®.

The Visible Female®'s cause of death was heart disease, induced by morbid obesity (Hamzelou, 2015). Subsequently, the Visible Female®'s body was donated by her husband to the VHP (Hamzelou, 2015). Male and female datasets from the VHP were recorded through high-resolution photographic images and biomedical imaging including CT and MRI by the University of Colorado Health Sciences Centre, along with the National Centre for Atmospheric Research. Serial sectioning, photographing and segmenting this data has led to 3D-reconstructions of the Visible Human® – which has been employed in medical education and utilised in clinical practice (M. Chung & Park, 2007).

To traditionally convert serially sectioned slices into a file suitable for 3D-printing, certain anatomical features must be segmented and converted into mono-material boundary meshes. Current studies have not taken advantage of high-resolution multi-material 3D-printers that allow for control over material droplets or 'voxels' to produce highly-realistic models of Visible Human Project® anatomy (M. Chung & Park, 2007; Kirana P. Kumara, 2012).

Criteria for Case Study 1

The focus of *Case Study 1* was to produce a bitmap-based 3D-printing workflow by creating a series of design experiments utilising the full-colour Visible Female® dataset, with a focus on replicating accurate anatomical colour. Focusing on gradients in colour (rather than gradients in density) using a bitmap-based 3D-printing workflow was a good starting point for investigations. Experimentation with scale was conducted to test the consistency of interpolation functions as well as how scale affected 3D-print fidelity.

CRITERIA

1. Explore and develop a bitmap-based 3D-printing workflow.

A bitmap-based 3D-printing workflow should be developed to 3D-print models of human anatomy with anatomically accurate colour. The workflow should be streamlined and work to create extremely detailed 3D-prints using a small amount of processing steps and programmes.

2. Show the human body at a high-fidelity and with realistic colour.

The bitmap-based 3D-printing workflow should produce 3D-prints constructed using the Visible Female® dataset. Using parallel prototyping, the preferred workflow will be chosen based on the quality of the resulting 3D-prints. These 3D-prints should preserve the most amount of original data possible.

3. Use the most effective bitmap-based 3D-printing workflow to create a final, high-fidelity model using the Visible Female® dataset.

The level of realism in the Final Design should be unprecedented to provoke thought about the future of 3D-printing in medicine and the contextual applications of the developed bitmap-based 3D-printing workflow. The final 3D-print should be evaluated by a process of self-reflection and discussion with expert opinions.

4.1.3

File Preparation

DATA ACQUISITION

A dataset is required to begin bitmap-based 3D-printing. High-resolution imaging data, provided by the VHP, was used to produce full-colour and high-resolution 3D-prints from a set of images. The VHP data was selected to test this novel bitmap-based workflow because of the open-source, diverse and high-fidelity nature of the imaging. 5,189 cross-sectional images of the Visible Female were downloaded and used for *Case Study 1*.

Figure 37. Cross-sectional images of the Visible Female®.

DIGITAL WORKFLOW

The Visible Female® dataset was volumetrically reconstructed to create a virtual model. The virtual model was scaled down during parallel and final design prototyping for cost saving purposes and an interpolation function was used to fill in missing slices to match the native 3D-printer z (axial) resolution. The prototyping process followed the workflow outlined in Figure 38.

Figure 38. Case study 1 digital workflow.

4.1.4

Design Experimentation

Note: All objects that are 3D-printed on the Stratasys J750™ 3D-Printer are coated in support material (SUP706™). SUP706™ coats and fills in any layers so that the 3D-printed model can build without failure. This material can be removed and the model post-processed. Typically, for Vero™ 3D-prints (hard), it is common to sand and polish the 3D-prints to create a clear finish. The 3D-prints are sanded starting with coarse (100 grit) working up to fine (1500 grit) wet-and-dry sandpaper and then are usually polished with a metal or plastic polish (available at most home hardware stores).

Left:

Figure 39. A bitmap-based 3D-printed section of the Visible Female® heart.

PHOTOGRAPHY & OBSERVATIONS

Figure 40. Images of 3D-print #1 (Visible Female® skull and brain).

1 / Skull & Brain

Aim

Scale 1:2

To 3D-print a section of the skull and brain to see the transition between two diverse areas of anatomy.

Discovery

The resulting 3D-print drew interest because, when held against a light-source, a detailed structure within the brain is visible.

Figure 41. Images of 3D-print #2 (Visible Female® scalp and skull).

2 / Scalp & Skull

Aim

To 3D-print the top of the head, including the skin and the top of the scalp.

Scale 1:2

Discovery

The resulting 3D-print was interesting, especially the skin area. The appearance of the 3D-print looked like some form of bruising and the blood vessels are visible. The area between the skull and skin is textured (potentially skin or hair follicles).

Figure 42. Images of 3D-print #3 (Visible Female® heart).

3 / Heart Cross-Section

Aim

Scale 1:2

Discovery

To 3D-print a complete slice through the heart in order to see the full details & visibility of structures within the heart/lungs.

Structures within the fat – “channels” - for blood to run through appeared vividly. With this said, other areas (such as the lungs surrounding the heart) appeared black with no observable detail.

Figure 43. Images of 3D-print #4 (Visible Female® heart).

4 / Heart Cross-sections (thin slices)

Aim

To 3D-print slices through different areas of the heart to understand 1:1 details.

Scale 1:1

Discovery

These 3D-prints were interesting between they showed a 1:1 representation of heart structures, The detail captured was of high-fidelity, but also dark which meant some parts of the 3D-prints were completely blacked out.

Figure 44. Images of 3D-print #5 (Visible Female® fat).

5 / Heart Fat

Aim

Scale 1:1

To 3D-print an area of 1:1 fat surrounding the heart. Since fat was executed well in 3D-print #3, this 3D-print aimed to look at the details further.

Discovery

The resulting 3D-print is extremely realistic. The transition between areas and layers is seamless. Because of the increase in scale, more VeroMagenta-V™ is spread through VeroPureWhite™ which means that the fat appears more translucent and less white and opaque.

Figure 45. Images of 3D-print #6 (Visible Female® fat with embedded support material).

6 / Heart Fat (with embedded SUP706™)

Aim

Scale 1:1

Discovery

To 3D-print the same file as 3D-print #5, but replacing the red or “blood” in every other layer with support structure, SUP706™. The aim of the was to see if the resulting 3D-print produced micro “channels” that “blood” could be injected into in the post-processing stages.

The resulting 3D-print was not the expected result but created an interesting texture on one side of the model. Instead of creating micro “channels”, the 3D-printed structure collapsed (producing texture).

Figure 46. Image of 3D-print #7 (Visible Female® brain slice).

7 / Brain Slice (with VeroClear™)

Aim

Scale 1:2

Discovery

To take a small slice through the brain (including areas such as the sinuses) to see and understand the appearance of the brain. This 3D-print utilized the full material range, including VeroClear™ within the brain structure.

The inclusion of VeroClear™ within the brain structure made the 3D-print dark. When the print is held up to a light-source, the VeroClear™ caused some parts of the model to appear bright green.

Figure 47. Image of 3D-print #8 (Visible Female® brain slice without clear material).

8 / Brain Slice (without VeroClear™)

Aim

To take a small slice through the brain (including areas such as the sinuses) to see and understand the appearance of the brain. The file was the same as 3D-print #7. This 3D-print utilised the full material range including VeroClear™. However, VeroClear™ was only used for the bounding box and was not used within the brain structure.

Scale 1:2

Discovery

Avoiding the use of VeroClear™ within the brain structure resulted in a 3D-print with colour that was more representative of cadaveric anatomy, mimicking anatomical colour much more realistically.

Figure 48. Images of 3D-print #9 (Visible Female® brain slice).

9 / Brain Slice (more layers)

Aim

Scale 1:3

Discovery

To take the same file as 3D-print #8, but add more layers to create a thicker 3D-print with more detail and depth.

The resulting 3D-print was detail, clear, & realistic – showing elements of anatomy such as the nose and ears.

Figure 49. Images of 3D-print #10 (Visible Female® breast).

10 / Breast

Aim

Scale 1:2

Discovery

To 3D-print a slice through the breast (including the heart, ribs and breast tissue) to see the intricacies in the breast such as fat, lobules and ducts.

Details such as fat, ribs (including the internal structure), structures within the breast and the nipple were all captured within the resulting 3D-print.

Figure 50. Images of 3D-print #11 (Visible Female® eyeball).

11 / Eyeball

Aim

Scale 1:2

To take a small section of the eyeball to see if the colours and translucency of the eyeball could be replicated.

Discovery

The eyeball appeared dark and black, but the muscle structures surrounding the eyeball were highly detailed and realistic. The scale was meant to be 1:1, but for some reason appeared much smaller, which meant that there was a glitch in the file-preparation method.

Figure 51. Images of 3D-print #12 (Visible Female® bendy fat).

12 / Bendy Fat

Aim

Scale 1:1

To 3D-print a slice of fat with Agilus30™ dispersed through the 3D-print to create some form of movement whilst preserving anatomical colour – laying the foundation for *Case Study 2*.

Discovery

Dispersing Agilus30™ through the fat meant that the 3D-print moved (had dynamics). Although some anatomical colour was preserved, a lot was lost and the 3D-print did not visually mimic anatomy in the same way as the Vero™ 3D-prints.

DESIGN EXPERIMENTATION REFLECTION & MODIFICATION

The parallel prototyping in *Case Study 1* mimicked anatomical colour realistically. Therefore, moving forward, the decision was made to 3D-print the half of Visible Female® from head to toe at a 1:12 scale. The 1:12 scale was decided upon because it was a way to show the capabilities of the Stratasys J750™ 3D-Printer without sacrificing logistics such as easy transportation and sustainable use of materials.

Figure 52. Image of full Visible Female® bitmap-based 3D-print (final model).

4.1.5
Final Design

Figure 53. Visible Female® in blue embedding media.

Figure 54. Visible Female® sections with blue embedding media removed.

Figure 55. Digitally halftoned Visible Female® bitmap images.

Figure 56. GrabCAD Print tray with the full 1:12 Visible Female® files.

FILE PREPARATION

Using the same workflow presented in the *Design Exploration* research phase, the Visible Female® bitmap images were prepared for 3D-printing. Originally, the female cadaver was embedded and frozen in an embedding media made of a 3% gelatine solution and blue dye (Westwood, 2002, p. 231). Therefore, a colour threshold was used to eliminate the blue embedding solution (Figure 53). The images were cropped down the centreline of the body and a boundary box was placed around the Visible Female (the black box seen in Figure 54).

The masked datasets were scaled into the Stratasys J750™ 3D-Printer's native X and Y resolutions and material dithering algorithms (digital halftoning) were used to create pixel combinations using the primary 3D-printer materials of VeroPureWhite™, VeroCyan-V™, VerowMagenta-V™, VeroYellow-V™ and VeroBlackPlus™. VeroClear™ was assigned to the bounding box.

Images were processed through GrabCAD Voxel Print Utility and were exported as a GrabCAD Voxel Files (.GCVF file). A total of 5,102 images were processed to complete the Visible Female® 3D-print. The Visible Female® was split into cross-sectional blocks with different thicknesses for the purpose of this study.

A total of 24 .GCVF files were processed and 3D-printed. The resulting 24 individual 3D-prints were stacked on top of each other to form the full 3D-printed Visible Female®, varying in slice thickness (highlighting that bitmap-based printing can produce thin slices or thick blocks). Thick blocks were used to show more detailed areas of anatomy (such as the hand and chest regions) and thinner slices were used to show detailed areas (such as the thigh).

Each pixel in the bitmap images is representative of one voxel being placed on the print tray.

Figure 57-67. Images of the final model of the Visible Female®.

The measurements of the 1:12 Visible Female® model are X = 28.55 mm , Y= 35.65 mm, Z= 137.75 mm.

Figure 57.

Figure 58.

Figure 59.

Figure 60.

Figure 61.

Figure 62.

Figure 63.

Figure 64.

Figure 65.

Figure 66.

Figure 67.

Figure 68.

Figure 69.

A

B

C

D

E

F

G

H

I

J

K

L

Figure 70. Photography taken on the trip to Melbourne for the 3D Technologies in Medicine conference. (A-C) Stratasys J750™ Digital Anatomy™ 3D-printed models. (D-G) Stratasys J750™ 3D-printed models shown at the Stratasys presentation. (H-I) Centre for Additive Manufacturing Lab Tour at RMIT including the 3D-printer studio and a 3D-printed skeleton. (J) New Experimental Technology (NExT) Lab Tour at the Melbourne School of Design. (K) Bio-printing lab. (L) A photo of me presenting (taken by the Stratasys marketing team).

