○ **Fashion and Textiles**

Developing parametric design fashion products using 3D printing technology

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Abstract

This study created wearable fashion products with parametric design characteristics, using 3D printing technology. The goal of the study was to understand what parametric design features can be simulated with 3D modeling and printing technology, as well as to demonstrate what techniques can be used to produce fashion products using 3D printing technology. This study created two different parametric motifs using an FDM-type 3D printer with TPU and ABS as the printing materials. With those motifs, we produced three garments and two accessories. The limitations found during the process were modeling the exact measurement of the motifs that will merge with the apparel design seamlessly while maintaining the parametric features, as well as attaching the printed motifs to fabric without ruining the integrity of the textile. A significant implication of this study is that it recreates parametric designs on the human body and utilizes 3D printing technology for fashion products. This paper cast a light on a discussion about the technique can be applied on fashion design with full-sized body and encouraged designers to explore further with technological advancements in the future.

Keywords: Parametric design, 3D printing, Fashion product

Introduction

Recently, interest in parametric designs has increased. Parametric designs, which can be realized through digital technology, facilitates convenient mass production in various fields. Parametric designs can also be altered into an infinite number of design possibilities using computer technology, and this method is quickly rising as one of the most suitable design approaches in today's digital age. Thus, it comes as no surprise to find parametric designs being actively utilized in numerous industries, such as architecture, fashion, and industrial design, to name a few.

Over the past few years, several studies have proclaimed that parametric designs produce greater effects when combined with 3D printing technology. The technology is being considered to be the most effective means to recreate the parametric design structural features (Taylor & Unver 2014). For example, a series of studies utilized 3D modeling to develop designs with parametric structural features and to produce sculptures using 3D printing technology (Naddeo et al. 2017; Park 2017; Segerman 2012). Other work includes a study in which parametric design methods were applied to calculate the

curvature of the body in order to develop sewing patterns for different forms of apparel (Tian et al. 2019). These studies all share some similarity in that they utilized 3D printing technology to recreate the parametric design structure, thus enabling countless design compositions while also maximizing the expression of creativity.

In a study combining 3D printing technology with fashion, one theoretical approach analyzed the characteristics and usage of 3D printing technology, applying it to fashion design process (Vanderploeg et al. 2017). Another study presented a theoretical model applicable to the fashion industry that focused on digital production methods of 3D printing (Sun & Zhao 2017). Design-related studies using 3D printing technology include research to develop 3D-printed fabric structures through the usage of various fractal modeling principles (Kim et al. 2019) and a study that concentrated on the production of fashion accessories (Yap & Yeong 2014).

With reference to previous studies, this study aims to expand the realm of fashion products by implementing parametric designs with 3D printing technology. After developing design motifs inspired by parametric structures, the motifs were applied to different fashion designs in order to produce wearable fashion products using a 3D printer. Various complications that arise during the manufacturing step were recorded precisely, which will be helpful for future researchers and designers. In addition, it was found to be more likely for the geometrical, organic, and atypical characteristics of parametric designs to have synergistic effects when combined with 3D printing technology. Furthermore, the fluid nature of the parametric design structure—previously seen only in architecture—can have artistic value when replicated on the human body with 3D printing technology.

This study aims to implement parametric design features on apparel using the 3D modeling and printing technology. Moreover, the purpose of the study is to uncover the limitations 3D printed fashion face in the current development. Ultimately, the study contributes to provide tested and demonstrated solutions for future studies regarding 3D printed fashion.

Literature review
Parametric design

Parametric design is based on algorithmic principles, using variable input and resulting generative design (Dino 2012). According to Dino, "The process of generative formation requires four elements: the start conditions and parameters (input), a generative mechanism (rules, algorithms etc.), the act of generation of the variants (output), and the selection of the best variant". The concept of parametric design is based on mathematical principles and is characterized by various designs being implemented while adjusting certain parameters with digital programs (Hernandez 2006). Using parametric design methods, designers are able to produce limitless designs with only a few simple tweaks of variations in existing models, representing a major strength with regard to mass production (Myung & Han 2001). Parametric design has traditionally been used in architectural fields. Architectural designers can test various designs before building the actual structure by adjusting the parameters through 3D modeling. They can also calculate the size of the space, which can be a useful guide tool (Dino 2012). Parametric designs with unstructured and non-linear structural characteristics have become

an overall trend in architecture, providing new designs never seen before (Wang 2014). The 3D CAD program allows the designer to effectively visualize the desired design, and plays an important role as a medium that enables the viewers to absorb design information (Sayem et al. 2010). Previously existing 3D CAD programs only allowed a single variable in order to model geometric structure. However, parametric design broadened the scope by allowing models to be more dynamic and variable (Nahm & Ishikawa 2006).

