Disruption in Digital Fabrication:
Exploring FDM 3D Printing and 3D CAD for a Wearable Apparel Product

by

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Abstract

Three-dimensional printing (3D printing) technology has been applied in several fields due to its advantages of customization, complex shape manipulation, and energy and material sustainability. Apparel designers and researchers are seeking ways to take advantages of 3D printing for wearable apparel product designs. However, there is limited previous systematic research focusing on this area. Existing 3D printed wearable apparel product designs provide limited information regarding detailed design processes and material properties, which makes it difficult for future designers and researchers to gain knowledge of and promote 3D printed wearable apparel products within their own designs.

This research aimed to provide more insights for the research gap by exploring the design process and user perceptions for a 3D printed wearable apparel product through two studies. Study 1 adopted a qualitative research through design (RTD) method to provide detailed 3D computer-aided-design (3D CAD) workflow and create different variations of 3D printed structures for property evaluations. During Study 1 (RTD), a 3D printed hooded sweatshirt was prototyped as the research outcome for evaluation. Study 2 employed quantitative research about design (RAD) method to examine users' perceptions of the 3D printed hooded sweatshirt.

Results from Study 1 confirmed the viability of employing the Rhino 3D CAD program and a FDM 3D printer to create five different variations of 3D printed structures. The five

variations of 3D printed structures provided different levels of properties in terms of softness, flexibility, cushioning, durability, etc. Four of the variations were sewn with traditional fabrics for property evaluations. Results also indicated that experience and knowledge gained from initial steps could optimize and enhance efficiency for subsequent design processes. The developed 3D printed structures provided several properties like stretchability, cushioning and durability, and could be sewed with traditional fabrics to form 3D printed wearable apparel products.

Results from Study 2 generally supported the idea that the Functional, Expressive and Aesthetic Consumer Needs Model (FEA model) could be applied to 3D printed wearable apparel products to predict users' satisfaction. Aesthetic perceptions played the most influential role in user satisfaction and purchase intentions, followed by the influence of expressive and functional perceptions. The results indicate the importance of aesthetic aspects of 3D printed wearable apparel products in users' adoption of these products. This research provides several theoretical and managerial implications for future explorations of 3D printed wearable apparel products.

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CHAPTER 1: INTRODUCTION

Background

Three-dimensional printing (3D printing) is a technology that fabricates objects "through the deposition of a material using a print head, nozzle, or another printer technology" (American Society for Testing and Materials, 2013, p. 1). This technology has drawn public attention in recent years, due to its advantages of customization, complex shape manipulation, energy and material sustainability, and so on (Lunsford, Grindle, Salatin, & Dicianno, 2016; MacDonald & Wicker, 2016). It has been applied in several fields, like industrial product manufacturing (MacDonald & Wicker, 2016), medical rehabilitation research (Dombroski, Balsdon, & Froats, 2014), and architecture construction (Kothman & Faber, 2016). 3D printing has great potential to disrupt traditional manufacturing by improving designs, reducing assembly workloads, and optimizing supply chain (MacDonald & Wicker, 2016).

Apparel researchers and designers are seeking ways to take advantages of 3D printing and apply it to wearable products, which means 3D printing also has great potential to disrupt traditional apparel industry. 3D printing may help customize fashion products, provide 3D printed structures with new functions and properties, simplify manufacturing process, and more. For example, the fashion trio threeASFOUR designed a collection of 3D printed apparel, and one of their dresses was composed with 3D printed white bubble shapes, making the model look as if

Figure 1. 3D printed white bubble shapes by the fashion trio threeASFOUR (Jacobson, 2017). Copyright 2017 by threeASFOUR.

she had just had a bath (Figure 1, Jacobson, 2017). Individual designer Danit Peleg used a small 3D printer to print wearable textures with geometric shapes but bouncy patterns for making 3D printed apparel collection (Figure 2, Marriott, 2015). This 3D printed wearable apparel product is becoming a new category of apparel, providing apparel designers with opportunities to innovate and enrich wearable apparel products. It has great potentials to disrupt the current apparel industry in several ways, including highly variable customization, complex shape manipulation, sustainability, as well as providing new flexible structures with different properties (e.g., customized 3D printed dress for burlesque dancer Dita Von Teese, Figure 3, Howarth, 2013; 3D printed shoe sole from Under Armour, 2017, Figure 4, Under Armour, 2017). It could be expected that in the near future, consumers could use a 3D printer to customize their own

Figure 2. Designer Danit Peleg's 3D printed apparel collection (Marriott, 2015). Copyright 2015 by Danit Peleg.

garments at home (Tarmy, 2016). With some key patents for 3D printing having expired (e.g., FDM and SLS), the price of 3D printing related equipment is dropping. For example, when FDM patent expired in 2009, the price of a FDM printer dropped from more than $10,000 to less than $1,000 (Schoffer, 2016). Further, the growing availability of various computer-aided design

(CAD) programs, 3D printed wearable apparel product has great potential to affect the traditional apparel industry (MacDonald, & Wicker, 2016; Mims, 2013; Smith & Burgess, 2001).

Figure 3. Customized 3D printed dress for burlesque dancer Dita Von Teese (Howarth, 2013). Copyright 2013 by Albert Sanchez.

Figure 4. The Under Armour ArchiTech Futurist (Under Armour, 2017). Copyright 2017 by Under Armour.

Problem Statement

The literature in the domain of 3D printed wearable apparel product design is in its nascent stages, with several research gaps and unsolved research problems. This study addresses three research problems that are critical to the advancement of the research in this space. First, there is limited example of detailed three-dimensional computer-aided design (3D CAD) workflow for 3D printed wearable apparel product design. 3D CAD design workflow is the core part of the 3D printed wearable apparel product design process. Compared to traditional apparel manufacturing, 3D printed wearable apparel products have various external and internal limitations. This study will focus on the internal limitations from the perspective of designers and researchers. The traditional apparel industry has relatively well-established knowledge, standards, design process, and mature manufacturing processes; designers can accomplish their design goals by following established design process and collaborating with manufacturers to create their final apparel products. However, the development of 3D printed wearable apparel products is still in the exploratory stages, thus, there is limited knowledge, or design process. Even though some designers have demonstrated their manufacturing process for 3D printed wearable apparel products, the details of their 3D CAD design workflow are unclear. Because there is limited 3D printed wearable apparel product design process to follow, designers have to explore 3D printed wearable apparel products individually from the beginning of the design process. Moreover, it is difficult for designers to gain knowledge, become inspired by another's 3D CAD design workflow, or share their 3D CAD design workflow with others.

Second, current 3D printed flexible structures are not as comfortable as traditional fabrics. They are relatively stiffer with limited functions. MacDonald (2016) argued that increased functionality is one potentially disruptive step in 3D printing evolution. In order to compete with the traditional apparel industry, 3D printed wearable apparel products should provide 3D printed structures with corresponding traditional fabric properties, and even new properties. Therefore, the ways in which 3D printed wearable apparel products demonstrate their advantages in textile properties and their great potential to disrupt the traditional apparel industry are crucial in this study.

Third, users' perceptions of 3D printed wearable apparel products are yet to be addressed in existing research and design of 3D printed wearable apparel products. In order to better evaluate 3D printed wearable apparel products and maintain trustworthiness of 3D printed wearable apparel product research, it is important to get evaluations and opinions from different perspectives, such as researchers, peers, and users (Gray & Malins, 2004). However, current 3D printed wearable apparel product designs and research are mainly evaluated from the designers and researchers' end. Few of them consider the needs and opinions from users' end. In addition, it is also necessary to evaluate 3D printed wearable apparel product in a more systematic way in terms of what specific users' perceptions of the 3D printed wearable apparel product would influence users' satisfaction.

Purpose of the Study

This study adopted the "Maker Movement" (Dougherty, 2012) as an overarching concept to provide theoretical supports. Further, in line with the three research problems, this study has three main objectives. First, this study provided two design phases to explore the role of the 3D CAD workflow in developing 3D printed wearable apparel products. Specifically, this study adopted a research through design (RTD) methodology (Jonas, 2007) and qualitative methods to explore Rhinoceros (a 3D CAD program) design workflow in developing 3D printed wearable prototypes. Second, this study aimed to integrate 3D printed flexible structures in a wearable apparel product to allow new properties and functions to emerge. Specifically, this study also adopted the RTD methodology (Jonas, 2007) and qualitative methods to explore the properties of 3D printed structures by manipulating the internal structure of thermoplastic polyurethane (TPU) materials using the Fused Deposition Modeling (FDM) method. Third, this study sought to evaluate users' perceptions of 3D printed wearable apparel products. Specifically, this study adopted a research about design (RAD) methodology (Jonas, 2007) and quantitative methods to examine whether users' perceptions of the 3D printed wearable apparel product influence users' satisfaction. Further, the Functional Expressive Aesthetic consumer needs model (FEA model; Lamb & Kallal, 1992) was adopted as a theoretical framework to investigate the user's functional, aesthetic and expressive perceptions in terms of a 3D printed wearable prototype.

Significance of the Study

First, this study provided two design phases to demonstrate design prototyping process and detailed 3D CAD design workflow for 3D printed wearable apparel products. These examples provided more insights for the research gap in that few 3D printed wearable apparel product designs provide a detailed 3D CAD design workflow. This study adopted RTD methodology and demonstrated a way to gain knowledge and optimize 3D CAD design workflow of 3D printed wearable apparel product during design practice. These examples of 3D CAD design workflow also calls on future designers to follow a similar path to record and reflect 3D printed wearable apparel product design process. It will allow 3D printing design knowledge to be communicated and shared, and 3D CAD design workflow to be improved in wearable apparel products. Specifically, under a similar design process, more design modules as well as open-sourced 3D printed flexible structures will be available to simplify and optimize the 3D CAD design workflow; design outcomes will become compatible and capable of being shared in order to inspire new ideas. Moreover, similar and simplified design process could bring 3D printed wearable apparel products to the general public.

Second, this study explored new functions and properties of 3D printed structures. It will enrich the 3D printed structure research by contributing to the exploration of new functions with new properties. Also, new functionality of 3D printed structure is one of the core reasons that 3D printed wearable apparel product may disrupt traditional fashion industry.

Third, this study evaluated the users' perceptions of a 3D printed wearable apparel product. According to Lamb and Kallal (1992), consumers' functional, expressive and aesthetic (FEA) perceptions of wearable apparel products positively influence their satisfaction. Thus, evaluating user's FEA perceptions of 3D printed wearable apparel products will help researchers better understand user's evaluations of 3D printed wearable apparel products, and further improve designs. Additionally, this study evaluated a 3D printed wearable prototype through several perspectives including the researcher, peers and users, in order to offer a more holistic and detailed understanding of the 3D printed wearable prototype. Evaluations from different perspectives help maintain trustworthiness of this study, and provided more insights for this research direction by providing detailed descriptions of the 3D printed wearable prototype from different perspectives.

Definition of Terms and Abbreviations

3D CAD modeling program: three-dimensional computer-aided design modeling program. A 3D CAD modeling program is usually a XYZ coordinate system based modeling program, which allows users to virtually model and visualize virtual product design prototypes using measurements in real world (Sun & Zhao, 2017) e.g., Rhinoceros and Fusion 360.

3D printed wearable apparel product: a product that is printed using a specially designed 3D printer employing a process that involves using different flexible materials, inks, or even fibers (Hayes & Venkatraman, 2015, p. 337).

3D printed structure: three-dimensional printed flexible and/or moveable structures printed with 3D printers. There are four common 3D printed structures: (1) flexible pattern pieces printed with soft materials (e.g., TPU or thin nylon; Figure 13, Armstrong, 2016a); (2) Chain mail or interlocking structure (e.g., Figure 6, Nervous System, 2014); (3) Lattice structure, 3D printing lattice has the functions of cushioning and stretchability (e.g., Figure 7; Kisliuk, 2014); (4) Mimicry of woven or/and knit fabrics, to share the knowledge and fabric properties from well-established traditional apparel manufacturing (e.g., Figure 8, Scott, 2016; Figure 10, Stephanie, 2016).

3D printed lattice: lattice structure that manipulates the internal structures with 3D CAD programs and is printed with a flexible material (e.g., TPU) using a 3D printer. It is used as a cushion and is also potentially used as stretchable or breathable materials for wearable apparel products (Kisliuk, 2014).

3D printing: the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology. (ASTM, 2013, p. 1).

ASTM: American Society for Testing and Materials. ASTM International is a globally recognized leader in the development and delivery of voluntary consensus standards. Its missions are to improve product quality, enhance health and safety, strengthen market access and trade, and build consumer confidence (ASTM, 2018).

Beauty: is defined as "a pleasurable subjective experience that is directed toward an object and not mediated by intervening reasoning." (Reber, Schwarz, & Winkielman, 2004).

CAD: computer-aided design, is defined as "the use of computer systems to assist in the creation, modification, analysis or optimization of a design" (Narayan, Rao, & Sarcar, 2008, p. 3)

Comfort: comfort is a neutral state that exists when an individual does not feel pain or discomfort when wearing a garment (Hatch, 1993).

Coolness: coolness is defined as a product to be "trendy, hip, appealing, fascinating and attractive," and people may "experience positive emotions ranging from pleasant surprise to excitement" when perceive a cool product (Im, Bhat, & Lee, 2015, p. 167).

Direct modeling: a 3D CAD method that allows designers to directly manipulate the geometry shapes of a 3D model in a 3D CAD program (Rudeck, 2013).

Disruptive technology: a technology that has the ability to substantially change markets, e.g., shorten lead time, improve manufacturing efficiency, simplify design or manufacturing process (Bower & Christensen, 1995).

Ease of donning/doffing: refers to the ease of putting on and taking off a garment. Ease of donning and doffing are less of a concern until users have trouble with these actions (Watkins, 1984).

FDM: Fused Deposition Modeling, the most commonly used and inexpensive 3D printing method. This 3D printing method heats thermoplastic filament (e.g., TPU, nylon) and extrudes it through a nozzle. The nozzle deposits thin layers of melted material in X and Y coordinates on a print bed. The print bed moves the deposited material in Z coordinates layer by layer to form the shape of the object (Locker, 2017)**.Fit**: garment fit refers to "a harmonious relationship of clothing to the human body" (Chen, LaBat, & Bye, 2010, p. 516).

Generative design: Generative design follow a similar way of nature evolution. It is an iterative design process that designers input design goals and parameters into a generative design program, then the program can quickly explore all the possible solutions. The tests of design iterations could provide feedback to improve final design solution (Swenson, 2016).

Injection molding: process of injecting melted material into molds and demolding into components (Lunsford et al., 2016).

ISO: International Organization for Standardization. ISO is an independent, non-governmental international organization. It brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges (ISO, 2018).

Knit fabrics: Knit fabrics are made by interlocking loops of yarns moving in one direction (Collier & Tortora, 2001; Textiles4u, 2018).

Lead time: manufacturing duration starting from the receipt of a consumer's orders to the final delivery of the products (Elsmar, 2013).

Machining: a subtractive manufacturing technique that using milling machines to carve solid blocks into desired shape (Lunsford et al., 2016).

Maker movement: a community of hobbyists, tinkerers, engineers, hackers, and artists who creatively design and build projects for both playful and useful ends (Martin, 2015).

Mobility: mobility in garment refers to garment fit during body movement; a functional garment design should meet specific mobility requirements for different tasks (Ashdown, 2011; Boorady, 2011; Huck, 1988).

Naturalistic inquiry: naturalistic inquiry is a qualitative approach that emphasizes the importance of "natural" settings, and the researcher is primarily the data generator through observing, describing and explaining the activities and experience of the targeted group of people (Lincoln & Guba, 1985).

Novelty: novelty from an aesthetic perspective refers to "the degree to which a product is seen as different from a prototypical object" (Noble & Kumar, 2010, p. 650). Novelty has a significant influence on users' visual perceptions and may further lead to positive aesthetic judgment and product satisfaction (Seifert & Chattaraman, 2017).

Nylon: a polyamide used for 3D printing. It is a strong, durable material, while flexible when thin (MatterHackers, 2018).

Parametric modeling: an algorithmic thinking process that enables design intent to define and clarify design response by changing the expressions of parameters and rules (Jabi, 2013).

PLA: polylactic acid, a biodegradable thermoplastic polyester derived from renewable resources (e.g., corn starch, tapioca roots, or sugarcane). It is one of the most eco-friendly material and one of the most common used 3D printing filament (MatterHackers, 2018).

Purchase intention: consumers' aim and willingness to purchase a product or service (Dodds, Monroe, & Grewal, 1991).

RAD: research about design, a research methodology in which designers play the role as observers to investigate the performance of the product without changing it (Jonas, 2007). Compared to RTD, in RAD, researchers do not involve in research and record their own data, but observe data from users' perspectives.

Reflection-in-action: data collection process during the design process. It is a process in which unusual situations happen, and designers should take actions that differ from those they have planned (Schön, 1983).

Reflection-on-action: data collection process right after the design process. It is a process of reflecting and analyzing the feelings, actions, and thinking of their design process (Schön, 1983).

Rhinoceros: XYZ-coordinate system–based 3D CAD modeling program that allows designers to use points and curves to form surfaces and solids without limits on complexity or size (Sun & Zhao, 2017; VisualARQ, 2017).

RTD: research through design, a research and design process intrinsic to design.

Research through design is a research approach that designers are involved in and study the design process, whereby the design process itself becomes a knowledge resource (Jonas, 2007). It is also used as a research methodology in this study. Compared to RAD, in RTD, researchers involve in research and record their own data, instead of obtaining data from users' perspectives.

Seamless garment: a kind of garment made of cloth that is fabricated into one piece without seams (Fashion2apparel, 2017).

SLS: Selective Laser Sintering, a 3D printing method that deposits powdered material and selectively sinters granules, layer by layer, to form an object (Locker, 2017).

TPU: thermoplastic polyurethane, a kind of flexible, abrasion-resistant plastic that could be used as a 3D printing material (MatterHackers, 2018).

Uniqueness: Uniqueness is defined as the degree to which users perceive a product is functional or aesthetic different from similar products (Sundar et al., 2014).

Woven fabrics: Woven fabrics are made by interlacing yarns (Collier & Tortora, 2001; Textiles4u, 2018). It is more flexible than other types of 3D printing materials for FDM.

CHAPTER 2: LITERATURE REVIEW

The literature review was organized within two sections. Section 1 introduced the Maker Movement, which provides overarching theoretical support for 3D printed wearable apparel product design. Section 1 also presented a background literature review concerning general 3D printing technology and its applications in wearable apparel products. Section 2 provided a more focused literature review concerning research questions and hypotheses development.

Background Literature Review

Maker Movement

The Maker Movement is a phenomenon that refers to "a community of hobbyists, tinkerers, engineers, hackers, and artists who creatively design and build projects for both playful and useful ends" (Martin, 2015, p. 30). Making is a kind of spiritual activity that benefits all makers (Hatch, 2014). The concept of the Maker Movement was initially adopted by a community of creative enthusiasts in order to practice their ideas. They could use free, open source maker technologies and inexpensive toolkits (e.g., user-friendly software, open source chipsets) to explore creative ideas by themselves (Patel, 2016). This concept was also applied to the field of education to provide guidance for students' self-learning and practice, as well as developing a making and innovation culture in education research (Dougherty, 2012; Martin, 2015; Mekolichick & Wirgau, 2017). Dougherty (2012) emphasized the virtues of *learning by doing* and further articulated that practice is an important part in the learning process.

In order to take advantage of the merits of the Maker Movement, fashion designers and researchers also formed an innovative ecosystem to inspire ideas and gain knowledge and skills through practice. For example, Levi's launched its Makers tag project to help fashion designers, like Alice Saunders create her Forestbound brand by using old, salvaged military fabrics (Voight, 2014). While the Maker Movement has its roots in different time periods, it needs support from contemporary technology and resources. Martin (2015) identified three elements of the Maker Movement related to contemporary needs of makers: (1) digital tools, which assist digital prototyping, (2) community infrastructure, which provides resources and spaces, and (3) the maker mindset, that is, designers' own values and beliefs.

In terms of its application to 3D printed wearable apparel product design, the Maker Movement guides 3D printed wearable apparel product design to form an ecosystem, which is supported by Martin's (2015) three elements, listed above. First, the maker mindset, in the context of 3D printed wearable apparel product design, refers to self-teaching and practice. Designers are willing to teach themselves and learn through practice, as well as generating ideas and knowledge for the development of 3D printed wearable apparel products (Dougherty, 2012; Martin, 2015). Second, community infrastructure, in the context of 3D printed wearable apparel product design, refers to forming a universal design process. A universal design process provides methods for communication, idea demonstration, and knowledge sharing. Designers could share 3D printed wearable apparel product design ideas with others and also be inspired by others' ideas (Dougherty, 2012; Viviano, 2017). Thus, forming a universal design process is crucial for designers to communicate and share idea, like using the same 3D CAD design programs, 3D printers with a universal design process, following a similar 3D CAD design workflow, and so on. Third, using digital tools, such as 3D CAD programs and 3D printer interfaces for 3D printed wearable apparel product design, is just like using a pen for writing a paper. Thus, the ease of use of a technology positively influences its acceptance (Davis, 1989). 3D CAD programs and 3D printers with a universal design process enable designers to communicate and help optimize and simplify these digital tools. In this circumstance, it helps bring 3D printing to the general users. Even people with only elementary knowledge of 3D printing could understand the design process and join in the ecosystem to share ideas and make contributions (Attaran, 2017).

The development of 3D printed wearable apparel products is still at early exploratory stage; therefore, the crucial questions are: how could apparel researchers and designers gain knowledge from 3D printed wearable apparel product explorations, and how could they contribute to enrich the field of 3D printed wearable apparel product design? The concept of the Maker Movement provides guidance for the initial exploration of 3D printed wearable apparel products and was thus employed as an overarching concept to guide this research.

The Maker Movement guided the 3D printed wearable apparel product design to form a virtuous circle ecosystem, in which (1) designers generate ideas and gain knowledge by self-teaching and learning through design practice; (2) ideas are communicated, and knowledge gained and shared through a universal design process and 3D CAD programs; (3) under the same universal design process, knowledge gained from design process helps optimize digital tools and

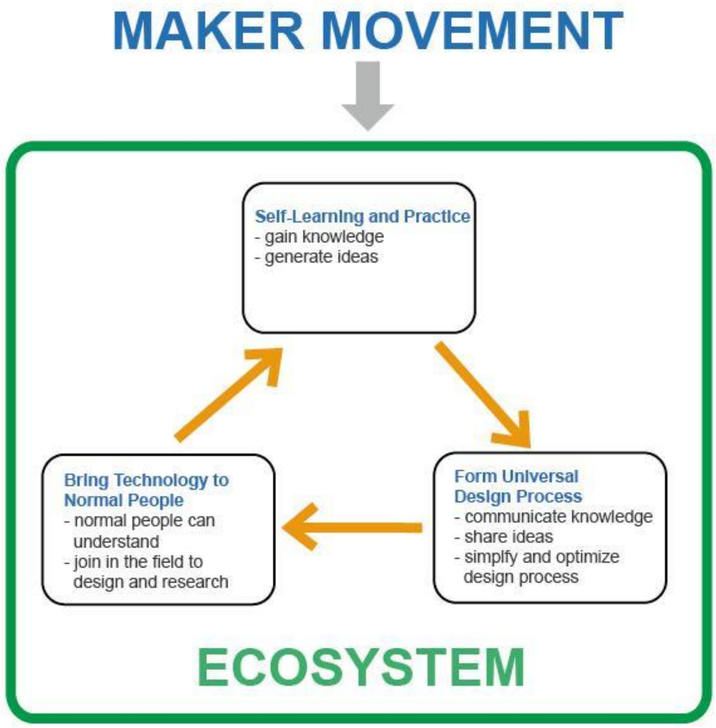


Figure 5. An ecosystem for the development of 3D printed wearable apparel product.

design process, so that general users could understand and join in design process, self-teaching, and design practice in order to share ideas. Such an ecosystem helps enrich the knowledge and improve the development of 3D printed wearable apparel product design. Based on the above discussion, this study proposed an ecosystem for the development of 3D printed wearable apparel product design (Figure 5).

3D printing Technology and its Disruption in Traditional Manufacturing

Three-dimensional printing (3D printing) is an additive manufacturing process, and defined as "the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology." (ASTM, 2013, p. 1). The working process of a 3D printer is similar to an inkjet printer; however, the difference is that a 3D printer prints a 3D object layer by layer with fusible materials instead of ink (Berman, 2012). According to America Makes (2014), 3D printing technology has several advantages: reduced lead time, potential for customization, fewer required parts, options for complex shape manipulations, and sustainability.

In order to thoroughly understand the advantages and benefits of 3D printing technology, it is essential to comprehend commonly used traditional industrial manufacturing methods. Traditional manufacturing methods mostly rely on subtractive manufacturing method. There are two types of commonly used industrial manufacturing methods: (1) injection molding, a process of injecting melted material into molds and demolding into components; and (2) machining, a subtractive manufacturing method that using milling machines to carve solid blocks into desired shapes (Lunsford et al., 2016). Injection molding allows the manufacture of a large number of products at a very low price per unit, but it is not likely to enable fast prototyping and customization due to the expense of new molds. Machining provides a certain level of customization, but the biggest disadvantage is the amount of wasted material it produces, because usually the carved parts are discarded (MacDonald & Wicker, 2016; Lunsford et al., 2016).

The comparisons with traditional industrial manufacturing reflect the advantages of 3D printing technology with respect to rapid prototyping (compared with injection molding) and avoidance of waste (compared with machining); and thereby its great potential to disrupt modern manufacturing. A disruptive technology refers to a technology that has the ability to change the way markets currently operate (Bower & Christensen, 1995). To be specific, a disruptive technology helps manufacturers gain advantages and be competitive in the markets; it also provides new ways to meet users' needs (Christensen, 1997). Five main advantages of this 3D printing technology are discussed next.

First, 3D printing enables rapid prototyping and manufacturing. In terms of rapid prototyping, 3D printing could save time by skipping the preparation of material, tools, and so on. Designers simply upload their digital design files to 3D printers, and prototypes could be accurately printed in a shorter duration (Attaran, 2017; King, 2012). For rapid manufacturing, 3D printing could reduce lead time and product components, accelerate the delivery of products to the customers (Attaran, 2017; Berman, 2012). Second, 3D printing enables low-cost, highly customized prototyping and manufacturing without molds (Berman, 2012), which meets the needs of users who require highly customized products that are difficult or expensive to obtain from traditional manufacturing, such as that which medical rehabilitation would typically use to customize foot orthoses (e.g., Dombroski, Balsdon, & Froats, 2014) and prostheses (e.g., Lunsford et al., 2016). Third, 3D printing has the capability to print several product components in assembled state within one printing job, while maintaining their functions. It reduces the number of product parts, simplifies or even eliminates assembling procedures, and saves time and labor costs (e.g., Krassenstein, 2015). Fourth, 3D printing allows efficient fabrication of complex shapes and structures in products that are traditionally expensive to produce in subtractive manufacturing processes. Complex shape manipulation helps reduce product components, simplify manufacturing procedure, and potentially introduce new properties and functions of the product parts (MacDonald & Wicker, 2016). Fifth, 3D printing enables material and energy sustainability. A 3D printer prints the products as they are virtually designed and only uses only material needed. Therefore, much less material is wasted in this process. Thus, 3D printing enables customized products at a much lower cost and reduces the material and energy budget for manufacturers (Attaran, 2017; Rifkin, 2012).

In summary, 3D printing potentially disrupts traditional manufacturing by making manufacturing process simpler, shortening supply chain, and improving industrial efficiency, such that common consumers could get access to 3D printing knowledge and 3D printing-related equipment (Attaran, 2017). Hence, one can claim that 3D printing is leading to a democratization and revolution of manufacturing. It will not be monopolized by industry, allowing consumers to become micro-manufacturers through self-learning and practice (Attaran, 2017; Gibson, Rosen, & Stucker, 2010).

3D printing Advantages and Applications in Wearable Apparel Products

Apparel researchers and fashion designers are exploring 3D printing, looking for new advantages for wearable apparel products (Hennessey, 2013). As “a process that involves using different flexible materials, inks or even fibers and then printing the product using a specially designed printer” (Hayes & Venkatraman, 2015, p. 337), 3D printing has already been applied to apparel design and wearable apparel products. Although its ability to disrupt the entire traditional apparel industry at this moment is debatable, it can definitely allow the fashion tapestry to evolve by integrating its advantages with traditional apparel (Sim, 2017). 3D printing may also potentially disrupt some sectors of the apparel industry, such as E-commerce retail (Peleg, 2017a) and brick-and-mortar retail (Williams, 2018). Its applications in wearable apparel product stem from core advantages of the technology discussed below.

First, 3D printing helps reduce lead time and simplify supply chain for wearable apparel products, make it convenient for users to design and prototype 3D printed wearable apparel products. In traditional manufacturing, lead time refers to a manufacturing duration starting from the receipts of a consumer's order to the final delivery of the products (Elsmar, 2013). The lead time for traditional apparel industry is usually several months. For example, the lead time for the Bangladesh garment industry includes fabric manufacturing, fabric inspection, garment manufacturing, final inspection, export for overseas shipping, and so on, requiring a total of 90 days (Asgari & Hoque, 2013). Shortening lead time has become an important strategy to be competitive in the apparel industry, especially in fast fashion markets, where consumers are more conscious of the latest trends (Christopher, 1998). 3D printing reduces lead time by connecting design directly to manufacturing, make it convenient for users to fabricate designs at home; designers simply upload their digital design files to the 3D printer, which will finish the production process in a shorter duration (Attaran, 2017; Berman, 2012). The close connection between design and manufacturing in the 3D printing manufacturing process enables small design studios and even individuals to do fast prototyping and produce a collection of 3D printed apparel in a short duration. For example, thanks to the convenience of the technology of 3D printing, designer Danit Peleg manufactured a full collection of apparel with 3D printed wearable textures using commercial 3D printers at home (Figure 2, Marriott, 2015).

Second, 3D printing enables highly customized fashion apparel with unique aesthetics and suitable body fit. For example, a highly customized 3D printed dress was designed for dancer, Dita Von Teese. The designers integrated fashion design with inspirations of architecture structure, customizing an articulated dress for her. The 3D printed dress was aesthetically appealing and exactly fitted her body size (Figure 3; Howarth, 2013). Dita Von Teese's 3D printed dress was an early exploration of 3D printed wearable apparel product, so the report did not show the customization process. While later 3D printed wearable apparel product designs provide more visual customizations, it is easy to get customized 3D printed wearable apparel products by only inputting consumers' personal body measurements. For example, design studio Nervous System (Figure 6-1, 6-2; Nervous System, 2014) developed an application called

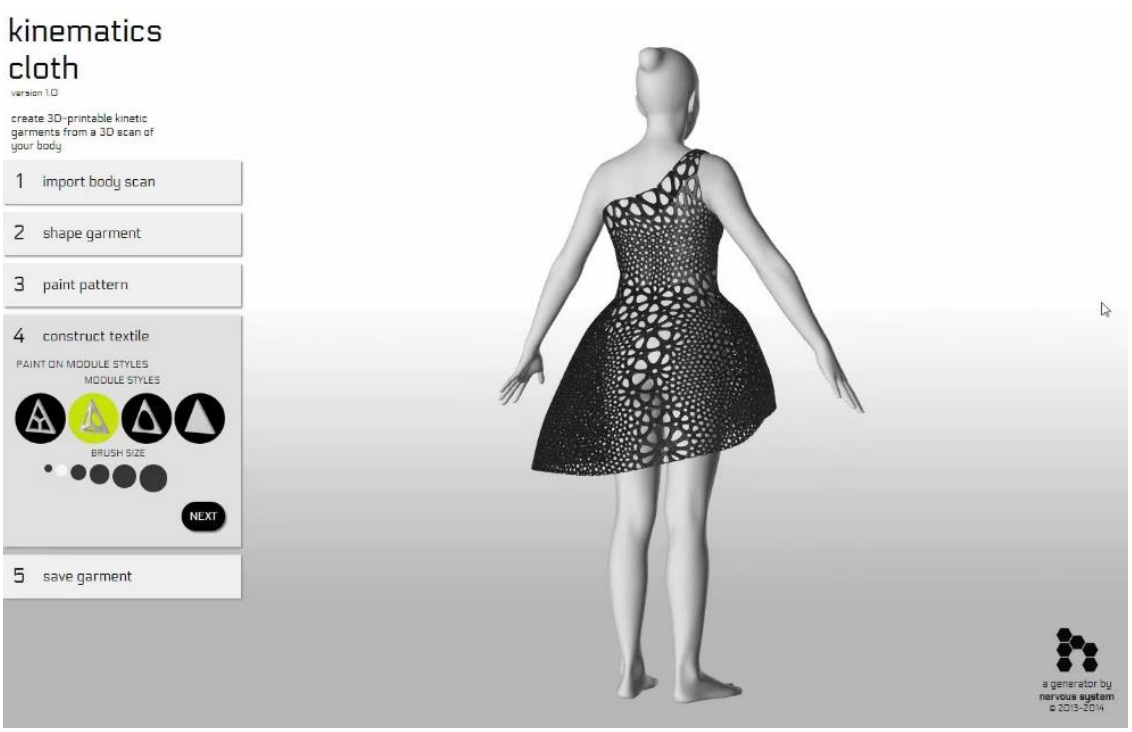


Figure 6-1. Kinematics dress from Nervous System (Nervous System, 2014). Copyright 2014 by Steve Marsel Studio.

Figure 6-2. Kinematics Cloth (Nervous System, 2014). Copyright 2014 by Nervous System, Inc.

Kinematics Cloth to customize 3D printed dresses. A user only needs to input her body scan measurements and customize her styles, patterns, and colors. The application could produce a 3D virtual dress to fit her body and preference, and it is ready to print. Just as designer Danit Peleg produced her 3D printing jacket, users could customize based on their preferences and view their customized jacket in a virtual fitting session. Once checked out, the customized 3D printing jacket will be 3D printed and shipped to the consumers (Figure 9; Peleg, 2017a). In the future, it could also be possible for customers to print a dress with their exact measurements at home (Marriott, 2015; Tarmy, 2016).

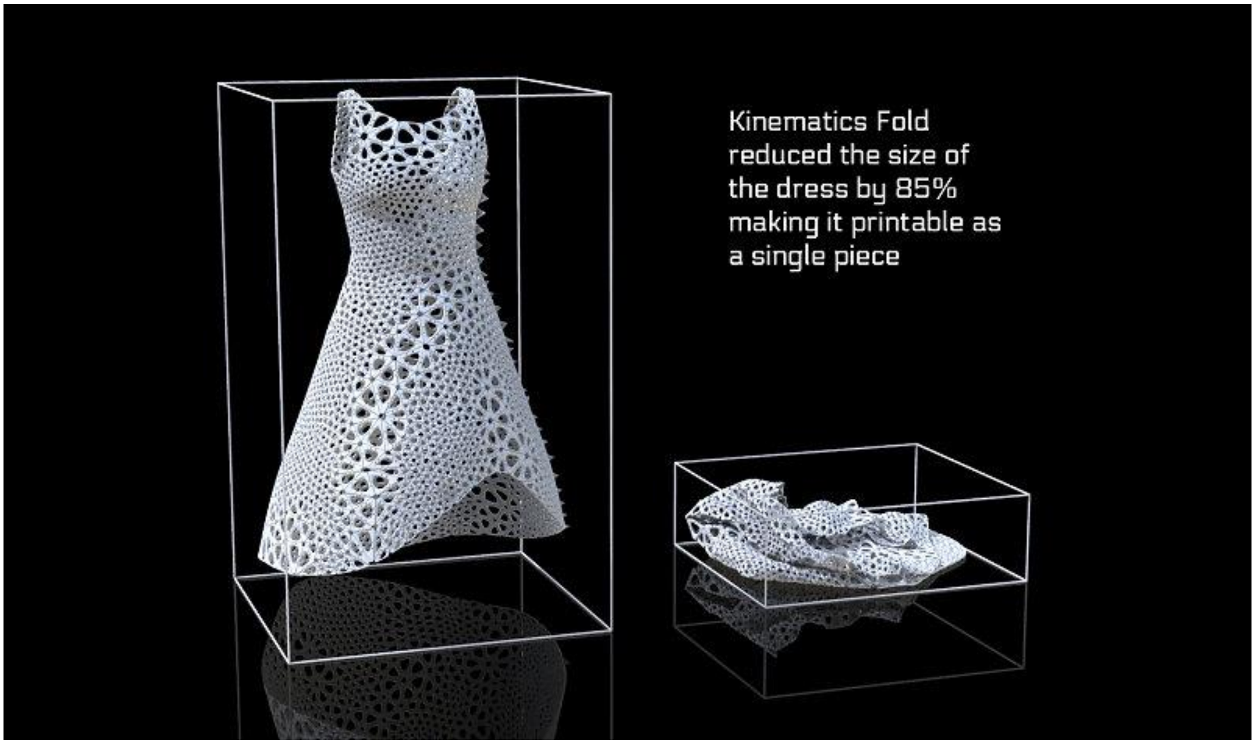


Figure 6-3. Kinematics Fold (Nervous System, 2014). Copyright 2014 by Nervous System, Inc.

Third, 3D printing could print moveable components in an already assembled condition in one printing job, so later sewing or assembly processes could be simplified or eliminated. For example, design studio Nervous System designed a kinematics dress, which is composed of many hinge parts. By using SLS printing method and an application called Kinematics Fold, the dress is printed as one single folded piece—no further sewing or assembly of 3D printed structures is needed (Figure 6-3; Nervous System, 2014). It not only simplifies the manufacturing process of wearable apparel products but also enables another important function—the creation of a seamless garment. A seamless garment is a kind of garment that is made of cloth fabricated into one piece without seams (Fashion2apparel, 2017). Seamless garments have the advantages of improved comfort, waste reduction, flexibility, and improved durability. However, the manufacturing of traditional seamless garments also has some disadvantages, like technical limitations to keeping equal tension in the fabric, costlier machines, and the possibility of knitting failure due to single mistake (Fashion2apparel, 2017; Jaggal, Garg, & Kumar, 2014). 3D printed wearable apparel products could still take advantage of the seamless garment option, but also overcome some of the disadvantages since the printing process is controlled by computers in order to limit failure.

Fourth, 3D printing could manipulate complex structures for wearable apparel products that enable certain functionality. For example, designers from Under Armour customized complex shoe sole structures for better cushioning and performance (Figure 4, Under Armour, 2017). They took the advantages of customization and complex shape manipulation from 3D printing and produced a 3D printing shoe sole with aesthetics and functions. It is more difficult to produce such an item using traditional shoe manufacturing methods (e.g., injection molding, machining).

Fifth, 3D printing improves the sustainability of materials, resources, and energy. 3D printing enables highly customized apparel at low cost, while doing so is difficult or costly using the manufacturing methods of the traditional apparel industry. The 3D printing technology prints the wearable apparel product exactly as it is designed, and it also allows seamless garments while controlling failure, thus, less material is wasted (Hardcastle, 2015). It could also manipulate complex inner shapes of fabrics and print them in one piece, which helps simplify assembly and fabrication process, save materials and energy (Gebler, Schoot Uiterkamp, & Visser, 2014).

Trends in 3D Printed Wearable Apparel Products

Given the advantages of 3D printed wearable apparel products, apparel designers and researchers are exploring how those advantages could be potentially integrated into 3D printed wearable apparel product, which would enable 3D printed wearable apparel products to be competitive with traditional apparel products, leading to a disruption in the traditional apparel industry. Three trends of 3D printing application in wearable apparel products could be concluded from existing 3D printed wearable apparel products.

First, the functions of 3D printed wearable apparel products have gradually received greater attention from designers. Early apparel designers and 3D printing adopters applied 3D printing in apparel and fashion design for aesthetic purposes (e.g., Figure 1, Jacobson, 2017; Figure 3, Howarth, 2013). More recently, functionality of 3D printed wearable apparel products has become more of a concern, initiating the trend of integrating function with fashion in the application of 3D printed wearable apparel products (e.g., Figure 2, Marriott, 2015; Figure 6-1, Nervous System, 2014). Even though the advantages of customization and complex shape manipulation enhance the aesthetic features of 3D printed wearable apparel products, this enhancement is in vain if the 3D printed wearable apparel product cannot compete with traditional apparel in terms of function. MacDonald and Wicker (2016) argued that increased functionality is one potentially disruptive step in 3D printing evolution. Thus, the trend 'beauty marries function' provides insight and conceptualization for this study (Lamb & Kallal, 1992; Quinn & Chase, 1990).

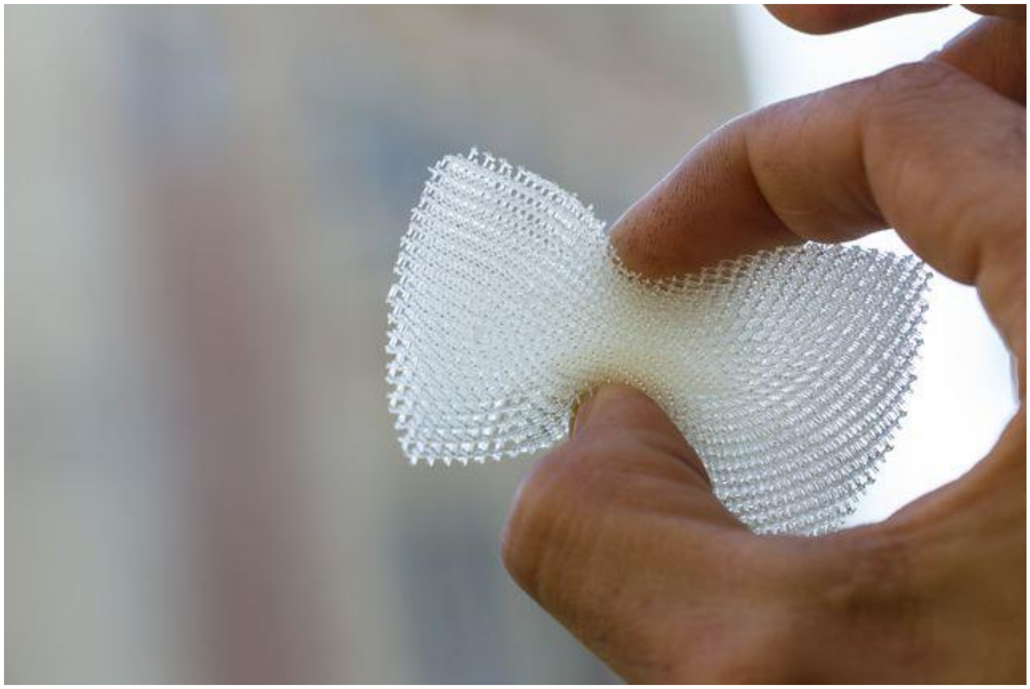


Figure 7. 3D printed lattice structure (Kisliuk, 2014). Copyright 2014 by Joanne Leung.