4.1.6

Evaluation and Reflection

To evaluate this area of research, *Case Study 1* was presented at 3D Technologies in Medicine (3DMED¹) conference in Melbourne, Australia, on 14-16 of November, 2019. Presenters were experts in their respective fields, including highly regarded surgeons, clinicians, designers, VR specialists, medical modelers (including Fusetec), 3D-printing specialists (including Stratasys), biomedical engineers and radiographers from around the world (see Appendix A). The opportunity of presenting *Case Study 1*, along with attending workshops and receiving feedback from highly esteemed professionals helped to shape the next stage of the research. Visiting design and manufacturing facilities – like the New Experimental Technology (NExT) Lab Tour at the Melbourne School of Design, Centre for Additive Manufacturing Lab Tour at RMIT, SBS Digital Learning Hub, and BioFab3D Tour at St Vincent’s Hospital Melbourne – was invaluable to the progress of this research.

Case Study 1 was also presented to specialists² in New Zealand.

MOVING FORWARD

Case Study 1 helped to develop a bitmap-based 3D-printing workflow that can accurately convert serially sectioned images of cryosectioned cadaver into a full-colour and highly realistic 3D-print of the Visible Female from the VHP.

Full-colour bitmap images were used as 3D-printer inputs instead of traditional mesh-based stereolithographic (STL) file formats to create a 3D-printed model of the Visible Female. The control over every 3D-printed voxel meant that a full colour model of the Visible Female could be created with unprecedented preservation of accurate anatomical colour and detail.

Moving forward, the project will focus on using the developed bitmap-printing workflow to produce models from live patient-specific data with graduated densities. This process is outlined in *Case Study 2*.

¹3DMED is Australia’s largest 3D technologies in Medicine conference.

²including the team at the Auckland Bioengineering Institute (ABI) and the Neurology team at the Wellington Hospital.

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CASE STUDY 1 REFLECTION AFTER ATTENDING 3D-MED

ENCOURAGING FACTORS

Case Study 1 helped to develop a bitmap-based 3D-printing workflow that can accurately convert serially sectioned images of cryosectioned cadaver into a full-colour and highly realistic 3D-print of the Visible Female from the Visible Human Project®.

Based on the feedback received from the 3DMED conference, it was clear that this method of 3D-printing is relatively new and unprecedented. Most people were unaware of the technique and were interested in its application and potential. The team at Stratasys were impressed by the use of their Voxel-Print Utility.

University anatomy teachers were interested in the application of this model for teaching purposes.

Case Study 1 highlighted potential applications of bitmap-based 3D-printing workflows using biomedical imaging data. This project expands on the VHP's original goal of expanding knowledge into new territory through technologies that offer the potential of generating new biomedical knowledge (The National Library of Medicine Visible Human Project, n.d.).

Anatomically accurate colour was achieved because of the discovery that the VeroClear™ can severely change the colour of the 3D-print, making the print darker and green.

I talked to the team at Materialise Mimics, Stratasys, 3Dsystems, and Auckland Hospital's 3D-Print Lab.

THINGS TO CONSIDER

Many suggestions were given for the future direction of this project. *Case Study 1* drew interest from surgeons, clinicians and biomedical engineers because this workflow could potentially incorporate patient-specific biomedical data (such as CT and MRI datasets) as well as integration of both soft (Agilus30™) and rigid (Vero™) materials in bitmap-based file formats. There was interest in creating gradients in material densities as many 3D-printed medical models are used for device testing, surgical simulation and skills acquisition and biomechanical research purposes and therefore realistic anatomical movement would be useful.

Some experts implied that replicating anatomical density through bitmap-based 3D-printing could be an extremely useful tool, especially if the models could be created by using live patient-specific data.

Stratasys released the Stratasys J750™ Digital Anatomy™ 3D-Printer at the 3DMED conference with new anatomical materials. Combining a bitmap-based 3D-printing workflow with the new Stratasys anatomical materials could produce anatomically accurate 3D-prints at a 14-micron resolution.

Figure 71. Case study 1 reflection brainstorm.

PRACTICAL ACTION RESEARCH

4.2 CASE STUDY 2

Replicating the Dynamic Movement of Human Anatomy using CT Imaging Data and a Bitmap-based 3D-Printing Workflow.

Left:

Figure 72. Digitally halftoned image of bitmap-based 3D-printed neonate.

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4.3.1

Overview

Case Study 2 focused on replicating the biomechanical movements of human anatomy by using patient-specific CT data and a streamlined bitmap-based 3D-printing workflow. The research focus shifted from replicating anatomical colour to mimicking anatomical density and biomechanics in 3D-printed models based on feedback and reflection regarding *Case Study 1*. This meant that the bitmap-based 3D-printing workflow developed in *Case Study 1* was altered to suit the new set of criteria developed for *Case Study 2*.

Models of neonatal anatomy have potential value, especially in the areas of surgical models for trainee education, open surgery and planning (Stramiello et al., 2020). Adequate training can help mitigate risks associated with complex paediatric intervention, improving survival and life quality, especially in perinatal acute care (Meurs et al., 2003). Due to the gap in knowledge around neonatal modelling, biomechanics and the limited amount of neonatal simulators available on the market, *Case Study 2* focussed on mimicking realistic movement in neonatal anatomy. Currently, paediatric and neonatal simulators “are of low physical fidelity therefore cannot provide qualitative insight into the procedure” (Thielen et al., 2019, p. 1).

Paediatric anatomy is intricate and data loss during the segmentation process can be detrimental to the quality of the 3D-print. Bitmap-based 3D-printing showed promise for neonatal modelling and paediatric high-fidelity dynamic modelling.

Anatomical density is captured through CT imaging rather than serially sectioned cadaver (such as the VHP). Turning greyscale images into volumetric models for 3D-printing using a bitmap-based workflow presents various challenges, such as the accurate replication of anatomical density and movement. However, one of the main advantages of using CT imaging data is that dynamic and tangible 3D-models can be produced from living patient data rather than from cadaveric material.

Cross-sectional CT images of anatomy can generate volumetric or a “voxel representations” of body parts by using an interpolation function that fills in missing pieces between CT layers. Interpolating, re-slicing and exporting CT image files at the Stratasys J750™ 3D-Printer native z resolution meant that 3D-printed models of anatomy were successfully produced from CT imaging data using a bitmap-based 3D-printing workflow.

Criteria for Case Study 2

The overall focus of *Case Study 2* was to outline the most successful workflow for converting CT imaging data into dynamic bitmap-based 3D-printed models that mimic human anatomical movement.

CRITERIA

1. Select an area of neonatal anatomy that will serve as a starting point for design exploration.

The chosen area of anatomy should contain a range of gradients (soft and hard areas) to test the material properties of the Stratasys J750™ 3D-Printer and a bitmap-based 3D-printing workflow

2. Explore and develop a bitmap-based 3D-printing workflow using a patient-specific biomedical imaging dataset.

A bitmap-based 3D-printing workflow should be developed to 3D-print sections of neonatal anatomy with anatomically accurate density. The workflow should be streamlined and work to create extremely detailed prints with integrated dynamics using a limited amount of processing steps and programmes.

Material ratios should be noted and addressed throughout the design process to develop a high-fidelity final bitmap-based 3D-print of the selected area of anatomy.

3. Use the most effective bitmap-based 3D-printing workflow to create a high-fidelity 1:1 dynamic medical model of an area of anatomy using a patient-specific biomedical imaging dataset.

By blending Vero™ (hard) and Agilus30™ (soft) using a bitmap-based 3D-printing workflow, the level of realism in the *Final Design* should be unprecedented to provoke thought about the future of 3D-printing in medicine. The final 3D-print should be evaluated by a process of self-reflection and discussions with expert opinions.

4.2.3

File Preparation

DATA ACQUISITION

The dataset used in *Case Study 2* was a high-resolution CT scan of a neonate. The area of anatomy chosen for initial experimentation was the foot. This is because a neonatal foot includes varying densities, from soft fat to hard bone. Biomechanical movement of the foot can be early indicators of conditions such as cerebral palsy and equinovarus (clubfoot) which develop in neonates (Aurell et al., 2002; Heineman et al., 2011). Therefore, the foot was a logical area for design exploration, especially for a designer without formal medical training.

Testing different bitmap-based 3D-printing workflows for the purposes of mimicking anatomical density from CT imaging data occurred through *Parallel Prototyping*. Once an appropriate workflow was established, further *Parallel Prototyping* and *Focussed Prototyping* occurred.

Figure 73. Bitmap baby CT scan (three planes).

DIGITAL WORKFLOW

The dataset was downloaded and volumetrically reconstructed to create a virtual model and an interpolation function was used to fill in missing slices to match the native 3D-printer z resolution. The prototyping process followed the workflow outlined in *Figure 74*. A total of 483 images were processed to complete each foot swatch.

4.2.4

Design Experimentation

Note: Vero™ material colours used throughout this process are interchangeable. Colour was used to identify each print from one another since they are all the same geometry and can easily get mixed up.

Left:

Figure 75. Neonatal foot swatch covered in support material before cleaning.

Volumetric Reconstruction (Stage One of Digital Workflow)

Figure 76. Volumetric reconstructions of neonatal foot (cross-section) with integrated 3D-print settings.

Digital Halftoning (Variable step in Stage Two, part b of Digital Workflow)

Figure 77. Cross-sectional 14-micron image slices of digitally halftoned neonatal feet.

Figure 78. Cross-sections of bitmap-based 3D-printed neonatal feet prototype models (two toes) straight off the 3D-printer bed and coated in SUP706™.

PHOTOGRAPHY & OBSERVATIONS

Figure 79. Bitmap-based 3D-printed neonatal feet prototype models (two toes) straight off the 3D-printer bed and coated in SUP706™.

Soapy water

Toothbrush

Toothpicks

Gloves

Support material (SUP706™)

Cleaned 3D-printed models in soapy water

Figure 80. Cleaning 3D-prints.

POST-PROCESSING 3D-PRINTS

The SUP706™ cleaning process can be challenging due to some intricacies in 3D-print structure, especially in anatomically complex models. The post-processing workflow used in *Case Study 2* is outlined below.

- 1) The 3D-prints were soaked in warm water with a small amount of dishwashing liquid to gently remove large clumps of SUP706™.
- 2) Once the large pieces of support material were removed, using a toothpick and toothbrush, the 3D-prints were brushed softly and any SUP706™ was scraped away on a dry surface to remove SUP706™ film left on the 3D-print. The object was dipped into a container full of warm water and dishwashing liquid periodically to remove any loose SUP706™ fragments.
- 3) The 3D-prints were then placed in a chemical cleaning bath available at the School of Design Innovation. The chemical cleaning bath dissolves support material in delicate areas of the print that cannot be removed by hand. If the objects are left in the chemical cleaning bath for too long, they can warp in shape, so it is important to consider this (approximately 1 hour is a good amount of time).

Figure 81. 3D-print #14.

Materials

Diffusion 100%

Stratasys J750™ 3D-Printer RGB colours representative of the primary 3D-printer materials.
More details available in the Practical Action Research Key on page 74.

Aim

To 3D-print with purely Vero™ materials (similar technique to *Case Study 1*) to understand which materials blend using bit-map-based 3D-printing from CT datasets (due to its translucency Agilus30™ makes it hard to see if materials are blending). The full neonatal foot was processed.

Discovery

Materials blended well with a high level of detail. The addition of VeroPureWhite™ made the 3D-print opaque and therefore some areas are not translucent, and details are hidden because of this.

14 / Foot 1

Figure 82. 3D-print #15.

Materials

Diffusion 100%

15 / Foot 2

Aim

Same aim as 3D-print #14 but only the soft tissues were processed (not including fat and skin).

Discovery

Removing the addition of VeroPure-White™ meant that the 3D-print was translucent and the blend between the two materials (VeroMagenta-V™ and VeroYellow-V™) is evident.

Materials

Diffusion 30%

Figure 83. 3D-print #16.

16 / Foot 3

Aim

To translate a CT scan dataset directly into a dynamic 3D-print. Interpolated greyscale CT images were digitally halftoned using black and white. Black was replaced with Agilus30™ using image thresholding techniques in an image editing, batch processing software.

Discovery

This 3D-print worked well. The materials blended, 3D-print detail was preserved, and it moved well whilst maintaining structural integrity.

Materials
Diffusion 40%

Figure 84. 3D-print #17.

17 / Foot 4

Aim

To replace greyscale values of a CT dataset with Stratasys J750™ 3D-Printer material RGB values in a volumetric reconstruction software. The densest (highest H.U. value) was assigned with VeroMagenta-V™ and the softest area (lowest H.U. value) was as-

signed with Agilus30™. Areas such as inside the bone were assigned with SUP706™ to create more realistic bone density.

Discovery

This 3D-print worked well. It moved realistically and maintained structural integrity. However, the materials did not blend much. The SUP706™ created interesting structures within the bone.

Materials

Diffusion 70%

Figure 86. 3D-print #18.

18 / Foot 5

Aim

To replace greyscale values of a CT dataset with Stratasys J750™ 3D-Printer material RGB values in a volumetric reconstruction software. The densest (highest H.U.) value was assigned with VeroCyan-V™ and the softest area (lowest H.U.) was assigned with Agilus30™.