Present studies focus on the structural characteristics of parametric designs by examining previous studies of parametric designs expressed in various fields. The modeling of parametric designs in these earlier works can be largely divided into the three following categories (Frazer 2016; Holzer, et al. 2007; Hudson 2008; Park & Dave 2014; Panchuk 2006; Schnabel 2007; Schumacher 2016; Skelton et al. 2014).

First, parametric designs have geometric structural characteristics. Geometric form refers to a simple or simplified motif, and the parametric design here refers to the formation of the geometry through reproduction or repetition through parameter variations (Casale et al. 2013). Geometric patterns realized through parametric variations show a similar structure: symmetrical, repetitive, or laid out from large proportions to smaller proportions, or vice versa. These structures can also be adjusted easily so that the spaces between the geometric patterns do not widen or overlap when the patterns are repeated (Yoon 2018). Previous studies showed that the geometric characteristics of parametric designs have demonstrated to be most effective when simple forms such as circles, triangles, and squares were used repeatedly to form more complex patterns.

Second, parametric designs have organic structural characteristics. There are two main organic properties in play: fluid organic curves and the emulation of shapes from nature. Organic curves of parametric designs form smooth and fluid shapes when combined with digital technology (Pottmann 2010). These design methods can also recreate shapes and images found in nature, such as spider webs, water crystals, butterflies, and leaves using, for example the 'Voronoi' algorithm. These images show soft curves (Kim & Yoo 2009).

Third, parametric designs have atypical structural characteristics. Being the most prominent characteristics in parametric design, atypical structural characteristics refer to an absence of regulation and restriction, with the design freely expressed in various forms. Atypical structural characteristics in parametric represent the embodiment of the maximizing aesthetic value of a sculpture while disregarding functions. In addition, form and/or meaning are not clearly defined, and the work is only characterized by visual instability (Park 2017). Thus, in architecture, parametric designs appear in fluid forms, curved surfaces, and dismantling or abstract structures, with ambiguities of the boundaries. However, although the present studies classify the characteristics of parametric designs into three categories, it is often difficult to distinguish between them because all three types can be revealed in a single design.

Parametric design and 3D printing technology

The parametric design methodology, which encompasses a variety of designs using digital technology, is actively utilized in various areas, including industrial design, architectural design, medical products, automobiles, lighting components, and most recently, in fashion design (Barros et al. 2011; Liu et al. 2018; Matcha 2007; Oya et al. 2006). The

parametric design is gaining more popularity in the fashion industry for its compatibility with 3D printing technology. Customizable 3D printing design allows consumers to access 3D models of the products they need online and select and print them directly with a printer. If this can occur, consumers will have the freedom continuously to print the same products with one model (Berman 2012). In addition, 3D printing technology can reduce the time required for manufacturing, which coincides with the latest tendency of rapidly changing marketplace needs (Attaran 2017).

Types of 3D printing methods include the selective laser thinning (SLS) method, which uses solid gypsum powder (Mazhar 2016); the stereolithography (SLA) method, using hardened liquid; and the fused deposition (FDM) method, which uses melted filaments of a plastic material. In particular, FDM 3D printers are widely used in general households in that they are easily accessible by beginners and easy to handle if the filament of the printer must be replaced. The filament is the main material in a FDM 3D printer, and these components are largely divided into two types: thermoplastic polyurethane (TPU) and acrylonitrile butadiene styrene (ABS). The TPU filament is a glossy and flexible plastic material, characterized by its viscosity when melted to a temperature of about 230 degrees Celsius. This material is suitable for products that require bendable movement, such as wrist pads and skirts, because the flexibility is consistent even after hardening. Meanwhile, the ABS filament is a matte, brittle plastic material that melts at approximately 240 degrees Celsius and retains its stiffness after hardening (de Leon et al. 2019). If consumers use a 3D printer while considering the characteristics of each material, they can easily create a design that cannot be created with human crafts while also shortening the time and reducing the cost of production. 3D printing technology has the advantage of being able to easily implement complex and fluid parametric form characteristics.