Second, in order to meet the functional needs, the properties of 3D printing structures should be explored. Previously, 3D printing usually produced solid parts for industrial products. While for wearable apparel products, softness and comfort are the big considerations. Designers are seeking ways to make 3D printed structures and patterns softer and more comfortable by testing different materials, manipulating different geometric shapes within the capability of current 3D printers, as well as integrating 3D printed structures with traditional fabrics (e.g., 3D printing lattice, Figure 7, Kisliuk, 2014; 3D printing soft textile by Electroloom, Figure 8; Scott, 2016). This trend indicates that the basic functional needs of garments, like fit and comfort, are essential and important for 3D printed wearable apparel products as well. Meeting basic functional needs are priorities for 3D printed wearable apparel products so they are able to compete with traditional fabrics. Currently, there are several explorations focused on making 3D

Figure 8. 3D printed soft fabric by Electroloom (Scott, 2016). Copyright 2016 by Electroloom.

printed structures softer and more comfortable that have demonstrated great potential of 3D printed structures to provide the same basic functional properties as traditional garment fabrics. This trend shows that more explorations are needed in the future to enrich the functional properties of 3D printed structures.

Third, as the key patents of 3D printing have expired (e.g., SLS), the cost of 3D printers and materials have dropped, providing more opportunities for individuals and small design studios (MacDonald & Wicker, 2016; Mims, 2013; Smith & Burgess, 2001). There is a growing trend that individuals and small design studios could impact the future market of 3D printed wearable apparel products, and the mode of homemade 3D printed wearable apparel products is likely to overwhelm the current apparel industry (Attaran, 2017; Tarmy, 2016). In the early stages of exploration of 3D printed wearable apparel products, only large companies and sponsored design studios were able to afford 3D printing machines and materials. As a result of the expiration of 3D printing key patents, decreasing the cost of 3D printing related equipment, as well as the availability of various 3D CAD programs, 3D printing is becoming more available to the general public (MacDonald & Wicker, 2016; Mims, 2013; Smith & Burgess, 2001). Applying 3D printing in wearable apparel product provides great potential for individual designers to realize their design ideas. Designer Danit Peleg pushed the exploration of 3D printed apparel even further by making her Bomber Jacket the first 3D printed apparel with FDM printing method that is available for sale (Goehrke, 2017). The webpage of Danit Peleg's 3D printed jacket is shown in Figure 9 (Peleg, 2017a). In the future, it could also be possible to print your customized garment at home (Marriott, 2015; Tarmy, 2016). This trend indicates that, within the era of information technology, 3D printing is becoming a more accessiable technology for the general public, and 3D printed wearable apparel products could evolve into a new mode

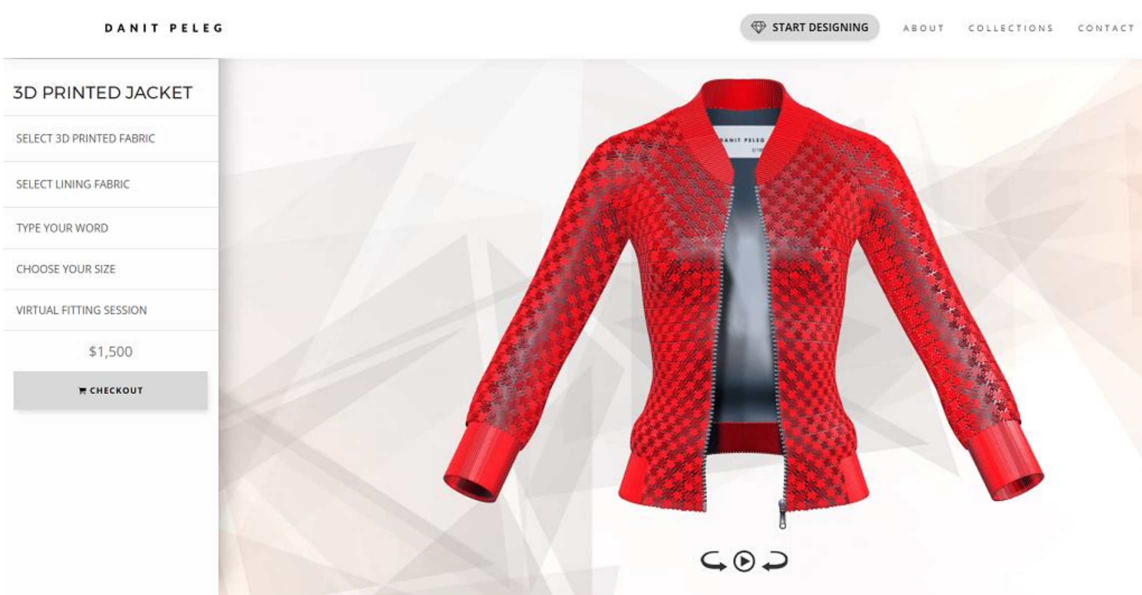


Figure 9. Danit Peleg's 3D printed bomber Jacket for sale (Peleg, 2017a). Copyright 2017 by Danit Peleg.

of design and manufacturing process. It also provides the insight that through available resources and self-exploration, individual customers could take part in the design and manufacturing process of 3D printed wearable apparel products, and may further become the major contributors of 3D printed wearable apparel products.

These trends demonstrate the current development trends of 3D printed wearable apparel products, but they also provide research ideas and directions for this study. These trends highlight the importance of designers' ability to explore 3D printed wearable apparel products, specifically, the functional properties required to provide correct body fit and comfort, which could ultimately contribute to the further development of 3D printed wearable apparel products.

Literature Review: Research Questions and Hypotheses Development

Design Process for 3D Printed Wearable Apparel Products

Within the maker community and the development of industry, 3D printing as an innovation has begun to see the rise of issues, the design and manufacturing standards being one of the most vital (Millsaps, 2016). In order to bring 3D printing to the general public in the future, both the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) International have proposed standards for 3D printing manufacturing, which help designers to interact in a meaningful way and improve the development of 3D printing (Armstrong, 2016b; Millsaps, 2016).

However, ISO and ASTM only focus on the standards of the 3D printing manufacturing process, not on the initial design process. The design process is one of the most important phases of 3D printing product (Paterson, Donnison, Bibb, & Ian Campbell, 2014). Thus, the standards of the design process cannot be neglected (Weiss, Tournavitis, Nan, Borysov, & Paul, 2017). In order to create standards for 3D printed wearable apparel product design, it is essential for initial practitioners to adopt a universal design process. Similar to 3D printing manufacturing standards, a universal design process could be formed by discussing and negotiating the 3D printed wearable apparel product designs that use a similar design process. Thus, at the initial exploratory stage, there would be examples of the design process of 3D printed wearable apparel products for designers to follow. Such examples could either be modified from traditional apparel design process, or be found in existing 3D printed wearable apparel product design, or both.

Traditional apparel design process. Traditional apparel design usually includes six processes: problem identification, preliminary ideas, design refinement, prototype development, evaluation, and implementation (Lamb & Kallal, 1992). Each activity could provide feedback on the previous activity and improve the design process (Min, DeLong, & LaBat, 2015). The traditional apparel design process includes a series of design decisions (e.g., specifications, materials), pattern and sample making, prototype testing and pattern revisions for manufacturing (Clothing Manufacturing Agent Bali, CMA, 2015). Pattern making is the first step as well as one of the most important steps in the traditional apparel design process. Patterns could be made through sketches or paper based outlines and used as templates; then fabrics could be traced and cut out based on patterns, and sewn into a sample for size and fit checks (Apparel Pattern Making LLC, 2018; CMA, 2015). Patterns would be adjusted based on size and fit checks of several samples before final manufacturing. (Apparel Pattern Making LLC, 2018; CMA, 2015). With the development of the apparel industry, CAD was gradually engaged in traditional apparel design process. CAD systems are important visual tools to facilitate apparel design process (Guo et al., 2011). The commercially available apparel CAD systems offer user-friendly design platforms, provide general apparel design modules that meet the manufacturing standards, as well as improving productivity and quality (Guo et al., 2011).

3D CAD modeling for 3D printed wearable apparel products. In order to understand the design process of 3D printed wearable apparel products, it is essential to focus on 3D CAD design workflow, as it is the key part of design process (Lunsford et al., 2016). Currently, 3D CAD programs for 3D printing require a high level of expertise to convert design ideas, 2D sketches, and renderings into 3D CAD modeling, thus, learning and exploring these programs are necessary (Lunsford et al., 2016). There are several 3D CAD programs available for 3D printing, and Rhinoceros is one of the most commonly used 3D CAD direct modeling programs. Rhinoceros is an XYZ-coordinate system–based 3D modeling software. It allows designers to use points and curves to form surfaces and solids without limits on complexity or size (Sun & Zhao, 2017; VisualARQ, 2017). The basic modeling logic for Rhinoceros is to use points to create curves, and use curves to create faces, and then use faces to form objects. The process usually starts from the bottom and moves to the top (Cheng, 2014). Rhinoceros is widely used in product design and architecture design to provide not only visual demonstrations, but also compatibility with product manufacturing (VisualARQ, 2017).

Direct modeling vs. parametric modeling. Direct modeling is a 3D CAD method that allows designers to directly manipulate the geometry shapes of a 3D model in a 3D CAD program (Rudeck, 2013). Direct modeling has several advantages: (1) freedom and flexible to change design shapes, (2) quick prototyping, (3) visual modeling, (4) manipulation of complex and aesthetic shapes, and (5) meet specific design goals (Alba, 2018; Rudeck, 2013). Rhinoceros is one of the common used direct modeling programs that enables fast 3D modeling for design ideas (Alba, 2018).

Besides direct modeling, there is another common used 3D modeling method called parametric modeling. According to Jabi (2013), parametric modeling is an algorithmic thinking process that enables design intent to define and clarify design response by changing the expressions of parameters and rules. In other words, instead of directly change geometry shapes of a 3D model, parametric modeling changes the parameters of a 3D model to instantly generate different variations of the model. Parametric modeling has been adopted by several 3D CAD programs (e.g., Grasshopper for Rhinoceros, Dynamo for Autodesk Fusion 360) to help product design and manufacturing (Gaget, 2018). Compared to direct modeling, parametric modeling has its advantages: once the algorithmic relationship between parameters and 3D model is established, it is easy and time-saving to adjust certain parameters to automatically update final 3D model (Alba, 2018). It is easy to capture design intent and define the changes of the 3D model (Brunelli, 2018). It is also an efficient modeling method to get several variations of the original 3D model, and it has been applied in industry manufacturing process to design a family of products (Brunelli, 2018).

While within parametric modeling, there is an innovative 3D modeling method called generative design. Generative design follow a similar way of nature evolution. It is an iterative design process that designers input design goals and parameters into a generative design program, then the program can quickly explore all the possible solutions. The tests of design iterations could provide feedback to improve final design solution (Swenson, 2016). Generative design (e.g., Autodesk Generative Design) has been applied to some field of manufacturing, such as art, architecture, product design (Keane, 2018). The generative design method evolves with the rapid development of modern IT technology. It takes the advantages of artificial intelligence algorithms and unlimited cloud-computing power, to provide large numbers of design options (Keane, 2018; Swenson, 2016). This 3D design method is suitable especially for industry to test and optimize final designs for manufacturing (Keane, 2018; Swenson, 2016).

This study focused on direct modeling, and the reasons are listed below.

Despite several advantages from parametric modeling, it has several drawbacks. Parametric modeling may take time and effort at early exploratory stage of design concepts, and it is not an efficient modeling method for a single designer to explore many different concepts in limited research timeframe. While direct modeling method enables designer's ideas to be presented quickly and easily, design complex and aesthetic shapes, and change any shape flexibly. In addition, considering limited research timeframe, workload, limited resources and knowledge of parametric modeling, direct modeling is a more suitable modeling method in this study. Nevertheless, parametric modeling is still worth of exploring in future 3D modeling research.

Examples of design process of 3D printed wearable apparel products. Regarding 3D printed wearable apparel product design, as it is still in the early stages of exploration, there is no established and widely accepted design techniques and workflows for 3D printed wearable apparel products. It could generally adopt traditional apparel design process, differing in some design phases based on specific conditions. Different from physical pattern making and sample testing in traditional apparel design process, the design process of 3D printed wearable apparel products relies on virtual 3D CAD modeling. 3D printed structures and patterns are virtually designed in 3D CAD programs and printed with 3D printers. 3D printed wearable apparel products could be printed directly into shapes that fit the body sizes.

There are several design examples of 3D printed wearable apparel product available. Three examples were introduced here.

Example 1, Danit Peleg's 3D printed fashion collection. Designer Danit Peleg (2017b) designed a 3D printed fashion collection of five pieces using 3D desk printers at home. Her personal website introduced the process that showed how the 3D printed fashion collection was printed at home:

(1) Problem identification: she started working on her graduate collection and wanted to check whether she could create a fashion collection with 3D printing, which is available to anyone;

(2) Preliminary ideas: for her first red dress design, her initial idea came from the famous painting, *Liberty Leading the People*, which inspired her with its triangular compositions and which she then used as basic shape for her 3D printed patterns;

(3) Design refinement, she used a 3D CAD direct modeling software called Blender to create the 3D jacket model with the triangular elements. She also sourced an existing zigzag structures online and modified it for her design;

(4) Prototype development: she did research on materials and printers while seeking to collaborate with professionals for technical support, ultimately deciding to use a strong but flexible filament called FilaFlex;

(5) Evaluation: she printed and tested small pieces with the filament and found it suitable for her red dress design;

(6) Implementation: she figured out how to use printers and the right material, and started to print the full fashion collection. The collection took more than 2,000 hours to print with several desk FDM 3D printers at home (Figure 2, Peleg's 3D printing fashion collection). Peleg

(2017b) demonstrated how the design process of a 3D printed fashion collection could follow a traditional garment design process, and still achieved her final goals of 3D printed fashion collection. She also proved that it is possible for an individual to design a full fashion collection with available 3D printing technology and open resources at home. Thus, an individual could contribute to the exploration of 3D printed wearable apparel products.

Example 2, Nervous System's kinematics dress. Design studio Nervous System created a kinematics dress, which is composed of many 3D printed hinge components (Figure 6-1; Nervous System, 2014). According to the website introduction and video demonstration, it appears that they used a design process similar to traditional apparel design:

(1) Problem identification: they wanted to design a 3D printed dress by taking advantage of 3D printing capabilities to customize the size of the dress and link 3D printed structures to form the dress;

(2) Preliminary idea: their initial ideas came from interlocking structure and a brace lace design;

(3) Design refinement: they explored interlocking structure and the brace lace design, and tried to apply it to a dress design, using hinge structure to connect brace lace patterns into a moveable dress;

(4) Prototype development: they had developed several textile prototypes for tests and evaluations;

(5) Evaluation: they used a 3D CAD application called kinematics cloth to simulate the dress in an avatar;

(6) Implementation: they used a CAD program called Kinematics Fold to fold the dress into a smaller space, so that it could be printed in the limited space of the a Selective Laser Sintering (SLS) printer for final manufacturing. Nervous System (2014) provided excellent visual demonstrations of how the kinematics dress was 3D printed and how flexible it was on a human body. However, they used the 3D CAD application, which may not be familiar to other designers. In addition, there was no detailed descriptions of the 3D printed structures. The most significant limitations were that they did not provide 3D CAD design workflow, demonstrate how the hinge structure was built in 3D CAD, explain what problems they encountered during 3D CAD design workflow, or how they solved them.

Example 3, Masaharu Ono's 3D printed knitted vest. Japanese designer Masaharu Ono designed a 3D printed knitted vest called Amimono (means knit fabric in Japanese), which used

Figure 10. Amimono, Japanese designer Masaharu's 3D printed knitted vest (Stephanie, 2016). Copyright 2016 by FREE-D.

3D printing to mimic the structure of traditional knit fabrics. His vest is a good example of how 3D printed wearable apparel product could integrate both aesthetics and functionality (Figure 10; Stephanie, 2016). Based on the introduction and video demonstration, the designer provided a little bit more about the 3D CAD design workflow than the previous example. He used a direct modeling 3D CAD program called Rhinoceros and a parametric design based plugin program called Grasshopper for the design (Figure 11; Stephanie, 2016). Rhinoceros is a commonly used, XYZ-coordinate system–based, 3D CAD direct modeling software; and Grasshopper is a parametric modeling plugin application for Rhinoceros, which is good at manipulating duplicated patterns (Sun & Zhao, 2017; VisualARQ, 2017). Both direct modeling and parametric modeling were used in this case. Rhinoceros was used to design the basic unit of the knitted structure, while Grasshopper was used to manipulate the knitted unit into repeated patterns and

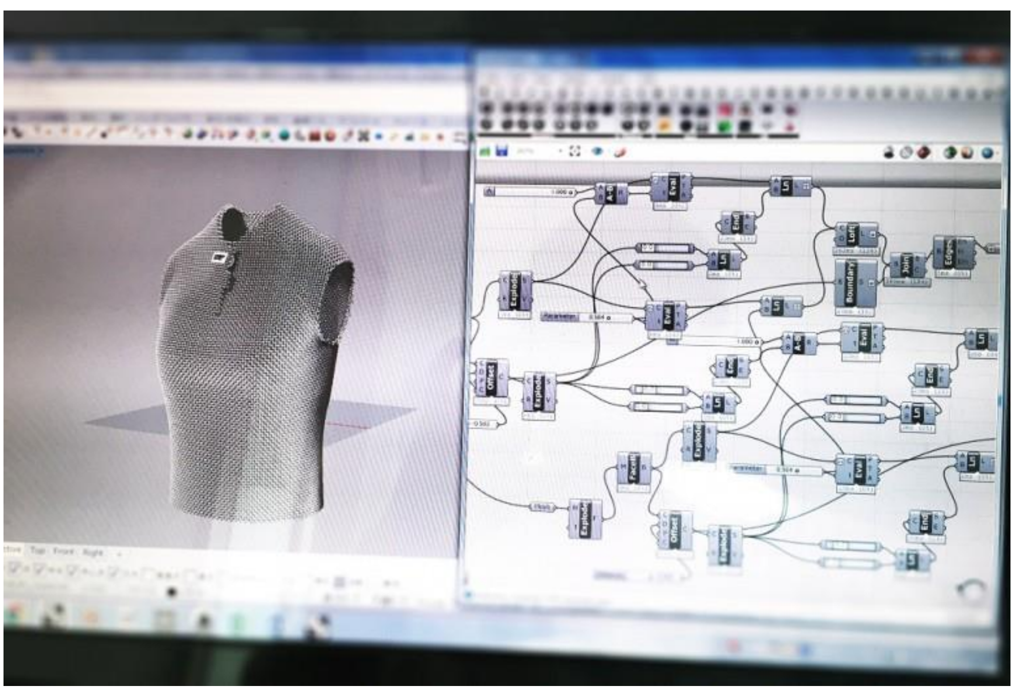


Figure 11. 3D CAD programs Rhinoceros and plug-in Grasshopper (Stephanie, 2016). Copyright 2016 by FREE-D.

change parameters, like radius of the knitted thread. Even though the designer provided excellent demonstrations of the performance of the 3D printed knitted vest, the snapshot of the design interface is vague, and it is difficult to tell the details of his 3D CAD design workflow and logic.

Despite the 3D printed wearable design product examples, which did not provide details of 3D CAD design workflow, there were some studies that highlighted the importance of 3D CAD design workflow in developing 3D printed wearable apparel products and provided comments and feedback. For example, a study from Sun and Parsons (2016) explored the effectiveness of 3D CAD–Rhinoceros for 3D printed wearable apparel product. They used a naturalistic inquiry approach and RTD methodology for their research. Their finding concerning 3D CAD design workflow for modeling wearable apparel product indicated that Rhinoceros is overall a user-friendly CAD tool for the traditionally trained apparel designer. It provides very useful tools, like the gumball tool and the lock/unlock tools. Further, the active use of object duplication and saving the basic format as a pattern motif may improve design efficiency.

In conclusion, the design process of 3D printed wearable apparel product could adopt a general design process from traditional apparel design. However, currently there is no examples and tutorials of 3D printed wearable apparel product design that provide details of the 3D CAD design workflows, maybe because the 3D CAD design workflows are part of the designers' intellectual property. In the future, the development of 3D printed wearable apparel product requires more details, feedback, and comments from 3D printed wearable apparel product designs to gain knowledge and form a universal design process.

3D printing. Given the important role of 3D CAD workflow in the 3D printed wearable apparel product manufacturing, as well as the lack of examples of 3D CAD workflow for wearable apparel products, the first research question, specifically applying RTD methodology, was proposed as:

RQ1: How the 3D CAD program can be utilized to develop flexible structures for 3D printed wearable apparel products by mimicking the structures of traditional woven/knit fabrics, using direct modeling method in Rhinoceros and TPU filament? How knowledge can be applied in this design process?

3D Printed Structures and Traditional Fabrics

What is the goal of 3D printed wearable apparel products? Initially, 3D printing was applied in fashion design for aesthetic purposes (e.g., Figure 1, Jacobson, 2017; Figure 3, Howarth, 2013). However, there is a trend that focuses more on softness and various functions, demonstrated in MacDonald's (2016) argument that increased functionality is one potentially disruptive step for 3D printing to compete with traditional fabrics. If, in terms of wearable apparel products, 3D printing cannot provide fabrics with corresponding or better performance than traditional fabrics, it cannot disrupt the traditional apparel industry, even with its several other advantages. Therefore, the future goal of 3D printed wearable apparel products is to be made from structures with properties that provide softness and comfort, and have better performance than traditional fabrics.

Traditional fabric types and properties. Traditional fashion and apparel in the United States has formed a relatively mature industry in design styles, manufacturing process, fabric research, and quality inspections (Collier & Tortora, 2001; Guo et al., 2011; U.S. Congress,

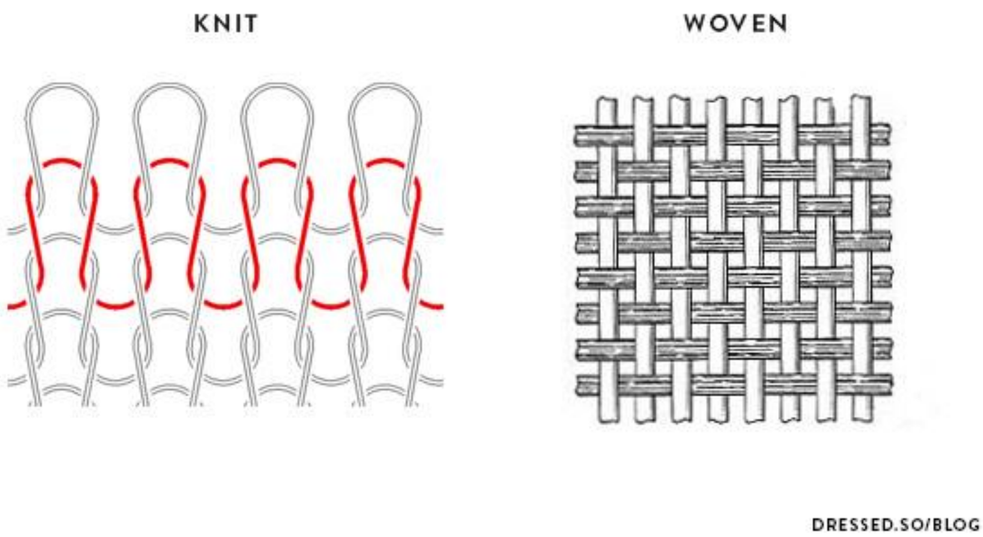


Figure 12. Woven fabric and knit fabric (Textiles4u, 2018). Copyright 2014 by dressed.so

Office of Technology Assessment, 1987). A textile fabric is the base that is used to manufacture a garment (Collier & Tortora, 2001). Many kinds of fabrics are available with properties that could provide different utilities, like strength, elongation, resiliency, flexibility, air permeability, heat transmission, absorbency, durability, and so on, to provide comfort in different situations (Collier & Tortora, 2001; Textile School, 2013). There are two main fabric construction methods, weaving and knitting. Woven fabrics are made by interlacing yarns, while knit fabrics are made by interlocking loops of yarns moving in one direction (Collier & Tortora, 2001; Textiles4u, 2018). The difference is shown in Figure 12. Both woven and knit fabrics provide different properties that meet different conditions. In general, woven fabrics are strong fabrics, not stretchy, easy to cut, and cool in temperature, while knit fabrics are stretchy and retain warmth (Textiles4u, 2018).

3D printed structures development and types. Compared to traditional fabrics, current

3D printed structures have several limitations. One of the important limitations is that 3D printed structures and patterns are stiffer than traditional fabrics, thus, they are not as comfortable as traditional ones (Jacobson, 2017; Tarmy, 2016). 3D printing filament commonly used for 3D printed wearable apparel products are polylactic acid (PLA), nylon, and thermoplastic polyurethane (TPU) (MatterHackers, 2018). PLA is a kind of solid plastic, and even though thin nylon and TPU are flexible, they are still not comfortable enough to be used in current 3D printed wearable apparel products (MatterHackers, 2018).

In addition, there are nine basic types of 3D printers, and two types are commonly used in printing 3D printed wearable apparel products (Locker, 2017). The first one is a Fused Deposition Modeling (FDM) printer, which is the most commonly used and inexpensive 3D printing method. This type of 3D printer heats thermoplastic filament (e.g., TPU, nylon) and extrudes it through a nozzle. The nozzle deposits a thin layer of melted material in X and Y coordinates on a print bed; meanwhile, the print bed moves the deposited material in Z coordinate, layer by layer, to form the shape of the object (Locker, 2017). Examples of 3D printed wearable apparel products using FDM method are Danit Peleg’s 3D printed apparel collections (Figure 2, Marriott, 2015). The second commonly used printer is Selective Laser Sintering (SLS) printer, which also prints objects, layer by layer. While different from FDM, SLS deposits powdered material and selectively sinters granules, layer by layer, to form an object (Locker, 2017). One of the important advantages of SLS is that the powder material could also be used as support material and is easy to clean. Thus, SLS is often used to manipulate the complex inner structure of 3D printed structures. Examples of 3D printed wearable apparel products using the SLS method are the shoe sole design from Under Armour (Figure 4; Under Armour, 2017), the kinematics dress from Nervous System (Figure 6-1; Nervous System, 2014), and Masaharu's 3D printing knitted vest (Figure 10, Stephanie, 2016).

In order to make 3D printed structures more flexible and resilient, as well as creating new properties (e.g., stretchability, venting, cushioning), researchers have tested different materials and manipulated the internal structures of them. For example, a University of California, Los Angeles (UCLA) led research team designed a 3D printed lattice by manipulating the internal structure of the material using the SLS method. The new material was soft and porous; it is designed to replace the foam inside football helmets (Figure 7, Kisliuk, 2014). Researchers even pushed their exploration of SLS into a new frontier: Electroloom, a 3D printing technology company, created a 3D printed piece that is soft and feels like a form of suede (Figure 8, Scott, 2016). The 3D printed piece looks like traditional fabrics, and the biggest advantage of 3D printing was that it created clothing without seams (Russell, 2015).

There are mainly four types of 3D printed structures/patterns that are currently being used to form 3D printed wearable apparel products:

(1) flexible pattern pieces printed with soft filament (e.g., TPU or thin nylon), the flexible patterns pieces could be connected to form a wearable apparel product (e.g., Figure 13, Armstrong, 2016a);

Figure 13. A 3D printed dress at New York fashion week 2016, created by ThreeAsFour (Armstrong, 2016a). Copyright 2016 by BusinessWire.

(2) Interlocking structure, the small 3D printed pieces have connection structures (e.g., chain mail, hooks, hinges), so that they could be linked to form flexible pieces (e.g., Kinematics Dress used hinges, Figure 6-1, Nervous System, 2014);

(3) Lattice structure, 3D printing has the unique capability to manipulate elaborate lattice structures, and the 3D printed lattice has the functions of cushioning and stretchability (e.g., Figure 7; Kisliuk, 2014);

(4) Mimicry of woven and knit fabrics, to share the knowledge and fabric properties from well-established traditional apparel manufacturing (e.g., Figure 8, Scott, 2016; Figure 10,

Stephanie, 2016). Current 3D printed wearable apparel products use one or a combination of these materials for different purposes.

Thus, considering the current development of 3D printed structures and the aim to compete with traditional fabrics in terms of properties and functionality, the second research question was proposed as:

RQ2: How the properties and functions of the 3D printed structures can be modified and evaluated in using a FDM 3D printer with TPU filament? How the 3D printed structures can be constructed with traditional fabrics and evaluated for final wearable apparel product prototyping?

3D Printed Wearable Apparel Products and Consumer Perceptions

Existing 3D printed wearable apparel products have demonstrated improvements in both aesthetics and functionality. Designers have provided demonstrations to indicate how their 3D printed wearable apparel products meet users' needs, in terms of aesthetics, flexibility of their design, comfort, and customization (e.g., Figure 6-1, Nervous System, 2014; Figure 10, Stephanie, 2016). However, the evaluations of the 3D printed wearable apparel products were mainly from the perspective of designers and news reporters, with a few of them reporting on users' evaluations on how the designs meet users' needs. In addition, it is also necessary to evaluate 3D printed wearable apparel products in a more systematic way with respect to specific user needs that may need to be met. This study will adopt the Functional Expressive Aesthetic consumer needs model (FEA model; Lamb & Kallal, 1992) to examine whether users' perceptions of 3D printed wearable apparel products influence users' satisfaction. Thus, the third research question was proposed as:

RQ3: What are the users' functional, expressive and aesthetic (FEA) perceptions of the 3D printed wearable apparel product?

FEA consumer needs model. The FEA consumer needs model (hereafter referred to as the FEA model) was proposed by Lamb and Kallal (1992) to evaluate functional, expressive, and aesthetic considerations to identify the needs consumers have from apparel design (Figure 14). In the FEA model, the target consumer or user is in the center of the model. As a user-centered model, it considers the clothing needs from the user's end (Lamb & Kallal, 1992; Stokes & Black, 2012). Consumers are surrounded by culture, which indicates that culture plays the role of mediator between the user and the needs they have from wearable apparel products (Lamb & Kallal, 1992). A successful wearable apparel product should be in consistent with a user's culture

Figure 14. FEA consumer needs model (Lamb & Kallal, 1992, p. 42). Copyright 1992 by Jane M. Lamb and M. Jo Kallal.

in order to provide corresponding designs (Stokes & Black, 2012). Further, three categories of needs are identified to influence users' perceptions of wearable apparel products; they are functional needs, expressive needs, and aesthetic needs. Functional needs consider utility, i.e., how the wearable apparel product meets the needs of the user to perform specific tasks (Lamb & Kallal, 1992; Stokes & Black, 2012). Expressive needs concern communicative and symbolic aspects of wearable apparel products, in other words, the wearable apparel product should match users' status and self-image (Lamb & Kallal, 1992; Stokes & Black, 2012). Aesthetic needs relate to the design and beauty of the wearable apparel products (Lamb & Kallal, 1992; Stokes & Black, 2012).

Aesthetic perceptions of the 3D printed wearable prototype. By applying Lamb and Kallal's (1992) FEA model, in this study, aesthetic needs depend on user's perceived aesthetics of the 3D printed wearable apparel product. The current study evaluates the aesthetic perceptions for a 3D printed wearable prototype based on perceived novelty and beauty of the 3D printed wearable prototype.

Novelty. Novelty refers to "the degree to which a product is seen as different from a prototypical object" (Noble & Kumar, 2010, p. 650). Novelty has a significant influence on users' visual perceptions and may further lead to positive aesthetic judgment and product satisfaction (Seifert & Chattaraman, 2017). Novelty in the beauty of 3D printed wearable apparel products provides new aesthetic format of textile patterns, which is unusual in traditional fabrics. For example, Nervous System's (2014) kinematics dress is composed of thousands of pieces of 3D printed triangular panels; it was innovative as no traditional garment was.

Most current 3D printed wearable apparel products are not as comfortable as traditional ones, however, novelty in new forms of 3D printed structures/patterns may lead to a greater visual impact, and compensate for the weakness in functions. Thus, novelty may enable users to allow future functional improvements, and still positively influence users' satisfaction. For example, in Shapeways's (2014) YouTube video of the kinematics dress, there were some comments like, "OMG, this is a dream come true," "Time to give something like this a try". Those comments implied that the design was innovative, they were very interested in an novel 3D printed wearable apparel product to be available in the near future. Even though the kinematics dress cannot meet the full functionality of a dress in terms of comfort, the novelty of the new aesthetic forms of garments may still lead to high levels of user satisfaction with 3D printed wearable apparel product. Novelty in 3D printed wearable apparel product increases future expectations of 3D printed wearable apparel products among users and leads to users feeling more satisfied with 3D printed wearable apparel products. Based on the above literature and anecdotal evidences, the current study hypothesized that:

H1a: Users' perceived novelty of the 3D printed wearable prototype will positively influence users' satisfaction with it.

Beauty. According to Reber, et al. (2004), beauty is defined as "a pleasurable subjective experience that is directed toward an object and not mediated by intervening reasoning. Humans have the desire for beauty, thus, beauty is one of the most important aesthetic considerations in designing functional garments (Lamb & Kallal, 1992). Existing studies of functional garments supported users' needs for beauty in functional garments. For example, Stokes and Black (2012) found that adolescent girls with disabilities had specific aesthetic needs for functional garments in terms of color and style, one of them provided detailed descriptions of her dream coat: “A brown pea coat with two buttons on the left side and the openings on the right. (p. 184)” Jin and Black’s (2012) study of aesthetic needs of young male tennis players indicated that these tennis players have a ‘beautiful tennis garment’ in their minds; for example, 73% of participants preferred T-shirt style shirts, with specific preferences for round necklines, set-in sleeves, and hip length.

Through customization, 3D printed wearable apparel products enable beauty in different colors, styles, and textile structures/patterns. For examples, Danit Peleg’s 3D printing garment collections provided 3D printing garments in combinations of different colors, styles (shirt, short, and long dresses, etc.), and textiles patterns. Thus, users could select and customize by choosing from these elements to form 3D printing garments that meet their aesthetic needs (Figure 2, Marriott, 2015). Some aesthetic-related evaluations concerning 3D printed wearable apparel products are also revealed in the comments of news reports or YouTube demonstration videos. For example, in reference to the kinematics dress by Nervous System, from Shapeways (2014), there were comments such as: “This is beautiful.” and “That’s amazing. Dress looks great.” The commenters were impressed by the ability of 3D printing technology to provide 3D printed wearable apparel products with beautiful appearance and aesthetic elements. Thus, based on the literature review above, it can be hypothesized that:

H1b: Users’ perceived beauty of the 3D printed wearable prototype will positively influence users’ satisfaction with it.

Expressive perceptions of the 3D printed wearable prototype. By applying Lamb and Kallal's (1992) FEA model, in this study, expressive needs depend on user's perceived expressive qualities of the 3D printed wearable apparel product. The current study evaluates the expressive perceptions for a 3D printed wearable prototype based on perceived coolness and uniqueness of the 3D printed wearable prototype.

Coolness. Coolness is an abstract concept, and has several dimensions. Coolness is defined as "trendy, hip, appealing, fascinating and attractive," and people may "experience positive emotions ranging from pleasant surprise to excitement" when perceiving a cool product (Im, Bhat, & Lee, 2015, p. 167). Holtzblatt (2010) concluded that coolness of a product is a game changer that may disrupt the market since it is beyond aesthetic appeal or surprise, and has a far-reaching influence on our daily life. A cool product is not necessary to be functional, but it is usually novel and trendy when compared to mainstream products. It importantly provides a unique user experience and enables users to express their personalities (Goodman, 2001; Holtzblatt, 2010). Sundar, Tamul and Wu (2014) indicated that a cool product is not only cool itself, but could provide "joy of life" (p. 169). In other words, the owning and using of a cool product allows users to feel cool and show their identities, leading to users' satisfaction. For example, Apple has several very successful cool devices, the most notable is perhaps the classic iPod. The iPod embodied many properties of cool products: large memory to store more music, color screen interface, unique wheel-shaped touchpad and simple package design. The integration of these features made iPod cool when compared to other products in the mainstream market, allowing it to provide a unique user experience (Sundar, et al., 2014).

In terms of 3D printed wearable apparel products, due to the application of the innovative 3D printing technology into apparel design, people perceive them to be cool, innovative, and feel enthusiastic about the difference that 3D printed wearable apparel products can make in the mainstream market. For example, in response to Peleg's (2015) YouTube video of how to 3D print clothes at home, there were some comments such as: "It's fashion for the future. Pretty cool", "That is so cool!", "this is some cool futuristic looking stuff". Some commenters even expressed the idea that owning such 3D printing clothes, would let them feel cool and different from others. Thus, based on the literature review above, it can be hypothesized that:

H2a: Users' perceived coolness of the 3D printed wearable prototype will positively influence users' satisfaction with it.

Uniqueness. Uniqueness is defined as the degree to which users perceive a product is functional or aesthetic different from similar products (Sundar et al., 2014). Consumers, in some extent, tend to obtain products or services that few others possess (Harris & Lynn, 1996). Lynn and Harris (1997) articulated that a unique product should meet one or more of the four features: (1) limited in number, (2) innovative, (3) highly customized, and (4) sold in small/unique stores (limited access). First, in terms of limited in number, 3D printed wearable apparel products are just emerging, and hence only a few people, like models in fashion show (e.g., Jacobson, 2017), fashion designers (e.g., Bauer, 2016) own 3D printed apparel. Second, in terms of product innovativeness, 3D printed apparel constitute an innovative product, emerging from the innovative 3D printing technology. Third, in terms of customization, customized products are different from regular mass-manufactured products, and they are relatively unique (Lynn &

Harris, 1997). 3D printed wearable apparel products can be highly customized to fit specific body size and aesthetic preference (Howarth, 2013). Lastly, in terms of being sold in small/unique stores (limited access), currently most of 3D printed apparel are being sold in a very limited array of stores, such as innovative startups/online stores (e.g., Jacobson, 2017) and individual designers (e.g., Bauer, 2016) that are able to produce 3D printed wearable apparel products. The desire for the unique 3D printed wearable apparel products enables users to evoke pleasure by being different from others, and allowing them to shape their identity and social status (Cassidy & Lynn, 1989; Snyder & Fromkin, 1980). These affordances have the potential to lead to enhanced satisfaction with 3D printed apparel. Thus, based on the literature review above, it was hypothesized that:

H2b: Users' perceived uniqueness of the 3D printed wearable prototype will positively influence users' satisfaction with it.

Functional perceptions of the 3D printed wearable prototype. By applying Lamb and Kallal's (1992) FEA model, in this study, functional needs depend on users' perceived functions of the 3D printed wearable apparel product. The functional perceptions of 3D printed wearable prototype can be evaluated based on fit, mobility, comfort, and donning/doffing of the 3D printed wearable prototype.

Fit. Generally, garment fit refers to "a harmonious relationship of clothing to the human body" (Chen, et al., 2010, p. 516). Dickson and Pollack (2000) indicated that fit is one of the two crucial factors (the other one is comfort) to influence user's satisfaction with sports clothing and physical performance. Chen, et al. (2010) further argued that apparel fit could be evaluated by apparel appearance and the user's perceptions of fit. Apparel appearance depends on the apparel designer's perceptions of fit, whereas the current study focuses on user's perceptions to understand apparel fit from different perspectives.

User's perceptions of fit depends on how well a piece of apparel is suited to the body (LaBat & DeLong, 1990). Several previous studies emphasized the influence of garment fit on user satisfaction. They evaluated users' perceptions of fit based on different functional needs and assessed key body measurement areas. For example, Kidd's (2006) study focused on garment fit needs of four women with disabilities. Dress length was identified as a major fit problem, as it is difficult for users to use assistive tools if a dress is too long. Stokes and Black's (2012) study focused on garment fit of adolescent girls with disabilities on several garment types. Their findings suggested that garment fit influences users' satisfaction; concerns are specifically in areas such as shoulder fit of dresses and waist fit of pants. A study from Jin and Black (2012) indicated that 37% of tennis player participants were not satisfied with the fit of tennis clothing because it did not account for the size of their bodies.

In terms of 3D printed wearable apparel products, fit is also emphasized by apparel designers. For examples, the kinematics dress from Nervous System (2014) is a custom-fit dress; it used an application called Kinematics Cloth to simulate the size of the 3D printing dress to fit a specific body size (Figure 6-2). Body fit is one of the important features of designer Danit Peleg's jacket, the first 3D printing garment using FDM printers for sale online. The bomber jacket is customizable by using a special virtual fitting app called Nettelo (Mau, 2017). By taking advantage of customization, designers highlighted body fit as one of the key features of their 3D printed wearable apparel products. However, there is a research gap in that limited study focused on fit satisfaction of 3D printed wearable apparel products from the users' perspective. Thus, based on the literature review above, this study hypothesized that:

H3a: Users' perceived fit of the 3D printed wearable prototype will positively influence users' satisfaction with it.

Mobility. Mobility has a close relationship with fit during body movement, and functional garment design should meet specific mobility requirements for different tasks so that body movements are not hampered (Ashdown, 2011; Boorady, 2011; Huck, 1988). Thus, mobility is another important dimension for evaluating functional garments. Existing studies confirmed the influence of mobility of a functional garment on user's satisfaction. For examples, Wheat and Dickson (1999) indicated that knit fabrics in shoulders and sufficient back length in female golfers' shirts enables female golfers to swing without restrictions. Jin and Black's (2012) study confirmed the influence of mobility on male tennis players' satisfaction with functional garments. Specifically, when serving tennis balls, male tennis players experienced high levels of dissatisfaction with the amount of sleeve fullness and the amount of fabric on the shoulders. A study of rock climbing pants from Michaelson (2015) indicated that rock climbing pants should be diverse in order to meet mobility requirements of different techniques and routes, thus leading to positive satisfaction ratings.

In terms of 3D printed wearable apparel products, mobility is also emphasized by apparel designers. For example, Nervous System's (2014) kinematics dress used interconnected hinges to connect nylon pieces, thus such structures enable flexibility and comfort in body movement.

While designer Masaharu Ono designed a 3D printing knitted vest called Amimono, which mimics the flexibility of woven fabrics (Figure 10; Stephanie, 2016). Ono indicated that there were limited exhibitions of current 3D printed wearable apparel products, while his Amimono can actually be put on a human body for daily wear, because such 3D printing woven fabrics are elastic in order to accommodate body movement (O'Neal, 2016). However, there is a research gap that limited study focused on mobility satisfaction of 3D printed wearable apparel products from users' perspectives. Thus, based on the literature review above, it can be hypothesized that:

H3b: Users' perceived mobility of the 3D printed wearable prototype will positively influence users' satisfaction with it.

Comfort. Comfort is a neutral state that exists when an individual does not feel pain or discomfort when wearing a garment (Hatch, 1993). Comfort is considered a quality aspect to evaluate functional garment performance and influences a user's satisfaction (Dickson & Pollack, 2000; Hatch, 1993; Mukhopadhyay & Midha, 2008). Satisfaction in fit and mobility of functional garments do not necessarily lead to satisfaction in comfort, as comfort is subjective and has three main comfort divisions: psychological, physical, and physiological (Kamalha, Zeng, Mwasiagi, & Kyatuheire, 2013; Mukhopadhyay & Midha, 2008; Slater, 1985). Psychological comfort is related to an individual's roles, values, and social being (Kamalha, et al., 2013). Physical comfort concerns sensorial and tactile comfort when garment fabrics touch the user's body or skin (Kaplan & Okur, 2009; Liu & Little, 2009). Physiological comfort considers body thermal regulation and the balance of body heat (Kamalha et al., 2013). This study focused on physical comfort when 3D printed structures interact with the human body/skin. Physical comfort highlights the interaction between garment fabrics and skin. By touching garment fabrics, tactile sensations like warmth, prickliness, stiffness, and roughness are perceived (Fan & Tsang, 2008; Kamalha et al., 2013). Existing studies confirmed the influence of physical comfort of a functional garment on users' satisfaction levels. For example, Stokes and Black's (2012) study found that adolescent girls with disabilities felt discomfort with excess fabric while confined to a wheelchair.

In terms of 3D printed wearable apparel products, even though 3D printed structures are not as comfortable as traditional fabrics, apparel designers and researchers are making efforts to explore new properties that would make 3D printed structures more comfortable. For examples, a UCLA-led research team designed a 3D printed lattice by manipulating the internal structure of the material using the SLS method. The new material was soft and porous (Figure 7, Kisliuk, 2014). Electroloom, a 3D printing technology company, created a textile that is soft and feels like a form of suede (Figure 8, Scott, 2016). From designers' point of view, the new 3D printed structures were improved to be more comfortable than previous ones, in terms of physical comfort (e.g., softer and smoother). Some physical comfort–related evaluations concerning 3D printed structures could be found in the comments of news reports or YouTube demonstration videos. For example, Shapeways (2014) posted a video on YouTube demonstrated the manufacturing process of the kinematics dress by Nervous System. Some comments below reflected user's concerns with the physical comfort of 3D printed structures. One comment read: "Why would you wear cold plastic?" This remark might indicate that such 3D printed structure was not comfortable as it cannot keep warm. Another comment asked, "What happens when you sit down?", which might indicate a concern that it is not comfortable to sit on such textile as it is stiff. However, there is limited study investigating evaluations of perceived physical comfort of 3D printed structures from users' perspectives. Thus, based on the literature review above, it could be concluded and hypothesized that:

H3c: Users' perceived comfort of the 3D printed wearable prototype will positively influence users' satisfaction with it.

Ease of Donning/Doffing. The ease of donning/doffing (putting on/taking off) a garment is less of a concern until users have trouble with these actions (Watkins, 1984). This is especially crucial for situations that require fast donning and doffing of garments for safety and protection. For example, the U.S. Army Test and Evaluation Command (2011) investigated soldiers' donning and doffing of clothing in terms of speed, reliability, durability, and performance in cold regions. Existing studies supported the influence of donning/doffing on users' satisfaction. For examples, Bitterman, Ofir, and Ratner's (2009) study on recreational divers reported that divers experienced problems in donning and doffing the wetsuit. Stokes and Black (2012) found that adolescent girls with disabilities experienced various donning and doffing problems, and the problems varied by type of garment and disability, for example, various fasteners are necessary to help them with different dressing situations. A study of rock climbing pants from Michaelson (2015) also supported this opinion, that is, rock climbers had few difficulties in donning and doffing rock climbing pants because the application of closures would make donning and doffing easy. In terms of 3D printed wearable apparel product, because it is still in its exploration stage, currently, there is no study focusing on donning and doffing of 3D printed wearable apparel products from users' perspective. However, 3D printed wearable apparel products are still garments and may experience similar donning and doffing problems as traditional garments. Thus, based on the literature review above, it was hypothesized that:

H3d: Users' perceived ease of donning and doffing of the 3D printed wearable prototype will positively influence users' satisfaction with it.

Purchase intention. Purchase intention is defined as consumers' aim and willingness to purchase a product or service (Dodds, et al., 1991). According to Ajzen and Fishbein's (1980), consumers' purchase intention is influenced by their attitudes towards a product. Product aesthetics is one of the important product features that positively influences users' perceptions of a product, and their purchase intentions (Bloch, 1995). Moreover, consumers often prefer cool and unique products that can express their personalities and style (Lynn & Harris, 1997), and often possess the desire to obtain such cool and unique products.

Since 3D printed wearable apparel products take advantages of complex shape manipulations and customization, they can be designed with various aesthetics elements. The aesthetic perceptions of the 3D printed wearable apparel products can evoke positive attitudes, and lead to purchase intentions. Further, the application of 3D printing technology into wearable apparel product is new and innovative. Thus, users perceive a 3D printed wearable apparel product as unique and cool, and desire to own such product to express their personality. However currently, the functions of 3D printed structures are not better than traditional fabrics (Jacobson, 2017; Tarmy, 2016). Even though users may have positive perceptions and evaluations of the functions of a 3D printed wearable apparel product, they may have low purchase intentions because they can always choose garments with traditional fabrics which provide better functions and competitive prices. However, it is reasonable to expect a positive relationship between functional perceptions and purchase intentions for 3D printed apparel. Thus, based on the literature review above, they were hypothesized that:

H4: Users' aesthetic perceptions: (a) perceived novelty and (b) perceived beauty of the 3D printed wearable prototype will positively influence users' purchase intentions.

H5: Users' expressive perceptions: (a) perceived coolness and (b) perceived uniqueness of the 3D printed wearable prototype will positively influence users' purchase intentions.

H6: Users' functional perceptions: (a) fit, (b) comfort, (c) mobility and (d) ease of donning and doffing of the 3D printed wearable prototype will positively influence users' purchase intentions.

Influence of users' satisfaction on users' purchase intentions. According to Ajzen and Fishbein (1980), users' satisfaction with the 3D printed prototype would form positive attitudes. Positive attitude towards the 3D printed prototype will positively influence users' purchase intention. Kim and Lee (2011) argued that users' satisfaction indicates likelihood of future purchase, and has a significant influence on purchase intention. Alavi, Rezaei, Valaei and Ismail's (2016) research supported the direct relationship between users' satisfaction and purchase intention, and confirmed that purchase intention is the result of satisfaction in a shopping mall environment. Chi's (2018) study also supported the significant impact of users' satisfaction on apparel purchase intention on mobile commerce websites. Thus, it is hypothesized that:

H7: Users' satisfaction with the 3D printed wearable prototype will positively influence users' purchase intentions.

The research model below (Figure 15) summarizes the hypothesized relationships in this study.

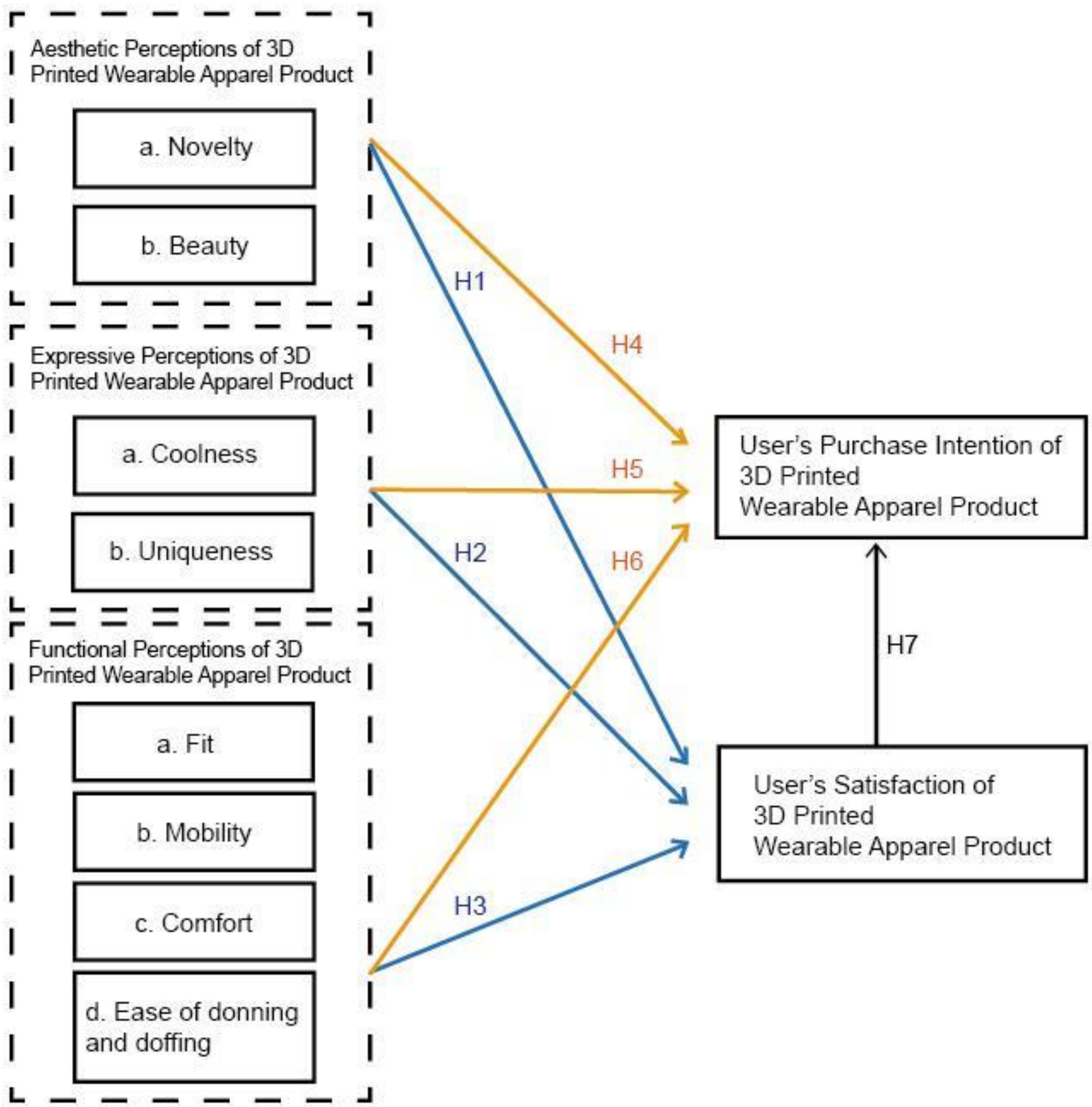


Figure 15. Model of users' perceptions of 3D printed wearable apparel product.

CHAPTER 3: METHODOLOGY

Chapter 3 is structured into two studies. Study 1 provided a qualitative method concerning **RQ1** and **RQ2**. It also introduced naturalistic inquiry as an overarching approach to enhance trustworthiness of the study. Further, it adopted a research through design (RTD) methodology and used systematic methods to record 3D CAD design workflow of 3D printed wearable apparel products, as well as exploring new properties of 3D printed structures.

Study 2 adopted a research about design (RAD) methodology and provided quantitative methods to answer **RQ3**. Study 2 adopted the FEA consumer needs model as the basic theoretical framework. A model of users' perceptions of 3D printed wearable apparel products including seven hypotheses was tested to evaluate users' FEA perceptions of 3D printed wearable apparel products. An online survey study was used to collect data through an online panel service for further analysis.

Exploration and Research Process

RQ1 and **RQ2** were explored using RTD methodology and data was collected from the perspective of the researcher. Then the outcomes of research (**RQ1**: reflective design journals of the 3D CAD workflow; **RQ2**: 3D printed structure designs) were evaluated by researcher as well as peer debriefing. Several iterations of evaluations provided feedback to improve the outcomes and provide a final 3D printed wearable prototype. **RQ3** was explored using RAD methodology to examine users' FEA perceptions of the final 3D printed wearable prototype. The collection and analysis of the data provided feedback for both researcher and peer debriefing to further improve the outcomes of the research. Figure 16 demonstrates the overall research process.

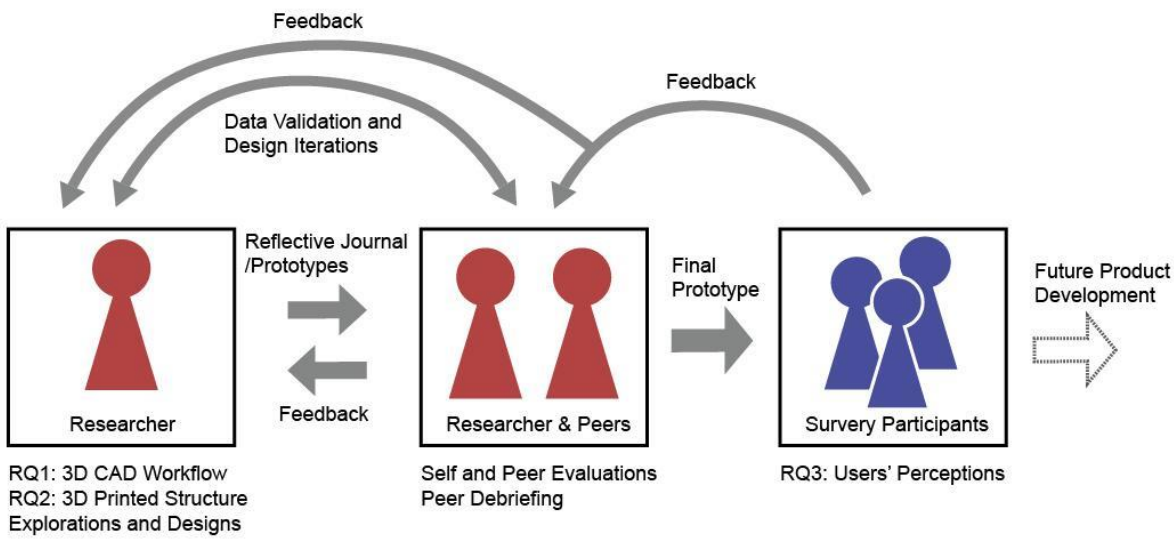


Figure 16. Research process

Methods for Study 1 – RTD: Exploring Design Process

Approach

Naturalistic inquiry. Naturalistic inquiry is a qualitative approach that emphasizes the importance of "natural" settings; and the researcher is primarily the data generator through observing, describing, and explaining the activities and experience of the targeted group of people (Lincoln & Guba, 1985). It is considered an appropriate research approach for a researcher to investigate in a real environment to maintain trustworthiness of the research (Robson, 1993). In quantitative research, the concepts of validity and reliability are used to describe the quality of the research (Lincoln & Guba, 1985). However, for a qualitative study, the quality does not rely on replicable outcomes, thus it is suggested that the term "trustworthiness" could be used in reference to the quality of qualitative research (Gray & Malins, 2004).

Bunnell (1998) further summarized six key characteristics of naturalistic inquiry, and the design researcher is the center of the research process. First, research is conducted in a natural setting. Second, tacit knowledge is important for researchers in the research process. Third, when practice-based methodology is emerging, researchers should focus and reflect on problems through actions. Fourth, the criteria for evaluating the research should relate to its research question and trustworthy context. Fifth, research outcomes are unique for the specific research but usually not generalizable. Sixth, the outcomes are capable of being assessed through peer debriefing (Lincoln & Guba, 1985). These characteristics were articulated in the methodology section. In this research, the researcher was also the designer to explore and record the whole design process alone in a workshop environment. Naturalistic inquiry was adopted as the overarching approach to guide this research and maintain its trustworthiness.

Research through design. The methodology for RTD has been redefined in various design fields. Thus, research that focuses on and reflects on problems through the design process is crucial to collect valuable data (Bunnell, 1998). It is important to gain new knowledge and form a long-term theory-building process from practice-based research (Jonas, 2007; Pedgley, 2007). Jonas (2007) articulated previous methodological issues for practice-based research and proposed research through design (RTD) methodology. RTD is defined as "a research and design process intrinsic to design. Designers/researchers are directly involved in establishing connections and shaping their research object" (Jonas, 2007, p. 191).

Methods

Reflection-in-action and reflection-on-action. Schön's (1983) concept of the reflective practitioner provided the idea that knowledge is gained from the practice of design; experience alone does not necessarily lead to learning, but deliberate reflection on experience is essential. Reflection on the design process could capture the knowledge from practice. Tacit experience and knowledge are crucial as analytical knowledge to design. Reflection on the design process enables the capture and rendering of tacit knowledge in order to make it explicit to be communicated with others, while the knowledge cultivated from the practice-based research helps ground theory for design research in the long term (Bye, 2010; Friedman, 2008).

Schön (1983) indicated that knowledge is found not only in the practice, but also in tacit form and implicit in the design process. Schön (1983) further articulated two reflective methods for interpreting the knowledge in practice: *reflection-in-action* and *reflection-on-action*. Reflection-in-action refers to the data collection process during the design process. It is a process in which unusual situations happen, and designers should take actions that differ from those they have planned. Reflection-on-action refers to the data collection process right after the design process. It is a process of reflecting and analyzing the feelings, actions, and thinking of their design process. Both methods help collect data from practitioner's own design process, reveal and render tacit knowledge, and maintain objectivity and trustworthiness of the research.

The background of the researcher in this study is industrial design, the knowledge of design process, design skills and model prototyping were the professions and main research focus in this study. Thus, the tacit knowledge was covered in the integration of industrial design background with apparel design. Applying industrial design process and skills in apparel design is relatively new, there is a research gap to explore. The tacit knowledge applications were found in this study concerning the following aspects: (1) whether 3D CAD direct modeling method could be applied in 3D printed structure design, what are the difference in CAD workflows between industrial product design and wearable apparel product design; (2) how to improve 3D CAD modeling proficiency for wearable apparel product; (3) how to gain and demonstrate knowledge and skills from 3D CAD workflow; and (4) how to optimize wearable apparel product function and aesthetic features in the iterations of 3D CAD direct modeling refinements, sample test printing and property evaluations of 3D printed structures.

Stages of design process. New technologies may have great impact on design to generate new knowledge and new product ideas (Cross, Naughton & Walker, 1981). Thus, document and study design process potentially shed light on new knowledge and thinking modes to inspire future design (Parsons & Campbell, 2004). In Study 1 (RTD research), by adopting Parsons and Campbell's (2004) approach of applying new technology to apparel design, Study 1 focused primarily on analyzing changes in the design process that occur when 3D printing technology is used to develop new 3D printed structures that could be integrated with wearable apparel products. In developing ways to integrate 3D printing technology with traditional fabrics for wearable apparel products, the researcher focused on ready-to-wear garments. Because ready-to-wear provided means to explore the potential applications of new technology, rather than customized garments to meet specific goals. This focus helps the researcher to think creatively without the constraint of specific design goals (Parsons & Campbell, 2004).

According to Parsons and Campbell (2004), the researcher in this study played the role as a methodology-oriented designer (m-designer). Unlike a practice-based designers (p-designer) focusing on end products, m-designers intent to document the design process of integrating the new technology and final products, are more suitable to the application of new technology to wearable apparel product, provide more detailed and clear documentable process. (Parsons & Campbell, 2004). Thus, based on Parsons and Campbell's (2004) approach, a six-stage design process was created. The basic components included for each design phase were as follows:

Stage 1: *Problem Identification*. Identifying design decision-making and technical issues that need to be explored, or sub-problems from previous design phases.

Stage 2: *3D CAD*. Using 3D CAD programs to visually explore 3D printed structures. It helps compare different ideations, and is easy to make changes and provide variations. In this research, Rhinoceros was used as the 3D CAD program.

Stage 3: *3D Printing*. Importing the 3D CAD files into a 3D printer to print them into physical 3D printed samples or prototypes. The FDM 3D printer used in this research was KLONER3D®240TWIN, a photo of this 3D printer is shown in Figure 17 left (Kloner3d, 2018). The white TPU filament (Diameter = 1.75 mm) is shown in Figure 17 right. The maximum printing size for the 3D printer is 360x240x140 mm. There are nozzles with two types of

Figure 17. KLONER3D®240TWIN printer (left). Copyright 2018 by Kloner3d.com. The white TPU filament (right).

diameters, 0.3 mm and 0.5 mm. Generally, there was no significant difference between these two nozzles when printing 3D printed structures, 0.3 mm nozzle performed slightly better. This stage helps evaluate the properties of 3D printed sample structures.

Stage 4: *Post Finishing*. Cleaning support parts and adhered joints. Due to the printing mechanism of FDM printer, it prints object layer by layer. Support parts (Figure 18) are needed to hold the shape when some structures do not touch the print bed. Thus, it may have many

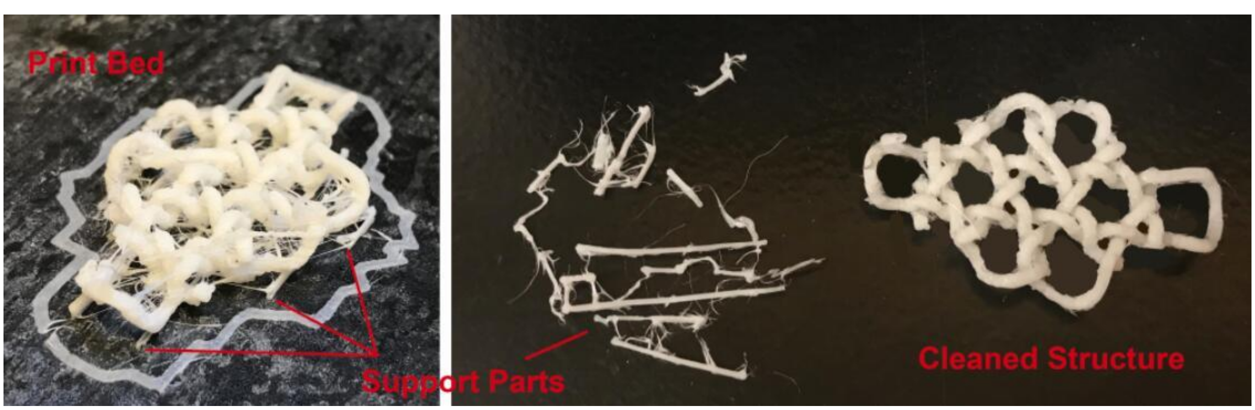


Figure 18. Support parts

support parts and adhered joints when printing complex structures. Post finishing is necessary to enable the 3D printed samples to perform in full function.

Stage 5: *Sample Sewing*. Sewing 3D printed samples with traditional fabrics. It helps evaluate how the 3D printed structures could be integrate with traditional fabrics.

Stage 6: *Prototyping*. Printing large piece of 3D printed structures, preparing fabrics, designing final prototype, sewing 3D printed structures as well as other fabric pieces together to form a 3D printed wearable apparel product.

Data Collection

In the context of the current research, both methods mentioned above were adopted for the data collection process. The research questions concerned the 3D CAD workflow of the 3D printed wearable apparel product and the properties of 3D printed structures. The reflection-in-action method was used during the design process. For 3D CAD workflow, the data collection process was periodically recorded in the format of 3D CAD screen recordings (key snapshots or video recordings); notes concerning immediate thoughts, ideas, problems and solutions during 3D modeling process. For the new properties of 3D printed structures, the data collection process followed the same way as 3D CAD workflow. While for the evaluations of the properties, both virtual evaluations from 3D CAD interface and physical sample evaluations were adopted. Data collection from virtual evaluations concerned the structures (e.g., hinges, woven structure) and parameters (e.g., radius, thickness). Data collection from physical 3D printing small sample printing concerned the capability of the 3D printer and evaluations of actual properties of the samples. The comparison between virtual 3D CAD model and physical sample provided feedback data to improve design.

The reflection-on-action method was used after each design process. This data collection process recorded in the formats of photography, sketches, and diary writing that concerned the feelings, thoughts, problems, and brainstorming solutions after the design process, as well as 3D printed small sample printing tests. This reflection was to summarize the current design phase, evaluations of 3D printed structure properties, and suggest implications and ideas for future design phases.

In order to better organize the reflection data files, a digital reflective design journal was created. In this digital file, the level 1 folder was a content. It contained an Excel file that

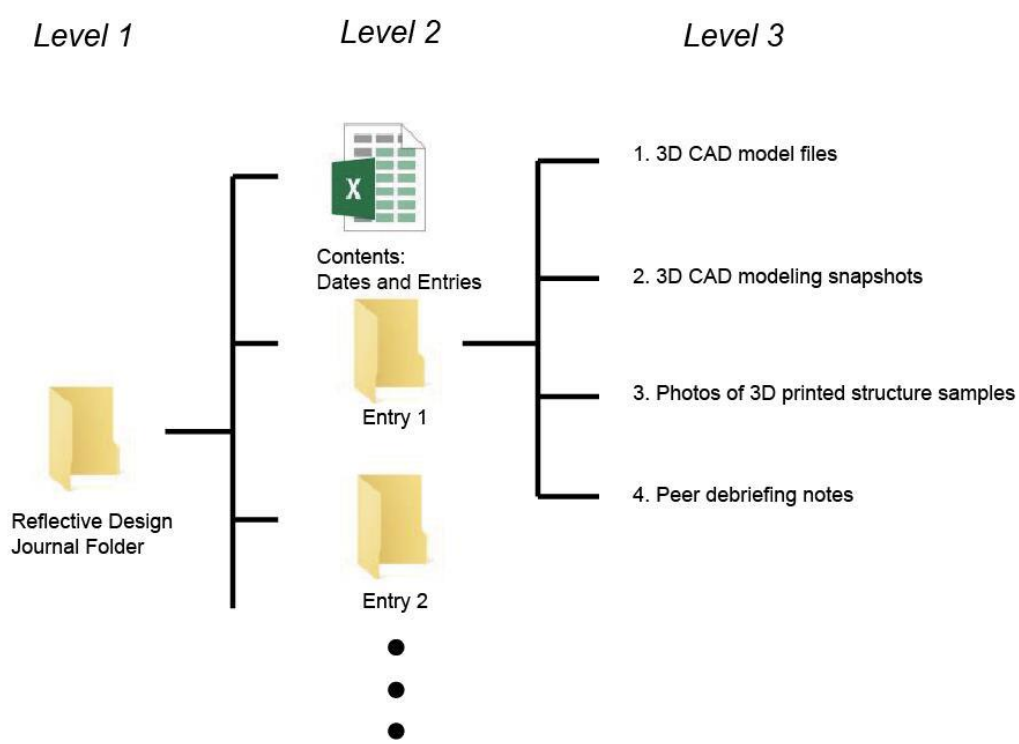


Figure 19. Components of the reflective design journal.

recording date and design entries; and level 2 folders, named by date and entry. Level 2 folders contained two level 3 folders, one for reflection-in-action files and the other for reflection-on-action files. Level 3 reflection-in-action folders contained (1) 3D CAD models, (2) 3D CAD modeling recordings (key snapshots), (3) photos of quick 3D printed structure samples, and (4) a document file of peer debriefing notes concerning snapshots and 3D printed structure samples. Level 3 reflection-on-action folders contained (1) a document file of diary writings concerning the feelings, thoughts, problems, and brainstorming solutions about the design process and the results of 3D printed structure sample testing, (2) photos of 3D printed structure big samples. Figure 19 shows the components of the digital reflective design journal. The digital reflective design journal was further reviewed through peer debriefing for analysis. In this case study, advisors and committee with design backgrounds were the peers.

Criteria for data collection. For Study 1, the research questions focused on (1) the 3D CAD workflow, specifically Rhinoceros modeling, and (2) the explorations of new properties of 3D printed structures. The criteria for exploring properties of 3D printed structure were evaluated from physical 3D printed samples. The criteria are listed in Table 1.

Table 1

Criteria for Data Collection

RQ1: Dimension of 3D CAD workflow	
Item	**Description**
1. 3D CAD design logic	The design logic to model 3D printed structures
2. Knowledge and skills needed	Knowledge and skills required to model the 3D printed structures
3. 3D printer and filament used	3D printer type and filament used, demonstrated in chart

4. Durations of the design process	Time durations for each step in the 3D CAD design workflow and the whole design process
5. Complexity of the 3D CAD modeling techniques and procedures	The complexity of 3D modeling process was evaluated at three levels (low, medium and high)
6. Joints/connections of 3D printed structures	connections of the 3D printed structures, advantages/disadvantages
7. Limitations of 3D CAD modeling program	Difficulties in 3D CAD due to the limitations of the CAD program, and solutions
8. Limitations of the 3D printer	Limitations that caused failure and low quality of 3D printed structures
RQ2: Properties of 3D printed structures	
1. Softness	Stiff – Soft
2. Flexibility	Not flexible – Flexible
3. Connections	Quality of the connections: Low – High
4. Breathability	Breathability: Low – High
5. Stretchability	Stretchability: Low – High
6. Cushioning	Cushioning: Low – High
7. Durability	Not durable – Durable
8. Weight	Heavy – Light
9. Complexity	Complexity: Low – High
10. Aesthetics	Not beautiful - Beautiful
11. 3D printing success	Success rate: Low – High

Note. The properties of 3D printed structures were evaluated based on the items above in a 7-point semantic differential scale.

A methodology flow chart that summarizes the content above is shown in Figure 20.

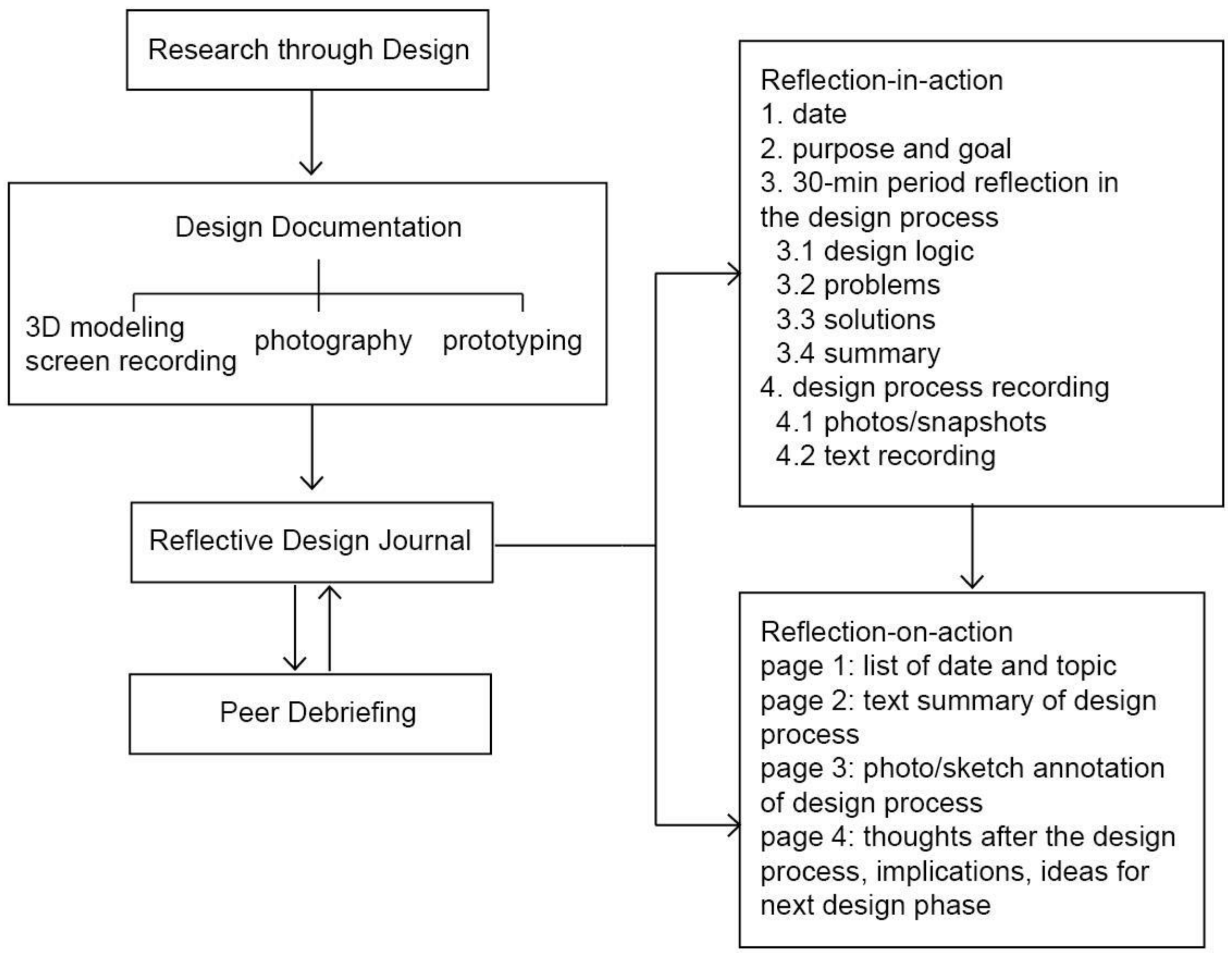


Figure 20. Data collection flow chart.

Data Trustworthiness

The trustworthiness of the research and data could be maintained in three ways. First, from a methodological perspective, naturalistic inquiry emphasizes that the research process should be conducted in a natural environment without controlling any variables in the environment (Lincoln & Guba, 1985). Such a natural setting enables objectivity of observed results and enhances trustworthiness.

Second, from the data screening and coding perspective, the reflective design journal should be screened for analysis. Not only the researcher objectively selected the meaningful and communicable data, but also peers and experts (e.g., Dr. Lushan Sun) from this field of research helped evaluate data and improve trustworthiness of the research.

Third, from the data collection and analysis perspective, the 3D printed structures and the wearable apparel product were evaluated from multiple perspectives. Gray and Malins (2004) suggested "triangulation" in data analysis and indicated multiple perspectives, like researcher's own thoughts, peer debriefing, existing practice, and analysis from contextual reviews, users' perceptions, and objective recordings. These perspectives could make sense of the data from RTD, maintain trustworthiness of the research, and ensure meaningful and communicable outcomes.

Data Analysis

Tools for data analysis. All the reflective data were collected and integrated into a reflective design journal. Gray and Malins (2004) suggested using an "elongated" matrix to reduce data and demonstrate them. The elongated matrix describes the activity content recorded with time. The content includes a reflective journal log, documentation, relationships of research to contemporary and historical context, and pace and progress of research, analysis, and other relevant information (Figure 21, Gray & Malins, 2004, p. 152).

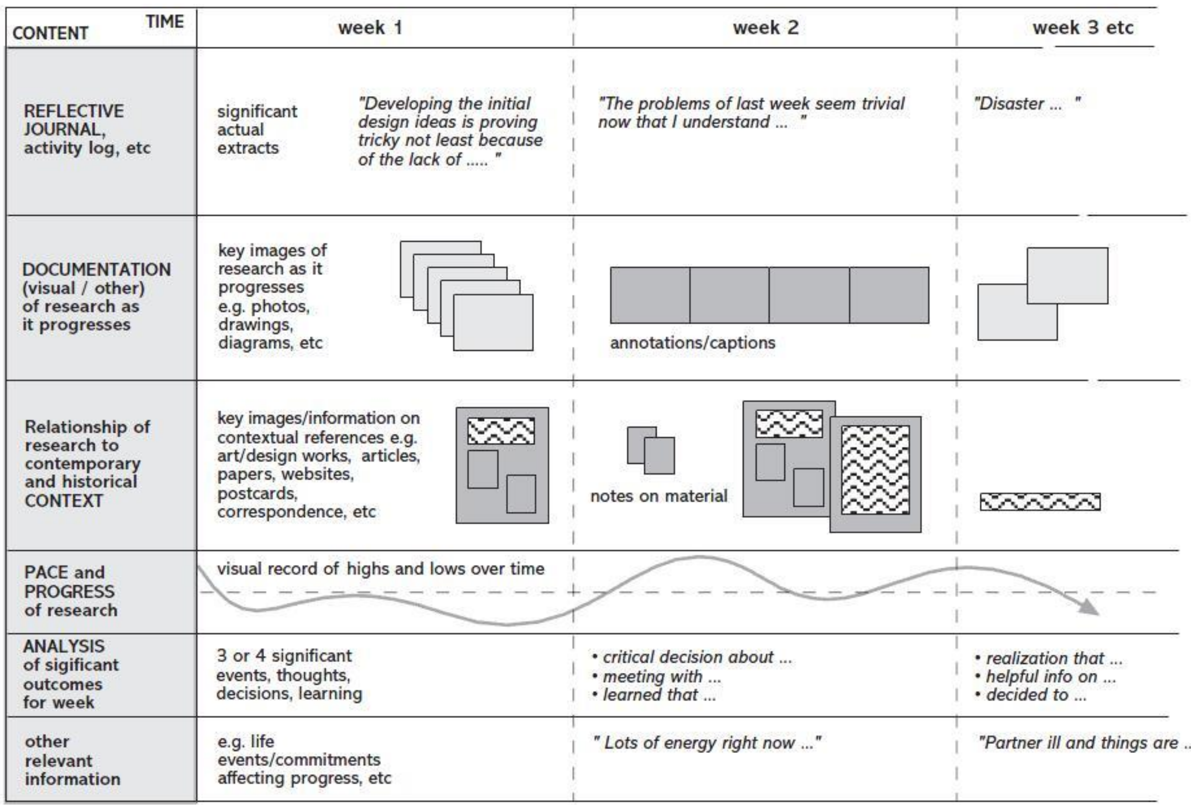


Figure 21. An example of chronological matrix for the analysis of a reflective journal (Gray & Malins, 2004, p. 152). Copyright 2014 by Carole Gray and Julian Malins.

Data analysis method. Content analysis was used to analyze the reflective design journal. The comments and notes reflected in the design process were transcribed into texts in digital version. The 3D CAD workflow and properties of 3D printed structures were evaluated based on the criteria (see Table 1). The evaluation criteria were discussed and decided by the researchers, peers and experts to ensure accuracy. Quantitative descriptive analyses were also used to interpret the data. The demonstrations and analyses of the durations of the steps in design process indicated gained knowledge, skills and improved efficiency.

Methods for Study 2 – RAD: Exploring User Perceptions

This study used an Internet survey to investigate the relationships hypothesized in **RQ3**. This study adopted the research about design (RAD) methodology, in which the researcher played the role as an observer to investigate the performance of the product without changing it (Jonas, 2007). A survey study examined the hypotheses, and the process is discussed below.

Research Design

An Internet survey study, constructed on Qualtrics, was employed to investigate the relationships hypothesized about users' functional, expressive and aesthetic (FEA) perceptions of a 3D printed hooded sweatshirt designed in Study 1. A survey hyperlink was generated in Qualtrics and posted on an online survey panel called Amazon mechanical turk (MTurk), to recruit the general population of consumers from US locations. Quantitative data collected in the survey were analyzed using multiple regression analyses to reveal the relationships among users' FEA perceptions on their satisfaction and purchase intention of the 3D printed hooded sweatshirt. The photos of the 3D printed hooded sweatshirt, and GIF format animations demonstrating human body movements when wearing the 3D printed hooded sweatshirt were included in the survey for evaluation and reference. Participants evaluated aesthetic perceptions concerning aesthetic novelty and beauty, expressive perceptions concerning coolness and uniqueness, as well as functional perceptions concerning fit, mobility, comfort, ease of donning and doffing of the 3D printed hooded sweatshirt. After data collection, IBM SPSS program was used for further data analysis.

Sampling and Procedure

Sampling. According to Tabachnick and Fidell (2001), when using stepwise regression analysis, the sample size should be equal or greater than 40m (m is the number of independent variables, in this study, m = 8). Thus, the desired sample size should be greater than 320. Amazon mechanical turk (MTurk) was used as the survey panel to recruit general participants. Preliminary requirements for screening participants were (1) US locations and (2) over 70% survey approval rate by previous survey requesters.

Procedure. The research proposal along with the details of recruitment method were submitted to the Institutional Review Board (IRB) at the university for review. Recruitment was then launched upon receiving IRB approval (see Appendix A). The survey was made and edited in Qualtrics, and then a survey hyperlink was generated to be pasted on MTurk as an external Human Intelligence Task (HIT, “HIT” is a term especially used in MTurk to refer to a survey task). MTurk workers (“MTurk workers” is a term especially used in MTurk to refer to survey participants, hereafter used “participants” instead) who met the preliminary requirements were able to see the HIT title in their HIT list, and were able to click this HIT and get brief information about the survey. The HIT information is shown in Table 2

Table 2

HIT Information

Setting items	**Setting information**
Title	Evaluating Users' Perceptions of 3D printed wearable apparel product
Description	Good pay, 15 min survey! Evaluate users’ perceptions of a 3D printed wearable apparel product
Keywords	3D printing, apparel design, users' perceptions
Rewards per assignment	$1.00

Number of assignments per task	357
Time allotted per assignment	15 minutes

After the information, a hyperlink was provided. By clicking the external hyperlink, participants were redirected to the Qualtrics survey, and a detailed information page was first displayed. Participants agreed to join in this survey by clicking the “Next” icon. There were three parts in the survey. The first part included participants’ knowledge and/or experience of apparel design and 3D printing technology. The second part was about users’ perceptions of the 3D printed hooded sweatshirt and user satisfaction with the 3D printed hooded sweatshirt. Before answering these questions, participants were separated into distinct survey flows by gender. Male and female participants saw photos and GIF animations with the 3D printed hooded sweatshirt on a model of their corresponding gender. This step was implemented to control the influence of gender on the results, since participants may perceive the unisex sweatshirt to be gender-specific if shown on a model of the opposite gender. The third part included demographic questions. Once participants finished the survey, a unique MTurk code was generated by the survey for each participant. Participants entered these codes on the MTurk HIT page to be compensated.

Instruments

A total of 46 scale items measuring users’ perceptions of the 3D printed hooded sweatshirt and user satisfaction toward the 3D printed hooded sweatshirt were included in the questionnaire, which contained four sections. The first section included measures for the dependent variable (DV), users’ satisfaction with the 3D printed hooded sweatshirt. The second, third and fourth sections included the independent variables (IVs), (a) users’ aesthetic perceptions of the 3D printed hooded sweatshirt (perceived novelty and beauty), (b) users' expressive perceptions of the 3D printed hooded sweatshirt (perceived coolness and uniqueness), and (c) users' functional perceptions of the 3D printed hooded sweatshirt (perceived fit, mobility, comfort, and ease of donning/doffing). The scale measurement items are listed in Table 3 and the complete questionnaire is included in Appendix B. The details of each scale are discussed below.

Users' satisfaction (DV). Three items measured users' perceived satisfaction with the 3D printed hooded sweatshirt. The three items were based on Rijsdijk et al.'s (2007) consumer satisfaction scale, with a reported the reliability (Cronbach's α) was 0.76 within their study. In the current study, using a 7-point Likert scale, participants were asked to rate their perceived satisfaction with the 3D printed hooded sweatshirt (see Table 3).

Users' purchase intention (DV). Three items based on Dodds, et al.'s (1991) purchase intention scale, measured users' purchase intentions for the 3D printed hooded sweatshirt using a 7-point Likert scale in the current study (see Table 3). Dodds et al.'s (1991) study reported the reliability (Cronbach's α) of the purchase intentions scale was 0.97.

Novelty (IV). Five items measured users' perception of the novelty of the 3D printed hooded sweatshirt. These items were based on Cox and Cox's (2002) Product Novelty Scale with a reported reliability (Cronbach's α) of 0.81. Using 7-point semantic differential scales, participants were asked to rate the perceived novelty of the 3D printed hooded sweatshirt on the following items: (1) old to new, (2) unoriginal to original, (3) common to unusual, (4) familiar to unfamiliar, and (5) typical to atypical (see Table 3).

Beauty (IV). Five items measured users' perception of the beauty of the 3D printed hooded sweatshirt. These items were based on Hirschman's (1986) Aesthetic Response scale with a reported the reliability (Cronbach's α) ranging from 0.82 to 0.96. Using 7-point semantic differential scales, participants were asked to rate the perceived beauty of the 3D printed hooded sweatshirt on the following items: (1) not attractive to attractive, (2) not desirable to desirable, (3) not beautiful to beautiful, (4) not exiting to exiting, and (5) does not make me like this product to make me like this product (see Table 3).

Coolness (IV). Six items measured users' perception of the 'coolness' of the 3D printed hooded sweatshirt. The first two items were based on Sundar, Tamul and Wu's (2014) measure for assessing coolness of technological products. Sundar, Tamul and Wu's (2014) study reported the scale reliability (Cronbach's α) was 0.91 for the total of five items. However in the current study, the first three items (original, unique and distinct) were deleted because they duplicated items in the novelty scale. Thus, only stylish and hip were retained from this original scale (see Table 3). Another four items were selected from Im, Bhat and Lee's (2015) new product coolness scale, with a reported reliability (Cronbach's α) of 0.89. Using a 7-point Likert scale, participants were asked to rate whether the perceived coolness of the 3D printed hooded sweatshirt is: (1) stylish, (2) hip, (3) trendy, (4) appealing, (5), fascinating and (6) attractive (see Table 3).

Uniqueness (IV). Five items measured users' perception of the uniqueness of the 3D printed hooded sweatshirt. The five items were based on Sundar, Tamul and Wu's (2014) measures for assessing uniqueness of technological products and had a reported reliability (Cronbach's α) of 0.90. Using a 7-point Likert scale, participants were asked to rate items such as: "People who wear this 3D printed hooded sweatshirt are people I would describe as being different from others" (see Table 3).

Fit (IV). Eight items measured users' perceptions of the fit of the 3D printed hooded sweatshirt. Among the eight items, six items are based on and modified from LaBat and DeLong's (1990) Fit Satisfaction Scale and asked users about their perception of fit when seeing the video that demonstrates how the sweatshirt fits the human body. Michaelson's (2015) study, which employed this scale, reported a reliability (Cronbach's α) of 0.779 for the scale. In addition to the above items, two items (head and high hip) were added to fit the research focus. Using a 7-point Likert type scale (1 = Strongly Dissatisfied; 7 = Strongly Satisfied), participants were asked to rate the nine upper body areas that relate to perceived fit of the 3D printed hooded sweatshirt: (1) head, (2) neck, (3) shoulder, (4) arm, (5) bust, (6) waist, (7) abdomen, and (8) high hip (see Table 3).

Mobility (IV). Four items measured users' perceptions of the mobility of the 3D printed hooded sweatshirt. The eight items were based on and modified from Huck, Maganga and Kim's (1997) Wearer Acceptability 9-point semantic differential scale and asked users about their perception of mobility when seeing the GIF animation that demonstrates how the 3D printed hooded sweatshirt fits the mobility of the human body. Michaelson's (2015) study, which employed this scale, reported a reliability (Cronbach's α) ranging from 0.782 to 0.869. Using 7-point semantic differential scales, participants were asked to rate the perceived mobility of the upper body when wearing the 3D printed hooded sweatshirt on the following items: (1) flexible to stiff, (2) freedom of movement of arms to restricted movement of arms, (3) freedom of movement of torso to restricted movement of torso, and (4) loose to tight (see Table 3).

Comfort (IV). Five items measured users' perceptions of the comfort of the 3D printed hooded sweatshirt. The five items are based on and modified from Fan & Tsang's (2008) Subjective Thermal Comfort Evaluation for comfort sensations before doing sports. Michaelson's (2015) study, which employed this scale, reported a reliability (Cronbach's α) of 0.786 for the scale. Using a 7-point semantic differential scale, participants were asked to rate the perceived comfort of the upper body when wearing the 3D printed hooded sweatshirt in terms of whether it is (1) not warm, (2) prickly, (3) stiff, (4) rough, and (5) uncomfortable (see Table 3).

Ease of donning/doffing (IV). Two items measured users' perceptions of the ease of donning and doffing the 3D printed hooded sweatshirt. The two items are based on the U.S. Army Test and Evaluation Command – Cold Regions – Environmental Testing of Individual Soldier Clothing: Test Participant Interview Form (2011) questions 8 and 9 for ease of donning and doffing. Michaelson's (2015) study, which employed this scale, reported the reliability (Cronbach's α) was 0.838. Using a 6-point Likert scale, participants were asked to rate the perceived ease of (1) donning and (2) doffing of the 3D printed hooded sweatshirt. All the items in this measurement were reverse-coded in data analysis in order to be consistent with other variables in terms of negative to positive wording (see Table 3).

All the scale measurements are shown in Table 3.

Table 3

Scale Measurements

Variable Category	**Variable**	**Measurements**

Users' satisfaction	Users' satisfaction	1. I am very satisfied with this 3D printed hooded sweatshirt. 2. This 3D printed hooded sweatshirt matches my ideal 3D printed wearable apparel product. 3. In general, this 3D printed hooded sweatshirt is better than expected.
Users' purchase intention	Users' purchase intention	1. I would consider buying the 3D printed hooded sweatshirt. 2. I will purchase the 3D printed hooded sweatshirt. 3. There is a strong likelihood that I will buy the 3D printed hooded sweatshirt.
Aesthetic perceptions	Novelty	I would perceive the 3D printed hooded sweatshirt to be: 1. Old – New 2. Unoriginal – Original 3. Common – Unusual 4. Familiar – Unfamiliar 5. Typical – Atypical
	Beauty	I would perceive the 3D printed hooded sweatshirt to be: 1. Not attractive – Attractive 2. Not desirable – Desirable 3. Not exciting – Exciting 4. Not beautiful – Beautiful 5. Does not make me like this product – Make me like this product
Expressive perceptions	Coolness	1. This 3D printed hooded sweatshirt is stylish. 2. This 3D printed hooded sweatshirt is hip. 3. This 3D printed hooded sweatshirt is trendy. 4. This 3D printed hooded sweatshirt is appealing. 5. This 3D printed hooded sweatshirt is fascinating. 6. This 3D printed hooded sweatshirt is attractive.
	Uniqueness	1. People who wear this 3D printed hooded sweatshirt are people I would describe as being different from others. 2. This 3D printed hooded sweatshirt makes people who wear it different from other people. 3. If I wore this 3D printed hooded sweatshirt, it would make me stand apart from others. 4. This 3D printed hooded sweatshirt helps people stand apart from the crowd. 5. The people who wear this 3D printed hooded sweatshirt are unique.

Functional perceptions	Fit	I perceive that this 3D printed hooded sweatshirt will fit my 1. Head 2. Neck 3. Shoulder 4. Arm 5. Bust 6. Waist 7. Abdomen 8. High hip
	Mobility	I perceive that the 3D printed hooded sweatshirt is 1. Flexible – Stiff 2. Freedom of movement of arms – Restricted movement of arms 3. Freedom of movement of torso (body) – Restricted movement of torso (body) 4. Loose – Tight
	Comfort	The 3D printed hooded sweatshirt is 1. Not warm 2. Prickly 3. Stiff 4. Rough 5. Uncomfortable
	Ease of donning/ doffing*	a. How do you rate the ease with which you would be able to don (put on) this 3D printed hooded sweatshirt? 1. Excellent 2. Very Good 3. Adequate 4. Not Quite Adequate 5. Poor 6. Extremely Poor
		b. How do you rate the ease with which you would be able to doff (take off) this 3D printed hooded sweatshirt? 1. Excellent 2. Very Good 3. Adequate 4. Not Quite Adequate 5. Poor 6. Extremely Poor

Note: *Reverse-coded items

Data Analysis

Descriptive analysis in IBM SPSS 22 software was used to analyze the demographic characteristics of the sample in terms of frequencies. Demographic characteristic included gender, education, ethnic groups, marital status, income and US location. Further, different statistics methods were used to analyze data.

First, due to the assumption that gender factor may influence the results, the 3D printed hooded sweatshirt on models with both genders were presented to the corresponding gender participants in the form of photos and GIF animations. Thus, ANOVA tests were conducted to check whether there were differences between users' perceptions of the 3D printed hooded sweatshirt, and their aesthetic judgments and purchase intentions between genders.

Second, because some of the scales used for this study were obtained by combining items from different studies, and these items were used for a new wearable apparel product integrated with 3D printing technology, thus, both the dimensionality and reliability of the scales needed to be examined. Dimensionality of the scales was examined using Exploratory Factor Analysis (EFA), and reliability of the scales was examined using Cronbach's α.

Third, research hypotheses were tested using a series of simple and multiple regression analyses to examine the relationships among the FEA variables, users' satisfaction and purchase intention.

CHAPTER 4: RESULTS

Results for Study 1

Chronological Approach to 3D Printed Wearable Apparel Products

Two phases were presented in RTD using the chronological approach. The two phases of the RTD case study were aimed at providing answers to **RQ1** and **RQ2**. The two research questions are shown here again for reference.

RQ1: How the 3D CAD program can be utilized to develop flexible structures for 3D printed wearable apparel products by mimicking the structures of traditional woven/knit fabrics, using direct modeling method in Rhinoceros and TPU filament? How knowledge can be applied in this design process?

RQ2: How the properties and functions of the 3D printed structures can be modified and evaluated in using a FDM 3D printer with TPU filament? How the 3D printed structures can be constructed with traditional fabrics and evaluated for final wearable apparel product prototyping?

Phase 1 mainly answered **RQ1**. Phase 1 was a preliminary study focusing on 3D CAD design workflow to explore viable 3D printed structure(s) that could be integrated with traditional fabrics. A hybrid structure (6-way woven X 6-way loop woven) was created. This 3D printed hybrid structure was sewed with red neoprene knit fabrics to form a beach vest. The 3D

CAD workflow was first evaluated by the criteria in Table 1 to answer **RQ1**. Then as a supplement, the design process was evaluated using a six-stage design process based on Parsons and Campbell's (2004) approach, to demonstrate challenges and provide solutions during the whole design process.

Phase 2 mainly answered **RQ2**. Phase 2 was an extensive exploration based on Phase 1, and focused on creating and evaluating functional properties of different variations of 3D printed structures. Five variations of 3D printed structures were created. After the functional evaluations, a 4-way woven X 4-way loop woven structure was finally selected to be integrated with gray fleece fabrics to create a 3D printed hooded sweatshirt. This 3D printed hooded sweatshirt was later used for the research survey of users' perceptions in Study 2. The properties of all the variations of the 3D printed structures were evaluated using the criteria in Table 1 to answer **RQ2**. Then as a supplement, the design process was evaluated using a six-stage design process based on Parsons and Campbell's (2004) approach, to demonstrate challenges and provide solutions during the whole design process.

Phase 1: "Hybrid Comfort"—3D Printed Beach Vest Design

The designed 3D printed hybrid structure and final 3D printed beach vest are shown in Figure 22 for reference. The progress chart (Figure 23) is also provided to demonstrate the time duration for each design process. The progress chart provides an overview for readers to understand the design stages and objectives in Phase 1.

Figure 22. 3D printed hybrid structure and final 3D printed beach vest.

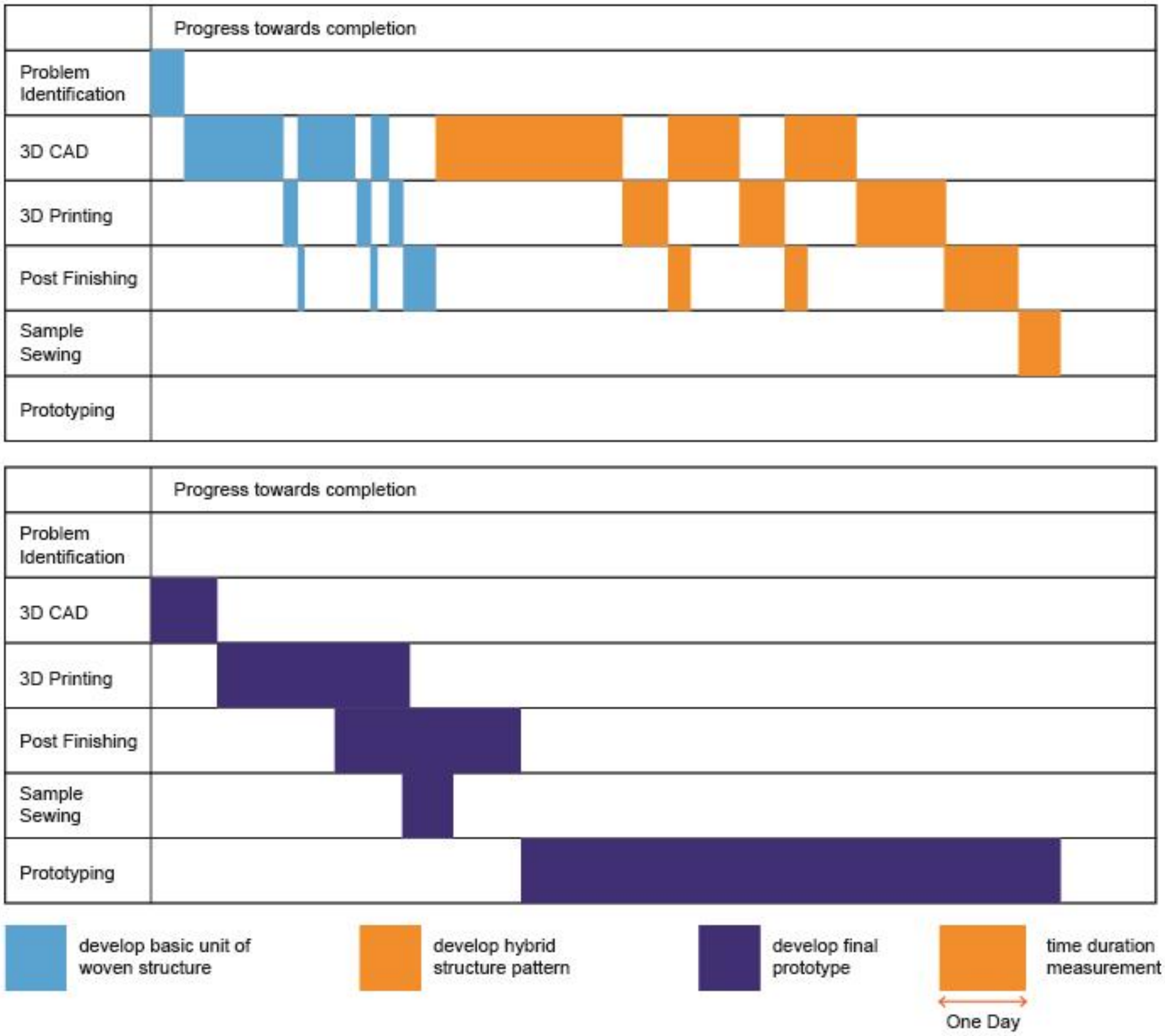


Figure 23. Progress towards completion for Phase 1.

Evaluations of 3D CAD design workflow. The evaluations of the 3D CAD design workflow were based on the criteria for RTD data collection shown in Table 1, aimed at answering **RQ1**. The evaluations of each item in the criteria are demonstrated in this section.

1. 3D CAD design logic. The general CAD design logic using Rhinoceros was to use control point curves to form 3D curves, use the pipe tool to form pipe solids, then use the array tool to apply curve to a rotational symmetric single unit and form repeated patterns. Detailed 3D

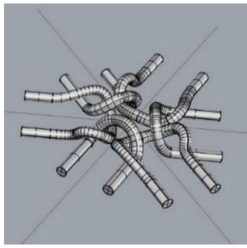
CAD design logic for each design step is demonstrated in Table 4, Column 1.

2. Knowledge applied. Knowledge involved in the 3D CAD workflow included both decision-making knowledge and technical knowledge. Decision-making knowledge helped decide the modeling logic for the creative design idea, while technical knowledge helped find the optimal way to accomplish modeling tasks. Both decision-making and technical knowledge involve tacit knowledge. The tacit knowledge had been gained from previous experience and could be applied to enhance the efficiency of the 3D CAD design workflow. Detailed knowledge used for each design step is demonstrated in Table 4, Column 3.

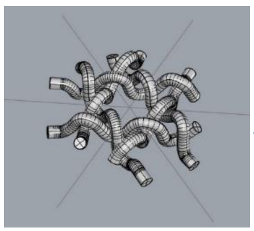
Table 4

Challenges in 3D Modeling Design Logic and Knowledge Applied

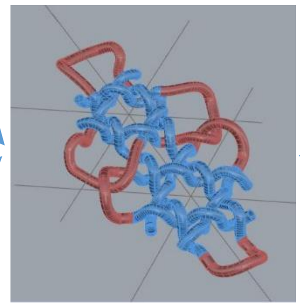
Design Logic Flow Chart With Rhinoceros Snapshots



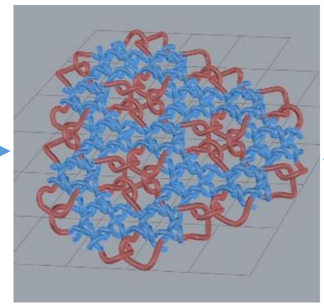
Loop Woven Unit



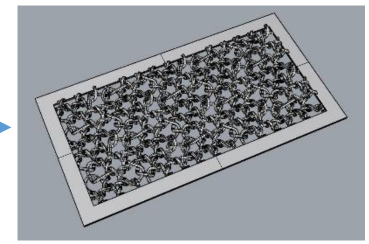
6-Way Woven Unit



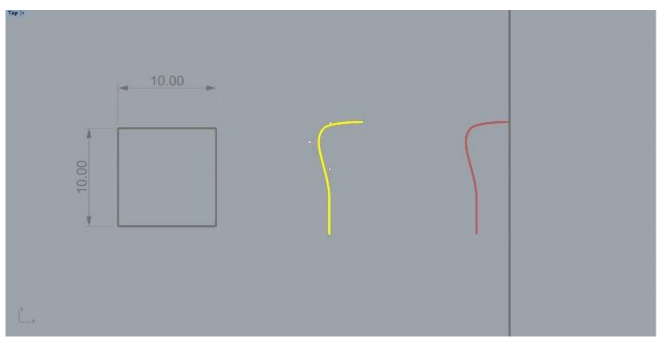
Hybrid Structure

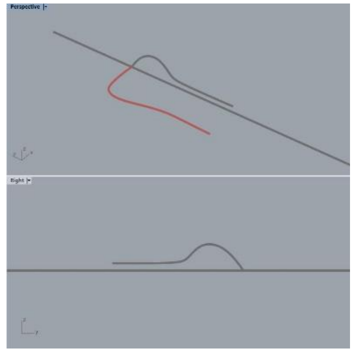
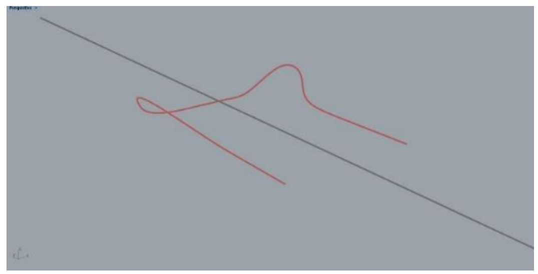
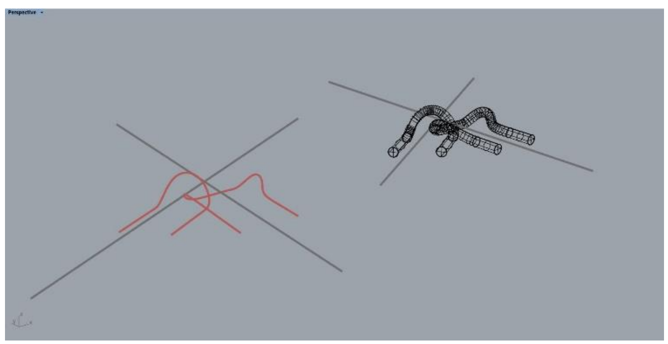


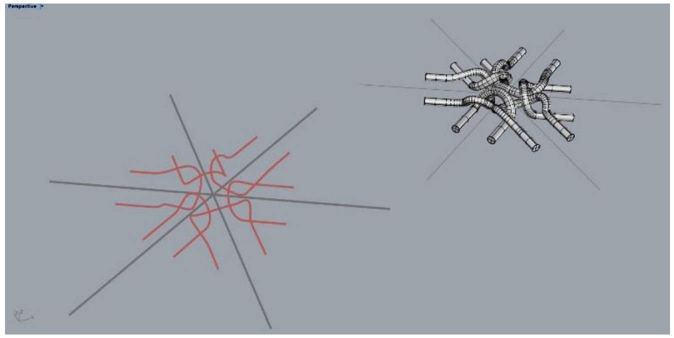
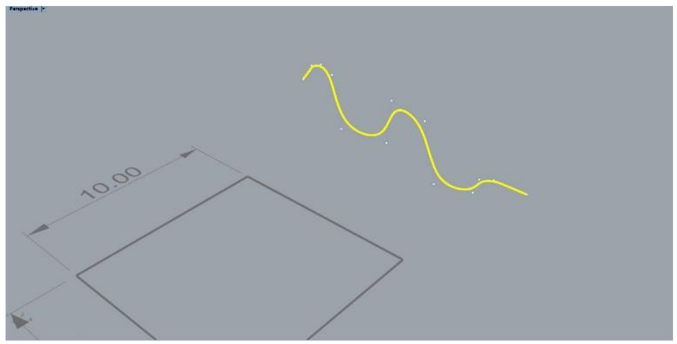
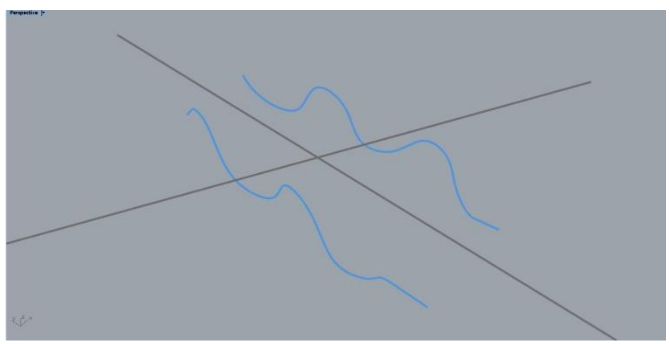
Repeated Pattern Sample

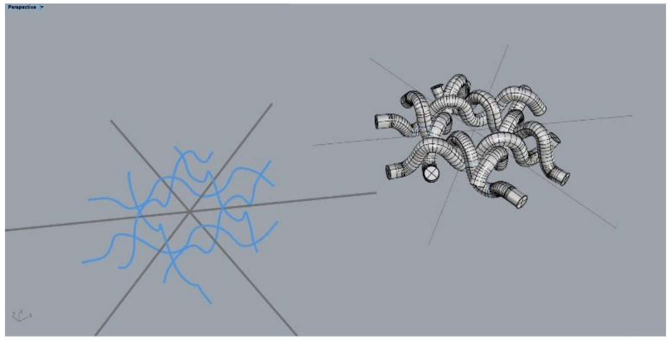
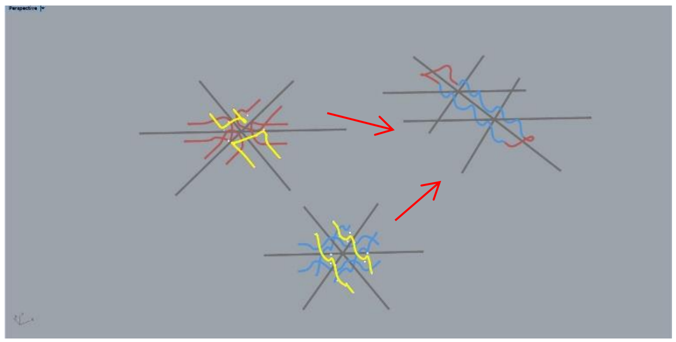
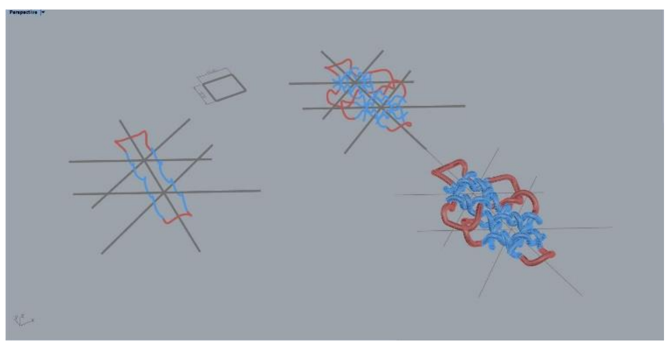


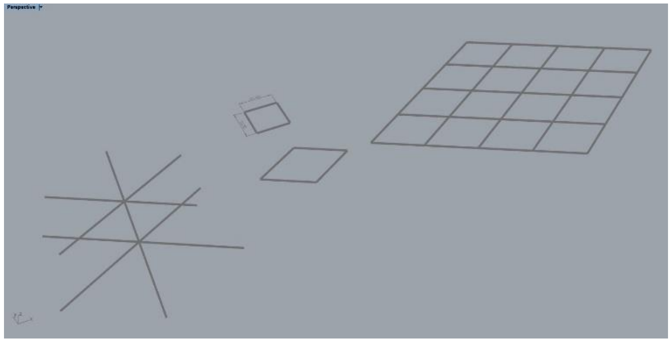
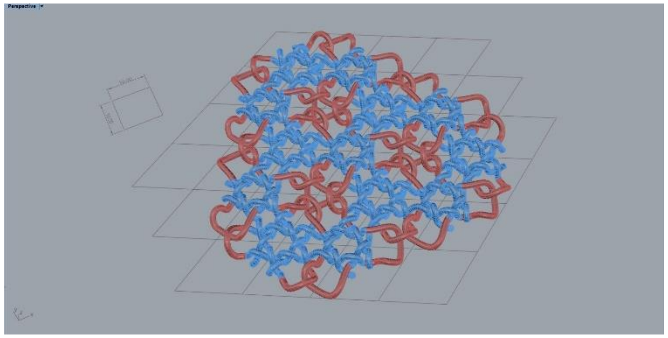
Repeated Pattern in 2 x 4 in. Frame

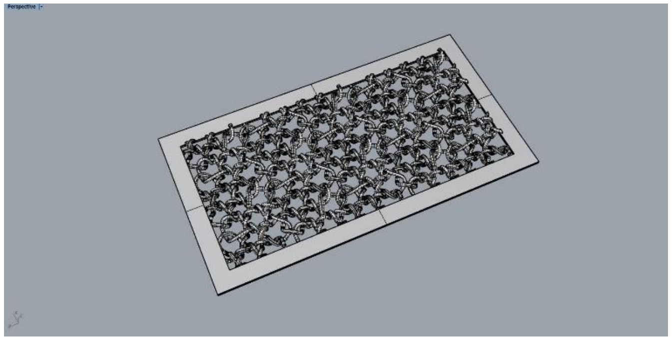
	1. Design logic	Rhino snapshot	2. Knowledge applied
Loop woven unit	***Step 1: Basic U-shape of loop woven unit***. Modify [control points] to change curve shape.	 Top view	*1. Loop woven shape (decision-making)*. This shape is the result of repeated modify-check tests to get the optimal shape.The top part is wider than the middle part to allow it to loop-connect with other units, and leave proper space to avoid collisions or large gaps between the 3D printing components. *2. Smooth connection (technical).* Making sure there is a smooth connection (tangency, or G1 connection) between curves. An unsmooth connection may cause the surface to crack when the pipe tool is applied.

	Step 2: Generate 3D curve + mirror. Draw a curve on right view (XY plane) → Use [curve from 2 view] tool to generate a 3D curve → [mirror] the curve → make curves smooth connection [match curve, G1 connection].	 Perspective view and right view  Perspective view	*1. Accuracy (technical).* Modeling accuracy makes components uniform and avoids unexpected problems. It is not accurate to use only control points to modify a curve into a 3D curve. In order to draw a 3D curve accurately, [curve from 2 views] is used. The 3D curve is mapped accurately based on the curves from top (XY plane) and right views (YZ plane).
Loop woven unit	***Step 3: Check connection of loop woven units.*** Use [pipe] to create pipelines via curves → Use [rotate 2-D w/copy] to make a copy and rotate 60° in XY plane → then flip over 180°.	 Perspective view	*1. Collisions and gaps (decision-making)*. In initial tests, collisions or gaps between components frequently happened. Thus, repeats from Step 1 to Step 3 were necessary to optimize the shapes. These checks to find the right shape took time and patience. *2. Center point (decision-making).* Deciding on a center point for [rotation] and [polar array] is crucial. The center point was decided by repeated modify-check tests to find an optimal point.

	Step 4: Generate the complete loop woven component. Use [polar array, N = 3] to generate the complete loop woven component based on the center point.	 Perspective view	1. *Collisions and gaps (technical)*. Collisons and gaps may still happen after using the polar array tool. Problems happened when (1) previous steps were not accurate (e.g., not symmetric), or (2) the right center point for the polar array was not found properly. Solutions were to check previous steps carefully to ensure accuracy, as well as to double-check the center point for the polar array.
6-way woven unit	***Step 5: Basic shape of woven unit***. Use [control point] to modify curve into a wave shape.	 Perspective view	*1. The 6-way woven shape (decision-making).* The single curve reflects a wave shape, and was adjusted by control points. However, too many control points may lead to an unsmooth curve, and not-easy-to-control shapes. Thus, three control points for a curvature is appropriate. This shape again is the result of repeated modify-check tests to get the optimal shape.
6-way woven unit	***Step 6: Mirror the woven unit.*** Use [rotate 2-D w/copy] to copy and rotate the curve 180° based on the center point.	 Perspective view	*1. Decide the symmetric type (technical)*. In some situations, it was not easy to decide which symmetric type (mirror/rotational) to use. The best way was to just use both symmetric tools to see the results. Loop woven is uaually mirror symmetric, while 6-way woven is usually rotational symmetric.

	Step 7: Generate the complete woven component. Use [polar array, N = 3] to generate the complete woven component based on the center point.	 Perspective view	Same as Step 4.
Hybrid woven unit	***Step 8: Integrate loop and 6-way woven components into a hybrid structure single unit.*** Use [match curve, G1 connection] to make smooth connection → use [control point] to adjust.	 Perspective view	*1. Smooth connection (technical).* Make sure there is a smooth connection (tangency, or G1 connection) between the two types of woven units. An unsmooth connection may cause the surface to crack when the pipe tool is applied.
Hybrid woven unit	***Step 9: Check connection of the hybrid structure.*** Use [polar array] to generate the full hybrid structure → use [pipe] to make curves into pipelines.	 Perspective view	*1. The gaps among repeat units (decision-making).* Connect four adjacent center points to form a single grid. The distances between the center points decide the scale of the single grid. Too big a scale may cause gaps between components and the hybrid structure to become loose. Too small a scale may cause collisions among components. Repeated modify-check tests were necessary to get the optimal scale.

Hybrid structure repeat	***Step 10: Create grid for unit repeat.*** Use [curve] to create one grid unit based on the center points → use [copy] to duplicate the grid unit into a big grid for hybrid structure repeat.	 Perspective view	*1. Snap to the right position (technical)*. The single grid decided on in Step 9 was used to form a big grid for woven unit repeat. Make sure to precisely snap the copies of the single grid to the end point of the existing grid to avoid problems.
	Step 11: Apply hybrid woven unit to the grid. Use [copy] to duplicate hybrid structure and snap to the grid to form a big pattern.	 Perspective view	*1. Auxiliary lines (technical).* Woven units need to be snapped to the grid intersections based on their geometric centers. Auxiliary lines (middle lines, center points) need to be reserved as references for unit repeats. Unit repeats are not accurate without auxiliary lines. Use [group] to group auxiliary lines with the referenced parts.

Final 3D CAD model	***Step 12: Final 3D CAD model.*** Use [rectangle] to create 2 x 4 in. rectangle → use [split] to cut hybrid structure pattern with the rectangle → use [offset] and [extrude closed planar curve] to create seam allowance.	 Perspective view	*1. Seam allowance connection to the hybrid woven structure (decision-making).* Make sure the seam allowance is connected to the hybrid structure part; that means the seam allowance should be partially overlapped with the hybrid structure, so that in final prints, two parts can be adhered together as one piece.

Note. The 10 x 10 (mm) rectangle shown in above snapshots is used as a scale reference. “[ ]” indicates the tool used in the Rhino 3D CAD process.

The key challenges and solutions regarding the evalutations of the 3D CAD design workflow were as follows:

(1) 2D sketch to 3D CAD model: Translating ideas from 2D sketches to a 3D CAD model is not an easy task. It took time to really look into the detailed structures and problems, which could not be observed from the 2D sketches. The final 3D CAD model was based on the initial 2D sketches, but went through many trials and tests to get the final workable shapes, which were different from the 2D sketches.

(2) Component collisions or large gaps: Component collisions were the most commonly seen problems throughout the whole CAD process. Because the curves were all 3D curves, it was not easy to control the overall shapes in one view. Thus, frequent repeat steps were necessary to optimize the curve shape and generate a workable structure.

(3) Scale: A workable structure is not necessary for the final 3D printed design, because the scale of the structure may influence the properties of the 3D printed pieces. Too large scale may cause big gaps, and the hybrid structure will become loose. Too small scale may cause collisions among components. The final scales should consider the performance of the 3D printed samples as well as the capability of the FDM 3D printer.

(4) Accuracy: An accurate modeling process enables workable 3D printed prototypes and largely reduces the time spent debugging problems. The woven parts were either mirror symmetric or rotational symmetric; thus, auxiliary lines were essential to maintain accurate modeling. Auxiliary lines should be kept and moved with the parts to which they refer. The changes made to the curves, or copying units, should also based on the auxiliary lines.

(5) Efficiency: The modeling efficiency was influenced by modeling accuracy and modulization. Accurate modeling reduces the time spent debugging problems. Accurate modelings were also based on auxiliary lines and the shapes were symmetric, so only a small part needed to be edited. The hybrid structure consisted of the same repeated units. Thus, the way to improve efficiency is to find the basic unit as a module, then repeat the module in a given grid.

3. 3D printer and filament used. KLONER3D®240TWIN FDM 3D printer and white TPU filament were used in this design process (Figure 17, Kloner3d, 2018).

4. Duration of the design process. The design process included three parts.The first part was to develop the basic unit of the woven structure. In this part, problem identification took around three hours, in which the researcher collected information and brainstormed design ideas. 3D CAD took the most time, around three workdays (8 hour/workday), as this part focused on 3D CAD to explore the possiblility of creating 3D printed structures. The 3D printing for each piece took around 15 minutes to one hour depending on the CAD model sample size; the total time was around three hours. Post finishing took around three hours; because of the limitations of the FDM printer, time was needed to clean the support parts. 3D CAD steps alternated with 3D printing and post finishing steps to provide feedback to improve 3D CAD designs.

The second part of the design process was to develop a hybrid structure pattern. This part was similar to the first part, but each process took around two to three times longer time. This was because the hybrid patterns were big, and they took more time in 3D CAD, 3D printing and post finishing steps. Sample sewing took around half a day (four hours).

The last part of the design process was to develop a final prototype. Alternations in steps between the 3D CAD and the 3D printed samples were not needed in this part, because of the gained knowledge and experiences from the previous design process. The design process was a linear process from 3D CAD to prototype: 3D CAD took around one day, 3D printing took around three days, post finishing took around two days, smaple sewing took around four hours, and final prototyping took around a week. The durations of the design parts are shown in Table 5.

Table 5

Durations of Design Processes for each Part of Phase 1

	Develop basic unit of woven structure	Develop hybrid structure pattern	Develop final prototype
Problem Identification	3 hours	-	-
3D CAD	3 days	5 days	1 day
3D Printing	3 hours	2 days	3 days
Post Finishing	3 hours	1.5 days	2 days
Sample Sewing	-	3 hours	4 hours
Prototype	-	-	5 days

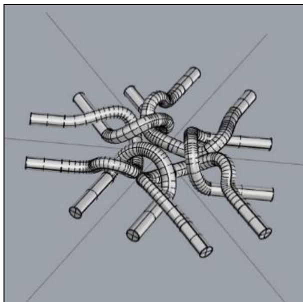
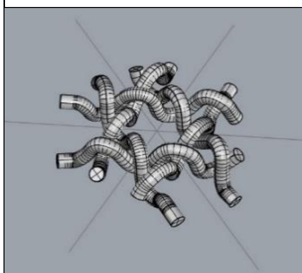
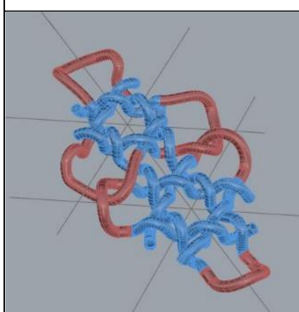
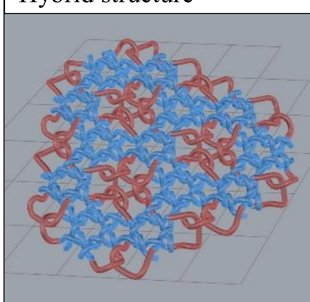
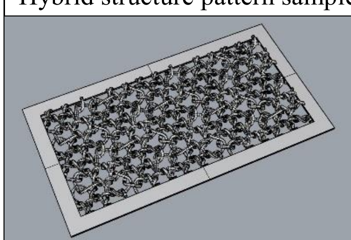
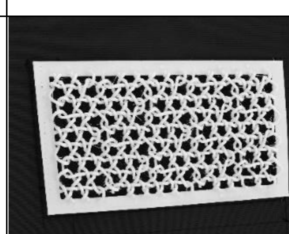
Note. One workday is 8 hours. Durations for each process show total accumulation.

5. Complexity of the 3D CAD modeling techniques and procedures. The complexity of the 3D CAD modeling techniques and procedures are shown in Table 6.

Table 6

Complexity of 3D CAD Modeling Techniques and 3D Printing Procedures in Phase 1

3D CAD model	3D printed sample	Complexity evaluation

 loop woven		Overall complexity level: High 1. Modify curve: High 2. Pipe: Low 3. Rotational array: Medium
 6-way woven		Overall complexity level: High 1. Modify curve: High 2. Pipe: Low 3. Rotational array: Medium
 Hybrid structure		Overall complexity level: Medium 1. Connect two woven structures: Medium 2. Modify grid: Medium
 Hybrid structure pattern sample		Overall complexity level: Low 1. Copy: Low
 2 x 4 pattern		Overall complexity level: Medium 1. Copy: Low 2. Trim: Low 3. Add seam allowance: Medium

Note. The complexity for each part was evaluated at three levels: Low, Medium and High.

6. Joints of 3D printed structures. The loop woven structure was inspired by the traditional knit structure, which are loops that hook with each other. The loop woven structure has the knit structure advantages of being flexible and stretchy. The 6-way woven structure was inspired by the traditional woven structure, which are interwoven threads. The 6-way woven structure has the woven structure advantages of being durable and strong.

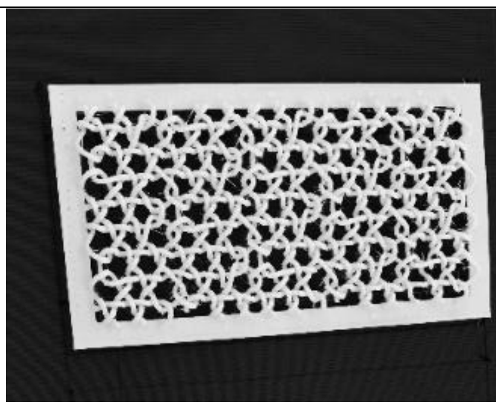
7. Advantages and limitations of 3D CAD modeling program. Rhinoceros was used as the 3D CAD modeling program in Phase 1. Compared to other commonly used CAD programs like Solidworks and 3ds Max, Rhinoceros is relatively small in file size, and its tools are easy to use. Thus, it is a feasible program for new users to learn, and makes it easy for fast 3D CAD prototyping. However, a limitation is that the complexity of the design shapes increases the file size, which further leads to a longer response time from the Rhinoceros CAD program. Additionally, Rhinoceros cannot auto-fix surface cracks. The file should be sent to a program called 3D builder to check and auto-fix cracks in the surfaces in the file. Further, Rhinoceros cannot optimize CAD file size; a larger file takes longer to process.

8. Limitations of 3D printers. Files exceeding 200 MB in size cannot be read by the 3D printer. In this case, the file size restriction limited the maximum measurements of the hybrid structure design. Thus, the larger piece had to be split into several small pieces, and manually glued together after printing. In addition, because the 3D models were thin and elaborate, the quality of the 3D printed models was largely influenced by the distance between the nozzle and the print bed. Too close may partially block the nozzle and reduce the volume of filament coming out, leading to burned filament in some parts of the structure. Too far may lead to the pieces not adhering firmly to the print bed. However, the print bed of the FDM 3D printer is not perfectly flat, so trying to print pieces with the same nozzle distance across the whole print bed may cause the problems described above. Thus, a certain nozzle distance may works for only specific areas of the print bed, limiting the size of the 3D printed pieces.

Evaluations of the properties of the 3D printed structure. The evaluations of the 3D printed structure were based on the criteria for RTD data collection shown in Table 1, aimed at answering **RQ2**. These evaluations are shown in Table 7.

Table 7

Evaluations of the Properties of the 3D Printed Structure in Phase 1



Key dimensions for exploring properties of 3D printed structure	**Evaluation** *7 schematic differential scale*	**Notes**
1. Softness	4 ■■■■□□□	Softness of the 3D printed structure is related the properties of the TPU filament. The structure is softer than other filament but not as soft as traditional fabrics.
2. Flexibility	7 ■■■■■■■	The 3D printed structure is flexible, and can be squeezed in hand.
3. Connections	5 ■■■■■□□	The 3D printed structure can be sewed with traditional fabrics by adding a seam allowance.
4. Breathability	7 ■■■■■■■	The 3D printed structure is a hollow structure, and

		extremely breathable.
5. Stretchability	6 ■■■■■■□	The 3D printed structure is stretchy, due to the loop woven structure.
6. Cushioning	4 ■■■■□□□	The 3D printed structure reflects cushioning, due to the interlaced woven structure.
7. Durability	4 ■■■■□□□	The 3D printed structure reflects medium level durability. Some parts were broken or showed low quality, because of the capability of the FDM printer.
8. Weight	6 ■■■■■■□	The 3D printed structure is low in weight.
9. Complexity	7 ■■■■■■■	The 3D printed structure is very complex.
10. Aesthetic judgment	7 ■■■■■■■	The 3D printed structure looks beautiful.
11. 3D printing success	4 ■■■■□□□	Success rate is at medium level.

Final prototype construction of the 3D printed beach vest. Challenges and findings during the prototyping process of the 3D printed beach vest are demonstrated here.

Pattern making. Because Phase 1 was an early stage of exploratory research to integrate 3D printed structures with traditional fabrics, the apparel pattern for the traditional neoprene knit fabrics used a relatively simple design. It was a vest without sleeves or hood. The seam lines were all straight, except for the neckline and cuffs. The pattern design is shown in Figure 24.

Auto stitching vs. manual control stitching. Regarding sewing, traditional fabrics usually use the auto-sewing mode of a sewing machine, because auto sewing is more efficient than manual sewing and enables neat stitch lines. However, the seam allowance of the 3D printed structures is thick, and auto sewing is fast; which made it easy to break the needle. Additionally, it is not possible to stitch 3D printed structures and the neoprene fabrics neatly when using auto sewing. Thus, manual control stitching was necessary for this project. Manual control stitching refers to manually rotating the sewing machine wheel to control the stitching speed. Manual

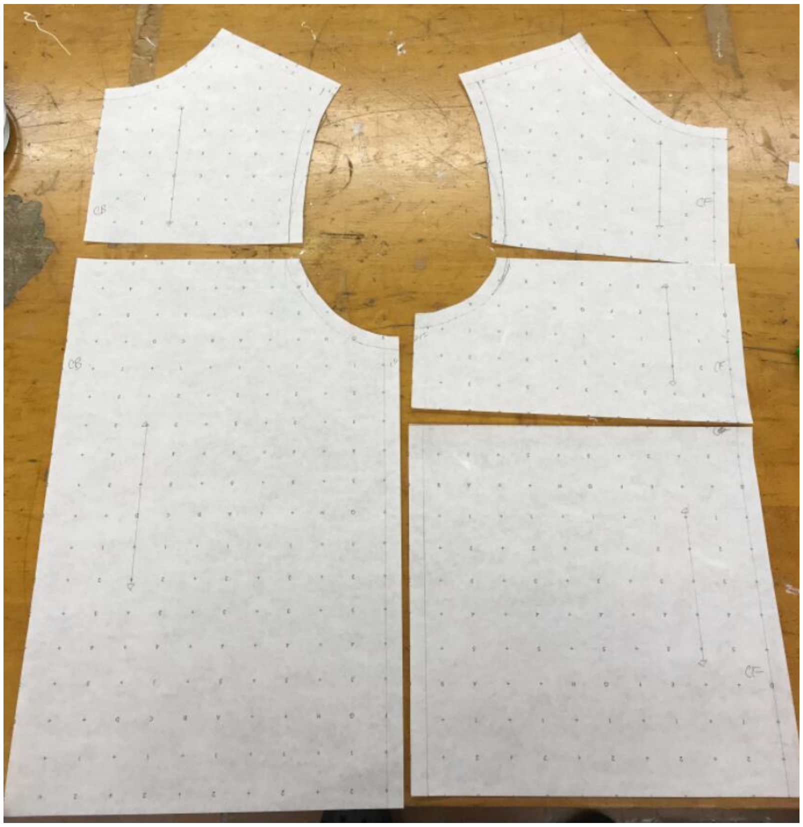


Figure 24. Pattern making for the 3D printed beach vest.

control stitching helped avoid breaking needles and kept the stitch lines neat.

Fold the stitch lines. In order to keep the vest's appearance simple and its aesthetic appealing, the seam allowance was stitched and folded to the backside. However, folding the stitch lines inside led to double layers of fabrics and one layer of seam allowance. This caused the stitching parts to be thick, which may affect the comfort of the wearable apparel product.

Symmetry. Keeping the symmetry of the wearable apparel design during the prototyping process was another challenge. There were two solutions. One solution was to leave cut markers along the seam lines. The other one was to keep an eye on the other side of the garment while stitching, and undo and redo the stitching where necessary.

The final prototype construction of the 3D printed beach vest is shown in Figure 25.

Prototyping Process

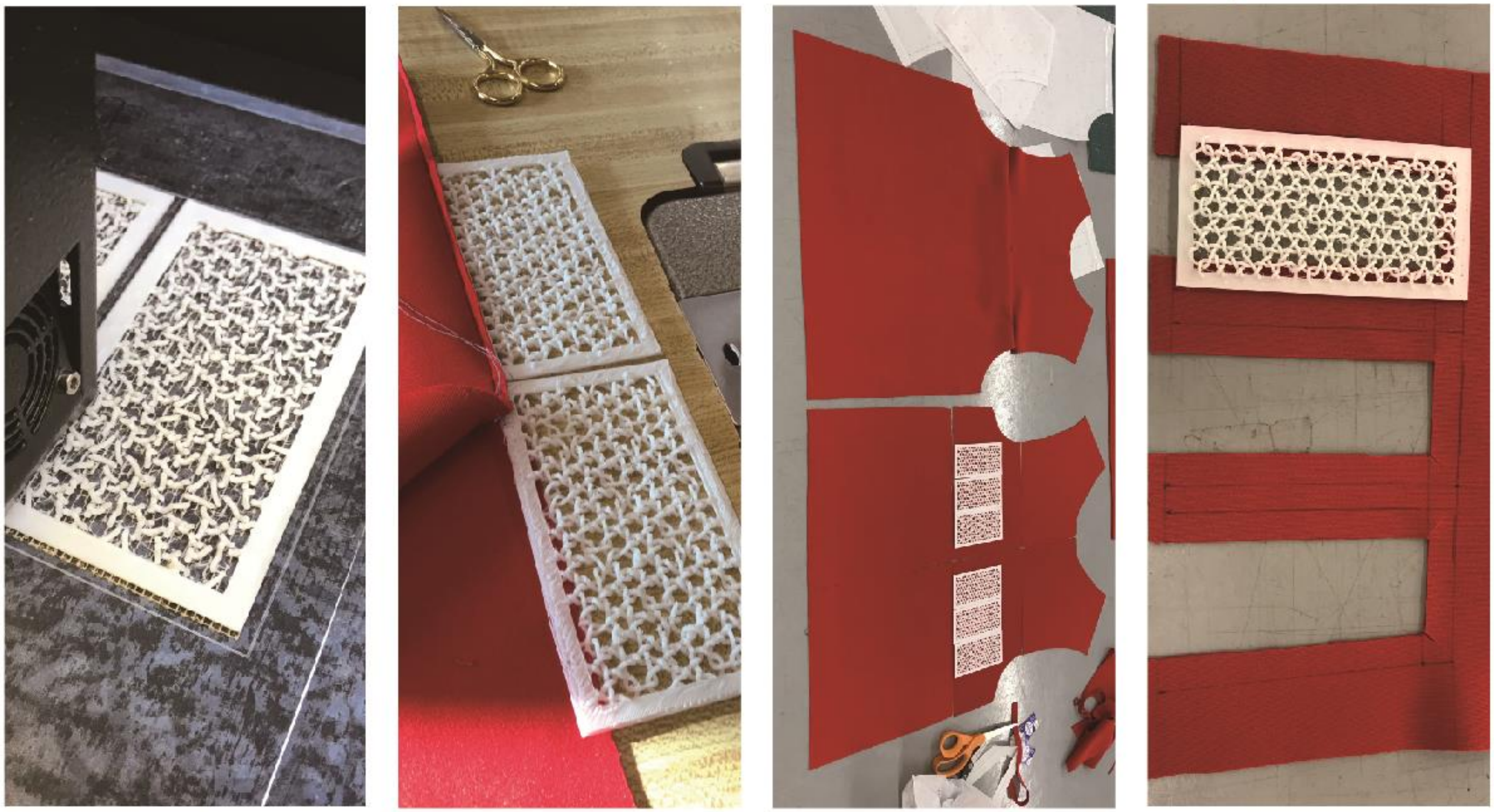


Figure 25. Final prototype construction of the 3D printed beach vest.

Challenges and Solutions in the Design Process

As a supplement, the design process of Phase 1 was evaluated based on a six-stage design process adopted from Parsons and Campbell's (2004) approach, to demonstrate challenges and solutions during the whole design process. All this information was organized in Table 8.

Table 8

Challenges and Solutions in the Design Process of Phase 1

Design Stage	Challenge Topic	Challenge	Solution
1. Problem identification	RQ1	Answer RQ1	1.1
2. 3D CAD	Verify design ideas	Verify the viability to create hybrid 3D printed structures.	2.1
	Unit connection	How to connect woven and loop woven structures. 4-way or 6-way.	2.2
	Aesthetics	Aesthetics is a crucial factor influencing the design decision-making process.	2.3
	Modify curves and connections	Modifying curves and connections for a hybrid structure are not as easy as drawing curves and link ends on a piece of paper. They are complicated technical issues.	2.4
	Measurement and pattern	(1) Radius of the curves, so the curves could form pipelines and leave enough clearance when printing. (2) Scale and thickness of a single unit; too big a scale may cause stiffness, while too small a scale cannot be 3D printed.	2.5
		Identifying symmetry types in the pattern	2.6
3. 3D printing	Check issues and printing quality	Small sample test: a small sample hybrid structure was exported from Rhino and imported into the FDM 3D printer.	3.1
	Capability of the FDM 3D printer	Issues concerning the FDM 3D printer happened when (1) the file size was too big to read, thus creating a need to reduce the number of basic units in the pattern to reduce the file size; (2) printing unexpectedly failed, usually caused by nozzle blocking, uneven print bed, fragments adhered to components, etc. Specific causes of some failures could not be identified.	3.2
4. Post finishing for 3D printed structure	Clean support parts and clip adhered parts	According to the printing mechanism of the FDM printer, in order to print complex structures with many gaps, it prints support parts to hold and keep the structure in the right shape. Thus, when finished, many support parts were left in the 3D printed pieces. They needed to be cleaned before testing. Further, due to the capability of the 3D printer (e.g., printing accuracy and nozzle radius), if the gap between components was too close, these	4.1

		components could adhere together, leading to the pieces being stiff and dysfunctional.	
5. Sample assembly	Sew 3D printed samples with traditional fabrics	First, different from traditional fabrics, the pipelines of 3D printed hybrid structure are thicker than traditional fabric threads, leaving large gaps. It may become loose when directly stitched onto traditional fabrics.	5.1
		Second, the 3D printed seam allowance was thicker and stiffer than traditional fabrics'. When using a sewing machine, auto sewing may lead to crooked seam lines, or even break the needle.	5.2
6. Final prototype construction	Decide on wearable apparel product type	The hybrid 3D printed structure is water-resistant, flexible, and porous and thus could provide a venting function (Cui & Sun, 2018).	6.1

Note: Refer to the number listed in this table, find the detailed description of the solutions below

Solutions and results.

1. Problem identification.

1.1 It confirmed the viability to use the direct modeling method and the Rhinoceros 3D CAD program to design a 3D printed structure that could be printed with a FDM 3D printer.

2. 3D CAD.

2.1 Instead of considering measurements, the overall shapes were emphasized first. This was because the first thing to confirm was the possibility of designing the "hybrid" structure. The basic unit structure lines of both woven and loop woven were created.

2.2 The simplest connection is a 4-way woven and a 4-way loop woven; the basic unit outline is a square shape. However, in this early exploration stage, it was not known whether a 4-way loop woven structure was durable enough; it might have been too loose. Thus, considering the limited timeframe, a 6-way woven and 6-way knit hybrid structure was decided on; the basic unit outline is a hexagon shape.

2.3 In order to make the piece aesthetically appealing, a slightly complex shape, like a hexagon, may be preferable. Repeated hexagon shapes consisting of hybrid woven and loop woven structures may have potentially greater visual impact.

2.4 (1) Line collision and overlap. Changing the shape or curvature of a 3D curve in one view may also change the shape in another view, which is a chain effect that may lead to line collision and overlap. Thus, repeating "change-check" actions is necessary when modifying curves and connections.

(2) Curvature. Certain curvatures should be maintained to enable smooth connections when

connecting two lines. Otherwise, with a too small curvature cracks and broken surfaces may happen when making lines into solid pipelines. Specific curvatures should be repeatedly tested to find the optimal one for a specific connection.

(3) Symmetry. Accurately identifying symmetry in the 3D CAD modeling process tremendously improves efficiency and reduces the amount of work. Because the logic is simple, for a symmetric shape, editing one part and copying it is more time-saving and accurate than editing two parts. There are basically two types of symmetries: mirror symmetry and rotational symmetry. Mirror symmetry is a symmetry according to a middle line, while rotational symmetry is a symmetry according to a center point. Problems may happen when if the symmetry type is wrongly identified, or if the wrong middle line/center point is found.

2.5 In an exploration of an innovative design, there is no standard for how to decide the measurements, only practice through repeated tests. Such tests usually are integrated with a 3D printer to print samples for evaluation and feedback. Once the single unit of the hybrid structure is decided, it is copied and pasted into a pattern.

2.6 There are two types of symmetry, mirror symmetry, which is based on a middle line, and rotational symmetry, which is based on a center point. Accurately identifying symmetry types in the pattern would reduce the amount of work and generate a more accurate structure pattern.

3. 3D printing.

3.1 A sample usually took several minutes to finish. The researcher needed to observe the whole printing process, and paused any time problems happened. If the components were too small, the printer would not print anything, leaving empty space. If the components were too big, the sample might feel stiff. The minimum printing width is 1mm according to the printer instructions, while in the repeated sample tests, a 0.5mm radius for the pipelines (1mm diameter) was not enough, as some parts were missing, and the overall shapes were not strong enough. The optical radius for the pipelines was 0.7mm (1.4mm diameter), and was used through the whole design process without any issue. A 2 x 2 x 1/4 in. swatch took around two hours to print, and one hour for post finishing.

3.2 Printing again, sometimes several times, solved most problems.

4. Post finishing for 3D printed structure.

4.1 Two tools were used for cleaning: a tweezer to clean the supports and other small messy threads, and a small pair of scissors to cut the adhered parts. Cleaning the adhered parts took the most time in the post finishing process. A 2 x 4 in. piece usually took one hour to clean. A problem discovered in the post finishing part was that, due to the complex structure, the adhered parts were not easy to clean, thus, sometimes those parts broke. The solution was to improve the 3D CAD model, leaving more space between two pipelines. Later samples showed that the number of adhered parts decreased, but still many were left, indicating that the extent of the 3D printer's capability may have been reached. Therefore, the final solution was to sharpen the researchers' skills to clean more efficiently and to avoiding breakages.

5. Sample assembly.

5.1 In this circumstance, a 1/4 in. wide 3D printed seam allowance was added to the 2 x 4 in.

hybrid structure to enhance the stitch tenacity.

5.2 The only solution was to manually roll the spinning wheel to control the speed, and stop immediately when problems happened.

6. Final prototype construction.

6.1 In this phase, a men's vest was developed for beach wear using neoprene knit and 3D printed hybrid structures. A total of eight 3D printed hybrid structure pieces were sewn with red neoprene fabrics; six were on the front midriff, with three inserted on each side. Two were on the back shoulder yoke. The beach vest also had a standup collar and a silver waterproof zipper on the center front (Cui & Sun, 2018).

Summary of Phase 1.

Phase 1 adopted a six-stage design process based on Parsons and Campbell's (2004) approach, mainly to answer **RQ1**. Phase 1 explored and confirmed the viability of using the direct modeling method and an FDM 3D printer to design a 3D printed hybrid structure that can be integrated with traditional fabrics. Phase 1 demonstrated the detailed design process, and the 3D CAD workflow was evaluated by the criteria listed in Table 1.

Phase 1 was the initial design research to provide detailed descriptions and illustrations of the design process for a 3D printed wearable apparel product. The design process was simplified and generalized into a flow chart (Figure 26). This flow chart was also used in Phase 2. In the future, the flow chart of the design process for the 3D printed wearable apparel product could be improved and applied to related 3D printed wearable apparel product design and research.

One 3D printed structure was designed in Phase 1 for property evaluation. However, only one sample was not enough. More variations of 3D printed structures were needed in the next design Phase to answer **RQ2** and provide holistic evaluations of 3D printed structures.

A 3D printed beach vest was prototyped in Phase 1. This prototype provided valuable knowledge about and implications of integrating 3D printed structures with traditional fabrics, and helped improve the 3D printed wearable apparel product design for the next phase.

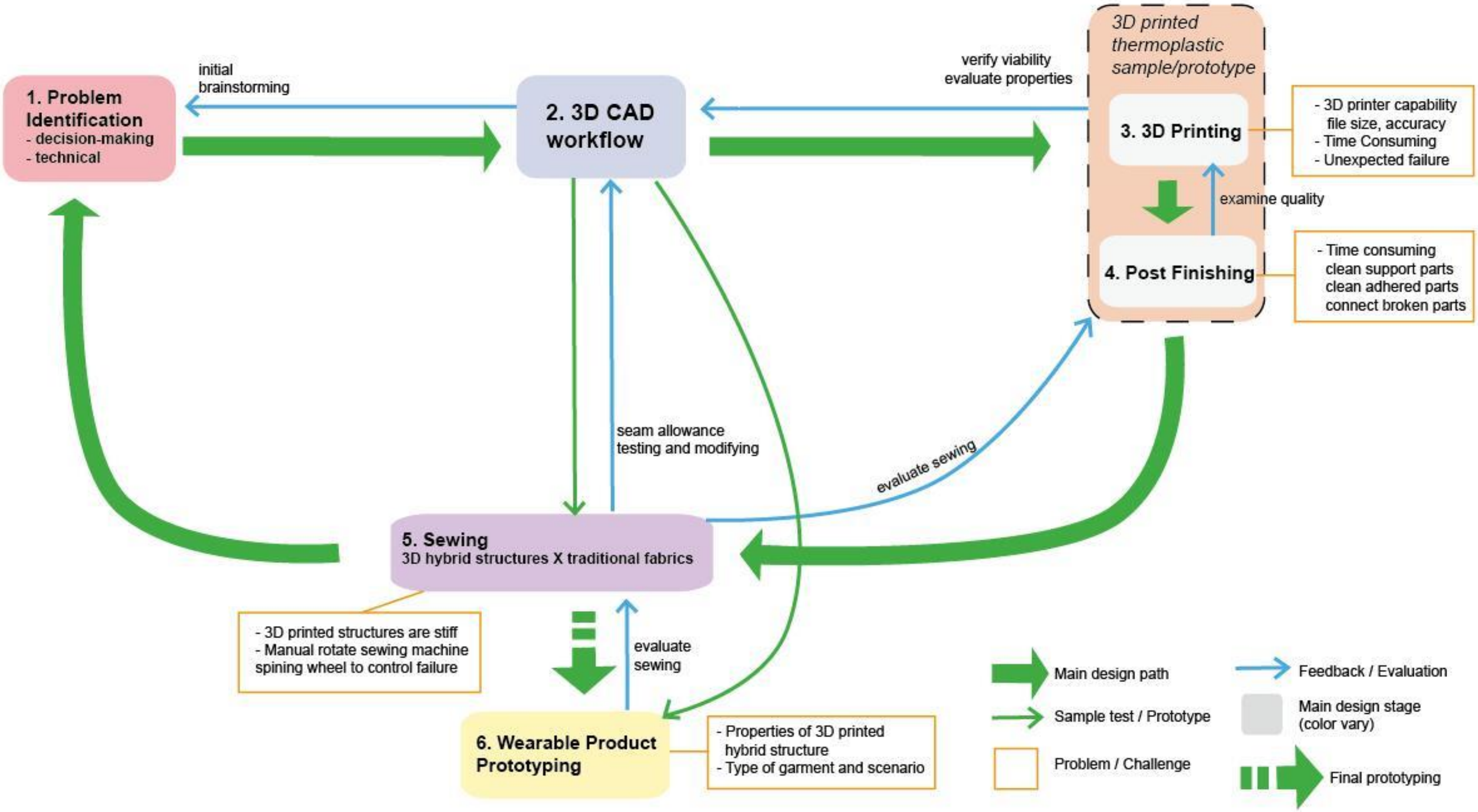


Figure 26. Flow chart of the design process for the 3D printed wearable apparel product.

Phase 2: Unisex 3D Printed Hooded Sweatshirt Design

The selected 3D printed structure and final 3D printed hooded sweatshirt are shown in Figure 27-1 (on a female manikin) and Figure 27-2 (on a male manikin) for reference. The original sample from Phase 1 and all five variations of 3D printed structures are shown (see Table 9). Additionally, the progress chart is provided (Figure 28) to demonstrate the time duration of each design process. The progress chart provides an overview for readers to understand the design stages and design objectives in Phase 2.

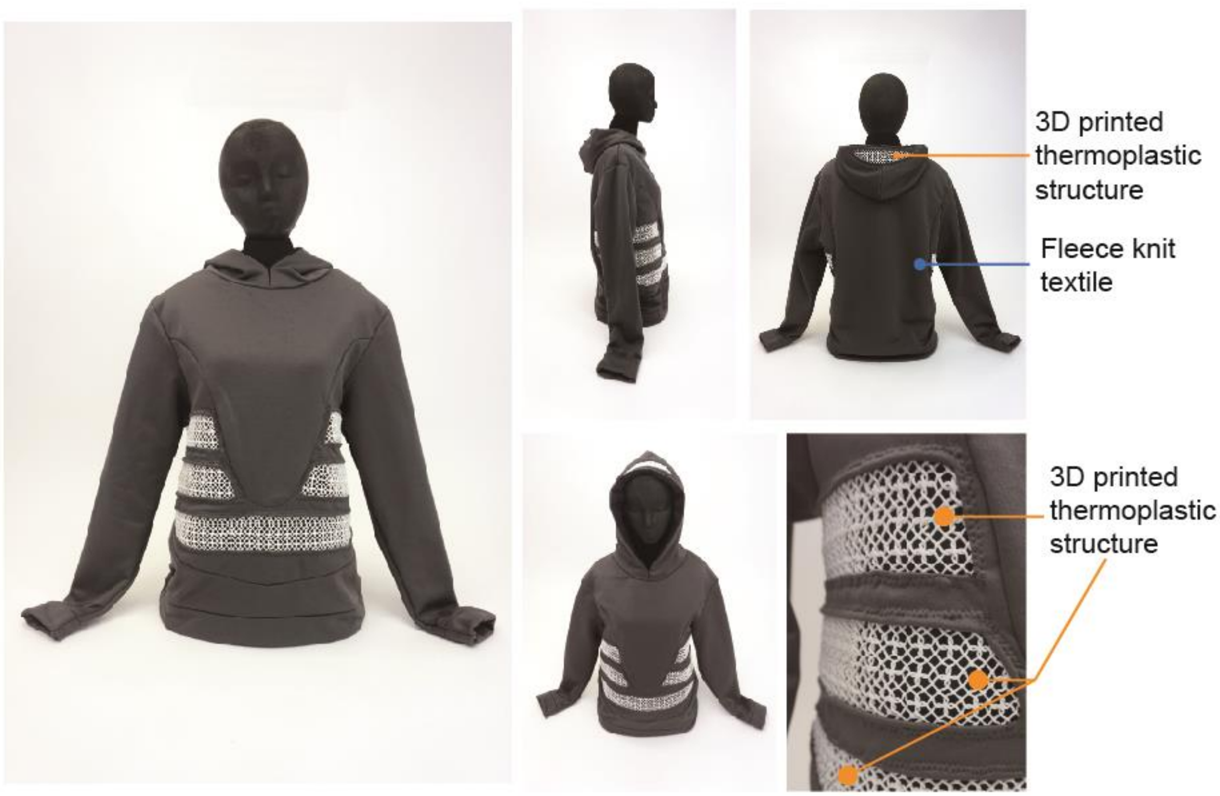


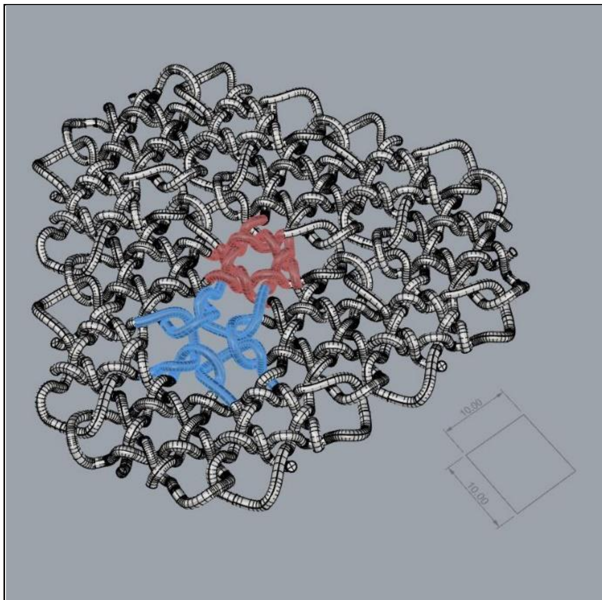
Figure 27-1. 3D printed hooded sweatshirt on a female manikin.

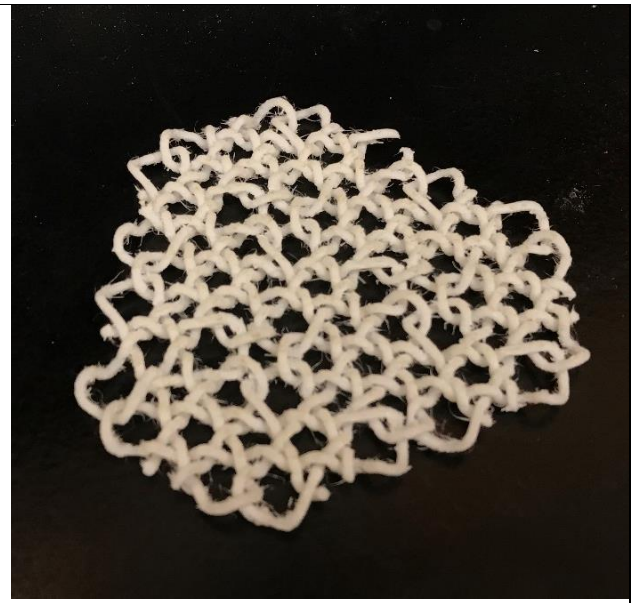
Figure 27-2. 3D printed hooded sweatshirt on a male manikin.

Table 9

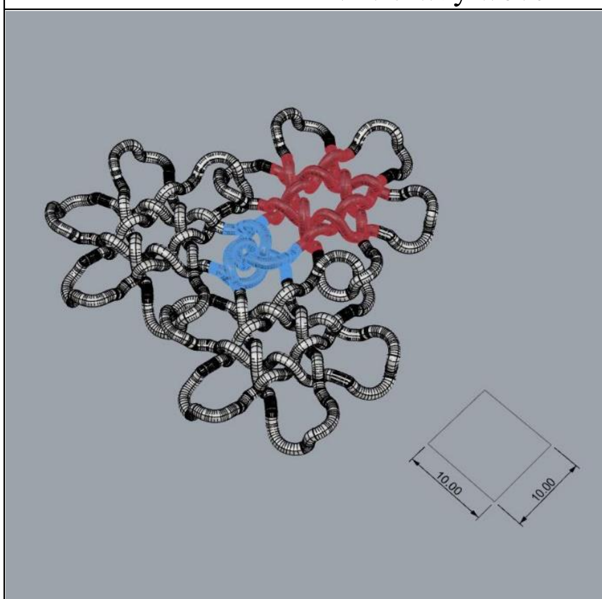
Variations of Woven Hybrid Structures

Note: (1) Variations 1 through 5 were marked V1 to V5. V0 was from Phase 1. (2) Different colors refer to different structures: Blue: Loop woven; Red: Woven	
3D CAD model	**3D printed structure**
V0: 6-way woven X 6-way loop woven hybrid structure designed in Phase 1	

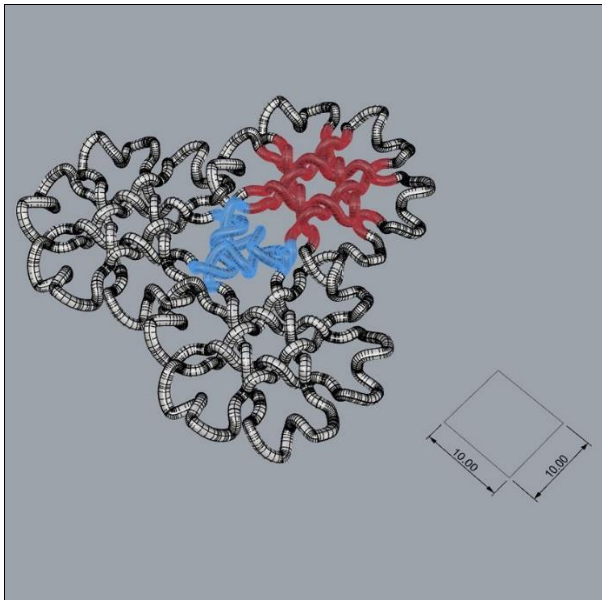
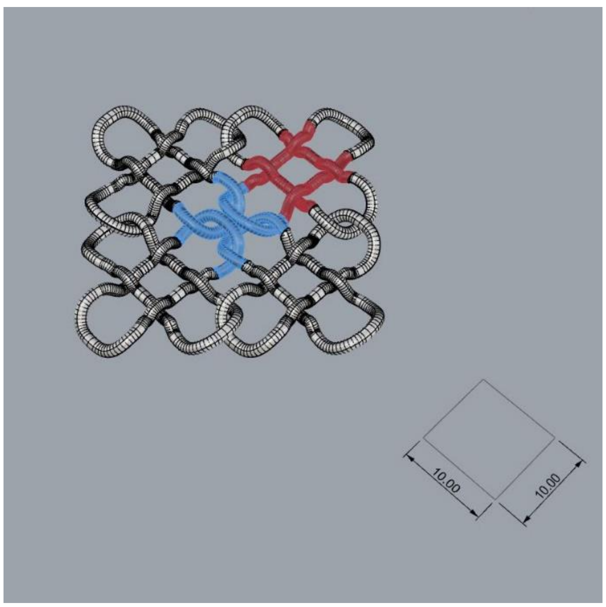
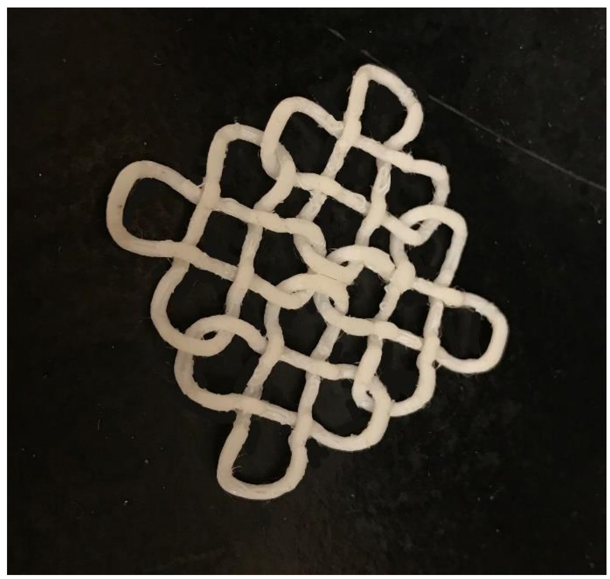


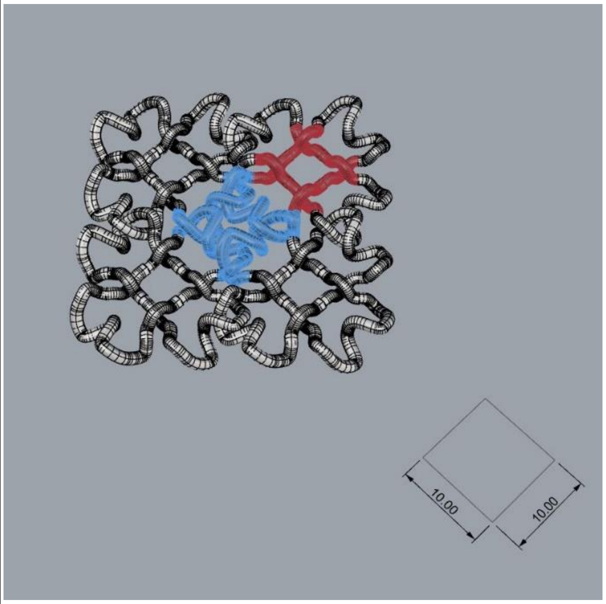
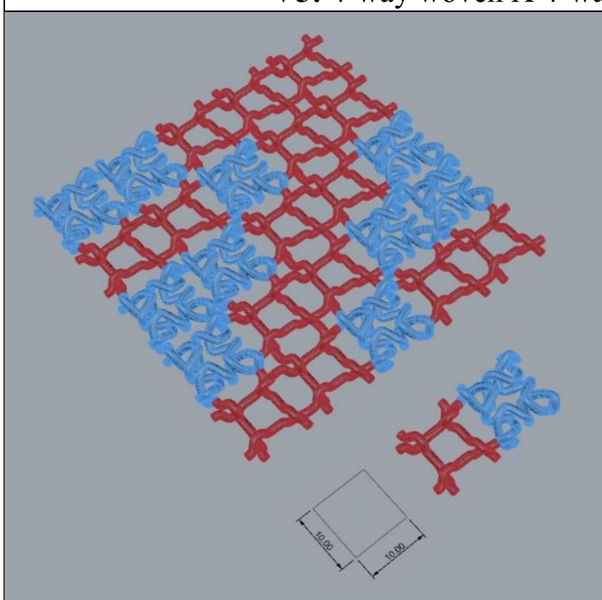
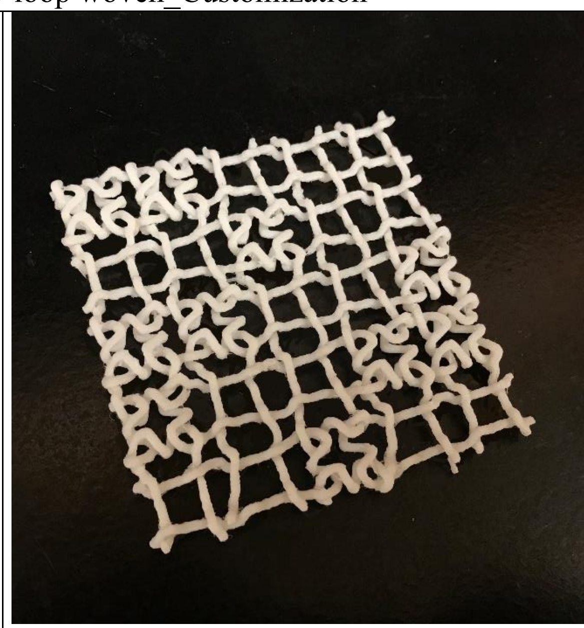


V1: 6-way woven X 6-way loop woven_Tight



V2: 6-way woven X 6-way loop woven_Loose

	
V3: 4-way woven X 4-way loop woven_Tight	
	
V4: 4-way woven X 4-way loop woven_Loose	

	
V5: 4-way woven X 4-way loop woven_Customization	
	

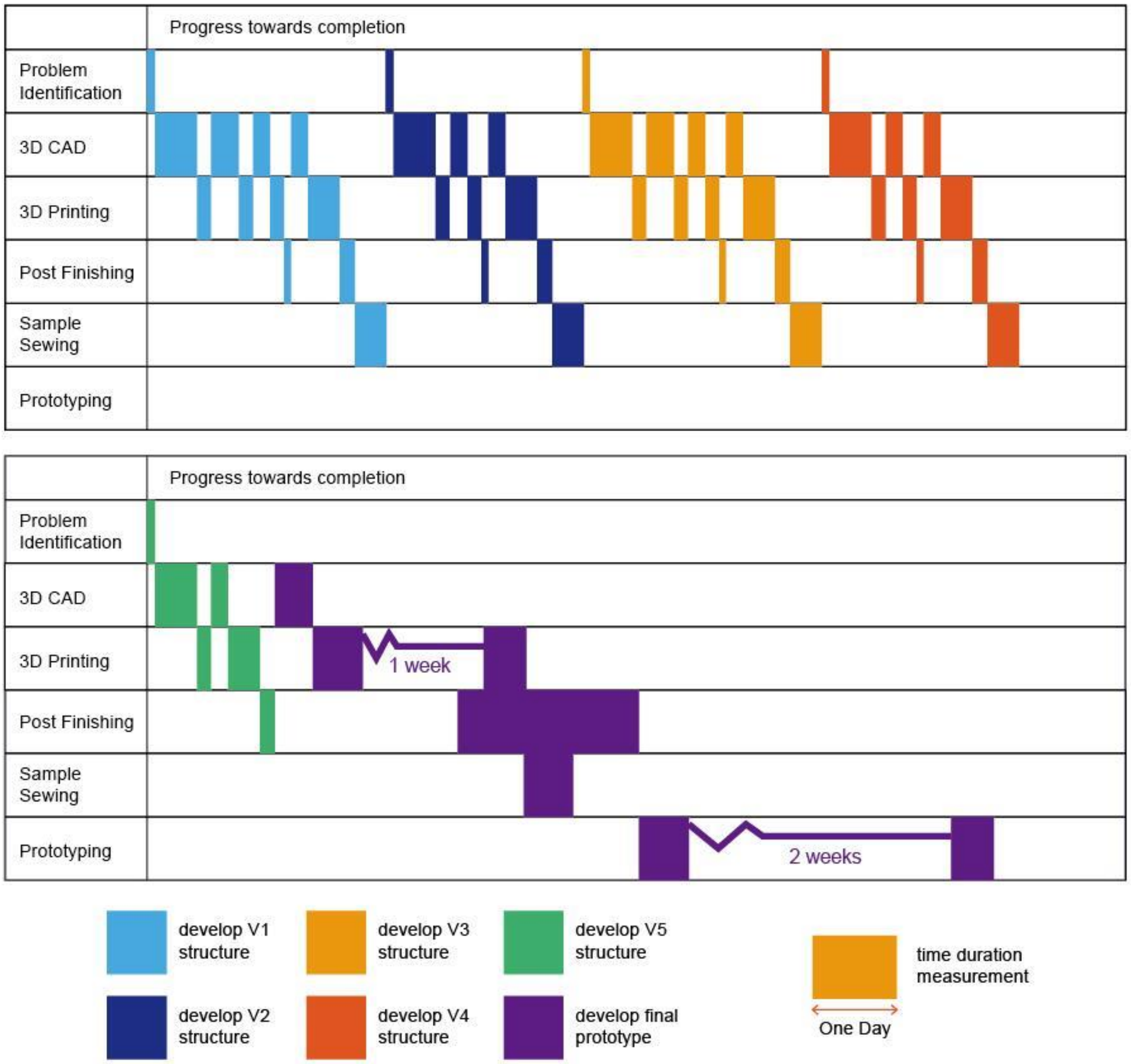
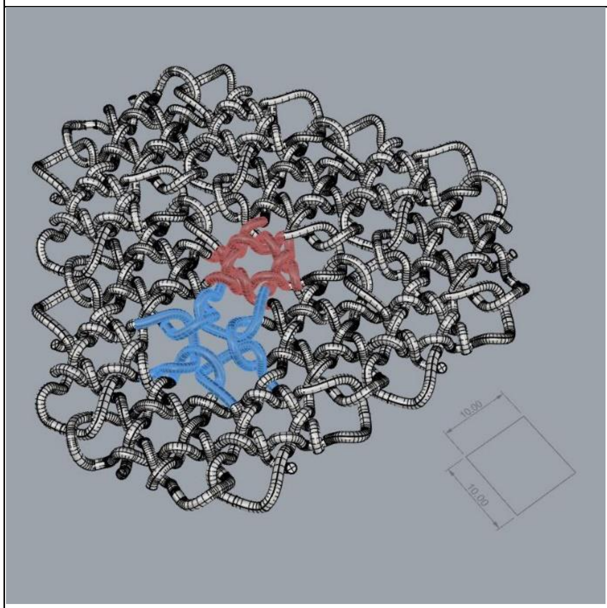


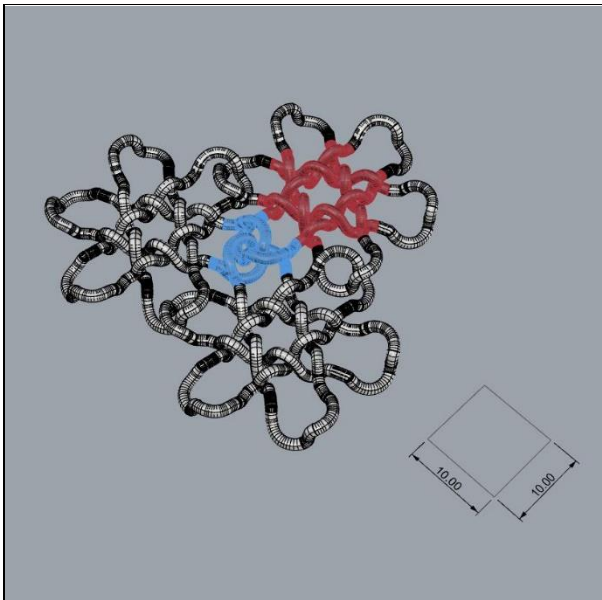
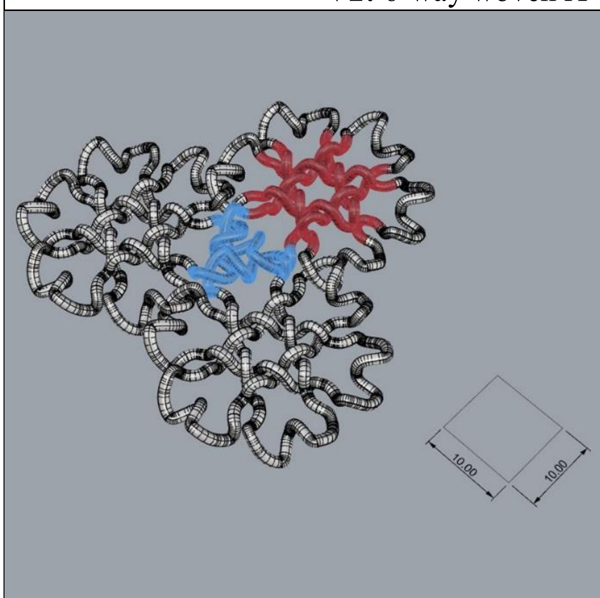
Figure 28. Progress towards completion for Phase 2.

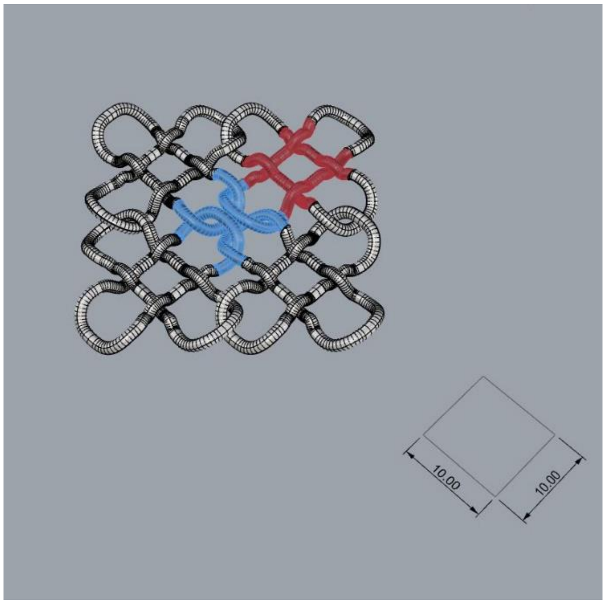
Evaluations of 3D CAD design workflow. The evaluations of the 3D CAD design workflow were shown in Table 10. The evaluations did not follow the criteria one by one, but were simplified to demonstrate major changes, because Phase 2 used the same design logic and the same knowledge and skills as Phase 1. Phase 2 adopted the existing model unit from Phase 1,with some small changes. Thus, the 3D CAD logic for Phase 2 mainly used curve editing and the rotational symmetric tool to create different variations. The design logic was simplified and the modeling efficiency was enhanced by using the existing model unit, knowledge, and skills for the new design phase.

Table 10

Evaluations of the 3D CAD Design Workflow for Phase 2

Note: (1) Variations 1 through 5 were marked V1 to V5. V0 was from Phase 1. (2) Different colors refer to different structures: Blue: Loop woven; Red: Woven	
3D CAD model snapshot	**Modifications**
V0: 6-way woven X 6-way loop woven hybrid structure designed in Phase 1	
	The V0 structure was designed in Phase 1. The blue part is a loop woven unit and the red part is a woven unit. The two units were adopted as basic units in Phase 2 to be modified into different 3D printed structure variations.
V1: 6-way woven X 6-way loop woven_Tight	

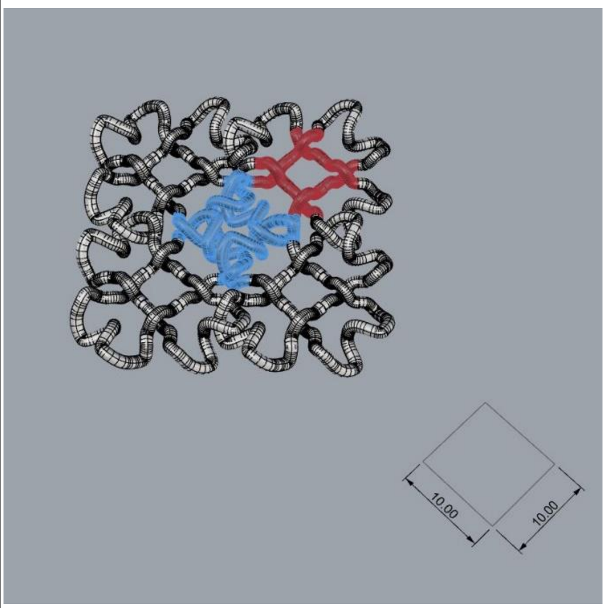
<table>
<tr><td>
</td><td>V1 adopted the 6-way loop woven and woven units from Phase 1. V1 only changed the 6-way loop woven unit to make it tighter. In order to make this change, the rotational symmetric center was modified. The center was moved closer to the loop woven unit to form this tighter loop woven structure.
The connections between the two units were slightly modified to ensure they were smooth.</td></tr>
<tr><td colspan="2">V2: 6-way woven X 6-way loop woven_Loose</td></tr>
<tr><td>
</td><td>V2 adopted the 6-way loop woven and woven units from Phase 1. V2 only changed the 6-way loop woven unit to make it looser. In order to make this change, the loop woven structure was modified to be more curved; it looked like a “W.”
The connections between the two units were slightly modified to ensure they were smooth.</td></tr>
<tr><td colspan="2">V3: 4-way woven X 4-way loop woven_Tight</td></tr>
</table>



V3 adopted the 6-way loop woven and woven units from Phase 1. V3 changed both the 6-way loop woven unit and the woven unit to 4-way. In order to make this change, the number of units for rotational symmetry was changed to 4 (instead of 6).

The connections between the two units were slightly modified to ensure they were smooth.

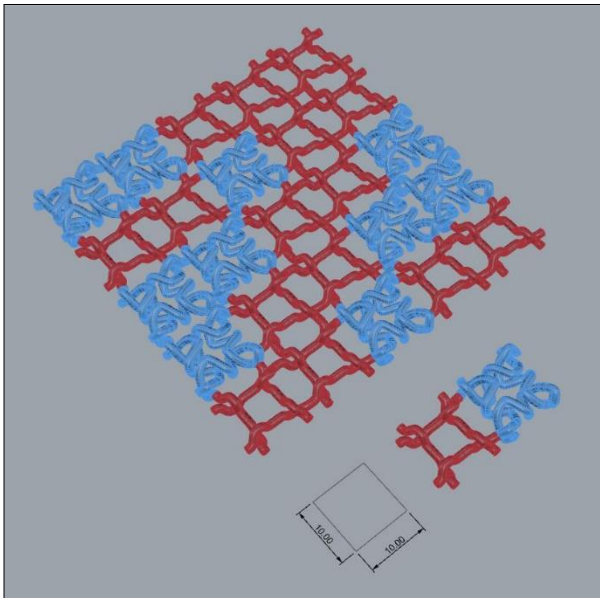
V4: 4-way woven X 4-way loop woven_Loose



V4 adopted the 6-way loop woven and woven units from V2. V4 changed both the 6-way loop woven unit and the woven unit to 4-way. In order to make this change, the number of units for rotational symmetry was changed to 4 (instead of 6).

The connections between the two units were slightly modified to ensure they were smooth.

V5: 4-way woven X 4-way loop woven_Customization

	V5 adopted the 4-way loop woven and woven units from V4. V5 changed the connections between the two units to make both units into same-size, interchangeable modules. The pattern could be customized. Adding more loop woven structures increased stretchability, while adding more woven structures increased durability.

Durations of 3D CAD modeling. Compared to the durations of the design process in Phase 1, Phase 2 demonstrated relatively shorter times for 3D CAD and post finishing for each sample, indicating improved efficiency in 3D CAD and gained knowledge and skills in post finishing. The durations of the design process are shown in Table 11.

Table 11

Durations of Design Process for Each Design Variation

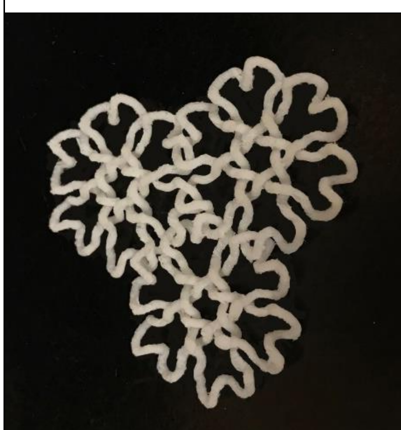
	V1	V2	V3	V4	V5	Develop final prototype
Problem Identification	15 min	15 min	15 min	15 min	15 min	-
3D CAD	1 day	6 hours	1 day	6 hours	6 hours	4 hours
3D Printing	1 day	6 hours	1 day	6 hours	5 hours	5 days/1 week
Post Finishing	2 hours	2 hours	2 hours	2 hours	1 hour	2 days
Sample Sewing	4 hours	4 hours	4 hours	4 hours	-	1 day
Prototype	-				-	10 days/2 weeks

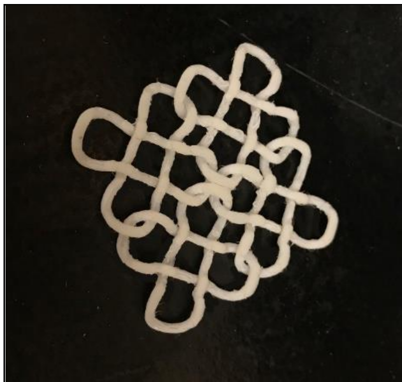
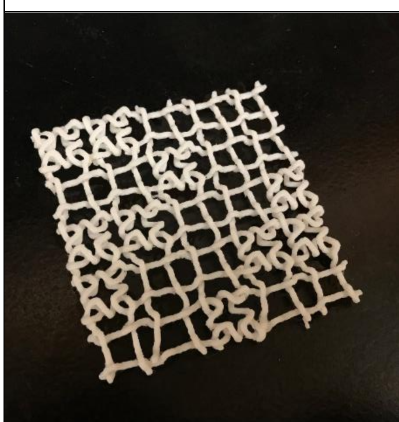
Note. One workday is 8 hours. Durations for each process show total accumulation.

Evaluations of the properties of the 3D printed structures. The evaluations of all the 3D printed structures were based on the criteria for RTD data collection, and aimed at answering **RQ2**. The evaluations of all the variations of the 3D printed structures are shown in Table 12.

Table 12

Evaluations of the Property of 3D Printed Structures in Phase 2

	Key dimensions for exploring properties of 3D printed structures	**Evaluation** *7-point schematic differential scale*
	1. Softness	4 ■■■■□□□
	2. Flexibility	6 ■■■■■■□
	3. Connections	5 ■■■■■□□
	4. Breathability	7 ■■■■■■■
	5. Stretchability	4 ■■■■□□□
	6. Cushioning	4 ■■■■□□□
	7. Durability	7 ■■■■■■■
	8. Weight	7 ■■■■■■■
	9. Complexity	7 ■■■■■■■
	10. Aesthetic judgment	5 ■■■■■□□
	11. 3D printing success	5 ■■■■■□□
	1. Softness	4 ■■■■□□□
	2. Flexibility	7 ■■■■■■■
	3. Connections	6 ■■■■■■□
	4. Breathability	7 ■■■■■■■
	5. Stretchability	7 ■■■■■■■
	6. Cushioning	6 ■■■■■■□
	7. Durability	4 ■■■■□□□
	8. Weight	7 ■■■■■■■
	9. Complexity	7 ■■■■■■■
	10. Aesthetic judgment	7 ■■■■■■■
	11. 3D printing success	3 ■■■□□□□
	1. Softness	4 ■■■■□□□
	2. Flexibility	6 ■■■■■■□
	3. Connections	5 ■■■■■□□
	4. Breathability	7 ■■■■■■■
	5. Stretchability	5 ■■■■■□□

	6. Cushioning	4 ■■■■□□□
	7. Durability	7 ■■■■■■■
	8. Weight	7 ■■■■■■■
	9. Complexity	7 ■■■■■■■
	10. Aesthetic judgment	5 ■■■■■□□
	11. 3D printing success	6 ■■■■■■□
	1. Softness	4 ■■■■□□□
	2. Flexibility	7 ■■■■■■■
	3. Connections	6 ■■■■■■□
	4. Breathability	7 ■■■■■■■
	5. Stretchability	7 ■■■■■■■
	6. Cushioning	6 ■■■■■■□
	7. Durability	4 ■■■■□□□
	8. Weight	7 ■■■■■■■
	9. Complexity	7 ■■■■■■■
	10. Aesthetic judgment	7 ■■■■■■■
	11. 3D printing success	3 ■■■□□□□
	1. Softness	4 ■■■■□□□
	2. Flexibility	7 ■■■■■■■
	3. Connections	6 ■■■■■■□
	4. Breathability	7 ■■■■■■■
	5. Stretchability	7 ■■■■■■■
	6. Cushioning	5 ■■■■■□□
	7. Durability	3 ■■■□□□□
	8. Weight	7 ■■■■■■■
	9. Complexity	7 ■■■■■■■
	10. Aesthetic judgment	7 ■■■■■■■
	11. 3D printing success	2 ■■□□□□□

However, not all of the evaluations of the criteria had a strong influence on the final selection for prototyping. One reason is that some of the properties were related to the filament itself. Also, even though some of the 3D printed structures had overall higher evaluations than others regarding their functional properties, they had relatively low quality and a high chance of printing failure, due to the limited capability of the FDM 3D printer. Low printing quality may also lead to low durability. Thus, five criteria were used to select the 3D printed structure for the final prototyping. They were: 3D printing success rate, stretchability, durability, structure complexity, and cushioning. 3D printing success rate was prioritized among other criteria, because 3D printed structure variations with low printing success rate would cost more time and waste more filament to get enough useful pieces, which is not sustainable. Other properties in the criteria can be manipulated by the researcher. All the criteria were evaluated using 7-point scale

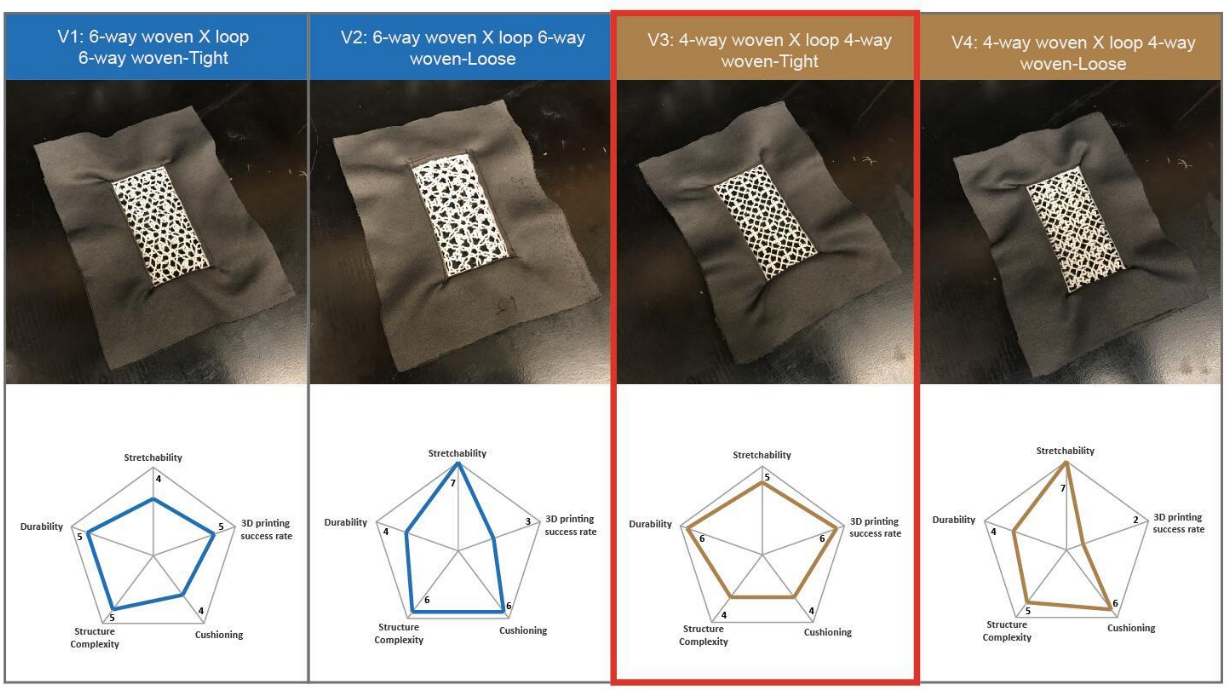


Figure 29. Selection of the 3D printed structure for final prototyping.

(low to high) to quantify the evaluation. Finally, V3 (4-way woven X 4-way loop woven-Tight) was selected for the final prototyping, because it had the highest 3D printing success rate, and overall high scores in the other criteria (Figure 29).

Final prototype construction of the 3D printed hooded sweatshirt. Challenges and findings during the prototyping process of the 3D printed hooded sweatshirt are related here.

Pattern making. The pattern for Phase 2 was an adaptation of the pattern from Phase 1. Phase 1 had confirmed the viability of integrating 3D printed structures with traditional neoprene fabrics. Thus, Phase 2 took a further step and tried a more complex pattern design, with sleeves and a hood, and a more curved design. A curved design makes the wearable apparel design more dynamic looking and aesthetically appealing. This pattern was designed with the aim to check whether it is viable to stitch 3D printed structures with fabrics along curved seam lines. It also took on the challenge to try to stitch traditional fabrics along curved seam lines. The pattern design is shown in Figure 30.

No seam allowance design. In Phase 1, the 2 x 4 in the 3D printed pattern was given a 1mm-thick seam allowance. Such a seam allowance increased the thickness of the seam lines and reduced the comfort of the wearable apparel product. In Phase 2, the researcher removed the seam allowance from the 3D printed structures and tried to stitch the 3D printed structures directly onto the fleece fabrics.

Zigzag stitching. The researcher had to consider that in Phase 1, the folded fabrics had increased the thickness of the seam lines, and that the traditional fleece fabrics used in Phase 2 are thicker than the neoprene fabrics used in Phase 1. Thus, the researcher tried to avoid folding

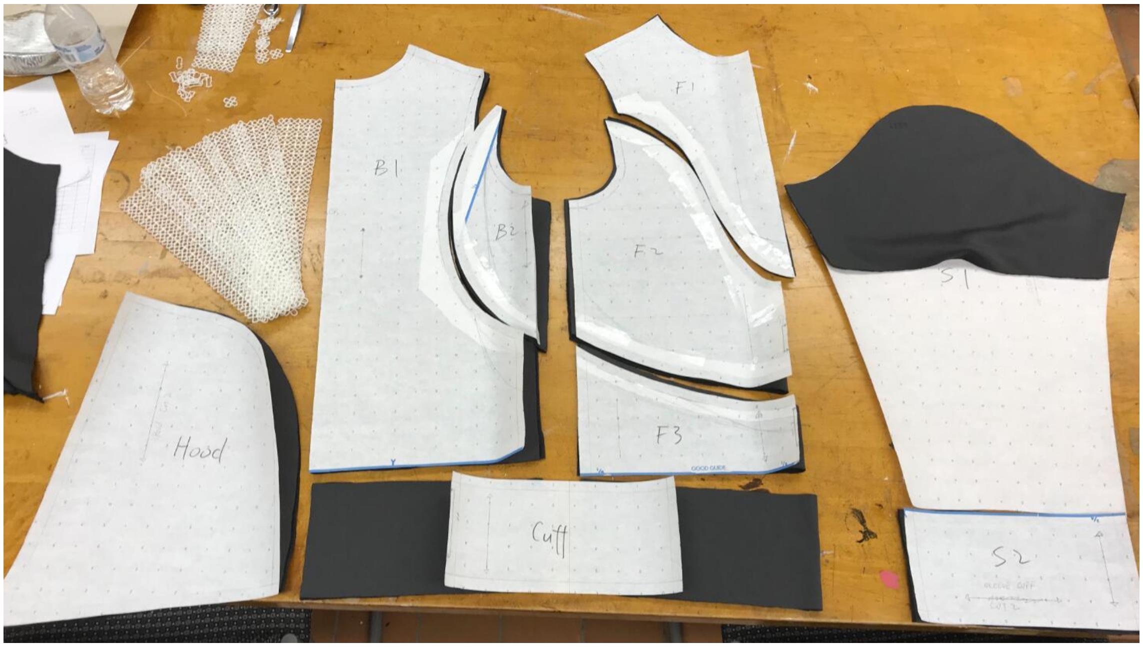
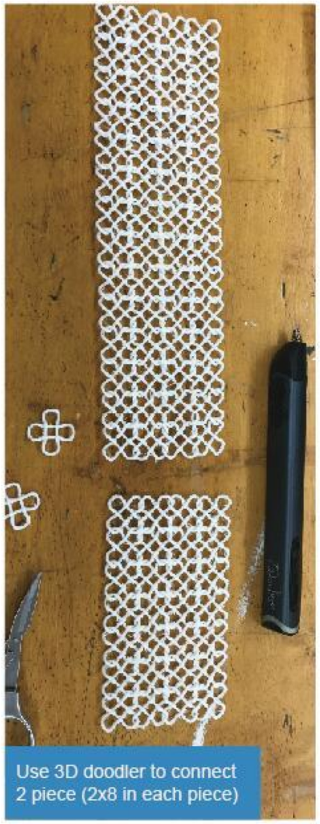


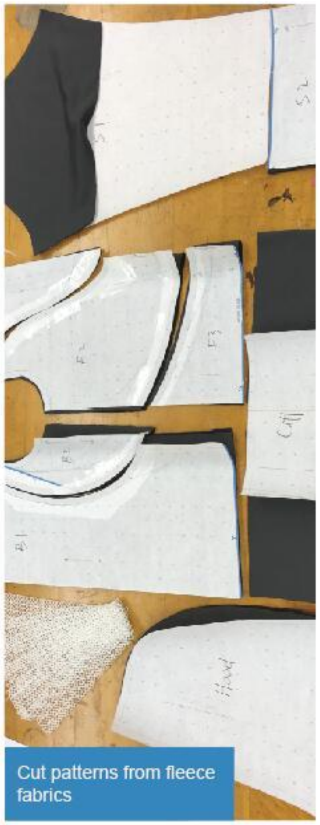
Figure 30. Pattern making for the 3D printed hooded sweatshirt.

seam lines, stitching the 3D printed structures directly onto the traditional fleece fabrics. However, straight line stitching could combine the two parts firmly. Based on peer review and feedback from a sewing expert, zigzag stitching was used to stitch the 3D printed structures onto the fleece fabrics. By using ballpoint needles and zigzag stitching, the two parts were able to be stitched together firmly.

Curve sewing. Curved sewing was a challenge in Phase 2. Curved sewing of the 3D printed structures and the fleece fabrics called for attention to symmetry, while sewing curved seam lines between two pieces of fabrics was more challenging. Too much curvature of the seam lines might have caused tension between the two stitched fabrics, and also may have led to asymmetry. The solution was to leave cut markers along the seam lines, and pay attention to the tension and symmetry during the sewing process. Redoing the stitching solved most of the sewing problems.

The final prototype construction of the 3D printed hooded sweatshirt is shown in Figure 31.


Use 3D doodler to connect 2 piece (2x8 in each piece)


Cut patterns from fleece fabrics


Sew 3D structures with fleece fabrics


Finish sewing the front pieces


Sew fleece patterns with curvature

Figure 31. Final prototype construction of the 3D printed hooded sweatshirt.

Challenges and Solutions in the Design Process

As a supplement, the design process for Phase 2 was evaluated based on a six-stage design process adopted from Parsons and Campbell's (2004) approach, to demonstrate challenges and solutions during the whole design process. All of this information was organized in Table 13.

Table 13

Challenges and Solutions in the Design Process of Phase 2

Design Stage	Challenge Topic	Challenge Description	Solutions
1. Problem identification	RQ2	Answer RQ2. Only one variation of the 3D printed hybrid structure was created in the RTD study's Phase 1, and the potential variations of hybrid woven structures and their unique properties remain unexplored.	1.1
2. 3D CAD	Verify design ideas	Create different variations of 3D printed structures.	2.1
	Modify curves and connections	Phase 1 created one hybrid structure CAD model. Phase 2 used and modified this existing CAD model to create more variations.	2.2
	Measurement and pattern	To use exiting knowledge of measurement and pattern.	2.3
	File size	Control file size.	2.4
	Unit connections	In Phase 1, a 6-way connection was created. Phase 2 explored to see what variations of connections could be created.	2.5
3. 3D printing	Design and printing parameters	Determine design and printing parameters to enhance printing success rate.	3.1
	Unexpected printing problems from the FDM printer	Allowance from nozzle head to the print bed strongly influenced the printing quality of the structure. Too close a distance may limit the volume of filament coming out of the nozzle, and lead to partially missing initial layers. Too far a distance may lead to the filament failing to adhere to the print bed.	3.2
		Filament warping. Due to some printed parts and support materials being too thin, they were more likely to warp when cooling down from the heated nozzle. Warping led to these parts stretching beyond their desired position, which could cause collision between other parts or adhesion to the nozzle head, and destroy the whole print.	
		Filament was contaminated, which led to nozzle block or partial block.	
		Wrong setting. The wrong setting would cause a printing failure. The finished samples were loose and light weight, and could not performance all of the desired functions.	

		A relatively larger-size structure has a higher chance of failure. This may be for two reasons. First, the print bed is not perfectly even. Small support parts may adhere to the nozzle when it moves within the uneven areas, and cause printing failure. Second, when printing large pieces, a large amount of small support parts are generated, and it is more likely for some small pieces to detach from the printing bed and cause problems.	3.3
4. Post finishing for 3D printed structures	Clean support parts and clip adhered parts	Same as in Phase 1.	4.1
	Connect two short pieces into one long piece	The FDM 3D printer can only print 2 x 8 in. pieces, but the final prototype required longer pieces. Manually connecting two of the 3D printed pieces was inevitable and became the biggest challenge here.	4.2
	Enhance functional quality of manual connection parts	When using the 3Doodler pen, the manual connection parts were weak and did not have the required quality. Also, the pen generated big chunks of filament that adhered to the connection part.	4.3
	Enhance aesthetic coherent of manual connection parts	The 3Doodle pen generated big chunks of filament that adhered to the connection parts.	4.4
5. Sample assembly	Sew 3D printed samples with traditional fabrics	Remove the seam allowance from the 3D printed structures.	5.1
6. Final prototype construction	Flat pattern design	The curved pattern design was not easy to stitch.	6.1
	Sew 3D printed structures with traditional fabrics	Sew 3D printed structures without seam allowance firmly on fleece fabrics.	6.2
	Sew all patterns together	Ensure symmetry.	6.3
		The order of the sewing.	6.4

Note. Refer to the number listed in this table, find the detailed description of the solutions below

Solutions and results.

1. Problem identification.

1.1 Phase 1 was a zero-to-one process that confirmed the possibility of integrating loop woven and traditional woven structures into a hybrid structure, and successfully printed it with a FDM printer. Phase 2 was a one-to-more process to explore variations of hybrid woven structures and their unique properties, during which properties and functions were emphasized.

2. 3D CAD.

2.1 The idea of integrating two kinds of woven structures into a hybrid structure has been confirmed to be viable (zero-to-one process). Thus in Phase 2, instead of verifying design viability, research focused on variations of hybrid structures (one-to-more process).

2.2 Time and effort were saved thanks to the accuracy of the existing CAD model, where most connection and collision problems were solved. Minor connection and collision problems happened in Phase 2 were solved based on the knowledge and experience gained in Phase 1. Thus, this step was not a big concern in Phase 2.

2.3 Phase 2 used the measurements from Phase 1 as a reference. Due to the tests and experiences from Phase 1, the optimal printing radius for curves in the CAD model was known to be 0.7 mm, and the thickness was 1/4 in. In terms of the pattern for unit repeat, it depended on the scale of the single unit. Center points and auxiliary lines helped generate the pattern.

2.4 Knowledge and experience gained in Phase 1 indicated that a file size exceeding 200 MB could not be read by the 3D printer. Thus, the maximum print size was a swatch around 4 x 4 in.. Also considering the design needs, the print bed size, and chance of printing failure, 4 x 2 in. was decided on as the final printing size for all variations.

2.5 Five variations. Two more variations of 6-way connections, one tight and durable, the other more stretchy and cushioning. Then, the two variations were extended to 4-way connection structures to create two 4-way connection variations. Further, interconvertible modules were considered to enable customization.

3. 3D printing

3.1 Based on the experience in Phase 1, the printing radius for the pipelines was 0.7 mm. The 3D printing was expected to verify the viability of the design ideas and test the properties of the 3D printed structures.

3.2 In most cases, carefully checking the setting and filament, then printing again, could solve unexpected failures.

3.3 Print on a specific area that was known to have a higher success rate. Printing again could solve the unexpected failure.

4. Post finishing for 3D printed structure.

4.1 Same as in Phase 1.

4.2 A 3D pen with white TPU filament (3Doodler create+ with FLEXY white TPU filament, WobbleWorks, 2018; Figure 32) was used to connect two pieces of 3D printed structure. The 3Doodler pen is a kind of portable nozzle using a similar filament to draw a 3D structure. For design Phase 2, the loop woven structure was first cut to allow it to hook with the other loop structure. Then, the cut part was fused and connected back using the doodler pen with the

Figure 32. 3Doodler create+. Copyright 2018 by WobbleWorks

same TPU filament. The process was clear, but the actual practice was challenging. There were two big issues, First, the quality. If the connection parts were not fused very well (e.g., partially fused), it could lead to weak spots. Such weak spots easily broke during moving and stretching, which affected the quality of the whole piece.

4.3 Only using the 3Doodler to squeeze the melted TPU filament patch on the spot was not enough to firmly fuse the two parts together; the spot was still weak. It needed some pressure to help blend the two parts with the melted patch. In practice, one's finger is the best tool to press the join spot. Let the melted patch cool down for around 5 seconds, then use a finger to quickly press the melted patch onto the joint spot. Press around three times until the patch became stiff, then use small scissors to trim the redundant patch.

4.4 The connected parts were not as smooth as the other parts, and thus needed to be cleaned and refined to match the other parts. An extra filament patch was attached to the connected parts during fusion, and thus needed to be cut off. In practice, due to the limitations of the tools and the small join parts, it was not easy to clean the join parts perfectly to match the other pipelines. But even though they were easy to distinguish from the other parts at a close look, they were fine when one looked at the sweatshirt as a whole.

5. Sample assembly.

5.1 Using a zigzag stitch could effectively firm the seam between the 3D printed structure and the traditional fabrics. However, another technical problem happened when some of the stitches formed not zigzag lines but straight lines, which could weaken the seam lines. An apparel sewing expert was consulted about this problem. She suggested using ball point needles for knit fabrics instead of general needles, and the problem was solved.

6. Final prototype construction.

6.1 Test sewing was necessary to verify the viability of the design. The test sewing results indicated that the overall quality of the curved sewing was viable, with some minor stitch tension problems. Thus, the fleece fabrics were cut based on the flat pattern design and prepared for the next design step.

6.2 During the 3D printing process, six 8 x 2 in. and several pieces of 4 x 2 in. 3D printed structures were printed. Moreover, during the post finishing process, the 3D printed structures were connected into five long pieces, and some 4 x 2 in. pieces were used as patches or backups. Finally, four 12 x 2 in. pieces and one 18 x 2 in. piece were prepared for sewing on the front side, and one 6 x 2 in. piece for the hood. The fleece fabrics and the 3D printed structures were sewed with a zigzag stitch, and a manual spinning sewing machine wheel was used instead of electric spinning in order to control the sewing speed and ensure the sewing quality. The finished pieces were ready for the next step.

6.3 The Phase 2 design has many curved lines; it was not easy to sew seam lines with big curvatures. The solution was to leave pins or cut markers on the seam allowance to indicate the right sewing positions, and check during and after the sewing to ensure symmetry of the sweatshirt. Despite following the markers, sometimes errors happened and the sewing still was not symmetric. Redoing the sewing can solve such problems.

6.4 The proper sewing order was to sew small pieces to bigger pieces, finishing the front and back patterns separately. The next step was to sew the front and back pieces together. The final step was to add the sleeves and the hood pieces.

Summary of Phase 2.

Phase 2 adopted the design process, used the 3D printed structure unit from Phase 1 to create five variations of 3D printed structures. Phase 2 indicated improved efficiency to adopt existing design process and 3D CAD structure unit for future design exploration.

Phase 2 mainly answered **RQ2**, provided detailed property evaluations across the five variations based on the criteria in Table 1. Property comparisons among five different variations of 3D printed structures could provide more holistic evaluations. The results indicated that some properties are related to the filament properties (e.g., weight, flexible, softness), some properties are related to the structure (e.g., connection, stretchability, cushioning), and some properties may influence the 3D printing success rate (e.g., complexity), and some properties may be influenced by the 3D printing success rate and quality (e.g., durability). Future study may consider the property evaluations to explore new variations.

Compared to Phase 1, durations of design process results from Phase 2 indicated improved efficiency in 3D CAD and post finishing. Because Phase 2 adopted the same design process and 3D CAD unit from Phase 1, modified the unit into five variations. For example,

(1) 3D CAD unit. It took around 48 hours to design only one CAD structure in Phase 1. While by adopting the knowledge and modifying the 3D CAD structure unit (V0) from Phase 1, Phase 2 only took around 9 hours to design one variation of CAD structure (V1).

(2) Post finishing. It took around 2 hours to clean a 2x4 in. 3D printed structure pattern in Phase 1, while with enhanced post finishing skill, it took only 1 hour to finish the same size of 3D printed structure pattern in Phase 2.

A comparison chart of durations between two phases is shown in Figure 33.

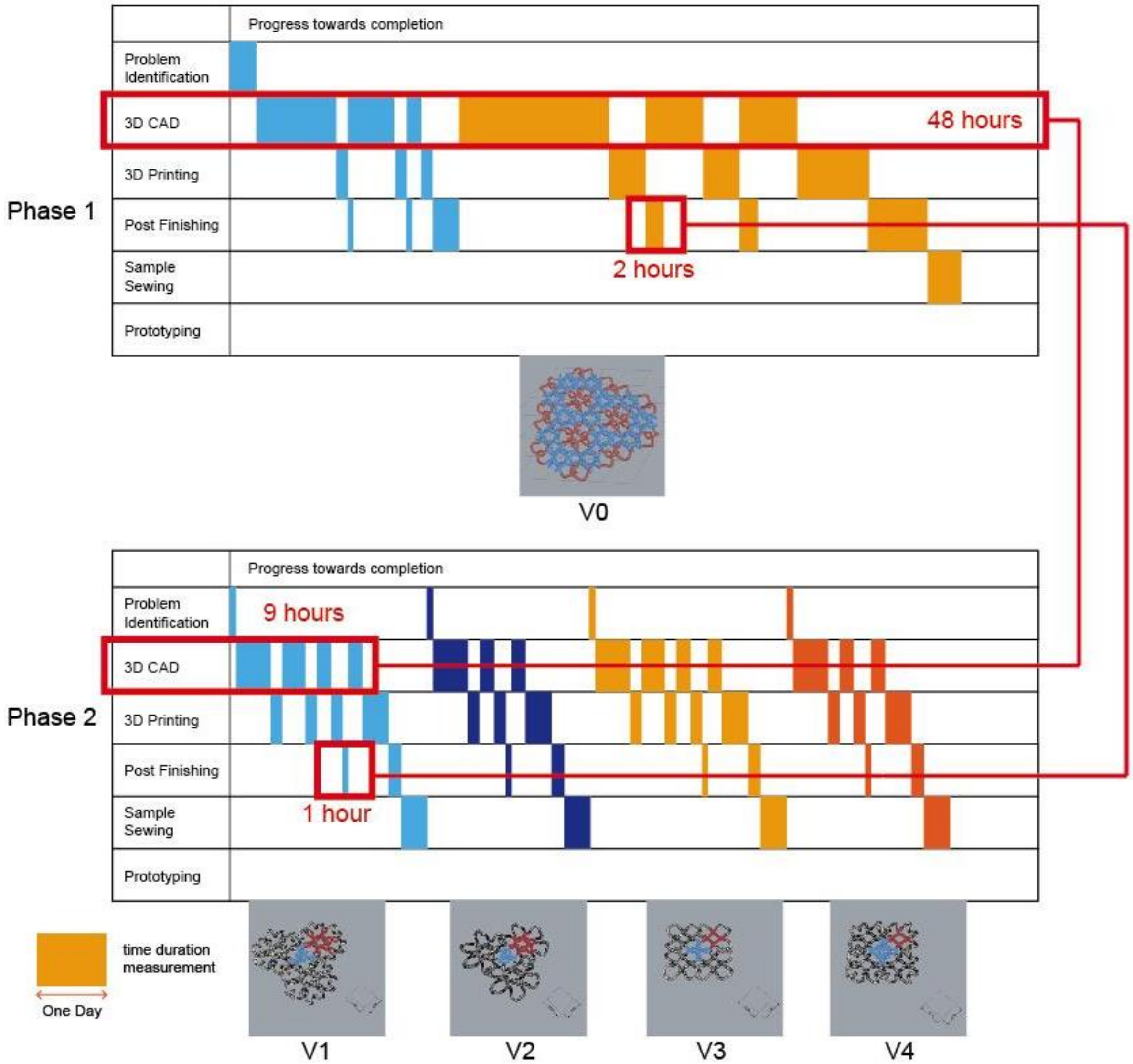


Figure 33. Comparison chart of time durations between Phase 1 and Phase 2

A 3D printed hooded sweatshirt was prototyped using one of the variation to be integrated with traditional gray fleece fabrics. This 3D printed hooded sweatshirt was used for Study 2 survey research to examine users' perceptions of the 3D printed wearable apparel product.

Results for Study 2

Sampling Characteristics

A total of 357 participants joined in this online survey. Among these participants, 332 finished the survey and passed at least two of the three attention check questions. Thus, the actual sample size was greater than 320, which met the desired sample size.

The usable sample consisted of individuals aged from 19 to 76 years (M = 34.84, SD = 10.56). Gender was fairly equally distributed in the sample with 165 females (49.7%) and 167 males (50.3%). With respect to race, the majority of participants were Caucasian/White (75.3%), followed by Asian/Pacific Islander (9.9%), African American/Black (8.1%), multiracial (2.7%), American Indian (2.1%), other (1.5%), and would not say (0.3%). Participants with bachelor's degrees formed the largest group (42.8%), followed by those who had master's degrees (20.8%), some college degree (16%), associate degree (11.1%), and high school diploma (7.5%). In terms of marital status, participants were either single (47.9%) or married (44.3%). Those with an annual household income of $30,000 to $49,999 (29.8%) formed the largest group within the income ranges, followed by those with incomes of $50,000 to $69,999 (21.1%), $10,000 to $29,999 (19.9%), more than $90,000 (10.2%), $70,000 to $89,999 (9.9%), and less than $10,000 (9.0%). In terms of location, participants hailed from California (21.7%), Texas (18.1%), New York (5.1%), and Florida (4.2%). Another notable aspect of the sample was that most of the participants had knowledge of and/or experience with apparel design (65.1%) and 3D printing technology (69.3%). The demographic characteristics of the sample are shown in Table 14.

Table 14

Demographic Characteristics of the Sample

Variable		*f*	%
Gender			
	Female	165	49.7
	Male	167	50.3
Education			
	High School Diploma	25	7.5
	Some College	53	16
	Associate Degree	37	11.1
	Bachelor Degree	142	42.8
	Master Degree	69	20.8
	PhD Degree	3	0.9
	Other	3	0.9
Ethnic			
	African American/Black	27	8.1
	Caucasian/White	250	75.3
	Asian/Pacific Islander	33	9.9
	American Indian	7	2.1
	Multiracial	9	2.7
	Would rather not say	1	0.3
	Other	5	1.5
Marital			
	Divorced	19	5.7
	Married	147	44.3
	Separated	6	1.8
	Single	159	47.9
	Widowed	1	0.3
Income			
	less than $10,000	30	9.0
	$10,000 - $29,999	66	19.9
	$30,000 - $49,999	99	29.8

	$50,000 - $69,999	70	21.1
	$70,000 - $89,999	33	9.9
	more than $90,000	34	10.2
US Location (> 10)			
	California	72	21.7
	Texas	59	17.8
	New York	17	5.1
	Florida	14	4.2
	Michigan	13	3.9
	Washington	12	3.6
	Georgia	10	3.0
Apparel Design Knowledge/ Experience			
	Yes	216	65.1
	No	116	34.9
3D Printing Knowledge/ Experience			
	Yes	230	69.3
	No	102	30.7

Data Analysis

Gender difference check. ANOVA tests were conducted to check whether there were gender differences in users' perceptions of the 3D printed hooded sweatshirt, as well as their aesthetic judgments and purchase intentions. Data from both genders could be merged if they were not significantly different ($p > .05$). ANOVA revealed that there were no significant differences between the genders with respect to all the variables, except uniqueness ($F = 4.38$, p

= .037, partial eta squared = .013) and mobility ($F = 4.73$, $p = .030$, partial eta squared = .014). Given that there were no gender differences for a majority of the variables, and that the effect size for the differences found with respect to the above two variables were very small, data from both genders were merged for further analysis.

Validity. The validity and dimensionality of dependent variables (aesthetic judgment and purchase intention) and independent variables (aesthetic, expressive, and functional perceptions) were evaluated before conducting further analysis for hypothesis testing. A series of exploratory factor analysis (EFA) using the principle components analysis procedure with varimax rotation were conducted to check potential latent variables and the structure of all measurements. Kaiser's eigenvalue criterion (retain factors with eigenvalue > 1.0) and scree plots (major eigenvalue drops on the plots) were employed to determine the number of factors to retain. Component loadings from rotated component matrices were examined to check underlying latent variables and ensure all components were clearly identified. Items with low loading scores (< .50) on all components or cross-loaded on multiple components were eliminated. Results from EFA indicated that, except for novelty and fit, items for all other variables loaded only one component with high loading values (> .50).

In terms of novelty, EFA with varimax rotation resulted in two components. The first two items describing novelty loaded high (> .80) on the second component and the last three items loaded high (> .80) on the first component, which was renamed typicality (see Table 15).

Table 15

Exploratory Factor Analysis Results for Novelty

	Loading	
Item	Typicality	Novelty
I would perceive the 3D printed hooded sweatshirt to be:		
Old – New		.874
Unoriginal – Original		.842
Common – Unusual	.844	
Familiar – Unfamiliar	.892	
Typical – Atypical	.874	
Eigenvalue	2.651	1.220
% Variance Explained	53.028	24.400

With respect to the variable perceived fit, EFA with varimax rotation resulted in two components. The first four items loaded high (> .50) on the second component, which was renamed perceived fit-upper body. The last four items loaded high (> .70) on the first component, which was renamed perceived fit-torso. Thus, the initial perceived fit variable was split into two variables: perceived fit-upper body and perceived fit-torso (see Table 16).

Table 16

Exploratory Factor Analysis Results for Perceived Fit

	Loading	
Item	Fit-Upper Body	Fit-Torso
I perceive that this 3D printed hooded sweatshirt will fit my:		
Head		.824
Neck		.773

Shoulder		.648
Arm		.511
Bust	.755	
Waist	.848	
Abdomen	.838	
High hip	.804	
Eigenvalue	4.185	1.088
% Variance Explained	52.307	13.598

Reliability. Reliability of all finalized scale items were accessed with Cronbach's α value. A Cronbach's α value of .70 or higher is considered to indicate adequate reliability (Nunnally & Bernstein, 1994). The results showed that the Cronbach's α values of all the variables except one were greater than 0.7, which indicated high reliability. Cronbach's α of novelty scale was 0.679, since there were only two items in this scale. The Cronbach's α values of all the scales are in shown in Table 17.

Table 17

Scale Reliability

Measure	**Cronbach's α**	**N of Items**	***N***
Users' satisfaction			
Product satisfaction	0.849	3	332
3D printed thermoplastic structure satisfaction	0.873	3	332
Purchase intention			
Purchase intention	0.941	3	332
Aesthetic perceptions			
Novelty	0.679	2	332
Typicality	0.857	3	332
Beauty	0.932	5	332

Expressive perceptions			
Coolness	0.927	6	332
Uniqueness	0.895	5	332
Functional perceptions			
Fit-Upper body	0.753	4	332
Fit-Torso	0.869	4	332
Mobility	0.902	4	332
Comfort	0.912	5	332
Ease of donning/doffing	0.861	2	332

Revised model. RQ3 raised the question of whether users' FEA perceptions of a 3D printed wearable apparel product influence their satisfaction with and their purchase intentions towards the product. Specific hypotheses were proposed based on the research model and modified based on exploratory factor analysis results:

H1: Users' aesthetic evaluations of perceived (a1) novelty, (a2) typicality, and (b) beauty of the 3D printed hooded sweatshirt will positively influence users' satisfaction.

H3: Users' functional evaluations of perceived (a1) fit-upper body, (a2) fit-torso, (b) mobility, (c) comfort, and (d) ease of donning and doffing of the 3D printed hooded sweatshirt will positively influence users' satisfaction.

H4: Users' aesthetic evaluations of perceived (a1) novelty, (a2) typicality, and (b) beauty of the 3D printed hooded sweatshirt will positively influence users' purchase intention.

H6: Users' functional evaluations of perceived (a1) fit-upper body, (a2) fit-torso, (b) mobility, (c) comfort, and (d) ease of donning and doffing of the 3D printed hooded sweatshirt will positively influence users' purchase intentions.

The revised model of users' perceptions of 3DP wearable apparel product is shown in Figure 34.

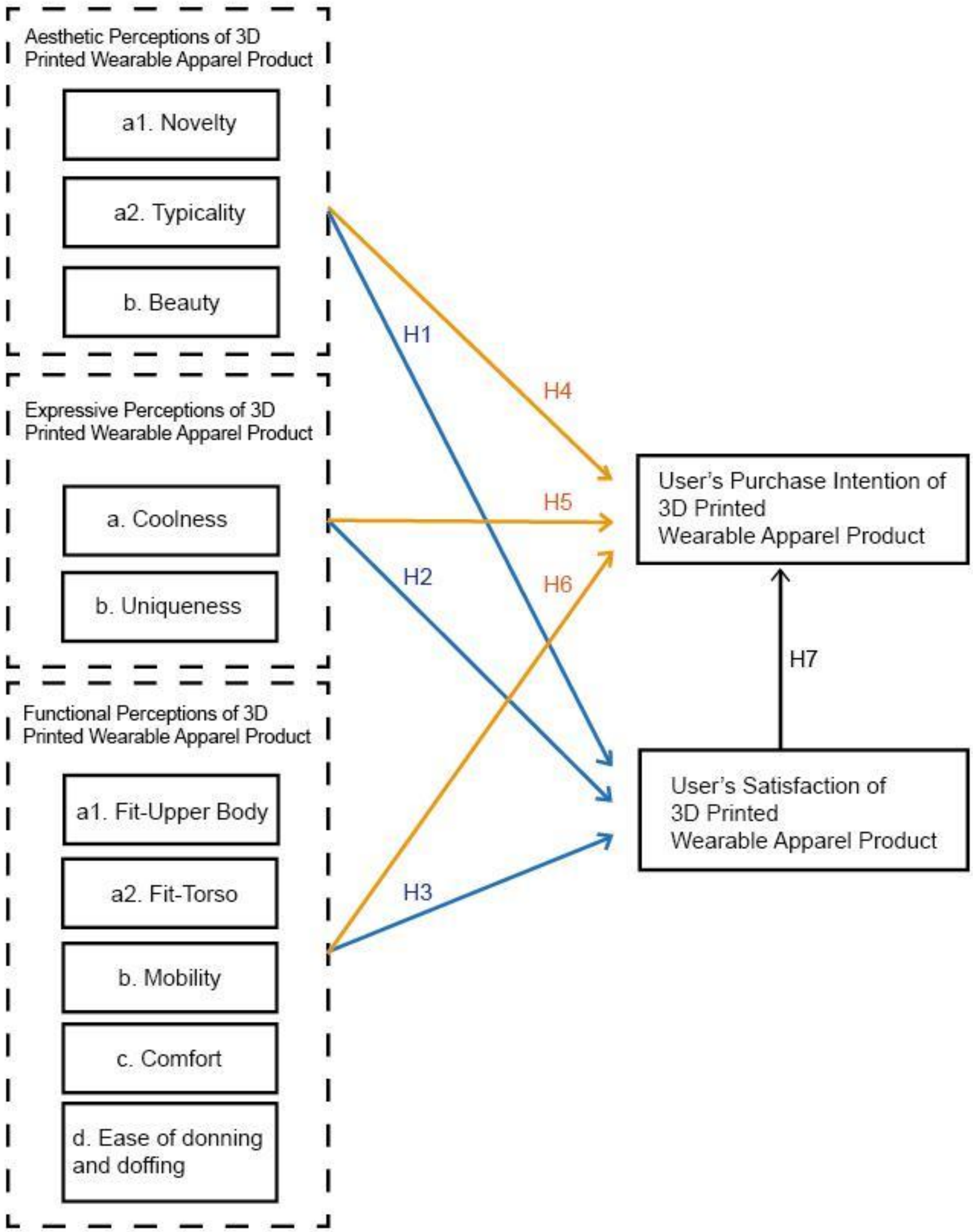


Figure 34. Revised model of users' perceptions of 3D printed wearable apparel product.

Hypothesis testing. Based on the revised research model, multiple linear regression analyses with stepwise method were conducted to predict users' satisfaction with and purchase intentions toward the 3D printed hooded sweatshirt based on 10 predictors: users' perceived novelty, typicality, beauty, coolness, uniqueness, fit-upper body, fit-torso, mobility, comfort, ease of donning/doffing. Stepwise method was used because it is suitable for exploratory research (Aron, Aron, & Coups, 2008). Levels of "use probability of *F*" to enter and to remove were set to corresponding *p* levels of 0.05 and 0.1, respectively, to adjust for familywise alpha error rates associated with multiple significance tests. Tolerance statistics were obtained for each predictor. If the tolerance value for each predictor was greater than 0.1, multicollinearity would not be a problem.

Hypotheses 1 to 3, which predicted users' satisfaction with the 3D printed wearable apparel product, were tested first. Results from multiple linear regression analyses with stepwise method showed that perceived beauty ($\beta = .45$, $p < .05$) [aesthetic perception], perceived coolness ($\beta = .35$, $p < .05$) [expressive perception], and perceived fit-upper body ($\beta = .09$, $p < .05$) [functional perception] were entered in the regression analysis. They explained 64.4% of the variance of users' satisfaction, indicating that perception of beauty, coolness, and fit-upper body significantly influence users' satisfaction of the 3D printed hooded sweatshirt. However, other variables were removed by stepwise method, which indicated non-significant influence. Thus, only H1b, H2a, and H3a1 were supported. The results were shown in Table 18.

Table 18

Multiple Regression Analysis with Stepwise Method Output for Predicting Users' Satisfaction of *the 3D Printed Hooded Sweatshirt (N = 332)*

Independent Variable entered	Variable category	Standardized Beta	*p*	Tolerance
Beauty	Aesthetic	.447	.000	.259
Coolness	Expressive	.351	.000	.250
Fit-upper body	Functional	.087	.014	.870

Next, Hypotheses 4 to 6, which predicted users' purchase intentions, were tested. Results from multiple linear regression analyses with stepwise method showed that beauty ($\beta = .56$, $p < .05$) [aesthetic perception], coolness ($\beta = .37$, $p < .05$) [expressive perception], and novelty ($\beta = -.18$, $p < .05$) [aesthetic perception] were entered in the analysis, and explained 68.8% of the variance in users' purchase intentions. This indicated that beauty, coolness, and novelty significantly influence users' purchase intentions toward the 3D printed hooded sweatshirt. Other variables were removed by stepwise method, which indicated non-significant influence. Thus, only H4b and H5a were supported. H4a1 was rejected, since perceived novelty negatively influenced purchase intentions. H6a to H6d were not supported. The results are shown in Table 19.

Table 19

Multiple Regression Analysis with Stepwise Method Output for Predicting Users' Purchase Intention of the 3D Printed Hooded Sweatshirt (N = 332)

Independent Variable entered	Variable category	Standardized Beta	*p*	Tolerance
Beauty	Aesthetic	.556	.000	.258
Coolness	Expressive	.366	.000	.251
Novelty	Aesthetic	-.181	.000	.816

H7 hypothesized that users' satisfaction will positively influence users' purchase intentions, and this relationship was tested using simple linear regression. Results indicated that users' satisfaction with the 3D printed hooded sweatshirt positively influences users' purchase intentions ($\beta = .786$, $p < .05$). Thus, H7 was supported.

The results are shown in Figure 35:

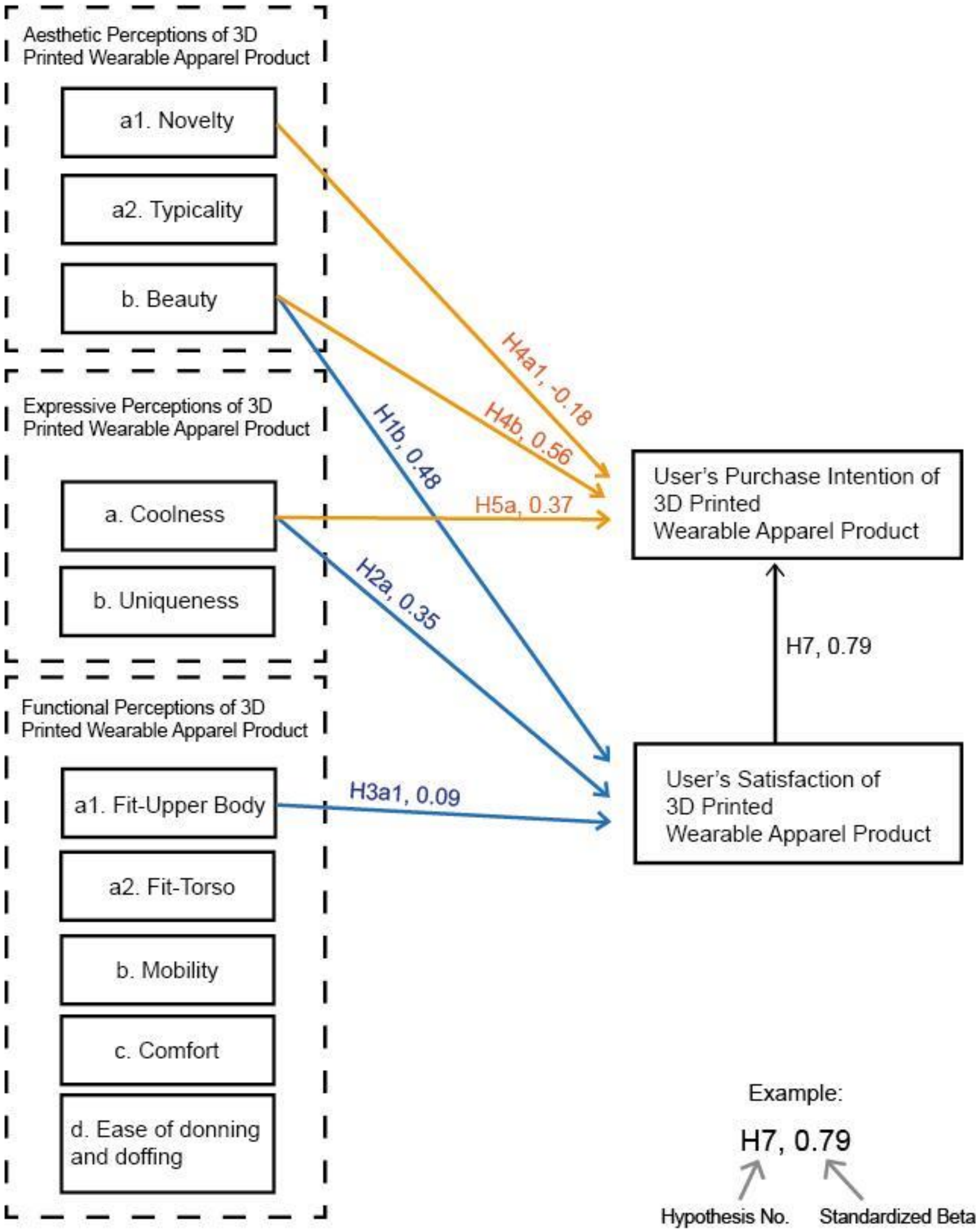


Figure 35. Results of hypotheses analysis

CHAPTER 5: DISCUSSION

Study 1

Study 1 adopted the term “Maker Movement” as an overarching concept to launch RTD research exploring **RQ1** and **RQ2**. The outcome of Study 1 confirmed its value to be applied in 3D printed wearable apparel product design, and provided a good example to practice this concept. Specifically, Maker Movement guided the 3D printed wearable apparel product design to form a virtuous circle ecosystem (self-learning and practice—form universal design process—bring technology to the public). Study 1 adopted the RTD method to explore 3D printed wearable apparel products with little previous research. Self-learning and practice played essential roles in gaining knowledge and skills, providing a detailed design process and valuable feedback for later design phases. Phase 2 adopted the same design process and the CAD model as a module to create five different variations of 3D printed structures, indicating the viability of adopting the same design process and sharing the same knowledge to optimize the design process for later design phases. However, Study 1 was only the initial step to apply the Maker Movement concept and provide an example of the design process. Thus, more future designs are needed to join this ecosystem to enrich this overarching theory for the development of 3D printed wearable apparel product designs.

By using RTD methodology, **RQ1** explored the 3D CAD design process of different variations of 3D printed flexible structures, and **RQ2** investigated and evaluated the properties of the designed 3D printed structures to be able to integrate with traditional fabrics. Previously, only limited research had adopted the RTD method to explore the apparel design process. In addition, few 3D printed wearable designs provided detailed 3D CAD design workflows. Study 1 was the research to adopt the RTD method to systematically record a detailed 3D CAD design workflow of 3D printed flexible structures and organize the data into a reflective design journal that systematically demonstrated related information and knowledge gained during the whole design process. An example of one page of the reflective design journal is shown in Appendix C. Further, Study 1 provided and evaluated different variations of 3D printed structures that can be integrated with traditional fabrics for this research and implications for future explorations.

Study 1 adopted and modified Parsons and Campbell's (2004) six design stages to demonstrate the design process to create the 3D printed structures. There are two design Phases in Study 1.

Phase 1

Phase 1 aimed to answer **RQ1**. Phase 1 was the initial trial to explore the viability of printing a 3D flexible structure and integrating it with traditional fabrics. Some apparel designers previously had explored 3D printed structures, trying to make them softer and more comfortable for use in wearable apparel products, like (1) soft thermoplastic TPU materials (e.g., Armstrong, 2016); (2) zigzag or interlocking structures (e.g., Marriott, 2015; Stephanie, 2016); (3) hollowed lattice structures (e.g., Kisliuk, 2014); and (4) mimicking traditional fabrics to print onto knitting or woven structures (e.g., Scott, 2016). While considering that mimicking the structures of traditional fabrics (e.g., woven and knit structures) may be viable through FDM printing and could improve the properties of 3D printed structures, the outcome of this Phase 1 was a hybrid structure (6-way woven X 6-way loop woven) and a 3D printed beach vest design. Phase 1 confirmed the viability to use Rhinoceros 3D CAD to design complex 3D printed structures for wearable apparel products. Further, it confirmed the capability of the FDM 3D printer to print relatively high quality and complex 3D printed structures. It also confirmed the viability of sewing 3D printed structures with traditional fabrics. These viabilities are very significant in this study, because they shed light on the research of 3D printed wearable apparel products, and provide knowledge, experience, and implications for future research.

Further, in response to the call from the Maker Movement, the value of Phase 1 was to adopt the RTD method to explore and form a design process for a 3D printed wearable apparel product. Detailed demonstrations and explanations of each design process, especially the 3D CAD design workflow, provided knowledge and implications. Even though the design process was specifically for Phase 1, it could be later refined and generalized into a universal design process that could be adopted for future research. If future 3D printed wearable apparel product research adopted a similar design process, using the same 3D CAD design programs, it is easy for designers to learn knowledge and implications from others' design, and share their own design process for future design. Even though currently the design of 3D printed structures and wearable apparel products require design expertise, a universal design process would be helpful for the development of 3D printed wearable apparel products that would allow people to learn from others' design processes and share their own designs with others. Thus, even the general public could make contributions in the future.

Key findings.

3D CAD. Using 3D CAD was more efficient than sketching to conceptualize design ideas and provide visual perceptions of complex 3D printed structures. Normally in an apparel/product design process, sketching is the best way to explore and express initial design ideas. However, regarding 3D printed structures, because they are interlaced, complex woven-shaped structures, sketching becomes time-consuming and it is difficult to provide details. One the other hand, 3D CAD (Rhinoceros in this Phase) is good at fast modeling, manipulating complex and symmetric structures, and providing views from different perspectives to show details, thus making it a better tool to generate initial design ideas for 3D printed structures.

Modify curves. Modifying curves in the 3D CAD workflow was only one step, but it took the most time. Rhinoceros is a relatively small CAD program with limited functions; it does not provide any model check function. Thus, manual checks of collisions and gaps were very important. Modify-check steps were repeated frequently during the 3D CAD workflow to ensure the quality and accuracy of the CAD unit. The accuracy of a single unit would help increase efficiency for the next design steps.

Capability of the FDM 3D printer. The exploration of 3D printed structures challenged the capability of the FDM 3D printer. The FDM 3D printer is not good at printing complex shapes with many support parts. Some printing issues happened, including disconnected parts, burned parts, and partially printed parts. Thus, low quality and failed pieces reduced the successful rate of printing. Printing issues could not be effectively controlled, so printing several pieces was the only solution to select relatively high quality 3D printed structures for testing.

Post finishing. Posting finishing was also time-consuming, because the FDM 3D printer generated a large quantity of support parts, and some parts of the 3D printed structure adhered to them. Post finishing was needed to manually clean all of the support parts and the adhered parts. A 2 x 4 in. piece usually took more than an hour to clean. When the researcher became familiar with the cleaning process and gained muscle memory, efficiency increased. Later, finishing took around half an hour.

Seam allowance. A 1/4 in., 1 mm thickness seam allowance was added to the 2 x 4 in. 3D printed structure. The seam allowance was added to allow sewing with traditional fabrics. However, the seam allowance somewhat limited the properties, decreasing the stretchability of the 3D printed structures. Future design will need to focus on this issue and eliminate the influence of the seam allowance.

Sewing. Phase 1 was the initial exploration of integrating 3D printed structures with traditional fabrics. Findings indicated that auto sewing did not work well. Because the 3D printed seam allowance was stiffer and thicker than traditional fabrics, when using auto sewing, some of the stitches were not straight, and too-fast auto sewing may even break the needle. Thus, the solution was to sew the two pieces by manually spinning the sewing machine wheel. That way it was easy to control the sewing speed and the quality of the stitches.

Phase 2

The Phase 2 results for **RQ2** indicated that the hybrid structure was complex, porous, stretchable, and flexible, but was low in durability. This was because the 3D printer often failed or printed low quality parts when printing complex structures. The overall structure was aesthetic appealing and easy to sew with fabrics when adding a seam allowance. Phase 2 adopted the same design process and shared the design knowledge and skills, adopted and modified the 3D CAD unit from Phase 1. The findings overall supported the concept of generalization. By adopting a similar design process, future design could use the existing knowledge and skills to enhance design efficiency. Design efficiency was improved in the following aspects:

First, the previous phase had confirmed the viability of the 3D printed structure. Thus, the unit of the 3D printed structure could be directly adopted and modified in this case. Using the existing workable unit as a module reduced the time of modifying and testing, and enhanced the efficiency of creating more variations of the 3D printed structure. Further, 3D printing using the same setting increased the printing success rate and helped save time and materials.

Second, the 3D CAD workflow was simplified. The 3D CAD workflow was an important part in Phase 1. It included initial modeling testing from lines to the final workable structure. Then in Phase 2, the main CAD work was to pattern the existing structure unit and modify the connections to form different variations.

Third, durations in the design process were reduced. The timetable for the design process are direct visual demonstrations of the increased efficiency. The timetable indicates that, compared to Phase 1, in Phase 2 Less time was spent in corresponding sections. For example, in Phase 2 we created five different variations of 3D printed structures in a similar timeframe, while in Phase 1 we created only one sample. Post finishing for a 2 x 4 in. piece usually took half an hour in Phase 2, while it had taken more than an hour in Phase 1.

Due to the capability of the FDM 3D printer, the evaluations of some relatively complex structures (e.g., V2 and V5) could not fully reflect their actual properties, because the printing quality of these complex structures was relatively low. Future research may use a more advanced 3D printer to print and test the properties of these relatively complex structures.

Key findings.

3D CAD. The 3D CAD in Phase 2 adopted and modified the structures from Phase 1 as a basic unit. Findings indicated that modifying the existing CAD model largely reduced the amount of work, and increased the efficiency of creating new variations of 3D printed structures, thanks to the accuracy of the 3D CAD modeling in Phase 1.

Printing success rate. The findings indicated that a more complex structure reduced the printing success rate and influenced the quality and durability of the 3D printed structures. Due to the capability of the FDM 3D printer, more complex structures (e.g., those with more curvature, or more stretch ways) increased the number of small support parts, which caused some parts to be disconnected, low in quality, or even burned. Thus, success rate becomes a prior factor in evaluating different variations of 3D printed structures and making a final selection for prototyping.

Properties. By comparing different properties, the findings suggest that some evaluation criteria were related to filament property (e.g., softness, flexibility, weight), and thus could not be changed. Those filament-related properties were not used for selecting the 3D printed structure for final prototyping. Other properties were influenced by the structure of the 3D printed structures, like connections, stretchability, and cushioning. For example, more curved shapes in the X-Y plane increased the stretchability of the structure, and more curved shapes in the Z direction increased the cushioning of the structure.

Seam allowance. Seam allowance was removed in Phase 2 to eliminate its influence on the properties of the 3D printed structures. Instead of using a seam allowance, Phase 2 used a different zigzag stitch method to sew 3D printed structures with traditional fabrics. The zigzag stitch performed well to combine two pieces firmly, while not limiting the properties of the 3D printed structures.

Study 2

Study 2 used RAD methodology and the survey research method to examine the relationships hypothesized in **RQ3**. By employing Lamb and Kallal's (1992) FEA model, Study 2 investigated users' functional, expressive, and aesthetic perceptions of the 3D printed hooded sweatshirt prototyped in Study 1. Specifically, it was hypothesized that users' FEA perceptions of the 3D printed hooded sweatshirt positively influence users' satisfaction and purchase intentions towards the 3D printed hooded sweatshirt.

Previous research investigating users' FEA perceptions focused on garments made from traditional fabrics; there was no existing research examining users' perceptions of 3D printed wearable apparel products. Study 2 aimed to provide more insights for this research gap, reviewing previous FEA research on garments with traditional fabrics, while applying the findings to hypothesizing FEA perceptions of 3D printed wearable apparel products. Given this extension, it was expected that discrepancies between the current results and previous findings could emerge.

Influence of Users' Aesthetic Perceptions on Users' Satisfaction

Novelty and typicality. Due to the application of new technology on wearable apparel products, there was limited previous research investigating users' perceptions of novelty on 3D printed wearable apparel products. Previous research on traditional apparel indicated that, novelty is one of the important visual aesthetic perceptions to influence users' satisfaction (Seifert & Chattaraman, 2017). Previous limited comments on 3D printed wearable designs (Shapeways, 2014) indicated that consumers had positive perceptions of novelty on 3D printed wearable apparel products. According to exploratory factor analysis results, the initial novelty items were split into novelty and typicality measurements, the final regression analysis indicated that users' aesthetic perceptions of novelty and typicality had no influence on users' satisfaction with the 3D printed hooded sweatshirt; thus, H1a1 and H1a2 were not supported. This result was inconsistent with previous findings that novelty influence users' satisfaction (Seifert & Chattaraman, 2017; Shapeways, 2014).

One possible reason for the inconsistent results compared to previous studies could be that the appearance of the prototype – the 3D printed hooded sweatshirt was more traditional than novel. Even though it was called "3D printed hooded sweatshirt," only a small portion of the sweatshirt consisted of 3D printed flexible structures, with most of the sweatshirt made of traditional gray fleece fabric. Thus, despite the fact that participants had been informed that 3D printed structures had been integrated into the wearable apparel product, it might not be perceived as novel as the fully 3D printed wearable apparel products discussed in Chapter 2 (e.g., Nervous System, 2014; Stephanie, 2016). On the other hand, it might not be perceived as typical as traditional garments because of the integration of 3D printed structures. Hence, participants may not have perceived it to be sufficiently novel or typical from traditional garments to positively influence satisfaction.

Another possible reason could be that users' perceptions of the product's novelty and typicality suppressed each other's positive influence, leading to neither of them influencing users' satisfaction. Previous research has indicated that the typicality of a product is 'goodness of example', and positively influences consumers' aesthetic preferences (Veryzer & Hutchinson, 1998). Previous research also has supported that fashion products with novel designs can stimulate consumers' arousal, resulting in consumers' positive aesthetic responses (Kwon & Workman, 1996; Seifert & Chattaraman, 2017). While Hekkert, Snelders, and van Wieringen's (2003) study of joint predictors of typicality and novelty indicated that typicality and novelty jointly influence consumers' aesthetic preferences, and that one may suppress the other's positive influence. The users might think the 3D printed hooded sweatshirt was too novel, their typicality preference offsetting the influence of novelty, thus leading to neither novelty nor typicality influencing users' satisfaction.

Beauty. Previous research has indicated that users' beauty perceptions of functional garments positively influence users' satisfaction with the garment (Jin & Black, 2012; Marriott, 2015; Shapeways, 2014; Stokes & Black, 2012). However, limited previous research has specifically investigated 3D printed wearable apparel products. Previous comments about 3D printed wearable apparel products has indicated that users' beauty perceptions positively influence their satisfaction (Shapeways, 2014). Results from multiple regression analysis confirmed users' beauty perceptions of the 3D printed hooded sweatshirt positively influence their satisfaction, thus supporting H1b. The result is congruent with Lamb and Kallal's (1992) finding that beauty is one of the most important aesthetic considerations in designing functional garments.

Influence of Users' Expressive Perceptions on Users' Satisfaction

Coolness. Due to the application of new technology on wearable apparel products, there was limited previous research investigating users' perceptions of the coolness of 3D printed wearable apparel products. Previous limited comments on 3D printed wearable designs (Peleg, 2015) indicated that consumers had positive perceptions of the coolness of 3D printed wearable apparel products. The final multiple regression analysis indicated that users' expressive perceptions of coolness positively influence users' satisfaction of the 3D printed hooded sweatshirt, thus supporting H2a.This is consistent with previous findings that coolness of a product provide users with exciting experience and help users to express their personalities, has a long-term influence on users' daily life (Goodman, 2001; Holtzblatt, 2010). The perceived coolness of this 3D printed hooded sweatshirt catches users' eyes and enables them to express their personalities.

Uniqueness. Previous research indicated that consumers tend to obtain unique products or services that are scarce, innovative, and customized, and that few others possess (Harris & Lynn, 1996; Lynn & Harris, 1997). 3D printed wearable apparel products are unique as they meet all of these criteria above. Thus, it was hypothesized that users' perceptions of the uniqueness of 3D printed wearable apparel products positively influence users' satisfaction. However, the final multiple regression analysis indicated that users' expressive perceptions of uniqueness had no influence on users' satisfaction with the 3D printed hooded sweatshirt; thus, H2b was not supported. This may be for the same reason as previously explained in context to novelty and typicality perceptions of the 3D printed hooded sweatshirt. The sweatshirt may have looked more like a traditional garment and participants may not have perceived much uniqueness in it. Thus, it led to no influence of perceived uniqueness on users' satisfaction.

Another explanation may be because of the moderating role of the desire for uniqueness consumer product (DUCP). Consumers have different tastes of unique products (i.e., different level of DUCP, Lynn & Harris, 1997). Previous research indicated that DUCP moderates the relationship between consumers' experience and consumers' attitude towards a unique product; consumers with high level of DUCP prefer unique products, while consumers with low level of DUCP have a low desire for unique products (Keng, et al., 2012; Simonson & Nowlis, 2000). The participants recruited in Study 2 might have a low level of DUCP, which may have led to no influence of uniqueness perceptions on users' satisfaction.

Influence of Users' Functional Perceptions on Users' Satisfaction

Fit. Previous research has emphasized the influence of garment fit on user satisfaction (Jin & Black, 2012; Kidd, 2006; Stokes & Black, 2012). Even though limited previous research had investigated the influence of body fit of 3D printed wearable apparel products on users' satisfaction, some 3D printed wearable apparel product manufacturers have highlighted body fit, like providing fitting applications for users to customize their own 3D printed wearable apparel products (Mau, 2017; Nervous System, 2014). Thus, it was hypothesized that users' perceptions of the fit of 3D printed wearable apparel products positively influence users' satisfaction. Based on exploratory factor analysis results, the initial fit items were split into fit-upper body and fit-torso measurements. The final regression analysis indicated that users' functional perception of fit-upper body positively influenced users' satisfaction with the 3D printed hooded sweatshirt, while fit-torso did not. Thus, H3a1 was supported and H3a2 was not supported. This implies that fit across the neck and shoulders influences user satisfaction for an upper body wearable product. Given that the sweatshirt style is not fitted through the remaining torso, fit-torso perceptions did not influence user satisfaction.

Mobility. Previous research has emphasized the influence of garment mobility on user satisfaction (Jin & Black, 2012; Michaelson, 2015; Wheat & Dickson, 1999). Even though limited previous research had investigated the influence of the mobility of 3D printed wearable apparel products on users' satisfaction, some 3D printed wearable apparel product designs have highlighted mobility, like using interconnected hinges among the 3D printed pieces to improve mobility (Nervous System, 2014), or mimicking the flexibility of woven fabrics (Stephanie, 2016) to enhance users' satisfaction. Thus, it was hypothesized that users' perceptions of the mobility of 3D printed wearable apparel products positively influence users' satisfaction. The final regression analysis indicated that users' functional perception of mobility had no influence on users' satisfaction with the 3D printed hooded sweatshirt. Thus, H3b was not supported. Three reasons could have contributed to this result. First, the sweatshirt was not a fitted garment that hindered mobility. Second, the location of the 3D-printed structures on the sweatshirt also did not hinder mobility. Third, participants did not wear the 3D printed hooded sweatshirt by themselves but only evaluated via visual perceptions. Hence, the participants may not have perceived mobility to be a significant factor in influencing their satisfaction with the 3D printed hooded sweatshirt.

Comfort. Previous research has emphasized the influence of garment comfort on user satisfaction (Dickson & Pollack, 2000; Hatch, 1993; Mukhopadhyay & Midha, 2008; Stokes & Black, 2012). Even though limited previous research had investigated the influence of comfort of 3D printed wearable apparel products on users' satisfaction, some 3D printed wearable apparel product manufacturers have acknowledged comfort issues in current 3D printed wearable apparel product designs—they are not as comfortable as traditional fabrics—and tried to improve the softness (Kisliuk, 2014; Scott, 2016; Shapeways, 2014). Thus, it was hypothesized that users' perceptions of comfort of 3D printed wearable apparel products positively influences users' satisfaction. The final regression analysis indicated that users' functional perceptions of comfort had no influence on users' satisfaction with the 3D printed hooded sweatshirt. Thus, H3c was not supported. Similar to the discussion of findings related to perceived mobility, since the sweatshirt is inherently a comfort-oriented garment, and participants did not wear the prototype, it is highly likely that perceived comfort did not play a significant roles in influencing user satisfaction.

Ease of donning and doffing. Previous research emphasized the importance of ease of donning and doffing garments, and indicated their positive influence on users' satisfaction (Bitterman, Ofir, & Ratner, 2009; Michaelson, 2015; Stokes & Black, 2012; Watkins, 1984).

Limited previous research has investigated the influence of donning and doffing of 3D printed wearable apparel products on users' satisfaction. The final regression analysis indicated that users' functional perception of ease of donning and doffing had no influence on users' satisfaction with the 3D printed hooded sweatshirt. Thus, H3d was not supported.

Among the variables of functional perceptions, only fit-upper body influenced users' satisfaction, while the others did not. Viewed holistically, there are two possible explanations.

First, the results might be largely related to the design of this specific 3D printed hooded sweatshirt. In other words, the upper body part of this 3D printed hooded sweatshirt design enabled users to perceive fit, and further led to their satisfaction. However, the fit-torso, comfort, mobility, and donning/doffing of the specific sweatshirt design was not perceived to be a concern for user satisfaction.

Second, participants evaluated their functional perceptions based only on photos and GIF animations. They did not physically touch or wear the 3D printed hooded sweatshirt themselves. They evaluated the functional perceptions according to the appearance of the 3D printed hooded sweatshirt on specific manikins and human models. The body sizes of the manikins and human models may be another factor that influenced their evaluations. Thus, the participants could not effectively evaluate the sweatshirt for functional aspects of comfort, mobility, and donning/doffing, and this may have led to their non-significant influence on satisfaction.

Influence of Users' FEA Perceptions of 3D Printed Wearable Apparel Product on Users' Purchase Intention

Previous research has indicated that product aesthetics positively influence users' perceptions of a product, help form their attitudes towards the product, and further positively influence their purchase intentions (Ajzen & Fishbein, 1980; Bloch, 1995). Moreover, consumers prefer scarce products that are cool and unique, and that can represent their personalities and styles (Lynn & Harris, 1997). Thus, it was hypothesized that users' aesthetic and expressive perceptions of 3D printed wearable apparel products positively influence users' purchase intentions. While, due to the functions of 3D printed structures were not as comfortable as traditional fabrics (Jacobson, 2017; Tarmy, 2016). The perceptions of low comfort of the 3D printed hooded sweatshirt may lead to low purchase intention. Thus, it was hypothesized that users' functional perceptions of 3D printed wearable apparel products have positive influence on users' purchase intentions. The final regression analysis partially supported the hypotheses. Specifically, beauty from aesthetic perceptions and coolness from expressive perceptions positively influence users' purchase intentions, while novelty from aesthetic perceptions negatively influence their purchase intentions. Thus, only H4b and H5a were supported. Other perceptions had no influence on users' purchase intentions.

Novelty and typicality were hypothesized to positively influence users' purchase intentions, while the results demonstrated a negative influence of novelty and no influence of typicality. These results can also be explained by Hekkert, et al.'s (2003) study of joint predictors of typicality and novelty. Possibly the users thought the integration of the 3D printed structures, and/or the curved design of the garment with traditional fabrics, were too novel. Thus, their typicality preferences kept them from purchasing this novel 3D printed hooded sweatshirt, leading to a negative influence of novelty and no influence of typicality.

Uniqueness was hypothesized to influence users' purchase intentions, but this hypothesis was not supported. The possible explanations are similar to those in context to the influence of uniqueness on users' satisfaction. Uniqueness did not influence their purchase intentions, perhaps because the 3D printed structures were only a small part of the whole garment and users did not perceive it as unique enough to influence their purchase intentions. Another explanation may be that the participants in study 2 had low level of DUCP, which led to no influence of uniqueness on users' purchase intention (Keng, et al., 2012; Simonson & Nowlis, 2000).

Functional perceptions were hypothesized to positively influence users' purchase intentions, but the results indicated the H6 hypothesis was not supported. The explanation may be similar to that of functional perceptions influencing users' satisfaction. Users either understood that the 3D printed hooded sweatshirt was a novel product and did not expect more about the functions, or users did not physically touch the 3D printed hooded sweatshirt, and thus could not reach accurate functional perceptions.

The influence of users' perceptions on their purchase intentions displayed a slightly different pattern from the influence of users' perceptions on their satisfaction. This is probably because when they evaluated satisfaction, users played the roles of observers, and tended to make holistic evaluations of the 3D printed hooded sweatshirt for others. When they considered purchasing, playing the role of actual buyers, they tended to be strongly attracted to and influenced by the visual aesthetic and expressive aspects of the 3D printed hooded sweatshirt.

The Influence of Users' Satisfaction with 3D Printed Wearable Apparel Products on Users' Purchase Intentions

Previous theory indicates that users' satisfaction of a product forms a positive attitude, and the positive attitude leads to users' purchase intentions of this product (Ajzen & Fishbein, 1980; Bloch, 1995; Lynn & Harris, 1997). The final simple linear regression analysis indicated that users' satisfaction with the 3D printed hooded sweatshirt had a positive influence on users' purchase intentions. Thus, H7 was supported. This is consistent with previous research that users' satisfaction of a product is an indicator of future purchase, and users' satisfaction positively influence their purchase intention (Alavi, et al., 2016; Chi, 2018; Kim & Lee, 2011). Thus, users' satisfaction of the 3D printed hooded sweatshirt played significant role to influence users' purchase intention.

CHAPTER 6: CONCLUSIONS AND IMPLICATIONS

The Study 1 (RTD) and Study 2 (RAD) research in the previous chapters provided valuable implications for understanding the 3D CAD design process for creating 3D printed flexible structures, properties of different variations of 3D printed structures, and users' perceptions of 3D printed wearable apparel products. The findings from the studies offer important theoretical, methodological, and managerial implications that are discussed in this chapter.

Theoretical Implications

For Study 1, this research is the very initial one to adopt the Maker Movement as an overarching theory for 3D printed wearable apparel products. Enriching this theory requires future 3D printed wearable apparel product explorations to join in the ecosystem, adopt a similar design process, practice and refine the knowledge and skills from previous designs to form a universal design process. A universal design process of 3D printed wearable apparel product enables designers and users to communicate and share ideas, make it easy to promote this technology integrated wearable apparel product to the general public. Therefore, normal people with less knowledge could gain knowledge and skills through self-learning and practice to contribute their ideas to the development of 3D printed wearable apparel product.

For Study 2, it provided more insights that extended and applied the FEA model (Lamb & Kallal, 1992) to 3D printed wearable apparel products, which limited previous research had done. The results showed that each perception category has one variable—beauty (aesthetic perception), coolness (expressive perception), or fit-upper body (functional perception)—that influences users' satisfaction with the 3D printed hooded sweatshirt. This indicated that, in general, the FEA model could be applied to predict users' satisfaction with 3D printed wearable apparel products. Previous research findings have emphasized functional issues and considerations in functional garments (Jin & Black, 2012; Stokes & Black, 2012), while in Study 2, users' satisfaction focused more on aesthetic perceptions than on other perceptions, indicating that aesthetic considerations are more influential in wearable apparel products that apply new technologies like 3D printing. Thus, future research focused on 3D printed wearable apparel products could examine other variables of aesthetic perceptions (e.g., unity, variety) to confirm the significant influence of aesthetic perceptions, help extend and modify the FEA model to fit the examination of 3D printed wearable apparel products, or even identify new technologies to be integrated into wearable apparel products. Moreover, even though functional perceptions had low influence on users' satisfaction, this category cannot be neglected. Due to the limitations of the survey study method and the study of currently non-popularized new technologies, users may not have known how to evaluate 3D printed wearable apparel products. However, in the future, the influence of functional perceptions may increase with the addition of new research methods and the popularization of the technologies. Thus, future research could examine functional perceptions to predict their increasing influence on users' satisfaction, and support the FEA model to fit the research of 3D printed wearable apparel products.

Further, this research investigated the influence of users' FEA perceptions on their purchase intentions. The results showed a slightly different pattern from those predicting users' satisfaction. Users' functional perceptions had no influence on their purchase intentions, while users' aesthetic perceptions played the most influential role in their purchase intentions. When evaluating users' satisfaction, users play the roles of observers; when evaluating users' purchase intentions, users are actual buyers. This led to different influence patterns. This part enriched the FEA model in that, with the application of new technologies, besides examining users' satisfaction when they are observers, this research also extends the model to examining users' purchase intentions when they are actual buyers. Thus, future research adopting the FEA model could also examine users' purchase intentions, because purchase intentions reflect users' egoism and real considerations of the wearable apparel products for themselves. Also, users' purchase of the wearable apparel products is the ultimate goal for designers to pursue; thus, users' purchase intentions are necessary to examine and enrich the theory.

Methodological Implications

Under the overarching concept of the Maker Movement (Dougherty, 2012), this research adopted both a qualitative (RTD) method to explore and record the design process of 3D printed flexible structures that could be integrated with traditional fabrics, and a quantitative (RAD) method to further examine users' FEA perceptions of the final 3D printed wearable apparel product. Limited previous research has used the RTD method to explore 3D CAD workflow and properties of 3D printed structures. In addition, previous research adopted the FEA model, using qualitative and quantitative methods to investigate users' perceptions of functional garments with traditional fabrics. This research was the first to examine users' FEA perceptions of a 3D printed wearable apparel product using a quantitative RAD method and survey study to provide valuable feedback for the qualitative RTD research.

In terms of the RTD method, previous studies have highlighted the significance of recording designers' own design process in a reflective design journal, and treating it as valuable data (Gray & Malins, 2004; Schön, 1983). The findings from Study 1 indicated that RTD is a suitable method to explore and record researchers' own design process, generate design data, and provide researchers' own evaluations. Study 1 adopted a chronological approach, following Parsons and Campbell's (2004) 6-step design to record and reflect designers' own design processes for the 3D printed wearable apparel product. All the records were organized into a reflective design journal. The reflective design journal was evaluated regarding 3D CAD design workflow and properties of 3D printed structures, based on the criteria provided in the methodology chapter (Table 1). Study 1 was the research adopting the RTD method to explore 3D printed flexible structures and 3D printed wearable apparel products. By following the RTD method, Study 1 presented well-organized data results and evaluations from the reflective design journal; provided self-reflections, evaluations of the design workflow, and properties of the 3D printed structures; and highlighted the tacit knowledge and solutions for each challenge encountered during the design process. The time duration for each step across two design cases demonstrated improved efficiency in creating new 3D printed structures and prototypes, and indicated increased knowledge and skills. This study provided an example of how to explore new technology to integrate into the traditional design process through the RTD method. Future research could refer to this research as an example of how to adopt and extend the RTD method; follow the design steps to collect self-practiced data; demonstrate the design process in an organic way; and deliver knowledge, skills, and unique design solutions for future reference.

In terms of the RAD method, previous studies have used both survey research and interview approaches on functional garments (Jin & Black, 2012; Stokes & Black, 2012). Study 2 adopted the RAD method and extended the survey research approach to examine the FEA model on 3D printed wearable apparel products. The findings from Study 2 generally supported the FEA model and indicate that RAD was a suitable method to examine the FEA model on 3D printed wearable apparel products, although the findings are different from those of previous research, showing that functional perceptions did not play significant role in influencing users' satisfaction. One reason is that the users were not familiar with 3D printing technology and 3D printed structures. They did not have physical contact with the 3D printed hooded sweatshirt and did not wear it themselves, leading to a low influence of functional perceptions on satisfaction. Future research could adopt a qualitative interview method following physical trials of 3D printed wearable apparel products, to collect richer feedback on functional perceptions.

Managerial Implications

This research provided empirical implications that, future designers and retailers who focus on 3D printed wearable apparel products can benefit from to improve design process, enhance users' convenience and purchase intention.

Maker Movement. The concept of Maker Movement changes people's view that everyone is a maker that could join in the design process to contribute to the development of 3D printed wearable apparel product. Knowledge monopoly and patent are past tense, while knowledge sharing is the future trend. Initially, designer and consumer are two distinguished characters. Designers have the design concepts and consumers have limited options to choose from. Maker Movement breaks the boundary of the two characters, consumer could also play the role as the designer. Sharing knowledge and ideas enable the general public to have access to the latest technology, gain knowledge and provide their own design ideas to the field of 3D printed wearable apparel product. Thus, future 3D printed wearable apparel product retailers and manufacturers could provide online platforms for designers and users to share design ideas, crowd funding for high voted 3D printed wearable apparel product designs for manufacturing. Retailers and manufacturers only provide printing services, serve as the facilities and filament providers. Growing body of makers in the 3D printed wearable apparel products ensure sustainable profit for future retailers and manufacturers.

In response to the call from the Maker Movement, this research provided two 3D printed wearable apparel product designs with detailed design process findings, both in 3D CAD and construction, and property evaluations of the 3D printed structures. However, this was exploratory research at an early stage of the 3D printed wearable apparel product study; also, the 3D printed wearable apparel products demonstrated in this research are only novelty cases, rather than repeated-use durable products. Thus, future designers and researchers should adopt the overarching concept of the Maker Movement, and follow the design process used in this research to check the viability and generalizability of the design process for future designs. In addition, longitudinal research is necessary to investigate and enhance the long-term durability of the 3D printed wearable apparel products in the future.

Guidelines. Previous designers have used different design CAD programs, different design logic and methods to finish their 3D printed wearable apparel products. However, detailed design processes for 3D printed wearable apparel products were not provided. Thus, it was difficult to communicate with other designers, or provide inspirations for future designs. Study 1 provided more insights for this research gap by providing a detailed process for designing 3D printed flexible structures that could be integrated with traditional fabrics. Thus, future designers and researchers of 3D printed wearable apparel products could refer to Study 1 as an example or framework by which to explore their own 3D design processes. Further, as more designers adopt similar design processes and methods, guidelines could be formed to integrate all of the knowledge and skills, optimize and simplify the design process, and enhance design efficiency. This way, it would be easy for designers and researchers to communicate with each other about their 3D printed wearable apparel products, as well as to be inspired by and collaborate with others to enrich this field of research and design.

Generalizability. By using the same guidelines for creating 3D printed wearable apparel products, future 3D printer manufacturers could enhance compatibility with other 3D printing related facilities so that wearable apparel products could be printed anywhere in the world. Finally, yet also importantly, by following the design guidelines, the general public or customers without professional design experience could participate in creating their own 3D printed wearable apparel products. Future 3D printer retailers could build up 3D printing hubs. Customers could either send their 3D printed wearable apparel product designs to an online 3D printing hub for printing and delivery, or they could go to a local 3D printing hub to load the file and pick up the product.

Design process. Even though the 3D CAD workflow was emphasized in the design process to answer the research questions, other steps in the design process could also provide valuable implications.

(1) Post finishing. Due to use of an FDM 3D printer, the post finishing process took a fairly long time, because it was necessary to clean the support parts and clip the adhered parts. In order to reduce the amount of work and enhance the cleaning efficiency in post finishing, a double check of the 3D CAD model is necessary to make sure there are enough allowances (> 1mm, because the minimum printing width is 1mm for the FDM printer used in this research) among the different parts, so that a few parts will be adhered after printing. A tweezer is suitable to clean the support parts, while a pair of small scissors is suitable to clip the adhered parts. Sometimes, parts may break during the post finishing process; thus, the 3Doodle pen is need to connect the broken parts together. With experience, designers and researchers will gain the skills to enhance the efficiency of the post finishing process. Future designs may also use more advanced 3D printers, like a SLS printer, to eliminate the support and adhered parts, and this may largely reduce the post finishing time.

(2) Pattern making. The sewing pattern for Phase 1 used a basic, simple vest pattern design with simple straight seam lines. Because it was at an early exploratory stage, a simple

design was appropriate to check the viability of integrating 3D printed structures with traditional fabrics. As the viability was confirmed, Phase 2 adopted and modified the Phase 1 pattern design, trying a more complex pattern design. The sewing pattern for Phase 2 added sleeves, a hood, and curved seam lines. There were challenges, like sewing curved seam lines, but the knowledge and sewing skills gained from Phase 1, as well as advise from peers and experts, provided solutions to these challenges. This suggested that future explorations of 3D printed wearable apparel products could initially adopt a basic apparel sewing pattern, starting with a simple seam line design to examine the viability of integrating 3D printed structures with traditional fabrics. Then the acquired knowledge and sewing skills could further help in designing a more complex pattern.

(3) Sewing. Phase 1 used a traditional sewing method, which added a 1mm thickness seam allowance along the 3D printed structures. However, this seam allowance increased the thickness along the seam lines. Phase 2 instead used a non-seam allowance design, with a zigzag stitching method to effectively reduce the thickness of the seam lines. Future research could continue exploring sewing methods to improve the integration of the 3D printed structures with the traditional fabrics, or even without sewing. For example, printing TPU structures directly onto the traditional fabrics around the same melting point (e.g., nylon fabrics) could provide better integration.

Users' satisfaction and purchase. Study 2 results revealed that beauty (aesthetic perception) was the most influential perception on users' satisfaction and purchase intention. Thus, future fashion designers and garment manufacturers should pay more attention to elevating the beauty of their 3D printed wearable apparel products, providing more varieties of 3D printed structures, so that the 3D printed wearable apparel products could provide visual beauty impact and cater to more customers.

However, typicality (aesthetic perception) and novelty (aesthetic perception) had no influence on users' satisfaction. Typicality (aesthetic perception) had no influence, novelty (aesthetic perception) had a negative influence on users' purchase intention. They could be explained by previous research that novelty and typicality suppress each other's positive influence (Hekkert, et al., 2003). Users might perceived the 3D printed hooded sweatshirt was too novel, and typicality preference suppress novelty perception into a negative influence on uses' satisfaction. This result provided implications for future fashion designers and garment manufacturers that, users tend to purchase 3D printed wearable apparel products which are not too novel and perceived visually like traditional garments.

Coolness (expressive perception) was also an influential perception on users' satisfaction and purchase intention. Thus, future fashion designers and garment manufacturers could provide more different styles of 3D printed structures, various selections of integrations of 3D printed structures and traditional fabrics, or even enable customized 3D printed structures by users. Thus, those style options could meet users' expressive needs, help users demonstrate the style and coolness of their personalities.

Uniqueness (expressive perception) had no influence on users' satisfaction and purchase intention. It may be because the 3D printed structures were a small portion of the 3D printed hooded sweatshirt, users did not perceive it as unique. Future research could explore and enhance the uniqueness of the 3D printed products by increase the portion of 3D printed structures, or even create full 3D printed wearable apparel products, so that users' perception of uniqueness could be influential.

Another reason may be the moderating role of DUCP (Keng, et al., 2012; Lynn & Harris, 1997; Simonson & Nowlis, 2000). The participants recruited in Study 2 might have a low level of DUCP, which have led to no influence of uniqueness perceptions on users' satisfaction. Future research may focus on the moderating role of DUCP to have a better understanding of users' satisfaction and purchase intention with 3D printed wearable apparel products based on their differing preferences for uniqueness in products.

Even though fit-upper body (functional perception) had a minor influence on users' satisfaction, future fashion designers and garment manufacturers still need to pay attention to the functional fit of 3D printed wearable apparel products. Previous research indicated the importance of fit in functional garments (Dickson & Pollack, 2000; Kidd, 2006). The influence of fit is minor, maybe because at this early exploratory stage of 3D printed wearable apparel products, users can understand that it is an application of a new technology and can tolerate the weaknesses in fit. However, the fit of a wearable apparel product is the fundamental goal that fashion designers and garment manufacturers should consider. If future 3D printed wearable apparel products still cannot compete with traditional garments in terms of fit, the development and applications of 3D printed wearable apparel products will be limited. With the improvement of 3D printed wearable apparel products in the future, users will eventually expect improved fit of 3D printed wearable apparel products.

Material cost estimate. For Phase 1 – 3D printed beach vest, the traditional red neoprene fabric cost around $24 plus tax (2 yards at $12/yard plus tax), and the white TPU filament cost around $1.50 plus tax (8 pieces, 9 grams/piece, 1,000 grams filament at $21 plus tax). The total cost was around $25.50 plus tax.

For Phase 2 – 3D printed hooded sweatshirt, the traditional gray fleece fabric cost around $24 plus tax (3 yards at $8/yard plus tax), and the white TPU filament cost around $2.60 plus tax (18 pieces, 7 grams/piece, 1,000 grams filament at $21 plus tax). The total cost was around $26.60 plus tax.

The material cost estimate only considered the raw materials of the final prototypes, while other parts, like sample printing and sewing tests, fail-printed parts, labor effort and time consumption, etc., were not included. Thus, future researchers and designers should consider using at least three times the total raw materials described above. In addition, labor effort and time consumption should also be considered during explorations of 3D printed wearable apparel products.

Limitations

This is one of the initial research to explore the design process of a 3D printed wearable apparel product, and examine users' FEA perceptions on users' satisfaction and purchase intention. Several limitations were identified during the research and design process.

Literature. There was limited previous research focusing on exploring the design process of 3D printed wearable apparel products. Even though several 3D printed wearable apparel product designs are available online, the descriptions, evaluations, and arguments were mainly from the designers themselves. Thus, it may cause potential credibility issues to cite these design information and descriptions, because designers tend to highlight the advantages of their 3D printed wearable apparel products, while diminishing or even neglecting the disadvantages.

Moreover, there was limited previous traditional research focusing on the FEA perceptions of 3D printed wearable apparel products. The literature review consisted mainly of previous research on traditional functional garments and comments from YouTube on 3D printed wearable apparel products. The literature review of previous research on traditional functional garments may not effectively explain users' perceptions on 3D printed wearable apparel products, as the disruption of a technology may have a different influence. In addition, comments from YouTube on 3D printed wearable apparel products were mainly positive opinions, as viewers who are not interested in 3D printed wearable apparel products may tend not to leave comments. Thus, hypotheses based on previous research on traditional functional garments and comments from YouTube may potentially be biased.

3D CAD method. This research used direct modeling method and Rhinoceros 3D CAD program to design 3D printed structures. Rhinoceros is a relatively small CAD program with limited functions but easy operation. It is suitable for early stage explorations to create limited variations of 3D printed structures for validating viability of this research, given limited research timeframe, funding, equipment and material. Even though Rhinoceros tools are easy to use and make changes, but it requires manual checks and adjustments almost every part of the structure. Thus, it becomes less efficient to create large amount of 3D printed structure variations, as it will be overwhelming and time-consuming work. Therefore, direct modeling method may potentially pose some limitations in developing 3D printed structures for wearable apparel product integration.

Previous literature review indicated the advantages of parametric design and generative design (Alba, 2018; Brunelli, 2018). In general, with a pre-developed equation or parameters, designers will only need to create a basic geometric shape or surface and change either manually or automatically to develop 10s or even 1000s variations in a shorter time. Thus, future design and research could adopt these efficient and advanced CAD methods to produce a large quantity of the same 3D printed structures for testing, evaluations, and even mass-customized manufacturing.

Capability of the FDM 3D printer. Previous 3D printed wearable apparel product designs used SLS (e.g., Nervous System, 2014) or FDM (e.g., Marriott, 2015) printers. These are the commonly used 3D printer types. SLS 3D printers can print delicate and complex structures but are high in cost for both equipment and printing prototypes. Compared to SLS 3D printers, FDM 3D printers, which print thermoplastic filament layer by layer, are relatively inexpensive. However, due to the mechanism of the FDM printers, they are not good at printing complex shapes on both soft and hard TPU material. Because they contain many support parts, they take a long time for post finishing. Moreover, sometimes they experience unexpected printing failures.

However, given that the FDM 3D printer is the only available option and that research support was limited, the researchers tried to exploit the potential of the FDM printer to print various 3D printed flexible structures. The capability of the FDM printer became an important evaluation factor because of the printing success rate. More complex structures frequently failed to print, which meant that some of the 3D printed structure variations printed with TPU filament could not be used for prototyping, because printing enough of some pieces would have used much more TPU material than others would. Thus, in Study 1 Phase 2, only one relatively simple variation was selected for final prototyping. Further, due to the limited printing area of the FDM printer (360mm x 240mm), large pieces needed to be manually connected. Manually connecting the parts may somewhat reduce the overall visual and structure qualities of the 3D printed structures, and the pieces required extra time for post finishing.

In the future, it will be interesting to see different variations of high quality flexible 3D printed structures using TPU filament and more advanced 3D printers, like the SLS. It will extend and enrich this study and provide more valuable evaluations and data.

Full vs. partial 3D printed wearable apparel products. Previous 3D printed wearable apparel products were full 3D printed, without integrating any traditional fabrics. This research focused on integrating 3D printed structures with traditional fabrics. Thus, the product was a partial 3D printed wearable apparel product. Full and partial 3D printed wearable apparel products may have different FEA perceptions among users because, when integrated with traditional fabrics, the 3D printed structures are only a portion of the garment. Its overall look is that of a traditional garment with some 3D printed decoration structures. Even though the results from Study 2 revealed a different pattern from previous FEA research on functional garments using traditional fabrics, still some variables did not influence users' satisfaction (e.g., typicality, uniqueness). This may be because, in general, users perceived the 3D printed hooded sweatshirt more as a traditional functional garment.

Due to the limited capability of the FDM printer and limited funding, timeframe in the current situation, it was less likely to print a full 3D printed wearable apparel product for this research. In the future, by using more advanced 3D printers, full 3D printed wearable apparel products with different variations of the 3D printed structures designed in this research could be printed. Investigating full 3D printed wearable apparel products will provide more holistic perceptions and understanding of 3D printed wearable apparel products.

Users' perceptions. Previous research used both quantitative survey and qualitative interview methods to examine users' perceptions of functional garments. Survey and interview methods provided users with visual and tactile perceptions of the functional garments, so that the evaluations were more holistic and accurate. While in Study 2 of this research, users' FEA perceptions were gleaned only from visual photos and GIF animations. Users did not wear the 3D printed hooded sweatshirt themselves, nor did they physically touch it. This may be a reason that many functional perception variables had no influence on users' satisfaction, which makes it a limitation of Study 2. Future research on 3D printed wearable apparel products should not only provide users with visual images, but also enable them to try on and touch/feel the 3D printed wearable apparel products. Holistic perceptions from users will provide more accurate data for researchers to evaluate and improve the design of 3D printed wearable apparel products.

Future Research

In summary of the implications and limitations in this chapter, here proposed some research questions for future explorations of 3D printed wearable apparel products.

1. How future explorations of 3D printed wearable apparel product could adopt the overarching

theory of the Maker Movement, join in the ecosystem to enrich the research of 3D printed wearable apparel product?

1.1 *Repeatability*. How could future designers adopt the same RTD method and design process used in this research to create new 3D printed wearable apparel products?

1.2 *Generalizability*. With more 3D printed wearable apparel product design adopting a similar design process, how do designers integrate these design process and evolve into a universal design process for the general public to understand and use?

1.3 *Efficiency*. How to create more 3D printed structures in a more efficient way, through (1) other 3D CAD programs, (2) enhancing the efficiency of 3D CAD design workflow, (3) adopting parametric design method, or (4) improving specific knowledge and skills?

1.4 *Durability*. How to adopt a longitude research method to investigate and examine the long-term durability of the 3D printed wearable apparel products?

1.5 *Property*. How new properties of 3D printed structures could be created and evaluated using various 3D printing materials?

1.6 *3D printing success rate and post finishing.* How to improve the 3D printing success rate and reduce post finishing time by (1) enhance 3D CAD design workflow and accuracy of 3D CAD models, (2) using more advanced 3D printing methods (e.g., SLS printers)?

1.7 *Sewing*. How to enhance the sewing method to integrate 3D printed structures with traditional fabrics, so that the sewing parts are firm, durable and comfort? Exploring (1) stitch lines, (2) structures of 3D printed pieces, (3) full 3D printed seamless apparel products.

2. How to extend and modify the FEA model to examine users' satisfaction and purchase intention with 3D printed wearable apparel products?

2.1 In terms of aesthetic perceptions, how to decide and manipulate the level of novelty of the 3D printed wearable apparel product, so that the design can maintain the balance between novelty and typicality, enable both novelty and typicality positively influence users' satisfaction and purchase intention?

2.2 In terms of expressive perceptions, how to enhance the uniqueness of the 3D printed wearable apparel product to positively influence users' satisfaction and purchase intention? Considering increasing the portion of 3D printed structures, or even full 3D printed wearable product. How the moderating role of DUCP influence users' satisfaction and purchase intention?

2.3 In terms of functional perceptions, how to design a feasible research method to enable users' to wear and have a physical touch of the 3D printed wearable apparel product, and enables users to have accurate functional perceptions.

2.4 Whether users' FEA perceptions of full 3D printed wearable apparel products influence users' satisfaction and purchase intention? What are the differences of users' FEA perceptions between partial 3D printed wearable apparel products and full 3D printed wearable apparel products

2.5 Are there any other variables that could be included in the FEA model to better predict users' satisfaction and purchase intention of the 3D printed wearable apparel products?

2.6 Is there any other theory or research model that could be adopted in the research to predict and examine users' satisfaction and purchase intention of the 3D printed wearable apparel products?

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Appendices

Appendix A

IRB Approval Form

Add this approval information in sentence form to your electronic information letter!

The Auburn University Institutional Review Board has approved this Document for use from 07/23/2018 to --- Protocol # 18-288 EX 1807

AUBURN UNIVERSITY

COLLEGE OF HUMAN SCIENCES

(NOTE: DO NOT AGREE TO PARTICIPATE UNLESS IRB APPROVAL INFORMATION WITH CURRENT DATES HAS BEEN ADDED TO THIS DOCUMENT.)

INFORMATION LETTER
for a Research Study entitled
"Evaluating Users' Perceptions of 3D Printed Wearable Products"

You are invited to participate in a research study to evaluate users' perceptions of 3D printed wearable products. The study is being conducted by Tianyu Cui, a doctoral candidate, under the direction of Dr. Veena Chattaraman and Dr. Lushan Sun, in the Auburn University, Department of Consumer & Design Sciences. We ask that you read this letter and ask any question you may have before agreeing to be in this continuing research.

What will be involved if you participate? Your participation is completely voluntary. If you decide to participate in this research study, you will be asked to complete an online questionnaire. Your total time commitment will be approximately 15 minutes.

Are there any risks or discomforts? The participation in this study would put you in no physical or psychological risks other than the minimal inconvenience of completing the questionnaire.

Are there any benefits to yourself or others? If you participate in this study, you can expect to shop and customize 3DP wearable products in the future, as product designers and marketers may have a better understanding of users' perceptions of 3DP wearable products, improve designs and sell them in the future. You may not directly benefit from this project.

Will you receive compensation for participating? You will be compensated for participating in this study through a panel company. The panel company will provide instructions how to redeem your compensation.

Are there any costs? If you decide to participate, there will be NO cost to you.

If you change your mind about participating, you can withdraw at any time by closing your browser window. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Once you've submitted anonymous data, it cannot be withdrawn since it will be unidentifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University, the Department of Consumer and Design Sciences.

Any data obtained in connection with this study will remain anonymous. We will protect your privacy and the data you provide by not collecting IP addresses from research participants. Information collected through your participation may be published in a professional journal, and/ or presented at a professional meeting.

If you have questions about this study, please contact Tianyu Cui at tzc0017@auburn.edu, Dr. Veena Chattaraman at vzc0001@auburn.edu, or Dr. Lushan Sun at lzs0064@auburn.edu.

If you have any questions about your rights as a research participant, you may contact the Auburn
University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or e-mail at IRBadmin@auburn.edu.

HAVING READ THE INFORMATION ABOVE, YOU MUST DECIDE IF YOU WANT TO PARTICIPATE IN THIS RESEARCH PROJECT. IF YOU DECIDE TO PARTICIPATE, PLEASE CLICK ON THE LINK BELOW.
YOU MAY PRINT A COPY OF THIS LETTER TO KEEP.

Tianyu Cui
Investigator
Date: 07/23/2018

Veena Chattaraman
Co-Investigator
Date: 07/23/2018

Lushan Sun
Co-Investigator
Date: 07/23/2018

The Auburn University Institutional Review Board has approved this document for use from _07/23/2018_ to ________. Protocol # 18-288 EX 1807

LINK TO SURVEY

Add this approval information in sentence form to your electronic information letter!

The Auburn University Institutional Review Board has approved this Document for use from
07/23/2018 to ---
Protocol # 18-288 EX 1807

Appendix B

Questionnaire

What is your gender?

Female

Male

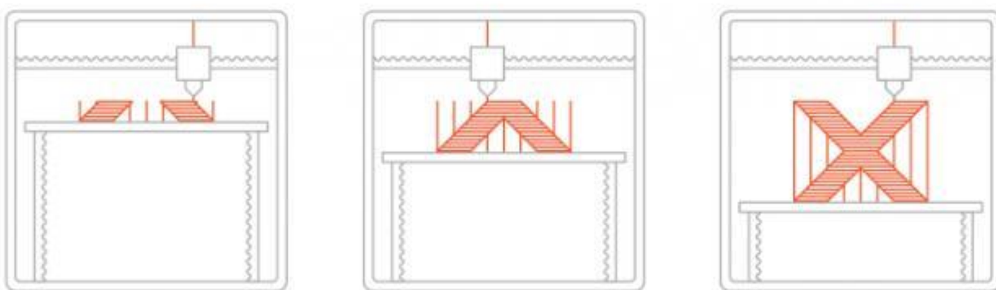
>>

PART 1:

In this part, you will be introduced the definition of 3D printing and working process of a 3D printer.

What is 3D printing?

Three-dimensional printing (3D printing) is an additive manufacturing process that creates a 3D object by using a 3D printer to incrementally add material layer by layer until the object is complete. See the illustration on how 3D printer works below.



In the next page, you will see some photos of a 3D printed hooded sweatshirt. Following which, you will be asked to evaluate this 3D printed hooded sweatshirt.

>>

PART 2:

The following photos demonstrate a 3D printed hooded sweatshirt on a female manikin. A GIF animation is also provided to show human body movement when wearing the 3D printed hooded sweatshirt.

The 3D printed thermoplastic structure (the white parts, printed with a flexible thermoplastic material) were sewed with traditional dark gray fleece knit textile. The photos and the GIF animation will be displayed in every question for your reference.

In this part, we are interested in your **satisfaction** and **purchase intention** of a 3D printed hooded sweatshirt and the 3D printed structure.

Please observe the photos carefully and indicate your evaluations of the scales below.

The following statements address your **satisfaction** with **this 3D printed hooded sweatshirt**. Please indicate your level of agreement with each of the following statements:

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
I am very satisfied with this 3D printed hooded sweatshirt.	O	O	O	O	O	O	O
This 3D printed hooded sweatshirt matches my ideal 3DP wearable product.	O	O	O	O	O	O	O
In general, this 3D printed hooded sweatshirt is better than expected.	O	O	O	O	O	O	O

The following statements address your **satisfaction** with **the 3D printed thermoplastic structure**. Please indicate your level of agreement with each of the following statements:

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
I am very satisfied with this 3D printed thermoplastic structure.	O	O	O	O	O	O	O
The 3D printed structure match my ideal 3D printed thermoplastic structure.	O	O	O	O	O	O	O
In general, the 3D printed thermoplastic structure is better than expected.	O	O	O	O	O	O	O

>>

The following statements address your **purchase intention** of this 3D printed hooded sweatshirt. Please indicate your level of agreement with each of the following statements:

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
I would consider buying this 3D printed hooded sweatshirt.	O	O	O	O	O	O	O
I will purchase this 3D printed hooded sweatshirt.	O	O	O	O	O	O	O
There is a strong likelihood that I will buy this 3D printed hooded sweatshirt.	O	O	O	O	O	O	O

>>

PART 3:

In this part, we are interested in your evaluations of **aesthetic** perceptions of this 3D printed hooded sweatshirt.

Please observe the photos carefully and indicate your evaluations of the scales below.

The following statements address your perceived **novelty** of this 3D printed hooded sweatshirt.

I would perceive this 3D printed hooded sweatshirt to be

Old	O	O	O	O	O	O	O	New
Unoriginal	O	O	O	O	O	O	O	Original
Common	O	O	O	O	O	O	O	Unusual
Familiar	O	O	O	O	O	O	O	Unfamiliar
Typical	O	O	O	O	O	O	O	Atypical

The following statements address your perceived **beauty** of this 3D printed hooded sweatshirt.

I would perceive this 3D printed hooded sweatshirt to be

Not attractive	O	O	O	O	O	O	O	Attractive
Not desirable	O	O	O	O	O	O	O	Desirable
Not exciting	O	O	O	O	O	O	O	Exciting
Not beautiful	O	O	O	O	O	O	O	Beautiful
Does not make me like this product	O	O	O	O	O	O	O	Make me like this product

>>

PART 4:

In this part, we are interested in your evaluations of **expressive perceptions** of this 3D printed hooded sweatshirt.

Please observe the photos carefully and indicate your evaluations of the scales below.

The following statements address your perceptions of **'how cool'** this 3D printed hooded sweatshirt is.
Please indicate your level of agreement with each of the following statements:

This 3D printed hooded sweatshirt is

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
stylish	O	O	O	O	O	O	O
hip	O	O	O	O	O	O	O
trendy	O	O	O	O	O	O	O
appealing	O	O	O	O	O	O	O
fascinating	O	O	O	O	O	O	O
attractive	O	O	O	O	O	O	O

The following statements address your perceptions of the **uniqueness** of this 3D printed hooded sweatshirt.

Please indicate your level of agreement with each of the following statements:

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
People who wear this 3D printed hooded sweatshirt are people I would describe as being different from others.	O	O	O	O	O	O	O
This 3D printed hooded sweatshirt makes people who wear it different from other people.	O	O	O	O	O	O	O
If I wore this 3D printed hooded sweatshirt, it would make me stand apart from others.	O	O	O	O	O	O	O
This 3D printed hooded sweatshirt helps people stand apart from the crowd.	O	O	O	O	O	O	O
The people who wear this 3D printed hooded sweatshirt are unique.	O	O	O	O	O	O	O

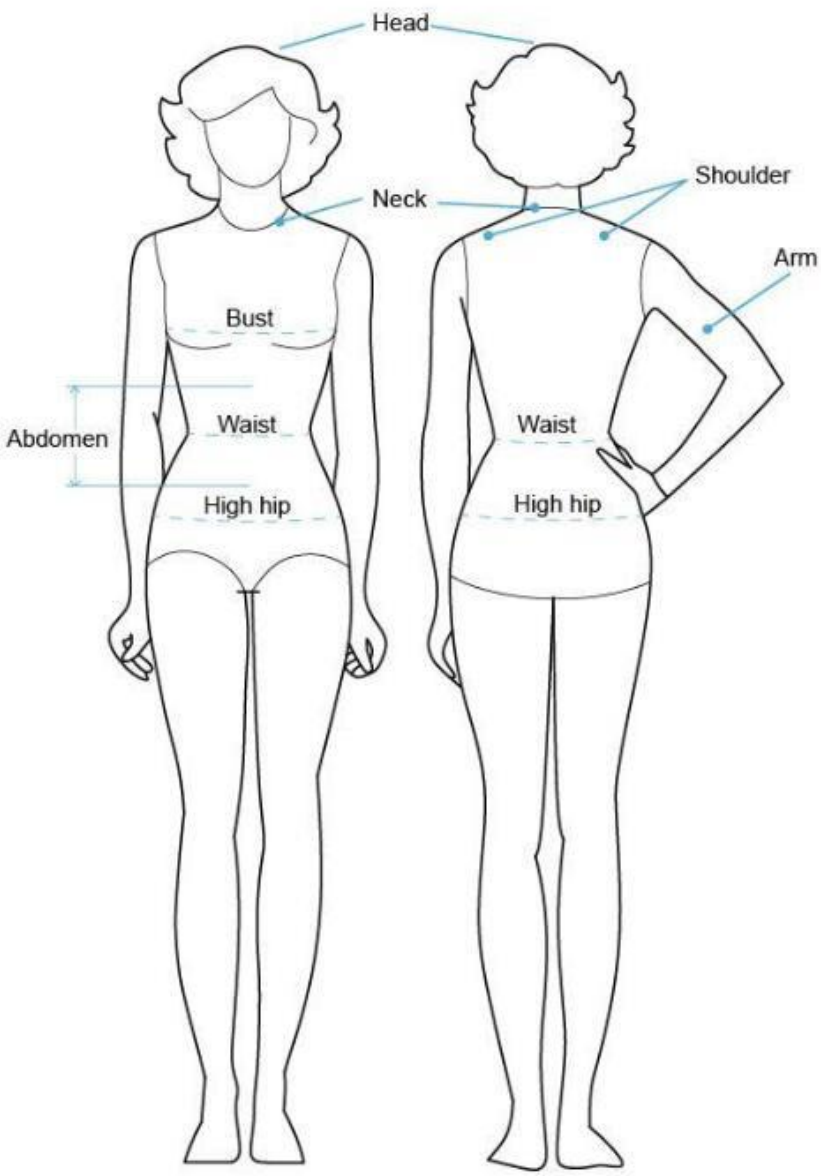
>>

PART 5:

In this part, we are interested in your evaluation of the **functional** perceptions of this 3D printed hooded sweatshirt.

Please observe the photos carefully and indicate your evaluations of the scales below.

Please use the figure below in reference to the questions stated under it



The following statements address your perceptions of **fit** of this 3D printed hooded sweatshirt. Please indicate your level of agreement with each of the following statements:

I perceive that this 3D printed hooded sweatshirt will fit my

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
Head	○	○	○	○	○	○	○
Neck	○	○	○	○	○	○	○
Shoulder	○	○	○	○	○	○	○
Arm	○	○	○	○	○	○	○
Bust	○	○	○	○	○	○	○
Waist	○	○	○	○	○	○	○
Abdomen	○	○	○	○	○	○	○
High hip	○	○	○	○	○	○	○

>>

Please indicate your perceived **mobility** of this 3D printed hooded sweatshirt.

I perceive that the 3D printed hooded sweatshirt is

Flexible	O	O	O	O	O	O	O	Stiff
Freedom of movement of arms	O	O	O	O	O	O	O	Restricted movement of arms
Freedom of movement of torso (body)	O	O	O	O	O	O	O	Restricted movement of torso (body)
Loose	O	O	O	O	O	O	O	Tight

The following statements address your perceived **comfort** of this 3D printed hooded sweatshirt. Please indicate your level of agreement with each of the following statements:

I perceive that the 3D printed hooded sweatshirt is

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
Not warm	O	O	O	O	O	O	O
Prickly	O	O	O	O	O	O	O
Stiff	O	O	O	O	O	O	O
Rough	O	O	O	O	O	O	O
Uncomfortable	O	O	O	O	O	O	O

>>

The following statements address your perceived **ease of donning (putting on)** and **doffing (taking off)** of this 3D printed hooded sweatshirt.

Please indicate your perceived ease of donning and doffing of the 3D printed hooded sweatshirt:

	Excellent	Very good	Adequate	Not quite adequate	Poor	Extremely poor
How do you rate the ease with which you would be able to don (put on) this 3D printed hooded sweatshirt?	O	O	O	O	O	O
How do you rate the ease with which you would be able to doff (take off) this 3D printed hooded sweatshirt?	O	O	O	O	O	O

>>

Do you have any feedback or comment on this 3D printed hooded sweatshirt?

Do you have any feedback or comment on the 3D printed thermoplastic structure (the parts printed with white thermoplastic material)?

>>

Below are a few questions regarding demographic information. Please check the answer that best matches your response in each statement.

What is your

Age

Level of Education

No High School Diploma

High School Diploma

Some College

Associate Degree

BA Degree

Master Degree

PhD Degree

Other

Ethnicity

- African American/Black
- Caucasian/White
- Asian/Pacific Islander
- American Indian
- Multiracial
- Would rather not say
- Other

Marital Status

- Divorced
- Married
- Separated
- Single
- Widowed

Annual pre-tax income

less than $10,000

$10,000 - $29,999

$30,000 - $49,999

$50,000 - $69,999

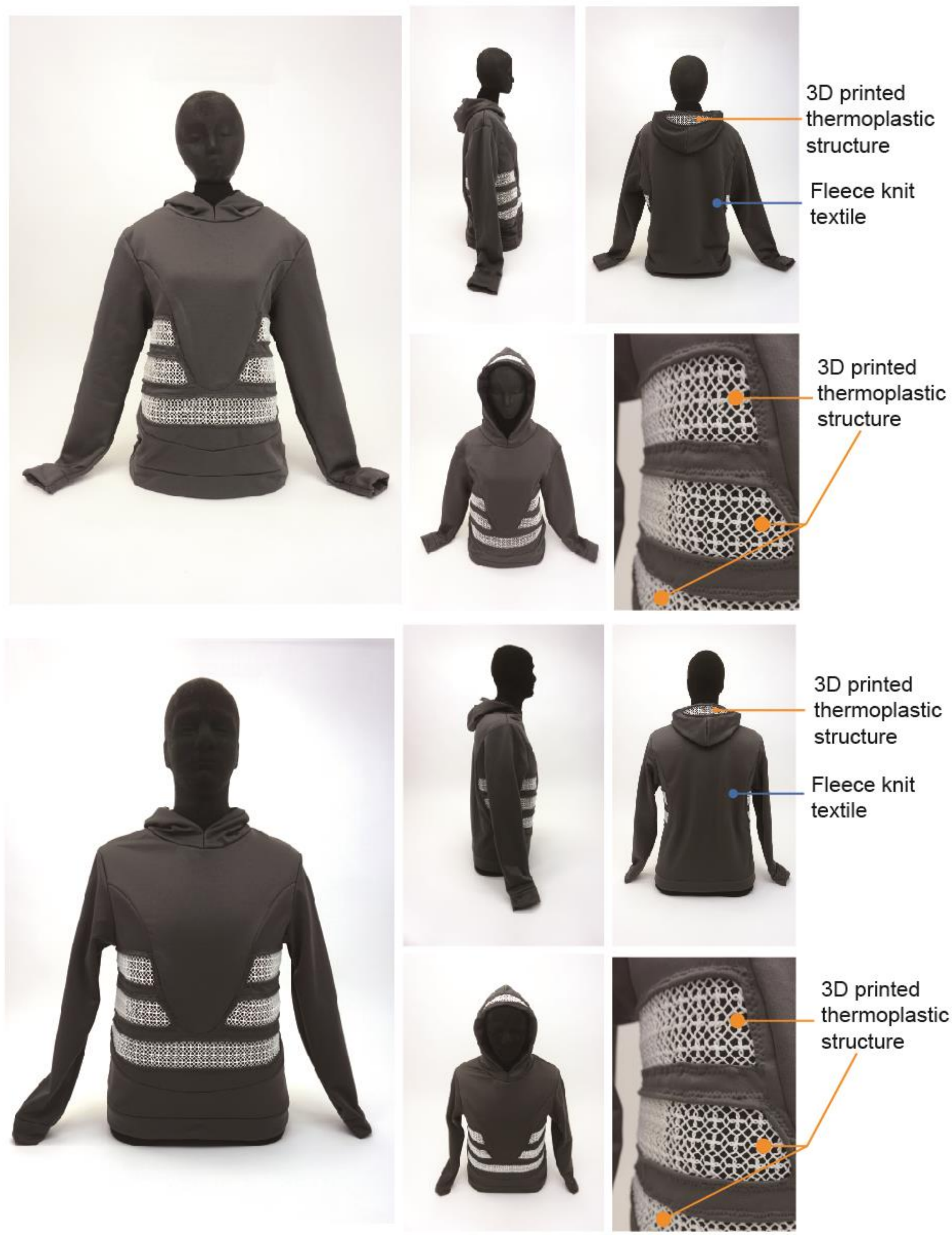
$70,000 - $89,999

more than $90,000

US Location (state in abbreviation, e.g., CA)

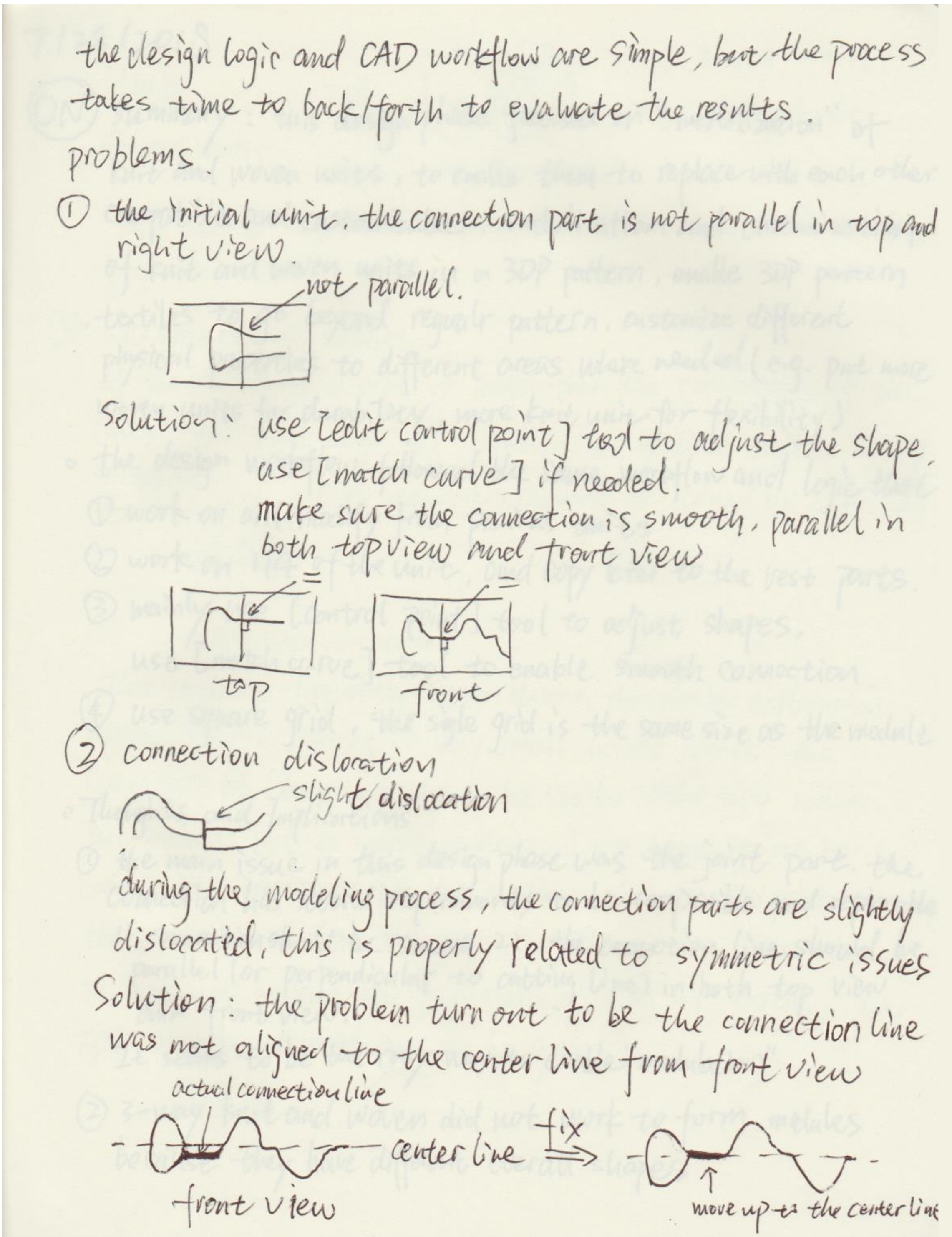
>>

Photos used in the questionnaire. The photos were demonstrated for each question



Appendix C

An example of one page of the reflective design journal



the design logic and CAD workflow are simple, but the process takes time to back/forth to evaluate the results.

problems

① the initial unit. the connection part is not parallel in top and right view

Solution: use [edit control point] tool to adjust the shape.
use [match curve] if needed.
make sure the connection is smooth, parallel in both top view and front view

② connection dislocation

during the modeling process, the connection parts are slightly dislocated, this is properly related to symmetric issues

Solution: the problem turn out to be the connection line was not aligned to the center line from front view

Appendix D

Fair use checklist of figures

Fair Use Checklist

Name:	Tianyu Cui
Institution/Department:	Department of Consumer and Design Sciences, Auburn University
Description of project:	Exploring FDM 3D printing and 3D CAD workflow for a 3D printed wearable product
Description of copyrighted work used and manner of use:	Figure 1. 3D printing white bubble shapes by the fashion trio threeASFOUR Figure 2. Designer Danit Peleg's 3D printing apparel collection Figure 3. Customized 3D printing dress for burlesque dancer Dita Von Teese Figure 4. The Under Armour ArchiTech Futurist Figure 6-1. Kinematics dress from Nervous System Figure 6-2. Kinematics Cloth Figure 6-3. Kinematics Fold Figure 7. 3D printing lattice structure Figure 8. 3D printing soft fabric by Electroloom Figure 9. Danit Peleg's 3D printing bomber Jacket for sale Figure 10. Amimono, Japanese designer Masaharu's 3D printing knitted vest Figure 11. 3D CAD programs Rhinoceros and plug-in Grasshopper Figure 12. Woven fabric and knitted fabric Figure 13. 3D printed dress at New York fashion week 2016 Figure 14. FEA consumer needs model Figure 17. KLONER3D®240TWIN printer and the white TPU filament Figure 21. An example of chronological matrix for the analysis of a reflective journal Figure 32. 3Doodler create+ For non-profit, dissertation research use

Based on this evaluation of my use of copyrighted materials for the described project, I believe I have acted in good faith to determine this is a fair use of the copyrighted materials.

Signature:______ Tianyu Cui ____________ Date:___3/21/2019________________

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☐ Transformative (use changes work for new utility or purpose)	☐ For publication
☒ Personal Study	☐ For public distribution
☒ Use is necessary to achieve your intended educational purpose	☐ Use exceeds intended educational purpose

Factor 2: Nature of Copyrighted Work

Weighs in Favor of Fair Use	Weighs Against Fair Use
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[ ] Factual or nonfiction work	[X] Highly creative work (art, music, novels, films, plays, poetry, fiction)
[ ] Important to educational objectives	[ ] Consumable work (workbook, test)

Factor 3: Amount and Substantiality of Portion Used

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Factor 4: Effect on Market for Original

Weighs in Favor of Fair Use	Weighs Against Fair Use
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