Discovery

The 70% diffusion of materials meant that materials blended well (created gradients), but a high percentage of VeroCyan-V™ within the Agilus30™ 3D-print stiffened the made the 3D-print more rigid.

Materials

Diffusion 25%

Figure 87. 3D-print #19.

19 / Foot 6

Aim

To replace greyscale values of a CT dataset with Stratasys J750™ 3D-Printer material RGB values in a volumetric reconstruction software. The densest (highest H.U.) value was assigned with VeroMagenta-V™ and the softest area (lowest H.U.) was assigned

with Agilus30™. The middle H.U. value was assignment with the middle RGB value that lies between the VeroMagenta-V™ RGB value and the Agilus30™ RGB value to create a smooth blend between materials.

Discovery

The combination of VeroMagenta-V™ and Agilus30™ produced the 'orange' middle H.U. value. The dispersion of VeroMagenta-V™ within the 3D-print made it rigid.

Figure 87. 3D-print #20.

Materials

Diffusion 35%

20 / Foot 7a

Aim

To translate greyscale CT scan data directly into a dynamic 3D-print without the need to assign materials with an Agilus30™ specific RGB colour. The CT dataset was resliced at 14-micron layer resolution and greyscale files were digitally halftoned in an image processing software.

Discovery

When adding these files to GradCAD the colour black is picked up as VeroBlack-Plus™.

Even though the image stack was digitally halftoned with black and white pixels, the GrabCAD 3D-Print software picked up

multiple greyscale values (based on black and white colour ratios). The lightest greyscale value was assigned with VeroCyan-V™ and the rest were assigned with Agilus30™.

Figure 88. 3D-print #21.

21 / Foot 7b

Aim

Same aim as 3D-print #20.

Material Mapping

Material	Red	Green	Blue	Alpha
VeroFlexBK	26	26	29	255
Tango+	78	78	78	255
Tango+	79	79	79	255
Tango+	80	80	80	255
Tango+	81	81	81	255
VeroPureWht	240	240	240	255

Discovery

Because of the interesting glitch in GrabCAD, the lightest greyscale value was assigned with Agilus30™, the middle greyscale value was assigned with VeroYellow-V™ and the darkest greyscale value was assigned with VeroCyan-V™.

The 3D-print was particularly interesting because it contained three materials even though the image stacks were dithered with only two pixel colours. However, two Vero™ colours created a visually complex but rigid 3D-print.

Materials

Diffusion 90%

Figure 89. 3D-print #22.

22 / Foot 8

Aim

To replace greyscale values of a CT dataset with Stratasys J750™ 3D-Printer material RGB values in a volumetric reconstruction software. The densest (highest H.U.) value was assigned with VeroMagenta-V™, the middle HU value was assigned with Agi-

lus30™ and the softest area (lowest H.U.) was assigned with SUP706™ to try and create a “softer” (more lifelike) model. An Agilus30™ “skin” must be added to these files during the post-processing stage to encapsulate SUP706™ within the 3D-print.

Discovery

The integration of SUP706™ made areas of the 3D-print fall apart, creating a surface texture. The areas of the 3D-print with Agilus30™ remains structural integrity. The 90% diffusion mean that VeroMagenta-V™ was dispersed throughout the 3D-print, hardening the 3D-print.

Figure 90. 3D-print #23.

Materials

Diffusion 60%

23 / Foot 9

Aim

This 3D-print is similar to 3D-print #22. However, the threshold of SUP706™ material in the 3D-print was adjusted to include more SUP706™ and less Agilus30™. A “skin” still must be added to these files during the post-processing stage.

The aim was for the SUP706™ to act as a “squishy” fat-like material.

Discovery

The integration of less SUP706™ made areas of the 3D-print fall apart, but the 3D-print has more structural integrity and was less rigid than 3D-print #22. A surface texture was created due to the inclusion of SUP706™ within the 3D-print.

Materials

Diffusion 30%

Figure 91. 3D-print #24.

24 / Foot 10

Aim

To assign two Vero™ materials (VeroMagenta-V™ and VeroCyan-V™) to the most dense areas of the CT scan. Then, the soft tissue was assigned with a yellow colour that was slightly lighter than the Agilus30™ RGB value. When these files

were post-processed, using digital halftoning algorithms that included the RGB values of Agilus30™ and SUP706™, the two materials blended together. The aim was to create 0.027 mm pockets of air within the model to produce a lighter, more realistic 3D-print.

Discovery

SUP706™ was dispersed evenly throughout the file mixing with Agilus30™ evenly. This meant the 3D-print was really flexible (feeling more flexible than Agilus30™) but still maintained structural integrity. Blending two Vero™ materials resulted in interesting colour gradients within the “bone”.

3D-print #25

3D-print #26

Figure 92. 3D-prints #25 and #26.

Materials

#25 Diffusion 100% #26 Diffusion 100%

25 & #26 / Foot 11 and Foot 12

Aim

#25 : To produce an area of the foot including the fat and skin. Fat was assigned with SUP706™ material. A black value was used as the SUP706™ value so that differentiation between black and yellow was more clear. A “skin” stroke was added in post pro-

cessing stages to encapsulate the SUP706™ within the 3D-print.

#26: Same aim as 3D-print #25. However, 3D-print #26 had more Agilus30™ material dispersed throughout the file.

Discovery

The skin 3D-printed but was too thin to maintain structural integrity which meant that during the cleaning process, the 3D-print fell apart. However, due to the inclusion of more Agilus30™, 3D-print #26 maintained more structural integrity than 3D-print #25.

Figure 93. The most successful bitmap-based medical modelling workflow using CT data.

DESIGN EXPERIMENTATION REFLECTION & MODIFICATION

The most successful 3D-prints were those that rendered out the greyscale images at the 3D-printer native z resolution and were assigned materials during the digital halftoning and batch processing stage of the process (such as 3D-print #16). The material combinations that were the most effective were using Agilus30™ in combination with Vero™ materials. Generally, including SUP706™ within a 3D-print has the potential to compromise the structural integrity of the model.

After determining the most successful bitmap-based 3D-printing workflow to produce dynamic anatomical models, a decision was made to 3D-print a 1:1 scale neonatal leg, starting with the ankle, knee, and hip joints. Including a variety of joints presented new challenges and helped to highlight the advantages and disadvantages of bitmap-based 3D-printing for medical modelling purposes.

The *focussed* and *final prototyping* during *Case Study 2* was informed by discoveries made in initial *design experiments* and followed the same digital workflow.

A

B

*4.1.5***Design Refinement***Left:*

Figure 94. Bitmap-based 3D-printed neonatal feet. (A) Skin and fat included. (B) No skin and fat.

Rendering in the Correct Scale

Obstacle

Exporting image stacks using medical imaging software can cause scaling errors. Determining the correct scale occurred by selecting a small area of anatomy, exporting this area of anatomy as cross-sectional bitmap image files, and evaluating which workflow resulted in a correct 1:1 medical model. The area of anatomy chosen for testing was a thin cross-section of the leg. The correct test should have a thickness 18.36 mm, the same measurement as the 1:1 scale volumetric visualisation.

Figure 95. Virtual reconstruction of neonatal leg.

Table 3. Testing File Exportation Settings

	TEST 1	TEST 2	TEST 3
X RESOLUTION	300 DPI	600 DPI	150 DPI
Y RESOLUTION	300 DPI	600 DPI	150 DPI
LAYER THICKNESS	.014	.014	.027
SCALE	.5x	.5x	1x
POST-PROCESSING	increase image size by 400%	None	increase image size by 200% change to 300 DPI
CORRECT SCALE	655 images 17.6 mm ✗	Fail <i>file size too large</i> ✗	680 images 18.36 mm ✓

3D-Printing Foot, Knee and Hip Joints

Once the correct scale was established, the joint files (foot, knee and hip) were exported and 3D-printed. If joint files are exported separately, there is a risk of the files not being consistent. The 3D-printed leg was exported and then cropped after exportation during the digital halftoning automated batch processing. A total of 2,282 images were processed to complete a bitmap-based 3D-print of a neonatal leg (without skin and fat).

To create the 1:1 full scale test 3D-prints of a neonatal limb joints, the bitmap images were scaled into the 3D-printer's native X and Y resolutions and digital halftoning algorithms were used to create pixel combinations using the primary 3D-printer materials of VeroMagenta-V™ and Agilus30™ with a 70% pixel diffusion ratio. Each pixel holds material specification information for the 3D-printer and the pixel combinations (ratios) and the overall aim was to reflect the greyscale attenuation values of the CT scan data in a physical model. The ratio of soft (Agilus30™) material to hard (Vero™) material determines the greyscale value.

Images were imported into the GrabCAD Voxel Print Utility and were exported as a GrabCAD Voxel Files (.GCVF file). A total of 2,282 images were processed to complete the full leg (without fat and skin), 1,494 images completed the foot, 2,019 images completed the knee and 2,232 images completed the hip.

Approximately 185 images completed the cross-sectional tests of each joint.

1,677 images completed the neonatal foot with bone, soft tissue, fat and skin.

Figure 96. Virtual reconstruction of neonatal leg (with skin and fat).

Figure 97. Cropped regions for joint 3D-prints.

Figure 98. Bitmap-based images of digitally halftoned 3D-printed neonatal joints.

27 / Foot (cross-section)

28 / Knee (cross-section)

29 / Hip (cross-section)

Figure 99. 3D-prints #27, #28 and #29 (cross-sections of joints).

Materials

Diffusion 70%

Aim

To 3D-print cross-sections of the joints to test the exportation settings and 3D-print quality before 3D-printing 1:1 scale joints.

Discovery

The cross-sectional 3D-prints were successful. The material gradated well, they were the correct scale and they bent and moved as hoped.

Figure 100. GrabCAD Print tray (neonatal joints).

Figure 101. 3D-printed joints coated in SUP706™.

3D-printing Full 1:1 Scale Models of a Neonatal Foot, Knee and Hip

Two versions of the full leg were produced from the exported interpolated data. One version of the leg was dithered at 70% diffusion (like the cross-sectional 3D-prints presented in Figure 99.) and the other at 30% diffusion (based on results from the cross-sectional 3D-prints).

For differentiation purposes:

The 3D-printed joints (foot, knee, and hip) that were dithered at 70% diffusion used the materials VeroPureWhite™ and Agilus30™.

The 3D-printed joints (foot, knee, and hip) that were dithered at 30% diffusion used the materials VeroMagenta-V™, VeroCyan-V™ and Agilus30™.

Figure 102. 3D-print #30.

Materials

Diffusion 70%

30 / Foot 1

Aim

To use a bitmap-based 3D-printing workflow to 3D-print a full 1:1 scale neonatal foot using 70% diffusion.

Discovery

The 3D-printed foot preserved a significant amount of anatomical detail and photographed well. However, the 3D-print remained quite rigid.

Figure 103. 3D-print #31.

Materials

Diffusion 30%

31 / Foot 2

Aim

To use a bitmap-based 3D-printing workflow to 3D-print a full 1:1 scale neonatal foot using 30% diffusion and coloured material.

Discovery

The 3D-printed foot preserved anatomical detail and photographed well. The 3D-print was substantially less rigid than 3D-print #40 and the visual gradients created using VeroMagenta-V™ meant that more anatomical details were captured visually.

Materials

Diffusion 70%

Figure 104. 3D-print #32

32 / Knee 1

Aim

To use a bitmap-based 3D-printing workflow to 3D-print a full 1:1 scale neonatal knee using 70% diffusion.

Discovery

The 3D-printed knee preserved a significant amount of anatomical detail and photographed well. The joint remained rigid but the ligaments had dynamic movement, exposing some interesting, small anatomical details.

Materials

Figure 105. 3D-print #33

33 / Knee 2

Aim

To use a bitmap-based 3D-printing workflow to 3D-print a full 1:1 scale neonatal knee using 30% diffusion and coloured material.

Discovery

The 3D-printed knee preserved anatomical details and photographed well. The 3D-print was substantially less rigid than 3D-print #42 and the visual gradients created using VeroMagenta-V™ meant that more

anatomical details were captured visually. The photographs captured the texture on the soft tissue and appeared lifelike in photography.

Materials

Diffusion 70%

Figure 106. 3D-print #34.

34 / Hip 1

Aim

To use a bitmap-based 3D-printing workflow to 3D-print a full 1:1 scale neonatal hip using 70% diffusion.

Discovery

The 3D-printed hip preserved a significant amount of anatomical detail and photographed well. The joint remained rigid, but the soft tissue surrounding the bone structure was soft. An interesting feature of this 3D-print was the spine (bone).

Materials

Diffusion 30%

Figure 107. 3D-print #35.

35 / Hip 2

Aim

To use a bitmap-based 3D-printing workflow to 3D-print a full 1:1 scale neonatal hip using 30% diffusion and coloured material.

Discovery

The 3D-printed hip preserved anatomical detail and photographed well. The 3D-print was substantially less rigid than 3D-print #4 and the visual gradients created using VeroCyan-V™ meant that more anatomical

details were captured visually. The visual qualities created through blending VeroCyan-V™ were interesting (not lifelike, but visually interesting, almost like a candy or ocean shell).

Figure 108. 3D-print #36

Materials

Diffusion 30%

Aim

To test an area of anatomy with fat and skin, although this was unsuccessful in initial design experimentation. It was important to test this with a whole area of anatomy rather than with just a cross-section.

Discovery

The 3D-print was successful. Applying a thicker layer of “skin” encased the SUP706™ successfully, creating a realistic medical model that can be cut open, exposing the fat, ligaments, and bone.

Figure 109. Application images of 3D-print #36.

36 / Foot with Fat and Skin

APPLICATION

To show how models such as 3D-print #36 can be contextualised and used in a medical setting.

4.2.6

Final Design

Note: To create the 1:1 full scale 3D-print of a neonatal limb, the images were scaled into the 3D-printer's native X and Y resolutions and digital halftoning algorithms were used to create pixel combinations using the primary 3D-printer materials of VeroMagenta-V™ and Agilus30™ with a 30% pixel diffusion ratio.

Left:

Figure 110. Digitally halftoned image of bitmap-based 3D-printed 1:1 scale neonatal leg (1/2,282 images processed for 3D-printing).

Figure 111-120. Images of the final 1:1 model of the neonatal leg. The dimensions for the 1:1 neonatal leg were X= 120.608 mm, Y= 244.941 mm, and Z= 61.587 mm.

Note. Back of knee.

Figure 111.

Note. Medial side of leg.

Figure 112.

Note. Medial side of leg (front of neonate).

Figure 113.

Note. Lateral side of leg (back of neonate).

Figure 114.

Note. Bird's eye view focussing on the knee.

Figure 115.

Note. Body midline (including a section of the spine)

Figure 116.

Figure 117. Close-up images of 1:1 bitmap-based 3D-printed neonatal leg. (A) Ligaments within the knee. (B) Close-up of the spine. (C) Texture and gradients down the body midline. (D) Close-up of side of the foot. (E) Bottom of foot. (F) Heel of foot.

Figure 118. Close-up images of 1:1 bitmap-based 3D-printed neonatal leg. (A) Lateral side of ankle. (B) Close-up of crossing over muscles in the thigh. (C) Close-up of toes and the transition between Vero™ and Agilus30™. (D) Lateral side of heel. (E) Medial side of knee. (F) Close-up of knee (patella).

A

B

Figure 119. (A-D) Moving bitmap-based neonatal ligaments with tweezers.

C

D

Figure 120. Articulating the bitmap-based neonatal toes demonstrating biomechanics.

Figure 121. Articulating the bitmap-based neonatal knee joint demonstrating biomechanics.

Figure 122. Close-up of bitmap-based neonatal leg (foot).

4.2.7

Evaluation and Reflection

Case Study 2 helped to develop an effective bitmap-based 3D-printing workflow for the conversion of CT data into dynamic 3D-printed models. This workflow was able to translate the biomedical imaging data into 3D-printed models with gradients in density, ranging from very soft 3D-printed material (mimicking fat) to harder areas of anatomy such as bone. Evaluation of the bitmap-based 3D-Prints conducted in *Case Study 2* was conducted through material property observation, tactile analysis, and photographic documentation. The 3D-prints were also presented via Video Call to an Expert Reviewer, Dr. Ali Mirijilili, who gave feedback virtually and in person at a MedTech Core meeting.

MOVING FORWARD

Based on the results of *Case Study 2*, an interesting avenue of exploration for future research would be to look into creating more realistic models with materials that are softer – mimicking the qualities of human anatomy to a higher degree of realism.

Evaluation of the bitmap-based 3D-Prints conducted in this Case Study was done through material property observation, tactile analysis and photographic documentation. The 3D-Prints were also presented via Video Call to an Expert Reviewer, Dr. Ali Mirjalili, who gave feedback virtually.

CASE STUDY 2 REFLECTION

ENCOURAGING FACTORS

Case Study 2 helped to develop an effective bitmap-based 3D-Printing workflow for the conversion of Biomedical Imaging data into dynamic 3D-printed models. This workflow was able to translate the Biomedical Imaging data into 3D-printed models with gradients in density, ranging from very soft 3D-printed material (mimicking fat) to harder areas of anatomy such as bone.

Based on tactile and visual analysis of the 3D-prints and feedback from expert opinions, it is clear that this workflow is relatively unprecedented as the use of soft (Agilus30™) and hard (Vero™) materials blended within bitmap-based 3D-prints. The method is novel and limited studies exist using this technique.

Case Study 2 highlighted the potential of bitmap-based 3D-printing using varying densities for the purpose of biomechanical research, medical education, preoperative planning and simulation.

THINGS TO CONSIDER

It is important to consider that there is no research conducted that quantified whether Stratasys J750™ 3D-printing materials are equivalent to anatomy. Evaluation of *Case Study Two* was qualitative and was based on whether a bitmap-based 3D-printing workflow was possible.

Although the softest material available to 3D-print with using the Stratasys J750™ 3D-Printer is Agilus30™, it is still not as soft as human tissue. The resulting 3D-prints moved in a similar way to human anatomy but still felt stiff in comparison. Also, Vero™, although hard like bone, maybe did not have the physical properties needed on bone. For example, for simulation purposes it is imperative that bone does not melt when drilled.

Dr. Ali Mirjalili commented that some very thorough traditional segmentation methods can produce highly accurate 3D-prints. Through a process of manual thresholding, you can achieve highly-detailed models even though the process can be quite time-consuming. Therefore, it will be important to compare:

- Voxel-printing using a High-Quality CT scan
- Voxel-printing using a Normal CT scan
- STL segmentation mesh-based 3D-printing using a clinically segmented model.

Following 3D-printing these three different types of models, a comparison can be conducted between the three models and the advantages and disadvantages should be outlined. Suggestions can be made for where each method could be implemented depending on the use and quality of the model.

Figure 123. Case study 2 reflection brainstorm.

PRACTICAL ACTION RESEARCH

4.3 CASE STUDY 3

Testing Novel Medical Modelling 3D-Printing Materials on the Stratasys J750™ Digital Anatomy™ 3D-Printer (DAP) released in November 2019.

Left.

Figure 124. Neonatal STL (mesh files) used to create the mesh-based neonatal feet on the Stratasys J750™ Digital Anatomy™ 3D-Printer.

Overview

Case Study 3 focussed on developing swatches and test 3D-prints of anatomy to test on the brand new Stratasys J750™ Digital Anatomy™ 3D-Printer based in Shanghai, China. The aim of *Case Study 3* was to 3D-print swatches of new (more developed) 3D-printing materials designed for medical modelling. In 2019, Stratasys released a new 3D-Printer and 3D-printing materials that aim to combat the rigidity of polyjet materials – a challenge that arose in *Case Study 2*. The key new base materials are TissueMatrix™ (the softest translucent material commercially available), BoneMatrix™ (a dense, yet flexible, material) and GelMatrix™ (a support material that can be easily removed) (Stratasys J750™ Digital Anatomy™ 3D-Printer, 2019). A combination (mixing ratios) of the six materials available for 3D-printing at one time on the Stratasys J750™ Digital Anatomy™ 3D-Printer can produce a range of ‘Digital Anatomy’ materials such as the ‘Myocardium’ or ‘Long Bone’. These materials used in combination have the potential to provide an unprecedented level of realism in medical models (Severseike et al., 2019).

3D-printed models were produced using a traditional mesh-based 3D-printing workflow. Generating meshes on CAD software meant that three-dimensional forms could be additively manufactured from computed generated geometries instead of bitmap images. Material swatches were produced using Autodesk Fusion 360 and were assigned with the Digital Anatomy™ materials using GrabCAD Print. The medical models of the neonatal foot were developed on medical imaging software using traditional thresholding, segmentation and computer processing methods. Currently, the available version of GrabCAD for the Stratasys J750™ Digital Anatomy™ 3D-Printer does not have a GrabCAD Voxel Print Utility add-on.

Parallel prototyping was used to produce a large batch of 3D-prints overseas.

4.3.2

Criteria for Case Study 3

Case Study 3 focussed on producing swatches of novel 3D-printing materials by creating a series of design experiments and swatches. The focus of *Case Study 3* was on testing the materials – reflecting on how they moved and felt in comparison to the Stratasys J750™ 3D-printing materials. CT imaging data in this *Case Study 3* was the same as *Case Study 2*.

CRITERIA

1. Explore the Stratasys J750™ Digital Anatomy™ 3D-Printer materials.

Using CAD software, a series of swatches should be developed to test every Digital Anatomy™ material available for 3D-printing on GrabCAD Print.

2. Using traditional mesh-based segmentation techniques, use the Stratasys J750™ Digital Anatomy™ 3D-Printer to create medical models that mimic anatomy to a high-fidelity.

Traditional segmentation techniques should develop sections of a paediatric foot using the same dataset as *Case Study 2*. The three anatomical focus areas are the bone, ligaments and soft tissues and fat. These segmentations should preserve the most amount of original data possible.

3. Use the information from both Case Studies 1, 2 and 3 outline the potential of bitmap-based 3D-printing (Voxel Print Utility) using the Stratasys J750™ Digital Anatomy™ 3D-printer materials.

By comparing the mesh-based model and bitmap-based model of the paediatric foot as well as materials using both machines will set up the groundwork for future studies using the Stratasys J750™ Digital Anatomy™ 3D-Printer. Speculating how the Voxel Print Utility add-on could function on the Stratasys J750™ Digital Anatomy™ 3D-Printer may provoke thought about the potential of bitmap-based medical modelling.

Figure 125. Stratasys J750™ Digital Anatomy™ 3D-Printer 3D-prints file-preparation (appearance on GrabCAD Print software with assigned materials).

Figure 126. Stratasys J750™ Digital Anatomy™ 3D-Printer 3D-prints coated in SUP705™.

Figure 127. Receiving and opening Stratasys J750™ Digital Anatomy™ 3D-Printer 3D-prints from Stratasys in Shanghai, China.

4.3.3

Material Exploration

Left:

Figure 128. Stratasys J750™ Digital Anatomy™ 3D-Printer material swatch.

Material Swatch File Preparation

Figure 129. Material swatch file preparation.

Key for DAP Material Swatches

Figure 130. How to read DAP swatch results.

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PHOTOGRAPHY & OBSERVATIONS

Figure

MATERIAL NAMES

- 1. Shore A level 30
- 2. Shore A level 35
- 3. Shore A level 40
- 4. Shore A level 50
- 5. Shore A level 60
- 6. Shore A level 70
- 7. Shore A level 85
- 8. Shore A level 95
- 9. Agilus30™
- 10. VeroMagenta-V™
- 11. VeroPureWhite™
- 12. VeroPureWhite™

Figure 131. 3D-print #38 material analysis.

38 / Stratasys J750™ Digital Anatomy™ 3D-Printer Swatch

Aim

To 3D-print a material swatch on the Stratasys J750™ 3D-Printer based at the School of Design to compare with Stratasys J750™ Digital Anatomy™ 3D-printing materials.

MATERIAL NAMES

BLOOD VESSEL

CLOT

- 1. Fibrotic
- 2. Highly Fibrotic
- 3. Soft

FIXTURES

- 4. 1
- 5. 2
- 6. 3
- 7. 4
- 8. 5
- 9. 6

FRAME

- 10. 1
- 11. 2
- 12. 3

Figure 132. 3D-print #39 material analysis.

39 / DAP Swatch 1

FRAME

- 1. 4
- 2. 5
- 3. 6
- 4. 7

INLETS

- 5. 1
- 6. 2
- 7. 3
- 8. 4

REINFORCEMENTS

- 9. 1
- 10. 2
- 11. 3

SOLID TUMOR

fail 12. A

Figure 133. 3D-print #40 material analysis.

40 / DAP Swatch 2

MATERIAL NAMES

SOLID TUMOR

- 1. B
- 2. C
- 3. D

VALVE ANNULUS

- 4. Soft
- 5. Moderately Stiff
- 6. Stiffened

VALVE LEAFLET

- 7. Moderately Stiff
- 8. Stiffened
- 9. Stiff

VASCULAR

CALCIFICATION

- 10. Soft Calcium Deposits
- 11. Moderately Stiff Calcium Deposits
- 12. Stiff Calcium Deposits

Figure 134. 3D-print #41 material analysis.

41 / DAP Swatch 3

VESSEL WALL

- 1. Compliant
- 2. Moderately Compliant
- 3. Slightly Compliant
- 4. Low Compliant
- 5. Semi-Rigid
- 6. Rigid

GENERAL ANATOMY

DENSE CONNECTIVE TISSUES

- 7. Soft
- 8. Rigid
- 9. Highly Rigid

HOLLOW INTERNAL ORGANS

- 10. Compliant
- 11. Moderately Compliant
- 12. Slightly Compliant

Figure 135. 3D-print #42 material analysis.

42 / DAP Swatch 4

- HOLLOW INTERNAL ORGANS**
- 1. Low Compliant
 - 2. Semi-Rigid
 - 3. Rigid
 - 4. Highly Rigid
- HOLLOW INTERNAL ORGANS**
- 5. Fiber Contraction 1
 - 6. Fiber Contraction 2
 - 7. Fiber Contraction 3
 - 8. Fiber Contraction 4
 - 9. Fiber Contraction 5
 - 10. Fiber Contraction 6
 - 11. Fiber Contraction 7
- MUSCULOSKELETAL**
- FACET JOINTS**
- 12. Soft

Figure 136. 3D-print #43 material analysis.

43 / DAP Swatch 5

- 1. Moderately Soft
 - 2. Stiff
- GENERAL BONE**
- 3. Porous
 - 4. Slightly Dense
 - 5. Dense
- INTERVERTEBRAL DISKS**
- 6. Normal
 - 7. Degenerated
- LIGAMENT**
- 8. Soft
 - 9. Moderately Stiff
 - 10. Stiff
- LONG BONE**
- 11. Miniature
 - 12. Typical

Figure 137. 3D-print #44 material analysis.

44 / DAP Swatch 6

MATERIAL NAMES

NERVES

- 1. Soft
- 2. Moderately Stiff
- 3. Stiff

RIBS

- 4. Moderately Stiff
- 5. Very Stiff

6. SKULL

VERTEBRA

- 7. Porous
- 8. Dense

STRUCTURAL HEART

MYOCARDIUM

- 9. Highly Contractile
- 10. Moderately Stiff
- 11. Stiffened
- 12. Very Stiff

Figure 138. 3D-print #45 material analysis.

45 / DAP Swatch 7

VALVE CHORDAE

- 1. Highly Extensible
- 2. Extensible
- 3. Stiffened

EXTRAS

- 4. SoftDM_400
- 5. SoftDM_400
- 6. SoftDM_400
- 7. SoftDM_400
- 8. Myocardium_HighlyContractile
- 9. GeneralAnatomy_HollowInternalOrgans_Compliant
- 10. GeneralAnatomy_HollowInternalOrgans_FibreContraction1
- 11. StructuralHeart_ValveAnnulus_SoftHealthy
- 12. StructuralHeart_ValveChordae_HighlyExtensible

Figure 139. 3D-print #46 material analysis.

46 / DAP Swatch 8

4.3.4

Design Experimentation

Note: All 3D-prints were coated in SUP706™ and cleaned as outlined in *Case Study 2*.

Left:

Figure 140. Sketch of neonatal STL (mesh files) used to create the mesh-based neonatal feet on the Stratasys J750™ Digital Anatomy™ 3D-Printer. Sketch shows internal “nested” meshes and cut outs within each STL mesh.

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DESIGN EXPERIMENTATION DIGITAL WORKFLOW

Figure 141. Case study 3 digital workflow.

Aim (3D-print #47 and #48)

To 3D-print a neonatal foot using a traditional mesh-based medical modelling workflow on the Stratasys J750™ 3D-Printer to serve as a base for comparison when the same model is produced on the Stratasys J750™ Digital Anatomy™ 3D-Printer using new materials.

Materials

Bone: VeroPureWhite™

SoftTissue: Agilus30™

Discovery

Soft tissue 3D-printed with Agilus30™ was flexible, but not as soft as human flesh.

#47 / Stratasys J750™ 3D-Printer Mesh-based Foot
without fat and skin

Figure 142. Images of Stratasys J750™ 3D-Printer foot (no fat and skin).

Materials

Bone: VeroPureWhite™

SoftTissue and Fat: Agilus30™

Figure

Discovery

#48 / Stratasys J750™ 3D-Printer Mesh-based Foot

Agilus30™ 3D-printed in large quantities is extremely rigid.

Figure 143. Images of Stratasys J750™ 3D-Printer foot.

Figure 144. Images of 3D-print #49.

Materials

Bone: GeneralBone_Porous

SoftTissue: SolidInternalOrgans_FibreContraction1

Aim (3D-print #49 and #50)

To 3D-print a neonatal foot using a traditional mesh-based medical modelling workflow (excluding fat and skin) on the the Stratasys J750™ Digital Anatomy™ 3D-Printer to test and compare novel Digital Anatomy™ materials.

Discovery

The most life-like and realistic model materials 3D-printed in the research. Is limited because the model contains no gradients in density and colour.

49 / DAP Foot 1
without fat and skin

Figure 145. Images of 3D-print #50.

Materials

Bone: Ribs_ModeratelyStiff

SoftTissue: Ligament_Soft

Discovery

Similar stiffness to Agilus30 3D-print # 47
(not as soft as 3D-print # 49).

50 / DAP Foot 2
without fat and skin

Figure 146. Images of 3D-print #51.

Materials

Bone: GeneralBone_SlightlyDense
 SoftTissue: Ligament_Soft
 Fat: StructuralHeart_ValveAnnulus_SoftHealthy

51 / DAP Foot 3

Aim (3D-print #51, #52 & #53)

Discovery

To 3D-print a neonatal foot using a traditional mesh-based medical modelling workflow (including fat and skin) on the the Stratasys J750™ Digital Anatomy™ 3D-Printer to test and compare novel Digital Anatomy™ materials.

The resulting 3D-print was rigid with a yellow tint.

Figure 147. Images of 3D-print #52.

Materials

Bone: GeneralBone_Porous

SoftTissue: VeroPureWhite™

Fat: VeroPureWhite™

Discovery

A mistake was made during GRABCAD processing and the internal structure 3D-printed in VeroPureWhite™. The external soft material was substantially less dense and more life-like than Agilus30™ in 3D-print #48.

Figure 148. Images of 3D-print #53.

Materials

Bone: GeneralBone_Porous

SoftTissue: Myocardium_HighlyContractile

Fat: SoftDM_400

Discovery

This was the softest and most life-like 3D-print using the complete neonatal foot file. Unlike 3D-print #36, the model could not be cut open revealing layers of skin and fat due to limitations of mesh-based 3D-printing.

Figure 149. Images of 3D-print #54.

54 / DAP Sample

Aim

To 3D-print a CAD modelled test swatch with GelMatrix™, bone, skin, and thin strips of fibrous material for simulation and skills acquisition purposes.

Discovery

The resulting 3D-print was easy to interact with. The fibres were able to be pulled out and the skin could be cut and peeled off.

4.3.5

Evaluation and Reflection

Without a doubt, the Stratasys J750™ Digital Anatomy™ 3D-printing materials are softer and the materials ‘bounce back’ (elasticity) and return to their original state at a faster pace than Stratasys J750™ 3D-printing materials. These new material qualities mean that 3D-prints produced are more realistic. This mitigates some of the frustrations caused by Stratasys J750™ 3D-Printer.

MOVING FORWARD

The next step of this *Case Study* considered the advantages of all three *Case Studies* to develop a hypothetical, yet realistic, bitmap-based medical modelling GrabCAD add-on. The workflow includes the realistic colour qualities of *Case Study 1*, the bitmap-based 3D-printing workflow of *Case Study 2* and the Stratasys J750™ Digital Anatomy™ 3D-printing materials presented in *Case Study 3*.

Figure 150. Case study 3 reflection brainstorm.

STEP ONE

Acquiring patient-specific medical data through data acquisition (CT scan).

4 . 3 . 6

STEP TWO

Manual Step: Uploading the patient specific medical data to GrabCAD.

Automated Step: Scan smoothing and interpolation of images to create a virtual volumetric voxel reconstruction of the scanned patient.

A

Figure 152. (A-D) A developed streamlined medical modelling workflow concept. The images present an idea for a software plug-in for GrabCAD Print using the Stratasys J750™ Digital Anatomy™ 3D-Printer using newly developed materials. These images have been designed using open-source resources from <https://www.mockupworld.co/free/workspace-imac-mockup-2/>.

STEP THREE

Manual Step: In this step, the user can crop the area of anatomy. Following this, the user has the ability to manipulate the model's colour, translucency, density, and threshold.

Automated Step: The software automatically figures out the attenuation properties of the scan and can automatically update the volumetric reconstruction according to the preference that has been adjusted. Then, the software will digitally halftone and interpolate the bitmap images with the native Stratasys J750™ Digital Anatomy™ 3D-printing materials at the native 3D-printer z resolution. 3D-printer materials would include TissueMatrix™ (in all CMYK colours) and BoneMatrix™ (in all CMYK colours) so that full-colour and realistic anatomical density can be achieved in a single 3D-print.

STEP FIVE

Interacting with the model – just like the user planned to!

D

05

DISCUSSION

The *Discussion* will outline the research findings, implications, justifications, value, limitations and recommendations for future research work.

Left:

Figure 153. Slicing through a bitmap-based 3D-printed foot (3D-print #36).

Figure 154. A bitmap-based 3D-printed knee (3D-print #33).

5.1 KEY FINDINGS

The purpose of this research was to understand the opportunities of a bitmap-based 3D-printing workflow using the Stratasys J750™ 3D-Printer range for the production of high-fidelity and patient-specific medical models of anatomy. The bitmap-based 3D-printing workflow presented in this research utilised biomedical imaging data to produce 3D-printed models of anatomy, with the ultimate aim of replicating realistic anatomical colour and density.

Three overarching research methodologies (Research *into* Design, Research *through* Design and Research *as* Design) worked in combination to form the research framework. Evolving design criteria were used throughout the research to narrow down the field of exploration, setting clear goals for each Research Stage. The design criteria served as the starting point – and means of assessment – for parallel, refined and final prototyping. The physical design process presented in the *Case Studies* followed a Practical Action Research Cycle. This involved observing, planning, prototyping, documenting and modifying designs to meet the design criteria.

The developed bitmap-based AM workflow successfully produced patient-specific medical models from different forms of medical data. The results of this research demonstrate the Stratasys J750™ 3D-Printer's capability to mimic anatomical colour and density within synthetic 3D-printed anatomical models, highlighting the advantages of bitmap-based 3D-printing for highly realistic and efficient medical modelling workflows.

This research found that the production of highly accurate models – with graduated densities, translucency, colour and flexion – overcame complexities that typically arise through traditional mesh-based medical modelling methods. Notably, the research results suggest that bitmap-based 3D-printing can create models that cannot be produced through any other manufacturing method. Bitmap-based 3D-printing affords the designer the ability to engineer complex material combinations, and control over the material quality and placement of every 14-micron voxel – opening up a world of opportunities in medical design, anatomical visualisation and communication.

5.2 INTERPRETATIONS

5.2.1

Case Study 1

In *Case Study 1*, anatomical colour was successfully mimicked using bitmap-based 3D-printing and the Visible Female® Dataset (cryosection images). Available literature suggests that the highly realistic replication of anatomical features and colour within a 3D-printed model (such as the 3D-prints presented in *Case Study 1*) is unprecedented. The results of *Case Study 1* demonstrate that realistic anatomical colour can be mimicked in synthetic models of anatomy using a bitmap-based 3D-printing workflow, appearing almost identical to the cryosection images of the cadaveric specimen.

Through iterative parallel prototyping, the most efficient bitmap-based 3D-printing workflow for the conversion of cryosection images to a 3D-printed model was reached (as outlined in Figure 38.). Comparing the bitmap-based 3D-prints with the full colour photographic images of the Visible Female® served as a method of colour accuracy evaluation.

The relationship between 3D-print #7 and 3D-print #8 suggests that VeroClear™ can significantly alter the appearance of anatomical colour, creating a green and dark finish. This discovery suggests that to generate realistic anatomical colour, full-colour bitmap images should be digitally halftoned using 100% pixel diffusion ratio (allowing materials to blend smoothly). VeroClear™ should only be utilised in small quantities or as a clear bounding box, but should not be included within the anatomical area of the 3D-print.

The differences between 3D-prints #5 and 3D-print #6 suggest that including thin layers of SUP706™ within a 3D-print may cause a collapse in structure, change in colour and the production of a surface texture. In 3D-print #6 SUP706™ was used to replace VeroMagenta-V™ on every other 27-micron bitmap layer. This may explain why one side of the 3D-print appears more yellow (due to the decrease in VeroMagenta-V™). In contrast, 3D-print #5 was produced using the same bitmap image stack as 3D-print #6, but was 3D-printed without the inclusion of SUP706™.

Figure 155. (A-E) Visible Female images presented in Case Study 1.

3D-print #12, which includes the material Agilus30™, was combined with Vero™ materials with the aim of producing a 3D-print with integrated dynamic movement as well as realistic anatomical colour. However, the resulting 3D-print suggests that when Agilus30™ is dispersed within a 3D-print, the colour fades substantially. Moreover, as soon as Vero™ is combined with Agilus30™, the 3D-print hardens. A plausible explanation for this could be that Vero™ works as a catalyst, and when even a small amount is added to Agilus30™, the 3D-print drastically hardens. This had significance in relation to the overall study because, when investigating 3D-printed dynamics in *Case Study 2*, the softest areas of anatomy had to sacrifice colour pigmentation.

Information gathered from parallel prototyping in *Case Study 1*, meant that a 1:12 full-colour model of the Visible Female® was 3D-printed using the developed bitmap-based 3D-printing workflow. The results of *Case Study 1* far outweighed the results that were expected from this section of the research. This is because the colour quality that was mimicked was far more realistic and details were of higher fidelity than initially expected.

Overall, all three criteria outlined for *Case Study 1* were successfully met because an efficient bitmap-based 3D-printing workflow was developed, a design experimentation was conducted, and a final model was produced with an unprecedented level of detail.

Case Study 2

Case Study 2 focussed on mimicking anatomical dynamics by using a bitmap-based 3D-printing workflow and patient-specific biomedical imaging data (CT data). A bitmap-based workflow that turns greyscale CT data into models with graduated densities and colour was successfully produced. However, results of *Case Study 2* indicated that 3D-printing materials available on the Stratasys J750™ 3D-Printer were not soft enough to mimic anatomical density and biomechanics to the highest degree of realism.

Successfully replicating anatomical density and movement from biomedical imaging data was a more difficult task than mimicking anatomical colour. Factors that influence the degree of 3D-printing difficulty include the resolution of the biomedical imaging data and material elasticity ('softness') – variables that are not always within the control of the designer. Unlike *Case Study 1*, the patient-specific CT data was greyscale and not full-colour. Accordingly, producing anatomical colour as well as density within a 3D-printed model using greyscale data was a huge challenge.

Case Study 2 presented bitmap-based 3D-printed models of a neonatal leg that included graduated density, translucency and colour after reaching the most suitable bitmap-based medical modelling workflow through initial design experimentation and refined prototyping. Initial design experimentation suggested that 3D-printed movements (dynamics) were most successful when the original greyscale bioimaging data was interpolated at the native 3D-printer z resolution, digitally halftoned using black and white pixels and assigned materials in the post-processing stage (on GrabCAD software). The results of the initial design experiments showed that this workflow preserved the highest amount of anatomical detail within the 3D-print (outlined in Figure 93.).

Before conducting *Case Study 2*, no previous research that quantified whether bitmap-based 3D-printing using Stratasys J750™ 3D-printing materials created synthetic equivalents to human anatomy. Moreover, there were no existing

bitmap-based 3D-printed dynamic models to use as design precedents. Therefore, the focus and evaluation of *Case Study 2* results involved a qualitative analysis – including stop motion photography, tactile observations and the presentation of work to experts in respective design, engineering and medical fields.

Combining Agilus30™ with Vero™ created the most structurally sound models. The results of *Case Study 2* suggest that integrating SUP706™ within a 3D-print can sacrifice structural integrity. Interestingly, as seen in 3D-print #24, evenly dispersing SUP706™ within Agilus30™ can create a softer, more flexible material whilst maintaining its structural integrity. Although this combination worked well for 3D-print #24, this technique can also allow for errors on the building platform – as observed in 3D-prints #22, #23, #25 and #26. The results might suggest that, because SUP706™ is not a material designed for modelling, SUP706™ sinks or collapses when 3D-printed as part of a model rather than as the support structure.

When thin layers of Agilus30™ skin are added to a 3D-print, such as 3D-prints #26 and #26, the skin risks being ‘pierced’ and peeling away, exposing the SUP706™ material (which can then wash away and distort the model form). This, however, was improved in 3D-print #36, where the skin was thicker and successfully encased SUP706™.

Pixel diffusion ratios within bitmap images aimed to reflect the greyscale H.U. values of the CT scan data. The ratio of soft (Agilus30™) material to hard (Vero™) material determines the approximate pixel greyscale value.

Digital halftoning algorithms were successfully used to create a 1:1 scale 3D-printed model of a neonatal leg. The leg was replicated to the highest degree of realism, with dynamics embedded within the 3D-print. The joints, however, did not articulate as hypothesised. Due to the rigid nature of Agilus30™, the joint 3D models and the full leg model did not articulate realistically when 3D-printed. However, thinner areas of the leg (such as the tendons) which contained less Vero™ and thinner layers of Agilus30™, moved with full flexion. 3D-prints #27, #28 and #29 suggest that when Agilus30™ is 3D-printed in thinner layers it is considerably more flexible than when it is 3D-printed in thicker layers such as 3D-prints #30, #32, and #34.

The full leg was 3D-printed using a 30% diffusion dithering algorithm due to the limited amount of flexion achieved through blending Vero™ into Agilus30™ at a 70% pixel diffusion ratio presented in 3D-prints #30, #32, and #34. It is important to note that a 0% diffusion pixel ratio means that no material blending occurs at all (like a mesh-based file) and, therefore, selecting the appropriate diffusion ratio is a critical step in the design process.

Figure 156. 70% diffusion

Figure 157. 30% diffusion

Overall, *Case Study 2* helped to develop an effective bitmap-based 3D-printing workflow for the conversion of CT data into dynamic bitmap-based 3D-printed models. This workflow translated the CT data into 3D-printed models with gradients in density and colour, ranging from very soft 3D-printed material (mimicking fat) to harder areas of anatomy such as bone. The final design, a 1:1 scale model of a neonatal leg, was unprecedented in its fidelity and workflow (blending both the density and colour of materials). However, the inherent rigidity of Stratasys J750™ 3D-printing materials meant that joint articulation was not achieved to its desired potential and therefore did not mimic the biomechanics of human anatomy to the highest degree of realism.

5.2.3

Case Study 3

In response to limitations identified in *Case Study 2*, *Case Study 3* focussed on testing novel Stratasys J750™ Digital Anatomy™ 3D-printing materials. The new Digital Anatomy™ 3D-printing materials were developed by medical professionals, along with engineers at Stratasys, and have undergone rigorous assessment in terms of their likeness to human anatomy. The results of *Case Study 3* suggest that the Stratasys J750™ Digital Anatomy™ 3D-printing materials are substantially softer than the Stratasys J750™ 3D-printing materials. The elasticity of the newly developed TissueMatrix™ material meant that the 3D-prints could move, bend, stretch and return to their original state, mimicking human anatomy to a higher degree of realism than materials used in *Case Study 1* and *2*.

Purely based on qualitative tactile observation, Digital Anatomy™ 3D-printing materials were compared to the Stratasys J750™ 3D-printing materials. The Stratasys J750™ Digital Anatomy™ 3D-Printer has six native 3D-printing materials including Tissue Matrix™, BoneMatrix™, GelMatrix™, Agilus30™ and two Vero™ materials. GrabCAD Print allows a designer to assign each mesh with over 100 different Digital Anatomy™ materials. This suggests that Stratasys J750™ Digital Anatomy™ 3D-printing materials on GrabCAD are comprised of voxel material combinations – ratios between the six native 3D-printer materials. It is hypothesised that the voxel ratios and diffusion dithering algorithms determine the density and microstructures within each Digital Anatomy™ material available for 3D-printing.

Case Study 3 concluded by creating a design concept for bitmap-based 3D-printing medical modelling software that is primarily automated with some user control.

Overall, *Case Study 3* explored new 3D-printing materials on the Stratasys J750™ Digital Anatomy™ 3D-Printer and concluded, based on tactile analysis, that Digital Anatomy™ materials are substantially more ‘human-like’ than Stratasys J750™ 3D-printing materials.

5.3 IMPLICATIONS

The results presented in this research portfolio have built on a small number of bitmap-based 3D-printing studies presented in published literature (Bader et al., 2016, 2018; Brunton et al., 2015; Hosny et al., 2018; Kolb, 2017; Stute et al., 2018), adding to the existing body of evidence that bitmap-based 3D-printing can create models with unprecedented material qualities due to the production of material gradients that can be engineered at a 14-micron voxel resolution. Previous research has had a strong emphasis on bitmap-based 3D-printing to produce Vero™ (rigid) models that do not have any form of flexion or dynamic movement. In comparison, this research commenced by producing 3D models using solely Vero™, but then progressed to integrating both soft (Agilus30™) and hard (Vero™) materials into one 3D-print – an area of research that has been relatively unexplored.

The results of this research portfolio provide new insights into the relationship between Agilus30™ and Vero™ materials, including how Agilus30™ and Vero™ interact in bitmap-based 3D-prints. All three *Case Studies* tackled relatively unexplored areas of research and provided a clearer insight into mimicking anatomy using patient-specific scans, bitmap-based 3D-printing workflows, and novel medical modelling materials.

5.3.1

Bitmap-Based Vs. Mesh-Based 3D-Printing

Case Study 2 and *3* both 3D-printed neonatal feet from the same CT dataset. *Case Study 2* used a bitmap-based 3D-printing workflow and *Case Study 3* used a traditional mesh-based 3D-printing workflow. Comparing the resulting 3D-prints from both *Case Studies* provides new insight into the advantages and disadvantages of both medical modelling workflows.

This research suggests that a bitmap-based 3D-printing workflow can produce patient-specific medical models in significantly less time and at a higher fidelity than traditional medical models.

Case Study 2 (bitmap-based) 3D-print

Case Study 3 (mesh-based) 3D-print

Figure 158. A comparison between a bitmap-based (3D-print #31) and a mesh-based (3D-print #49) 3D-printed neonatal foot.

TIME AND COST

The results of this research build on the existing body of evidence that suggests that traditional mesh-based medical modelling workflows are time consuming, resulting in anatomically inaccurate 3D-prints caused by human error, data loss and multiple post-processing steps (Bader et al., 2018, 2018; Hosny et al., 2018; Huotilainen et al., 2014). The research results suggest that bitmap-based 3D-printing files for medical modelling (GCVF files) require a significantly less time to generate than complex mesh-based files (STL files) due to the automated nature of the workflow and the synonymy between medical bio-imaging datasets and bitmap-based 3D-printing files.

Bitmap-based 3D-printing not only bypasses thresholding steps used in traditional segmentation methods, it also reduces the amount of computer processing power needed to create multi-material 3D-prints. Traditional medical modelling workflows include a processing step, which requires the designer to perform what is known as a “Boolean” or “Cut out” of every anatomical “nestled” anatomical feature (no meshes can intersect). Because shape specification is inherently linked to one colour and density, each mesh needs to be separate from another if they require a different material. This “Boolean” step is time-consuming and entails a huge amount of computer processing power (especially if the model is complex and requires a range of different materials).

Figure 159. Boolean function.

In *Case Study 3*, the mesh-based files were difficult to produce and prepare for multi-material 3D-printing in comparison to bitmap-based 3D-printed files presented in *Case Study 2* (even though the mesh-based 3D-prints only included three different anatomical STL meshes). The automatic nature of a bitmap-based 3D-printing workflow eliminates the need for manual file processing including the need to “Boolean” mesh-files. This study therefore challenges the efficiency of traditional segmentation techniques and emphasises that current production methods completely overlook the production of heterogeneous material distributions created through bitmap-based 3D-printing (Bader et al., 2016).

A recent economic analysis of the cost-saving potential of 3D-printed anatomical models for surgical applications shows that 3D-printed anatomical models drastically decrease operating room costs secondary to shortening procedure times (Ballard et al., 2020, p. 1103). The use of 3D-printed medical models resulted in a mean reduction time of 62 minutes and USD \$3,720 per operation due to shorter and more efficient procedures (Ballard et al., 2020). Because preparing bitmap-based files for 3D-printing required far less processing time, there is considerable potential for bitmap-based 3D-printing to save additional costs associated with labour intensive and mesh-based medical modelling. Bypassing the traditional segmentation conversion process streamlines the medical modelling workflow, decreasing time and, subsequently, the costs associated with model production.

USING A 3D-PRINTED MODEL

Time saved in surgery

62 min
operating room time / case
(Ballard et al., 2020)

Money saved from
reduced operating
room time

3,720
USD saved / case
(Ballard et al., 2020)

Decreased risk of
surgical site infections
(SSI)

30 min
longer operating time
=
2x likelihood of developing SSI
(Cheng et al., 2017)

Frees up surgeon time &
**increases
productivity**

Treating an infection in England
costs approx. **100,000
pounds** per patient.

("Getting It Right First Time": Orthopaedic Peer Review
Report, 2014)

These advantages would decrease the length of the patient's stay in hospital,
surgical tool costs and treatment failure costs (Choonara et al., 2016, p. 27)

Increasing utilisation rates by using 3D-printing in 20% of cases
could result in up to **USD \$518,358** operational time cost savings alone.
(Ballard et al., 2020)

MEDICAL MODELLING WORKFLOW

PRIMARILY AUTOMATED WORKFLOW

Average segmentation
time per complex model

143 min
(Ballard et al., 2020)

5 min

to create volumetric
visualisation of chosen
anatomical feature

Average Boolean
operation time

20 min / mesh

0 min

GrabCAD material
assignment

5 min / mesh

1 min / complete model

Manual segmentation
software

USD \$20,000

USD \$0

COST SAVINGS:
Salary per person conducting
manual segmentation

Figure 160. Time and cost savings of bitmap-based 3D-printed models.

DETAIL

The level of detail achieved through bitmap-based 3D-printing for the production of medical models with gradated density and colour is superior to any form of mesh-based 3D-printing. This is evident in the 3D-print of the Visible Female® presented in *Case Study 1*. Blending colours at a high-fidelity using a bitmap-based 3D-printing workflow would be impossible to achieve through any other mesh-based 3D-printing workflow. Like 2D-printing, bitmap-based 3D-printing workflows can blend colours to produce photo realistic 3D-printed models. A previous study texture mapped realistic anatomical colour to surface voxels around a white 3D-printed core, rather than throughout an entire 3D-printed model (Brunton et al., 2015). The results presented in *Case Study 1* challenge the concept of needing a white core embedded within a 3D-print to produce photorealistic colour. Instead, removing VeroClear™ and integrating an appropriate amount of VeroPureWhite™ can create more realistic colour within a 3D-print.

The differences in detail between the traditionally segmented mesh-based and bitmap-based 3D-printed neonatal feet highlight some of the advantages of bitmap-based 3D-printing workflows using biomedical imaging data. By comparing files produced in *Case Study 2* and *3* to create 3D-printed neonatal feet, the amount of data integrated within to the bitmap-based 3D-print in *Case Study 2* is far greater than the integrated data in the mesh-based 3D-print produced in *Case Study 2*.

Each 3D-printed neonatal foot (3D-print #30 and #31) created in *Case Study 2* was produced by sending 1,494 cross-sectional bitmap images to the Stratasys J750™ 3D-Printer. Each of those cross-sectional bitmap images was comprised of a pixel matrix containing 1,483,524 pixels (1,483,524 3D-printed voxels). This means that each bitmap-based 3D-printed foot presented in *Case Study 2* was constructed from 2,216,384,856

voxels (1,483,524 pixels x 1,494 images). Material qualities and details produced by having control over every one of the 2,216,384,856 14-micron voxels constructing the 3D-printed neonatal foot far surpasses the potential detail achieved through mesh-based 3D-printing workflows. In comparison, the same neonatal foot presented in *Case Study 3* (3D-print #49) was created from two individual surface meshes (less detail) but involved a longer processing time.

Control over every voxel also presents other advantages over mesh-based 3D-printing workflows. Anatomical features using bitmap-based 3D-printing files are not restricted to one material specification – meaning that the 3D-prints can contain gradients in both density and colour, mimicking human anatomy to a higher degree of realism.

Figure 161. Bitmap-based 3D-printing vs. mesh-based 3D-printing (detail).

5.3.2

3D-Printing Theory and Practice

THE ROLE OF THE PHYSICIAN AND THE DESIGNER

This research should be considered when addressing the future of 3D-printing theory and practice. Medical modelling using novel technology and a bitmap-based 3D-printing workflow is inherently an inter-disciplinary area of research requiring a range of different skill sets. From medical clinicians to creative design thinkers – a variety of strengths are required to develop bitmap-based medical modelling. A common language of communication and adaptable skills are required to propel this area of research forward. This, in turn, presents a new way of thinking and considerable potential for new professions that lie in the intersection of design and medicine.

AUTOMATION IN MEDICINE

The application of artificial intelligence (AI) systems has grown drastically in virtually every discipline including medicine, design and data processing (Ferretti et al., 2018, p. 320). AI systems with integrated machine learning have the ability to learn and complete tasks on their own or guided slightly by human supervision (Ferretti et al., 2018, p. 320). An increase in research is currently being conducted into the applications and validity of automated and semi-automated segmentation techniques for medical modelling (Rizwan I Haque & Neubert, 2020; Sharma et al., 2010). The value of automated segmentation techniques lies in its ability to achieve fast and accurate results which are not influenced by influences such as fatigue or human error in manual segmentations steps (Sharma et al., 2010). Results presented in *Case Studies 1* and *2* show that high-fidelity medical models can be produced through automated machine learning using a bitmap-based 3D-printing workflow. In turn, decreasing manual labour time and costs. Results presented in *Case Studies 1* and *2* contribute to a clearer understanding of the future direction on machine learning for the efficient production of high-fidelity medical modelling.

Cultural Implications

Under the Code of Health and Disability Services Consumers' Rights (HDC Code 1996), every patient in New Zealand has the right to be fully informed (Right 6), along with the right to make an informed choice, and to give informed consent (Right 7). These rights, however, rely heavily on a patient's ability to balance facts, accessible information, and provide an uninfluenced acceptance of treatment. Physical patient-specific models have considerable potential to cross cultural and language barriers, as well as helping patients with deficiencies in hearing and sight. It is, therefore, important to consider the cultural and social impacts of patient-specific medical models for informed consent practices and medical communication.

In te ao Māori, for example, the hauora model of wellbeing encompasses the physical (Taha tinana), mental and emotional (Taha hinengaro), social (Taha whānau) and spiritual (Taha wairua) dimensions of health (Well-being, hauora, n.d.). Decisions regarding an individual's health with a collective cultural framework means important medical decisions are taken by a wider group, not just the individual (Kerse & Dyll, 2013). Acknowledging and respecting cultural aspects of health have shown to increase overall wellbeing in patients (Kerse & Dyll, 2013). Taking a patient-specific medical model home and engaging with a patient's community may aid collective decision making, creating cultural and social engagement by democratising important information about health that cannot always be interpreted through 2D visualisations or verbal communication.

5.4 LIMITATIONS

SOFTWARE

Case Studies 1 and *2* build on the existing evidence that CAD tools are currently inadequate for bitmap-based 3D-printing workflows. Successful bitmap-based 3D-printing is based on the designer's ability to explore different software tools and processes, developing their own workflows (Stute et al., 2018). A substantial limitation of bitmap-based 3D-printing workflows is that there is no universal and developed bitmap-based 3D-printing file creation software. Therefore, some design choices were constrained by the lack of developed software for bitmap-based 3D-printing workflows. For example, there is no bitmap-based 3D-printing preview function, which means that bitmap-based 3D-printed models cannot be previewed (like mesh-based models) before 3D-printing, compromising colour accuracy.

MATERIALS

A limitation of this research was the durability and physical limitations of the Stratasys J750TM 3D-printing material range. Agilus30TM was not soft enough to mimic soft tissue to the highest degree of realism and therefore articulating joints in the 1:1 neonatal leg was not achieved. Agilus30TM can split at different parts of the models (due to its lack of elasticity), creating breaks and microtears in the material. Polyjet 3D-printing materials are currently plastic and cannot be recycled or reused. Therefore, the sustainability and elasticity of materials is a considerable research limitation.

COVID-19

COVID-19 and the subsequent Victoria University of Wellington campus closure affected the progression of on-site research using the Stratasys J750TM 3D-Printer. The impact of the pandemic also meant that conducting additional testing on the Stratasys J750TM Digital AnatomyTM 3D-Printer based in China (including bitmap-based 3D-printing using Digital AnatomyTM) could not occur.

EVALUATION OF RESULTS

It is beyond the scope of this research to quantify the value and results of the research in a clinical setting. Material qualities of the 3D-printed models need clinical evaluation to quantify their likeness to human anatomy and implementation value.

DIGITAL ANATOMY 3D-PRINTER

A traditional medical modelling workflow was used in *Case Study 3* because the currently available version of GrabCAD for the Stratasys J750TM Digital AnatomyTM 3D-Printer does not have a GrabCAD Voxel Print Utility add-on.

5.5 RECOMMENDATIONS

BITMAP-BASED 3D-PRINTING ON THE DAP

The capabilities of bitmap-based 3D-printing using the GrabCAD Voxel Print Utility can produce models with an unprecedented level of detail. Further research could test bitmap-based 3D-printing on the Stratasys J750™ Digital Anatomy™ 3D-Printer, blending voxels using the novel and highly realistic medical modelling materials including GelMatrix™, TissueMatrix™ and BoneMatrix™. This has considerable potential to produce the most realistic medical models to date by combining the most successful elements of *Case Studies 1, 2 and 3* (workflow of *Case Study 2* and materials from *Case Study 3*).

DEVELOPING BITMAP-BASED 3D-PRINTING SOFTWARE

Future research could focus on developing a software for the efficient production of bitmap-based 3D-prints. This could mitigate frustrating factors regarding the limited available software tools that are currently used to develop bitmap-based 3D-printing files. The envisioned software would include an automatic 3D-printer z resolution interpolation function, automatic colour mixing and digital halftoning, a bitmap-based 3D-print colour and geometry preview. It is important to acknowledge how future software could develop a medical modelling process by streamlining the process of converting biomedical bioimaging data into highly realistic bitmap-based 3D-printed models. This could occur by incorporating semi-automated segmentation and the accurate conversion of CT H.U. values to dynamic 3D-printed material combinations that mimic anatomy to the highest degree of realism.

DEVELOPING 3D-PRINTED MATERIALS

Future studies should take into account that the development of pigmented soft materials (like TissueMatrix™) in Cyan, Magenta, Yellow, Black, White and Clear could produce models that incorporate the visual realism of *Case Study 1*, the workflow used in *Case Study 2* and the tactile realism of materials used in *Case Study 3*. Future 3D-printing material studies should also take into account the sustainability of materials and potential ways to repurpose and recycle medical modelling Polyjet materials.

QUANTIFYING THE RESEARCH VALUE

A high-fidelity bitmap-based 3D-printing medical modelling workflow offers exciting opportunities for medical education, informed consent practices, and surgical simulation for skills acquisition and pre-operative planning. Technical factors such as the accuracy of a bitmap-based 3D-printing medical modelling workflow, the tactile realism of 3D-printing materials, and the differences between mesh-based and bitmap-based 3D-printing workflows should be evaluated through clinical studies. The resulting quantifying evidence would justify the contextual value of bitmap-based medical modelling for different healthcare applications.

0 6

CONCLUSION

Left:

Figure 162. Bottom of bitmap-based 3D-printed neonatal foot (3D-print #36).

Figure 163. Medical students (models) learning anatomy using a bitmap-based 3D-printed model and a virtual reconstruction of the anatomical part.

6.1 CONCLUSION

This research analysed the results of a creative design exploration presented in the form of three different *Case Studies*. It highlighted the opportunities offered by 3D-printing patient-specific and high-fidelity medical models on multi-material 3D-printers, with a focus on developing a bitmap-based 3D-printing workflow using biomedical imaging data.

To better understand and develop the presented bitmap-based modelling workflow, materials and results, future studies could address how voxel-based 3D-printed medical models could be developed using Stratasys J750™ Digital Anatomy™ 3D-printing materials. Further studies may quantify the value of bitmap-based 3D-printed medical models for different contextual applications, such as surgical simulation, pre-operative planning and skills acquisition. By challenging traditional medical modelling workflows, this research addressed the lacuna in existing knowledge. It successfully produced bitmap-based 3D-prints that – with graduated densities, translucency, colour and flexion – overcame complexities that arose due to opaqueness of the human body. A bitmap-based medical modelling workflow has considerable potential to create more detailed models at a faster rate than traditional mesh-based segmentation workflows. Ultimately, this research challenged the way that physical objects are created and has the potential to revolutionise 3D-printing as a whole.

Design is the mover, agent and catalyst for change. This research has demonstrated how design can explore novel technology and translate, in an approachable manner, its potential to society. The presented research highlights the role of the designer and the importance of creativity to challenge, change and advance new manufacturing possibilities. Hopefully, it will encourage collaboration between designers and medical professionals to explore new technologies. Drawing from expertise from across different areas of speciality may advance the quality of medical modelling, with a considerable potential to improve healthcare, save lives and democratise important information about technology and anatomy. In turn, making medical information about anatomy understandable for everyone.

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6.3 APPENDIX A

Appendix A presents the programme for the 3D Technologies in Medicine (3DMED1) conference in Melbourne, Australia, on 14-16 of November, 2019.

#3dMed19

14-16th November 2019

Institutional Partners

Platinum Sponsors

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Women in 3D Technologies Networking Drinks Sponsor

2019 ORGANISING COMMITTEE

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Payal Mukherjee
Mathilde Desselle
Toan Pham
Iari Chao
Tracie Barber

Abstract Review Committee

Blake Cochran
Tracie Barber
Mathilde Desselle

VENUES

3D Med Australia 2019 (November 15-16)

AAMI Park
Olympic Blvd
Melbourne VIC 3000
<https://www.aamipark.com.au/arrive-and-access/maps/>

Preconference Workshops (November 14)

Anatomical Modelling Workshop

Electrical Engineering Room 121
Building 193, Parkville Campus
The University of Melbourne
<https://maps.unimelb.edu.au/parkville/building/193>

Stratasys & Fusetec Workshop - the New J750 Digital Anatomy Technology

Electrical Engineering Room 121
Building 193, Parkville Campus
The University of Melbourne
<https://maps.unimelb.edu.au/parkville/building/193>

Women in 3D Technologies Networking Event

Milk the Cow Carlton
323 Lygon St
Carlton VIC 3053
<https://milkthecow.com.au/pages/locations>

VENUES

Preconference Tours (November 14)

VR Buffet Tour @ SBS Digital Learning Hub

Room W313, Medical Building
Building 181, Parkville Campus
The University of Melbourne

<https://biomedicalsciences.unimelb.edu.au/study/dlh#contact-us>

New Experimental Technology (NEXt) Lab Tour @ Melbourne School of Design

Glyn Davis Building
Melbourne School of Design
Building 133, Parkville Campus
The University of Melbourne

<https://msd.unimelb.edu.au/contact>

BioFab3D Tour @ St Vincent's Hospital Melbourne

Clinical Sciences Building
St Vincent's Hospital Melbourne
29 Regent St
Fitzroy VIC 3065

<https://www.biofab3d.org/>

Centre for Additive Manufacturing Lab Tour @ RMIT

Advanced Manufacturing Precinct
RMIT Melbourne City Campus
58 Cardigan St
Carlton VIC 3053

<https://www.rmit.edu.au/about/our-locations-and-facilities/facilities/research-facilities/advanced-manufacturing-precinct/contact-us>

Preconference Workshops and Tours

TIMES AND VENUES

Thursday November 14

0830-1000	Anatomical Modelling Workshop	Electrical Engineering Room 121 Building 193, Parkville Campus The University of Melbourne
1000-1200	Stratasys & Fusetec Workshop - the New J750 Digital Anatomy Technology	Electrical Engineering Room 121 Building 193, Parkville Campus The University of Melbourne
1200-1300	Break	
1300-1400	VR Buffet @ SBS Digital Learning Hub	Medical Building Building 181, Parkville Campus The University of Melbourne
1400-1430	NEXt Lab Tour @ Melbourne School of Design	Glyn Davis Building Melbourne School of Design Building 133, Parkville Campus The University of Melbourne
1500-1530	BioFab3D Tour @ St Vincent's Hospital Melbourne	Clinical Sciences Building St Vincent's Hospital Melbourne 29 Regent St Fitzroy VIC 3065
1600-1700	Centre for Additive Manufacturing Lab Tour @ RMIT	Advanced Manufacturing Precinct RMIT Melbourne City Campus 58 Cardigan St Carlton VIC 3053
1700-1800	Break	
1800-Late	Women in 3D Technologies Networking Drinks (all welcome!)	Milk the Cow Carlton 323 Lygon St Carlton VIC 3053

Program Outline

Friday November 15

0800-0830	Registration	Foyer
0830-0845	Frank McGuire MP, Parliamentary Secretary for Medical Research	Lecture Theatre
0845-0900	Prof Guy Maddern, Royal Australasian College of Surgeons	Lecture Theatre
0900-1030	Presurgical Planning Plenary: Jason Chuen	Lecture Theatre
1030-1100	Morning Tea	Trade Area
1100-1215	Cardiovascular Applications	Lecture Theatre
1215-1315	Lunch	Trade Area
1315-1445	3d Visualisation Keynote: Charles Sevigny	Lecture Theatre
1445-1515	Afternoon Tea	Trade Area
1515-1700	Innovation and Industry Keynote: David Ackland	Lecture Theatre
1700-1800	Quickshot Session 1	Lecture Theatre

Saturday November 16

0800-0830	Quickshot Session 2	Lecture Theatre
0830-1030	Bioprinting Plenary: Mia Woodruff Keynote: Gordon Wallace	Lecture Theatre
1030-1100	Morning Tea	Trade Area
1100-1245	Synergy & Design	Lecture Theatre
1245-1345	Lunch	Trade Area
1345-1500	Ethics & Governance	Lecture Theatre
1500-1530	Afternoon Tea	Trade Area
1530-1800	Validation in 3D Technologies Keynote: Blake Cochran	Lecture Theatre

Sessions

Friday November 15: Presurgical Planning

Jason Chuen	Plenary: New Technologies	0900-1915
Xiaowei Wang	3D FLECT- Fusion Imaging and Emerging Technologies	0915-0930
Amy Baker	Optimising Imaging for 3D Planning	0930-0945
Joseph Ischia	3D Visualisation in Complex Urooncological Surgery	0945-1000
Felix Sim	3D Printing Craniofacial Implants	1000-1015
	Panel Discussion	1015-1030
	Morning Tea	1030-1100

Friday November 15: Cardiovascular

Carmine Gentile	Cardiac Bioprinting	1100-1115
Niranjan Hiremath	3D Printing in Complex Aortic Arch Disease	1115-1130
Pujith Vijayaratnam	3D Printing Technologies in Experimental Fluid Dynamics Models of Bridged Arteries	1130-1145
Jasmine Coles-Black	A Technique to Produce Physician Modified Stent Grafts	1145-1200
	Panel Discussion	1200-1215
	Lunch	1215-1315

Friday November 15: Visualisation

Charles Sevigny	Keynote: The Virtual Heart	1315-1330
Mathilde Desselle	No more boring stints in hospitals waiting rooms! Serious games for patient education	1330-1345
Ben Loveridge	VR and Presurgical Planning	1345-1400
Michelle Rank	Bending the knee: can VR rule clinical training paradigms?	1400-1415
Andrew Hardidge	3D Printed Acetabular Models for Prosthesis Sizing	1415-1430
	Panel Discussion	1430-1445
	Afternoon Tea	1445-1515

Friday November 15: Innovation and Industry

David Ackland	Keynote: Engineering the Human Jaw Joint	1515-1530
Mark Roe	Dissecting Anatomy- An Entrepreneur's Perspective	1530-1545
George Dimitroulis	Digital Advances in Maxillofacial Surgery	1545-1600
Richard Stratton	Patient's Perspective	1600-1615
Karen Reynolds	MDPP- Supporting Medical Innovation	1615-1630
Anna Ridgers	3D Printing a Tracheobronchial Tree for Bronchoscopy Training	1630-1645
	Panel Discussion	1645-1700
	Quickshot Session 1	1700-1800

Sessions

Saturday November 16: Bioprinting

	Quickshot Session 2	0800-0830
Mia Woodruff	Plenary: Directions of Bioprinting	0830-0900
Claudia di Bella	3D Bioprinting: A Surgeon's Perspective	0900-1915
Michael Mueller	Bioprinting at CSIRO	0915-0930
Payal Mukherjee	The Journey of the Bioprinted Ear	0930-0945
Behzad Shiroud Heidari	Bioengineering of Hard-Soft Tissue Interfaces	0945-1000
	Panel Discussion	1000-1015
Gordon Wallace	Keynote: Bioprinting	1015-1030
	Morning Tea	1030-1100

Saturday November 16: Synergy and Design

Icaro Ibanez Arricivita	The Aesthetics of Prosthetics	1100-1115
XiaoPeng Li	Implant design	1115-1130
Tegan Cheng	Designing and developing medical devices for children	1130-1145
Tom Williamson	Self-Driving Tools and Surgical Instrument Flight: Developing Robotics for the OR	1145-1200
Toh Yen Pang	Designing Prostheses	1200-1215
Mark Midwinter	VR and Simulation of Uncommon Time Critical Medical Interventions	1215-1230
	Panel Discussion	1230-1245
	Lunch	1245-1345

Saturday November 16: Ethics and Governance

Cathal O'Connell	Don't Print Your Heart Out: The Dangers of Sensationalism in Science	1345-1400
Paul Fennessy	Department of Health and Human Services – An Evidence Review of the Surgical Applications of 3D Printing	1400-1415
John Skerritt	TGA- Regulatory Reforms to Personalised Medical Devices	1415-1430
Kate Fox	The Fun Patent Talk	1430-1445
	Panel Discussion	1445-1500
	Afternoon Tea	1500-1530

Saturday November 16: Validation

Blake Cochran	Keynote: 3D Printing Awesomeness	1530-1545
Kate Dunn	3D Printed Surgical Simulation and Haptics	1545-1600
Peter Lee	ARC Training Centre for Medical Implant Technologies: Building Multidisciplinary Teams and Projects	1615-1630
Karel Habig	3D Printing in Helicopter Retrieval	1630-1645
Atandrilla Das	3D Visualisation in Robotic Surgery	1645-1700
Nathaniel McTaggart	Starting a 3D Printing Service at Auckland City Hospital	1700-1715
Stewart Ryan	3D Printing in Veterinary Education	1715-1730
	Panel Discussion	1730-1745
	Closing Ceremony	1745-1800

6.4 APPENDIX B

Ethics documents are presented in *Appendix B*. These documents allow the researcher to converse and receive comments from industry experts.

Professional perspective, gaining an expert opinion from industry

INFORMATION SHEET FOR PARTICIPANTS

Thank you for your interest in this project. Please read this information before deciding whether or not to take part. If you decide to participate, thank you. If you decide not to take part, thank you for considering my request.

Who am I?

My name is *(Student add name)* and I am a Masters student in the Masters of Design Innovation Programme at Victoria University of Wellington. This research project is work towards my thesis and design composition.

What is the aim of the project?

This project is part of the MADE¹ Research Group that is focused on the design of products and services that may have commercial potential or are allied to industry.

During the design process it is beneficial to evaluate ideas and theories by gaining an expert opinion. This acknowledges the intuitive awareness professionals have and provides a balance in any scholarly critique.

This research has been approved by the Victoria University of Wellington Human Ethics Committee (2014/24294).

How can you help?

If you agree to take part I will meet with you at your Company or the University. I will present my design work that may include models, images and/or video, I would then appreciate your feedback based on your professional opinion and the following question. *'How does this academic design research relate to the industry and how might it be applied commercially or conceptually within your company or the field in general?'*

The presentation will take no more than 30 minutes and I would like to audio record your response with your permission and write up notes later.

What will happen to the information you give?

¹ MADE <http://made.ac.nz/about-made/>

Multi-property Additive-manufacturing Design Experiments – MADE – is the concerted manifestation of 15 years of research and knowledge at Victoria University of Wellington (New Zealand) into emerging digital technologies – specifically 3D printing – and its commitment to educating students for a changing and challenging new world.

The information you provide as feedback will be confidential until you consent to publication. If you require (prior to any publication) I will provide you with a proofing document that clearly shows what I wish to publish and how you and your company may be referenced, this will require your and your organisations consent (provided you have the authority to agree to this on behalf of the organisation). Only my supervisors and I will read the meeting notes. Audio recordings will be kept securely and destroyed 1 year after the research ends.

What will the project produce?

The information from my research will be used in Masters Thesis and/or academic publications and conferences. Having Industry perspectives will assist in developing research relationships that foster critique of academic and professional practice.

If you accept this invitation, what are your rights as a research participant?

You do not have to accept this invitation if you don't want to. If you do decide to participate, you have the right to:

- ask for the recorder to be turned off at any time during the interview
- ask any questions about the study at any time
- read over (comment as required) a proofing document and consent to publication
- be able to read any reports of this research by emailing the researcher to request a copy.

If you have any questions or problems, who can you contact?

If you have any questions, either now or in the future, please feel free to contact either:

Student:

Name:

University email address:

(Note: students should not provide personal cell phone numbers)

Supervisor:

Name: Bernard Guy

Role: Lecturer

School: Design

Human Ethics Committee information

If you have any concerns about the ethical conduct of the research you may contact the Victoria University HEC Convenor: Dr Judith Loveridge, email [REDACTED]

Professional perspectives, gaining an expert opinion from industry

CONSENT TO INTERVIEW

This consent form will be held for 3 years.

Researcher: *(Student Add Name)*, School of Design, Victoria University of Wellington.

- I have read the Information Sheet and the project has been explained to me. My questions have been answered to my satisfaction. I understand that I can ask further questions at any time.
- I agree to take part in an audio recorded interview.

I understand that:

- The information I have provided will be destroyed 1 year after the research is finished.
- Any information I provide will be kept confidential to the researcher and the supervisor
- I understand that the results will be used for a Masters Thesis and/or academic publications and/or presented to conferences.
- I consent to information or opinions which I have given being attributed to me/my organisation in any reports on this research and have the authority to agree to this on behalf of the organisation: Yes ☐ No ☐

Or

- I would like to review a proofing document prior to any publication. Yes ☐ No ☐
- I would like to receive a copy of the final report and have added my email address below. Yes ☐ No ☐

Signature of participant: _____

Name of participant: _____

Date: _____

Contact details: _____

—

BENEATH THE SKIN

by

ANA MORRIS

*School of Design Innovation
Victoria University of Wellington*

2020

200