Fashion and 3D printing technology

3D printing technology has been developing rapidly and being utilized in various fields. For instance, in academia, utilizing 3D printing technology in fashion products has shown steady increase in recent years. On developing fashion products, Kim et al. (2019) conducted a study on developing and improving fashion products using an FDM type 3D printer. They determined the limitations of the 3D printed clothing production process and suggested complementary measures to offset those limitations. Using TPU or ABS as main printing materials, they developed three different types of 3D printed clothes. The researchers concluded that more diverse and active attempts to utilize 3D technology should be pursued by those who develop various fashion products. Pasricha and Greeninger (2018) aimed to apply zero-waste and sustainable notion to the fashion industry using the 3D printing technology. The researchers used Rhinoceros 5, Tinkercad, MakerBot Replicator 2 desktop 3D printer, and polylactic acid filament to create elaborate jewelry designs. They employed design strategies to create objects without the use of rafts and supporters in order to minimize creating print waste. The study concluded that there is a considerable potential to use 3D printing technology in fashion, designing and creating products that are unique, sustainable, and made on demand.

Some researchers turned their focus on 3D printing techniques and methods. Mpofu et al. (2019) focused on the fabric properties affecting the adhesion of PLA polymer. They selected different fabrics made from cotton, polyester and acrylic, and used 3D printing technology, printing the PLA polymer onto the fabric surface. The study indicated that fabric areal density, warp and weft count, fabric thickness and fabric handle indicated a positive correlation with adhesion of PLA onto woven fabrics. Unger et al. (2018) viewed combining fashion and 3D printing technologies as an innovative advantage which significant physical properties can be created. The study suggests a new method to improve the adhesion of a 3D printed object on a textile by coating the textile surface with a polymer layer prior to printing. They concluded the added adhesion can be substantially enhanced without significantly changing the bending stiffness and haptic properties of a fabric.

Others adopted a more inclusive conceptual approach. Lyu et al. (2018) took a market focused approach to 3D printed fashion products, and examined millennial consumer's adoption of 3D printed fashion products by exploring personal values and innovativeness. In particular, they explored how different traits, such as personal values and innate innovativeness can predict a positive attitude towards 3D fashion products through domain-specific variables such as fashion innovativeness and fashion leadership. Sun and Zhao (2017) focused on 3D printing and its involvement in supply chain integration. They conducted a conceptual study in order to examine the potential impacts and challenges of integrating Direct Digital Manufacturing methods, specifically 3D printing technology, in the fashion industry. The research concluded that 3D printing technology was impacting four major areas in the fashion industry; design and product development, sourcing and manufacturing, retail, distribution and consumer, as well as the sustainability optimization. Choi (2017) explored the formative characteristics of 3D printing jewelry based on the formation of fractal geometry. The study concluded that the morphological characteristics of 3D printed jewelry can be categorized into their constitutive shapes by the repetition of the unit, and the fractal geometry design was determined by overlapping the systematic shape by distortion caused by distortion, and the variation in scaling.

Kwon et al. (2017), on the other hand, approached 3D printed fashion as a possibility for developing an education coursework. The researchers aimed to have a general overview of 3D printing technology in fashion and its integration in fashion education. Programs such as Rhinoceros and FINEBOT were most commonly being used for 3D object design and printing, respectively. The compiled studies can be seen in Table 1.

The comprehensive implications of the preceding studies above are that they have made practical and technical contributions to the development of 3D printing fashion products. However, the implications on developing parametric fashion design with 3D printing technology were left unexplored. In this study, we verified the practicality of the 3D printing fashion product production process and methods of the above studies by reenacting their techniques.

Parametric fashion and 3D printing technology

In the realm of fashion, 3D printing technology has the advantage of being able to implement ornate parametric designs on the body. Recently, the boundary between design and

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Table 1 Previous studies on 3D printed fashion

	Research title	Keywords
Fashion Product Development	A study of the development and improvement of fashion products using a FDM type 3D printer (2019)	3D printer, Fashion product, Fused Deposition Modeling (FDM)
	Exploration of 3D printing to create zero-waste sustainable fashion notions and jewelry (2018)	3D printing, Zero-waste, Sustainability, Fashion, Technology
3D Printing Techniques	Use of regression to study the effect of fabric parameters on the adhesion of 3D printed PLA polymer onto woven fabrics (2019)	3D printing, PLA, Fabric thickness, Fabric handle, Regression
	Increasing Adhesion of 3D Printing on Textile Fabrics by Polymer Coating (2018)	3D printing, Composite, Adhesion, Polymer coating
Conceptual Studies	Understanding millennial consumer's adoption of 3D printed fashion products by exploring personal values and innovativeness (2018)	3D printed fashion products, Consumer innovativeness, Personal values, Attitude, Behavior hierarchy, Diffusion of innovation, Fashion leadership
	Envisioning the era of 3D printing: a conceptual model for the fashion industry (2017)	3D printing, