Molding and Filament Winding of Spatially Graded Material Properties through Computational Design

by

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B.Arch, ITESM-CCM (2008)

Submitted to the Program in Media Arts and Sciences in partial fulfillment of the requirements for the degree of Master of Science in Media Arts and Sciences

at the

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Abstract

Three-dimensional printing and computational design have enabled designers to spatially vary material properties in objects. Nevertheless, this technology has current limitations that include material durability, cost and speed. In this thesis I demonstrate two novel fabrication processes that I developed, multi-material molding and casting and crafted filament winding, this processes allows for the gradation of material properties in a low cost and fast process. Then, I applied this method to two design scenarios, a mid-sole for a running shoe and a prosthetic socket for trans-tibial amputees. The thesis details the design workflow from computational data driven design to the fabrication of low-cost functionally graded material systems.

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Chapter 1

Introduction

My primary research interest in this thesis is the development of two novel multi-material fabrication methods for customized objects and high performance design applications. Through developing two design scenarios, a multi-material mid-sole for a running shoe and a multi-material prosthetic socket, I demonstrate a novel design workflow that uses hierarchical computational tools to translate data into a spatially varied material properties.

This thesis contributes to the field of digital fabrication by introducing two methods of low-cost fabrication to allow designers to distribute material properties without the use of three-dimensional printing. Multi-material molding and casting is a novel fabrication method that can be applied in a wide range of design applications, and allow for the tunning of material properties across the volume of objects. Crafted filament winding is a novel hybrid technique that allows a human to wind an object following computer instructions. Both of these fabrication methods are lower in cost, faster in fabrication time and have higher material durability when compared with three-dimensional printing.

In this section I describe the related background of this thesis with topics that includes nature, fabrication and computational design.
1.1 Nature

Nature is driving researchers and designers to innovate in the field of design and digital fabrication. The main goal for this thesis is to research novel strategies of computer-aided design and computer-aided manufacturing to achieve gradients of material properties.

1.1.1 Multi-materials in Nature

Figure 1-1: Human Skin, from left to right: Robert Mapplethorpe, Human Skin Google Image, SEM Stratum Corneum - Karolinska Institutet Sweden

The human skin is a useful case study to analyze the grading of material properties according to specific functions. [Bischoff et al., 2000] It is interesting to explore how, through geometric variation, material properties can be tuned to result in different mechanical properties. For example, by understanding how the thickness of the skin changes at different sites along the body designers could translate this property in the designing of materials along surface areas of objects. [Sandby-Møller et al., 2003]
1.1.2 Functionally Graded Fiber Systems in Nature

Bombyx mori silk cocoons are a relevant case study in analyzing the way in which nature fabricates a composite material with continuously varying mechanical properties. [Chen et al., 2012] The natural silk that the bombyx mori produces is made out of two materials: fibroin and sericin, the latter of which is a protein that acts as glue and keeps the fibers together. [Omenetto and Kaplan, 2008]

Interesting properties of a silk cocoon include the fact that it is made out of a continuous fiber that is approximately one kilometer in length, has zero material waste in the fabrication process, and creates a structure with different mechanical properties. For example, the interior of the cocoon is made of thinner silk than the exterior of the cocoon. For this thesis I am interested to explore the translation of the fabrication process of a silk cocoon into a digital fabrication methodology.

This process of fiber based fabrication found in nature has inspired me to research how it may be possible to achieve gradients of fiber distributions as a novel fabrication method in the designing of prosthetic sockets.
1.2 Material properties

1.2.1 Functionally Graded Materials

Functionally Graded Materials (FGM) is an interesting set of advanced materials that vary their properties across the dimensions of an object. The relevance of this type of material in the design of products is in the possibility of designing materials for specific functions in a wide range of design applications including aerospace, defense, medicine, etc. [Mahamood et al., 2012] This property inspired me to research novel methods of low-cost fabrication that could allow for FGM.

1.2.2 Variable Impedance

In general terms, mechanical impedance defines the relationship between forces and motions at various points. For this thesis, variable impedance is measured and defined by the specific material property of damping capacity at different areas of an object. [Bruel & Kjaer, 1977] This mechanical property inspired me to research the fabrication of local load deformation in objects through the design of variable impedances in materials.

1.3 Fabrication Methods

1.3.1 Multi-material Additive Manufacturing

Three-dimensional printing as a method of additive manufacturing has enabled designers to fabricate objects with functional anisotropic material gradients. [Oxman,] Research has shown that it is possible, through computational tools, to design and control material properties in objects. [Oxman,]
For this thesis one of the challenges is to present novel methods of digital fabrication that could allow for the grading of material properties without the use of 3D printing. The motivation for this is to democratize fabrication strategies, increase fabrication speed, and allow the use of more varieties of materials.

1.3.2 Filament-winding

Filament winding is one of the most efficient and least expensive fabrication methods. [Peters, 2011] The advantages of this fabrication method include the possibility of winding nonsymmetrical and noncylindrical shapes, creating lightweight structures and winding different patterns. Furthermore, as it is shown, by controlling the design of the band pattern, different systematic structures with different mechanical properties can be fabricated to cover the mandrel. [Peters, 2011]

As part of the contributions of this thesis are the designing of winding patterns informed by MRI data. Then, through the filament-winding process, fabricate low
cost prosthetic sockets with tuned material stiffnesses in different areas. Some of the biggest challenges in this kind of fabrication process are in the determination and design of the mandrel from MRI volume data and the design of the path generation for winding carbon-fiber filament.

1.4 Data

1.4.1 Foot Plate Sensor Data

Foot plate sensor data is the pressure that a person exerts between the foot and the support surface. This data is important to understand both gait and posture analysis for diagnosing lower limb problems, footwear design, sports biomechanics, injury prevention and other applications. [Razak et al., 2012] The relevance of using this data in a customized mid-sole design relies on the possibility of distributing material stiffness according to pressure values.

1.4.2 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is an important tool widely used in clinical analysis to generate a series of images of the surface and interior of the body in an non-invasive manner. [Nacher, 2007]

1.4.3 Actuated Test Socket Data

Actuated Test Socket (ATS) data is a research tool developed by Arthur Petron at the Biomechatronics Group in the MIT Media Lab. This tool is a ring that surrounds the residual limb and has 14 points to collect ATS data which evaluates the pressure response at different tissue displacements. [Tsai, 2013] In this thesis I incorporated this data in the computational design workflow to determinate local tissue stiffness of the residual limb. This process informed the distribution of fiber densities in the fabrication of a prosthetic socket.
1.5 Computation

1.5.1 Computer Aided Design in Additive Material Distribution

Previous research at the Mediated Matter Group and by Professor Oxman has focused on developing computer aided design methods to distribute material properties. Oxman showed, in the development of the Carpal Skin prototype, that it is possible to distribute material properties according to customized pain maps of patients with carpal tunnel syndrome. Oxman also showed that rapid diffusion algorithms could be used to distribute material stiffness according to specific areas on the glove. Furthermore, the differences between the material properties allowed for different functions such as increased flexibility, enhanced circulation and relieved pressure on the median nerve. [Fabrication and Heterogeneous, 2008]

1.5.2 Computer Aided Design in Fiber Based Fabrication

Over the past forty years the use of computer-aided design (CAD) in the process of filament winding has advanced considerably. These efforts have transformed filament winding from academic research into an industry of composite manufacturing.
The relevant steps of the use of CAM in filament winding presented in this thesis are:

1. Mandrel definition: three-dimensional representation of the surface to be wound within a CAD program.

2. Path generation: creating feasible and stable trajectories for winding the fibers on the defined surface.

3. Post processing: in this thesis I translated three-dimensional positions for a machine into craft instructions for a human to wind the fibers.
Chapter 2

Problem Statement

2.1 Mid-sole

Mid-soles and running shoes belong to a family of orthotic devices designed by the industry for different foot mechanics. Although such products are fabricated from lightweight foams and rubbers with different stiffnesses they are limited in their capacity to offer customized local control of material stiffness for the optimization of impact forces, stability, comfort or performance. Further research is needed to improve the effectiveness of these devices.
thermore my interests are in developing a fabrication method that could allow for
the control of shoe properties and potentially alter the mechanics of muscle and bone
while running with the goal of preventing injuries [Wright et al., 1998].

My contributions include a novel design workflow and a low-cost multi-material
fabrication method that enables the customization of mid-soles for running shoes. In
the thesis I present a novel process of computer-aided design that translates foot plate
sensor data into a gradient of geometries for informing a novel method of low-cost
multi-material computer aided fabrication.

2.2 Prosthetic Sockets

![Prosthetic Sockets](image)

Figure 2-2: Prosthetic Sockets currently available in the market

Prosthetic sockets belong to a family of orthotic devices designed for amputee rehabil-
itation and performance augmentation. Although such products are fabricated from
different polymers and lightweight composite materials and are designed in optimal
shapes and sizes, they are limited in their capacity to offer local control of variable
impedance [Gerschutz et al., 2011].

In this thesis I present a novel process of computer aided design that translates
MRI and ATS data into gradient geometries for informing a novel method of low-cost
variable impedance computer aided fabrication.
Chapter 3

Aims and Goals

My main goal in this thesis is to bring programmability into objects by translating data into a gradient of material properties. I am interested in spatially grading material properties in the fabrication of customized orthoses. This work contributes to the efforts of democratizing fabrication. [Gershenfeld, 2012]

The motivation for exploring novel methods of fabrication other than three-dimensional printing includes some of the current limitations of this technology: cost and material durability. This motivation represents an exciting opportunity to contribute to the field of digital fabrication with novel ideas and low-cost fabrication methods.

![Data → Design](image)

Figure 3-1: Thesis design workflow

3.1 Multi-material Molding and Casting Mid-sole

The technical goal for designing a multi-material mid-sole for a running shoe is to passively tune material stiffness across surface areas and present a novel low cost fabrication method that allows for tuning material properties without the use of 3D printing. The motivation on the design application is to allow for the customization of running shoes and to enhance human mobility as well as prevent pathologies related
to knee and hip problems in runners that are caused by wearing shoes with poor support. \cite{Kerr2009}

3.2 Functionally Graded Filament-wound Carbon-Fiber Prosthetic Sockets

In the year 2005 1.6 million persons were living with the loss of a limb in the United States. It is estimated that in the year of 2050 the number will be more than the double. \cite{Ziegler-Graham2008} The motivation of the design application is to enhance the comfort of prosthetic sockets. The technical goal for filament-winding a prosthetic socket is to fabricate an orthoic device with variable impedance, allow for thermal exchange, and present a novel low-cost fabrication method that allows for tuning material properties without the use of three-dimensional printing.
Chapter 4

Relevant Research

Relevant research for this thesis includes novel approaches to the design of orthoses and novel methods of digital fabrication.

4.1 Application

4.1.1 Variable Impedance Mid-sole Running Shoe

Relevant research includes previous work developed by Professor Herr in the design of limb exoskeletons, specifically, the design of the Springbuck shoe. [Herr, 2009] The relevance of this research is in the fabrication of a running shoe with a carbon composite elastic mid-sole designed to reduce the metabolic rate by two-percent and improved shock. [Herr, 2009] Furthermore this research inspired me to envision a design scenario where shoes could be customized according to the necessities of each runner and potentially allow for human augmentation.

Figure 4-1: Springbuck Shoe, Hugh Herr, Image from [Herr, 2009]
Research done at the New Balance Research Lab helped me to understand the complexity in designing a customized mid-sole for a running shoe. The collaboration with the company enabled me to collect and relate to foot pressure sensor data and translate this data into a customized design of a mid-sole.

4.1.2 Variable Impedance Prosthetic Socket

Relevant research for this thesis includes previous work developed by the Mediated Matter Group in the design of a variable impedance “4D-printed” prosthetic socket [Tsai, 2013]. The research developed in the Biomechatronics Group on the design and fabrication of a variable impedance prosthetic socket informed by MRI data helped me to understand data driven design and multi-material fabrication in prosthetics. [Sengeh and Herr, 2013] Previous work on the use of CAD and CAM in the design of customized prosthetic sockets guided me to explore a novel parametric computational design process. [Smith and Burgess, 2001] [Topper and Fernie, 1990] These efforts helped me to understand how to implement different CAD and CAM tools to translate ATS Data and MRI Data into a gradient of material properties in a prosthetic socket.

Figure 4-2: Design-Fabrication Process, Elizabeth Tsai, Image from [Tsai, 2013]
4.2 Methods

4.2.1 Multi Material Additive Manufacturing

Relevant research for this thesis includes the design method of Functionally Graded Rapid Prototyping (FGRP) [Oxman et al., 2008] by the Mediated Matter Group. This novel design approach differentiates material properties informed by different sources of data. This research demonstrated that it is possible to control spatial gradation of material properties through gradients in components. [Oxman et al., 2008]

4.2.2 Filament-wound Carbon Fiber

Research has been done in the influence of filament winding patterns in mechanical properties of reinforced composites. [Mertiny and Ellyin, 2002] In this thesis I explore how the design parameters of filament winding influence the performance of objects fabricated in this way. However, no research has been done to date that confirms whether the performance of a prosthetic socket can be improved by the design of the filament-winding pattern. The fabrication design parameters that are relevant to this thesis are fiber angle and fiber wall thickness. [Mertiny and Ellyin, 2002]
Chapter 5

Previous Work

The projects presented in this section informed the direction of the thesis and is focused on the methods by which to achieve a gradient of material properties through the exploration of different methods of fabrication.

5.1 Micro-macro Fluidic Systems

Figure 5-1: Micro Fluidic Experiments
Microfluidics is an enormous field that allows the distribution of multiple fluids through micro-channels and performing complex operations. The experiments that I developed consisted of a series of basic tests that helped me to understand how different polymers could be distributed through a network of micro-channels. The results of these experiments showed that it was possible to explore microfluidic systems as a method of multi-material additive manufacturing.

![Figure 5-2: Micro-Macro Fluidic Initial Experiments, Radial Fractal Sample, Single Layer Laser Cut Acrylic](image)

The basic experiments that I developed helped me to understand and explore different methods of fabrication for rigid and flexible micro-macro fluidic systems. The fabrication methods I used in these experiments included laser cutters, 3 axis CNC micro-machining and 3D printing.

![Figure 5-3: Micro-Macro Fluidic Initial Experiments, Multi-layer Laser Cut Acrylic](image)

The micro-macro fluidic systems that I fabricated using a 3 axis CNC router were the most successful. The materials that I selected to machine were HDPE
polyethylene and Delrin acetal resin. The tests consisted of basic microfluidic circuits that I named Single Input - Single Output components.

Figure 5-4: Micro Fluidic Experiments, Single Input - Single Output components, Delrin acetal resin machined using a 3 axis ShopBot Desktop with a 1/32” 2 Flute Endmill.

The results of the experiments showed that microfluidic systems could be implemented as a novel method of multi-material fabrication. The workflow consisted of the injection of multiple polymers through embedded polydimethylsiloxane (PDMS) channel networks. PDMS was chosen due to its because of the following properties: ease of fabricatation, captures the micro details of molds when casted, elasticity and surface properties. [Kuncová-Kallio and Kallio, 2006]

Figure 5-5: Micro-Macro Fluidic Initial Experiments, Multi-material Color Gradient Sample, PDMS Matrix with two color polymer injected
5.2 Cabinet of Experiments, Bombyx Mori Silk-worms

Bombyx mori silkworms are an example of how nature distributes material according to specific functions and environmental conditions. In a previous research project, I developed a collection of basic research experiments using silkworms to study different patterns of material deposition in artificial environments.

The “Cabinet of Experiments” is a collection of basic research experiments to study silk structures fabricated by Bombyx mori silkworms. Initial experiments demonstrated that the shape of the silk structure fabricated by silkworms was defined by the conditions of the artificial environment. When we deployed a silkworm on a flat surface a flat layer of silk was fabricated. When we deployed a silkworm in an environment with a third dimension a cocoon was fabricated. This fact informed the design and fabrication of four different series of platform experiments with specific...
design configurations.

“Single Dice” was an initial series of platform experiments where I investigated the environmental conditions required for a silkworm to fabricate a silk cocoon around a single central pole of varying heights. The series consisted of square platforms with dimensions of 8cm x 8cm and with a center pole with variable height from zero to 24mm. The results are analyzed on the following figure showing that silkworms need at least a height of 21mm to fabricate a silk cocoon.

Figure 5-7: Cabinet of Experiments, Analysis Platforms, Single Dice face configurations [Oxman et al., 2012]

This Cabinet of experiments is relevant for this thesis in that it demonstrates how nature achieves a gradient of fiber densities according to environmental parameters. How could a similar level of material deposition be achieved through computational algorithms, generative design and digital fabrication?
Figure 5-8: Cabinet of Experiments, Analysis Platforms, 4-Dice face configurations

4-Dice face configurations. L to R: Digital representation of anticipated stress for membrane structure based on 4 poles calculated within SolidWorks; physical model with digital representation as base. The silkworm is shown to the right; physical model juxtaposed with silk fiber by the Bombyx mori silkworm. Denser fibers appear between poles along boundaries as anticipated by the FEM model. [Oxman et al., 2012]

This work was presented at the eCAADe 2013 [Oxman et al., 2012].
Chapter 6

Design Scenarios

This thesis describes the development of two exciting design scenarios: a variable impedance mid-sole and a variable impedance prosthetic socket.

6.1 Variable Impedance Mid-sole Running Shoe

Designing and fabricating a variable impedance mid-sole is a very exciting design scenario to explore data driven design and multi-material fabrication. My contributions include the development of a novel low-cost fabrication methodology that could potentially allow for the customization of mid-soles for running shoes.
Running shoes are a challenging design scenario where the engineering of the mid-sole could improve the deformation of the shoe according to customized foot mechanics and potentially allow for human augmentation [Shorten, 1993]. The long term vision of this research is to allow the fabrication of customized running shoes for optimal ergonomic fit and mechanical performance. The benefits of this research could help to reduce pathologies related to knee, hip and back problems caused by wearing shoes with poor mechanical support for external loads [Kong et al., 2009].

Further research could direct the fabrication of a real time sensor mid-sole using flexible conductive polymers that could transmit impedance data in real time [Vogt et al.,]. In combination with paraffin actuators [Lee and Lucyszyn, 2005], the fabrication method that I present in this research could allow for tuning the shape and stiffness of the mid-sole in real time.

### 6.2 Variable Impedance Prosthetic Socket

![Variable Impedance Prosthetic Socket, Design Workflow Diagram](image)

Figure 6-2: Variable Impedance Prosthetic Socket, Design Workflow Diagram

Prosthetic sockets are a challenging design scenario to which different methods of computer aided design and computer aided manufacturing can be applied to translate MRI data into a customized prosthetic with variable impedance according to tissue stiffness.
My interests as a designer and architect are towards achieving structural performance and thermal exchange through approaching the design of the socket as a building facade.

Further research could potentially lead to the design of multiple customized lightweight orthoses and exoskeletons for different sports and activities such as diving, swimming, rowing, etc.
Chapter 7

Methodology

![Design Workflow, Data driven design](image)

Figure 7-1: Design Workflow, Data driven design

The challenges in computer-aided design for this thesis include the development of a design workflow that allows the translation of data into objects with a gradient of material properties.

7.1 CAD

In the past forty years computer-aided design (CAD) has enabled designers to create, analyze and optimize complex designs using different methods of geometrical representation and scripting languages. [Keeter, 2013] [Tornincasa and Torino, 2010] The challenges for this thesis are in the translation of data into three-dimensional CAD workflows to inform computer aided manufacturing (CAM) and bring programmability into objects.
In this thesis I used open source parametric environments to translate different sources of data into hierarchical computational tools. The CAD process that I implemented involved the translation of input data to output a gradient of three-dimensional geometries. This process allowed me to fabricate objects with a gradient of material properties.

![Design Workflow, CAD informed by CAE and CAM](image)

**7.1.1 Multi-material Molding and Casting Mid-sole Running Shoe**

I used foot plate sensor data to generate a gradient of 3D geometries through hierarchical computational design tools. Then I used this data to inform the design and fabrication of two two-part molds and proceeded to fabricate the mid-sole. The first pair of molds allowed for the casting of the stiff material and the second pair of molds allowed for the casting of the soft material.

![CAD design process diagram](image)

**Figure 7-3: CAD design process diagram**

40
In this process I used GenerativeComponents (GC), an open source parametric scripting environment, to visualize the data collected at the New Balance Research Sports Lab. The computational tools that I used allowed me to visualize the variation in pressure that an athlete does over a single foot strike over the shoe. The visualized data is the average over a foot strike data collected using a force plate embedded in the floor and pressure sensor embedded in the shoe. The data corresponded to the inputs of 99 spatially distributed sensors sampled 100 times over the course of one foot strike.

Figure 7-4: Initial diagrams, data driven computational design

The next step involved transforming the data into hierarchical geometries with a continuous transformation. These geometries - cells - defined the first two-part molds which allowed the fabrication of part A - the stiffer part of the mid-sole.
I used the MR 1400 v2 shoe from New Balance as a mid-sole template with small modifications on the alignment of the upper surface and bottom surface of the mid-sole due to 3 axis CNC machining constrains. It is important to notice that this CAD workflow allows for the fabrication of multiple designs since it is a generative tool.

The parametric workflow within GC allowed me to hierarchically link geometries and create a dependency between the data file and the design of the midsole. In this process I implemented scripts and parametric modeling in the following steps:

1. I created a parametric model within GC to import the CAD file, which contained the design template information of the MR 1400 v2 mid-sole. (This information was shared by New Balance)

2. I transformed the CAD file into a parametric model and generated a field of geometries to control the distribution of the material within the molds. In this process I implemented a series of scripts that allowed me to control the dimensions of the geometries through the values of the impedance data. The resolution of the parametric model matched the resolution of the 99 sensors of the foot pressure sensor.
3. In the next phase I implemented a series of parametric modeling steps to define the geometries and create solid representations of the molds. An important step consisted in the calculation of the height of the features within the mold. My solution consisted of writing a script that calculated the thickness of the mid-sole at each individual cell and multiplied the value by a scaling factor of one third.
Figure 7-8: Two-side Mold Design, Part A, GenerativeComponents Render

Figure 7-9: Two-side Mold Design, Part B, GenerativeComponents Render

Figure 7-10: Two-side Mold Design Diagram, both parts, GenerativeComponents Render
4. Before fabrication, I imported the file into Maya to prepare the mold for fabrication. In this process I extruded the outlines of the mid-sole and examined the alignment of the features between the two part molds.

Figure 7-11: Two-part Design Mold, visualization of the two part mold in longitudinal section

Figure 7-12: Multi-material mid-sole render
7.1.2 Variable Impedance Prosthetic Socket

The CAD process that I developed in the design of a variable impedance prosthetic socket allowed me to generate gradient of fiber distribution through hierarchical computational design tools informed by MRI data and ATS data. I used this information in the fabrication process of crafted filament winding.

Figure 7-13: CAD design process diagram

In this process I used GC to visualize the differences in tissue stiffness over a three-dimensional digital file generated from MRI data. The ATS and MRI data was collected by the Biomechatronics Research Group at the Media Lab, MIT.

Figure 7-14: MRI Data reconstruction, GC Vertical sections for mesh reconstruction
To process the ATS data I used python scripts to do a first series of plots of force versus distance. Then I calculated the slope of each subplot to obtain the stiffness value of the tissue in each of the measurements. The data that I used corresponded to 14 radial sensors equally distributed, and eight vertical sections.
Once I processed the eight vertical sections of the ATS data, I created a radial plot within python to visualize the difference in stiffness values across different sections.

Figure 7-17: Force vs Distance ATS Data, Each subplot corresponds to the measurements of each sensor in different vertical sections

The next step consisted of mapping stiffness data over a parametric model generated by MRI data. To map the resolution of the collected data with the three-dimensional model, I reconstructed the mesh generated by MRI data and matched the subdivision of the mesh grid with the data grid.

Figure 7-18: Mapping of Tissue stiffness over a mesh generated by MRI data, Mesh grid corresponds to data grid, GC render
Once I generated a hierarchical parametric model, I started testing different algorithms to distribute continuous curves, which I used as an abstract representation of the filament-winding process.

Figure 7-19: Initial Sketch of a continuous curve simulating the fabrication process of filament-winding, GC render

In parallel, I explored the control of fiber distributions according to different inputs. This process helped me to understand how to translate tissue stiffness data into a gradient of fiber densities across the volume of an object.
Figure 7-20: Abstract representation of fiber based distribution A, GC render
The final approach for distributing fiber densities consisted of designing a parametric rig that allowed me to control the winding pattern. The design of the rig was
informed by mapping tissue stiffness across the digital model generated by MRI data.

Figure 7-23: Abstract representation of fiber based distribution in plant, Parametric Rig Diagram, GC render
7.2 CAE

Computer-aided engineering enables analysis and optimization of designs to predict performance. In this thesis I developed basic experiments that could inform further research into how to predict the deformation of a customized multi-material mid-sole and a customized multi-layered filament-winding prosthetic socket.

7.2.1 Multi-material Molding and Casting Mid-sole Running Shoe

The design workflow that I implemented showed local control of geometry deformation in the global design of the mid-sole. This control is informed by customized impedance data. Further research could guarantee an optimal performance of a mid-sole by controlling geometry deformation by material performance and customized impedance data.
7.2.2 Functionally Graded Filament-wound Carbon-Fiber Prosthetic Sockets

Figure 7-25: Abstract representation of fiber based distribution informed by MRI Data, Parametric Rig Diagram, GC render

The design workflow that I developed informed by MRI and ATS data showed control on the fiber distribution in the global design of the prosthetic socket. Further research could improve the performance of a prosthetic socket by distributing fibers informed by tissue stiffness data and material performance.
7.3 CAM

Computer aided-manufacturing (CAM) has enabled the fabrication of complex objects
by computer controlling machine tools. CAM is computer software that translates
CAD information into codes that drive computer numerically controlled (CNC) ma-
chines. Different CAM tools allow for the fabrication of 2D and 3D parts and drive
machines to add or subtract material [Edwards, 1989].

The challenges for this thesis are in the identification of low cost CAM workflows
that enable tunable material properties within objects through various fabrication
methods. The CAM process that I followed consisted in the translation of data into
geometrical representations in 2D and 3D. During the CAD process I implemented
CAM constraints within a parametric environment to add variation and precision in
the fabrication of parts.

In this thesis I experimented with hybrid processes that involved the use of CAM
and crafts. In the first part of the fabrication process I used CAM tools to drive CNC
machines to subtract material. In the second phase of the fabrication process I used
crafts as a method for additive manufacturing.

7.3.1 Multi-material molding and casting mid-sole running
shoe

The CAD process that I implemented in the design of a multi-material mid-sole
allowed the construction of a generic CAM tool for a 3-axis CNC router. In the
computational design process I incorporated machine constraints to guarantee a suc-
cessful fabrication process. The parameters that I included in the CAD process were
tool size (i.e., end-mill width and length dimensions) and machine capabilities (i.e.,
three axis).
7.3.2 Functionally graded filament-winding prosthetic sockets

The CAD process that I implemented in the design of a variable impedance prosthetic socket allowed the construction of a generic CAM tool for the process of crafting filament-winding. In the computational design process I incorporated the fabrication method as a parameter to distribute material stiffness. The parameters that I included in the CAD process were fiber dimensions, winding angle and fiber density distribution.

This CAM process allows for a novel hybrid fabrication method that uses crafting to follow computer instructions. This process could also be implemented with the use of a 5 axis CNC machine or a 6 axis robotic arm. Nevertheless, the ultimate fabrication result would be more or less the same.
Chapter 8

Fabrication

To implement the multi-material molding and casting as well as the crafted filament winding, I developed two novel fabrication processes to functionally grade material properties.

8.1 Multi-material Molding and Casting

Multi-material molding and casting enables control of mechanical properties of products by embedding designed lattices in matrices. This technique integrates molding, casting and macro-fluidics into a hybrid method. First, I would fabricate a complex matrix with geometric channels, and then inject various polymers to fill the channels. [Oxman, Neri; Gonzalez, 2014] After curing, the polymer lattice and matrix form a multi-material product at a lower cost than 3D printing.

8.1.1 Initial Experiments

Initially, I experimented with many materials and machining processes to find the most reliable, integrated process.
The fabrication steps consisted of machining with a 3 axis CNC router a 1-part mold the negative of the channels. To keep a high definition aspect ratio of each feature I used 1/2” rigid high density polyethylene (HDPE) and machined it with a 1/32” 2 flute end mill. In the next step, I casted PDMS to create the positive matrix around the channels, at the same time I cast a flat 1 mm layer of PDMS to seal the top of the channels.

To bond both layers of PDMS I de-molded both parts after allowing 75% of the total curing time (45 minutes at 150°F). Then I de-molded and placed the top layer to seal the channels, and finally baked the matrix for 45 minutes at 200F. After the matrix was fully cured, I proceeded to inject low viscosity urethane plastic (Smooth-On Smooth-Cast 300) and let it cure for 10 minutes.

In the second phase of experiments, I explored using fluidic logic to create a
gradient of colors with the polymers injected through the channels. The results were consistent, and I achieved a full color gradient using two colors, injected through two perpendicular inlets.

Figure 8-3: Multi-material Molding and Casting 2.5D 1-Part Side Mold Fabrication, PDMS Matrix cast with an injection of Smooth-Cast 300 two colors

The next challenge was to design and fabricate three-dimensional lattices embedded in a matrix using two-sided molds, machined on a 3 axis CNC router.

### 8.1.2 2.5D Double Sided Mold Fabrication

The design workflow I developed consisted of fabricating a two-part mold machined with a 3 axis CNC router. In order to allow for machining high definition features, I selected HDPE as the material for the mold. To achieve the fine details of the channels I used a 1/32” 2 flute single end mill.
Once the mold was fabricated, I cast medium viscosity silicone rubber with a tensile strength of 200 psi and let it fully cure for 4 hours at room temperature. After the matrix was completely cured I demolded and injected a high viscosity strong rubber (Smooth On Mold Star 30) with a tensile strength of 420 psi in each of the cells. The rubber flowed through the vertical channels and filled the network. The main differences from the two-dimensional experiments using PDMS are the absence of the top layer that seals the channels and the vertical connections between the bottom and top channels.
Figure 8-6: Multi-material Molding and Casting 2.5D Sample with Multi-material injection, Silicone Rubber Matrix with a 200 psi strength injected with Smooth On Mold Star 30 with a tensile strength of 420 psi

8.1.3 3D Double Side Mold Fabrication

Figure 8-7: Multi-material Molding and Casting 3D Two-part Design Mold, 3-axis CNC machined Machinable Wax, Mold A

While the workflow described above reliably produced multi-material products, it could not create the continuous thickness variation necessary to fabricate the MR 1400 v2 shoe mid-sole from New Balance. For this reason, I moved to a 3D Double Side Mold workflow.
This design workflow consisted of the fabrication of two three-dimensional double-sided molds machined using a 3 axis CNC router. The material that I selected to make the molds was machinable wax because it is easy to machine and keeps high definition in small features. To complete the multi-material injection process it was necessary to fabricate two separate double-side molds. Mold A (Figure 8-7) defined the interior matrix and allowed the distribution of stiff material. Mold B (Figure 8-8) defined the exterior shape of the mid-sole and contained the soft material during the injection of the second cast.

Figure 8-8: Multi-material Molding and Casting 3D Two-part Design Mold, 3-axis CNC machined Machinable Wax, Mold B
8.1.4 Multi-material Casting

In the casting experiments with the mid-sole molds described above, I experimented with many different materials of varying properties and colors. The only constraint on material selection is the ability to cast it into the mold.
Figure 8-10: Micro-Macro Fluidic Multi-material Cast, Multi-material Mid-soles

The workflow for mold A involved mixing the casting material, degassing it in a
vacuum chamber, injecting it using a plastic syringe and finally letting it cure.

Figure 8-11: Multi-material Molding and Casting, Mold A and Mold B fabrication setup

Figure 8-12: Multi-material Molding and Casting, Matrix inside mold B / Multi-material mid-sole final cast
Figure 8-13: Multi-material Molding and Casting, process

Once the cast in mold A was fully cured, I removed it and placed it inside the mold B. Then I used a similar process as with mold A to inject the material for mold B.

I repeated these steps several times to fabricate different mid-soles with different materials to achieve variable impedances and different color effects.
Figure 8-14: Multi-material Molding and Casting, Mold A and Mold B fabrication setup
8.2 Crafted Filament Winding

The crafted filament-wound carbon-fiber process is a novel, low-cost technique for the fabrication of customized, lightweight orthoses with variable impedance and ergonomic fit. For this thesis I used MRI data to inform this process, creating a hybrid technique using CAM and craft together.

8.2.1 Initial Experiments

The novelty of this method is in the creation of customized filament-winding patterns that differentiate fiber density to achieve variable impedance. In my first experiments, I developed numerous tests using small molds as mandrels. To compress the fibers I tried vacuum bagging and compression molding, finding the first to be the most successful.

![Crafted Spatially Graded Composite Filament Winding Carbon Fiber, 3 axis CNC router mold making / Small scale socket initial molds](image)

The crafted filament-winding process uses CAD instructions to guide a human in laying carbon fiber. With this methodology I was able to control the density of the fibers and the winding pattern. The success of this experiment lead me to scale up to a full size prosthetic socket.
Figure 8-16: Crafted Spatially Graded Composite Filament Winding Carbon Fiber, Scaled Socket Initial Fabrication Trials
8.2.2 Mold Making Full size Socket

To create the madrel for the full sized test, I had to make duplicates from a residual limb mold given to me by the Biomechatronics group. To do this, I made a negative mold using a silicone base material (Smooth-On Ecoflex 00-20). This mold allowed me to create multiple copies using different materials such as Drystone, Flex Wax and Machinable Wax.

Figure 8-18: Residual Limb negative mold fabrication, Ecoflex 00-20 Silicone, Positive limb mold from Biomechatronics Group, Mold Making Process
Figure 8-19: Residual Limb mold for fabrication, Flex Wax 120 Cast

Figure 8-20: Residual Limb mold for fabrication, Drystone
Figure 8-21: Residual Limb mold for fabrication, Machinable Wax

Figure 8-22: Residual Limb mold for fabrication, Machinable Wax
8.2.3 Spatially Graded Rig for Filament-winding Carbon Fiber

The craft instructions come in the form of a winding rig placed on the bottom of the mandrel, with hooks spatially distributed according to the GC model based on the tissue stiffness data. I used these hooks to precisely control the density of fiber during the winding process.

To fabricate the rig I cut 6 mm thick sheets of acrylic using a laser cutter, building a three-dimensional structure by snap-fitting two-dimensional parts. To calculate the tolerance of the snap fits I did a small test, varying the width incrementally by .05 mm. Once I found the right dimensions I used this parameter to modify my design within GC to recalculate the dimensions in all the parts.

![Image](image1.jpg)

Figure 8-23: Parametric rig for filament winding, snap fit test, Laser cut acrylic

![Image](image2.jpg)

Figure 8-24: Parametric rig for filament winding, Laser cut acrylic
Figure 8-25: Parametric rig for filament winding, Laser cut acrylic - flexible wax mold
Figure 8-26: Parametric rig for filament winding, Laser cut acrylic - machinable wax mold
Figure 8-27: Parametric rig for filament winding, Laser cut acrylic - machinable wax mold, mlexible wax mold and drystone mold
8.2.4 Crafting Filament Winding Carbon Fiber

The filament winding process follows a simple routine, repeated many times. Figure 8-28 shows an abstract representation of different possible winding routines. In the first test I followed pattern C.

![Figure 8-28: Winding patterns, abstract representation, GC drawing](image)

For this test, I used West Systems 105 epoxy resin because of its high strength and room temperature cure. My workflow consisted of following steps:

1. Apply a thin layer of resin to wet the carbon fibers.

2. Wrap the model with a perforated plastic as a release layer.
3. Wrap the model with a double layer of breathable material to absorb the excess of the resin.

4. Enclose the model with a vacuum bag.

5. Pull a vacuum on the model for three hours.

6. After curing, use a dremel rotary tool to trim the profile of the socket.

In my work with these epoxy resins, I followed all required safety procedures, including wearing gloves and a respirator.

Figure 8-29: Crafted filament-winding carbon fiber, variable densities informed by tissue stiffness data
Figure 8-30: Vacuum bagging process

Figure 8-31: Socket in curing process
8.2.5 Crafting Filament Winding Carbon Fiber and Aramid

To fabricate this socket I implemented the same fabrication process described above. To crafted wind the fibers I using pattern C for carbon fiber and pattern A for aramid showed in Figure 8-28.

Figure 8-32: Crafted filament-winding carbon fiber and aramid, variable densities informed by tissue stiffness data
Figure 8-33: Vacuum bagging process

Figure 8-34: Socket in curing process
Figure 8-35: Crafted filament-wound prosthetic socket, carbon fiber and aramid
Figure 8-36: Crafted filament-wound prosthetic socket
Chapter 9

Evaluation

9.1 Variable Impedance Mid-sole Running Shoe

The evaluation method consisted of measuring impedance values across the surface of different mid-sole samples. The mass spring damper diagram represents the evaluation method that I implemented to test the variable stiffness of the multi-material mid-soles. The method that I used to calculate the material stiffness of the mid-sole was based on Figure 9-1 where \( m = Z \) the constant vertical travel distance of the drill press, \( k = \) the constant spring resistance measured by the Gates 7401-0076 and \( c \) represent the stiffness value in Newtons (normalized by the thickness of the mid-sole and the area of the tool-tip).

![Mass spring damper diagram](image.png)

Figure 9-1: Mass spring damper diagram

The methodology consisted of placing the mid-soles within mold B to level them on a flat surface, then measuring the stiffness of the material using a Gates 7401-0076
pencil type tension tester. The pencil type tension tester was fixed into a drill press and the z axis travel distance was mechanically limited to 1/2”. Using a physical CAD template I preformed 99 discrete measurements on the mid-soles that matched the foot plate sensor data collected by New Balance. The results showed a variable impedance across surface area. Figure 9-3

Figure 9-2: Variable Impedance Measurement using a Drill Press with a Gates 7401-0076 pencil type tester
In collaboration with New Balance we proceeded to assemble a wearable prototype using one of the mid-soles that I fabricated and the New Balance MR 1400 v2 upper. After succeeding in this test I wore the shoe and surprisingly it provided significant support yet was flexible to normal walking motion. Further mechanical and durability evaluation test should follow to evaluate the prototype.
Figure 9-5: Assembling process at New Balance Prototype Lab
Figure 9-6: Multi-material midsole, New Balance 1400 V2
9.2 Variable Impedance Prosthetic Socket

The fabrication results of the carbon fiber socket showed variable impedance but the rigidity of the prosthesis was less than expected. Nevertheless this fabrication technique allowed for the creation of a light-weight prosthesis, which was one of the initial goals.

![Figure 9-7: Crafted filament-wound prosthetic socket, carbon fiber](image)

The results of the carbon fiber and aramid did not show variable impedance but the rigidity of the socket improved from [Figure 9-6](image). However, further research and a more detailed design on the mandrel could considerably improve the mechanical properties of the socket.

One aspect to be improved in the fabrication process is the bottom part of the socket, which is required to be flat to interface with the metal fixture.
Figure 9-8: Crafted filament-wound prosthetic socket, carbon fiber and aramid
Figure 9-9: Crafted filament-wound prosthetic socket, carbon fiber and aramid, BiOM Ankle System
Figure 9-10: Crafted filament-wound prosthetic socket, carbon fiber and aramid, BiOM Ankle System
Chapter 10

Future Applications

The design process that I developed in this thesis can be applied to a wide range of future applications. My intentions were to prove that it was possible to tune material properties through data driven computational design and fabrication work-flows that exclude three-dimensional printing. This process opens the opportunity to envision future applications in different budgets, scales and design scenarios.

The future of this thesis is to incorporate a feedback loop where initial data informs the design, but the design then returns performance data to further inform the design process. Furthermore, the collected data could inform embedded quasi-active actuators to allow for local deformations in orthoses providing real-time performance adaptations for the user.

Figure 10-1: Future applications diagram
10.1 Multi-material Molding and Casting

The results showed in multi-material molding and casting are very exciting to envision different design applications. The fabrication workflow that I developed allows for scaling up and down the process in size, resolution and repetition. The advantages of this fabrication method when compared to 3D printing are numerous in terms of cost, speed and material flexibility.

Further design applications could include medical devices, prosthetics, automotive design, furniture design, architecture, electronics, etc. The process of multi-material molding and casting makes this research accessible to any FabLab around the world and to any design that requires tuning material properties to increase the performance.

10.2 Functionally Graded Filament-wound Carbon-Fiber

The results showed in CAM-crafted filament winding are very exciting to envision different design applications. The advantages of this fabrication method when compared with three-dimensional printing include material durability, performance, weight savings, wall thickness, cost and speed.

Further design opportunities include architecture, product design, automotive design, industrial design, medical devices and prosthetic devices. The process of utilizing computer-aided design to inform CAM-crafted filament-winding processes makes this research accessible to any FabLab around the world. I envision this technique being applied in the fabrication of customized prosthetic sockets in the future.
Chapter 11

Conclusions

This thesis includes a range of research inquiries for design applications incorporating sophisticated design methodologies and fabrication processes. The first design application was the creation of a multi-material mid-sole for a running shoe. My focus was to spatially vary mechanical properties of the mid-sole, and show how such technology could be applied to improve the performance of running shoes. The second design application was designing a variable impedance prosthesis for a trans-tibial amputee. I aimed to create a low-cost, lightweight customized socket driven by tissue stiffness data to create a more comfortable device. I can conclude that my contributions to both design scenarios include a novel multi-disciplinary design perspective that incorporated unusual methods of fabrication and computer design.

Below, I summarize the results and discuss limitations and failures of the design methodologies and fabrication processes.

11.1 Design Methodology

11.1.1 Multi-material CAD to CAM/craft distribution

In this work, I translated foot pressure data into customized designs through parametric environments. I found that parametric scripting and modeling techniques are useful tools to create dependencies between data and geometry. In this process I
succeeded in generating geometric gradients for varying material stiffness that could directly interface with the fabrication tools.

These techniques, however, are somewhat limited in the number of geometric entities that can be processed at one time. After creating more than a few thousand dependencies, GC slows down considerably and has effectively limited functionality.

Additionally, my own developing skills in performing multi-material finite element analysis (FEA) limited my ability to confirm the functional gradients of my designs.

11.1.2 Crafted Filament-winding CAD to CAM/craft distribution

In these experiments, I used parametric scripting and modeling techniques to translate MRI and ATS data into a gradient of fiber distribution within a GC design for customized prosthetic sockets. To do this, I represented the fiber abstractly as a continuous curve on the surface of the limb with greater repetition in areas with soft tissue (as specified by the ATS data). I used this representation to generate aids for the craft filament winding process.

As above, my designs likely could have been improved with greater skill in performing FEA to simulate mechanical performance of the composite prosthetic socket.

11.1.3 Novelty

I can conclude that the novel method in both of these areas was using GC as a software platform to translate relevant data into customized, functionally-graded orthoses.

11.2 Fabrication

11.2.1 Multi-material Molding and Casting

In this work, I developed new multi-material molding and casting workflows to create highly customized objects without the use of three-dimensional printing. Further-
more, the material properties of the fabricated objects showed variable impedance across their surface.

The limitations of this fabrication workflow come from the inherent difficulty in producing highly complex molds. Nevertheless, creativity and design effort could increase the complexity of the products fabricated using these techniques.

### 11.2.2 Crafted Filament-winding

In these experiments, I translated data-driven computer designs into instructions that could be performed as craft technique. In several tests, I showed that the orthoses produced in this way reproduced the spatially varying fiber density of the intended design. Further, this technique shows promise for producing low-cost, lightweight prostheses.

One limitation of this technique comes from preserving the positions of the fibers during the curing process. One solution is to add features to the mandrel, but this could interfere with the fiber compaction that is necessary for high-strength parts. Nonetheless, I am convinced that more sophisticated design of the mandrel could balance these competing concerns, to achieve more complex winding patterns and improve the comfort of prosthetic sockets.

### 11.2.3 Novelty

In digital fabrication, the main contributions of this thesis are two flexible workflows for producing low-cost, spatially graded products.
Bibliography


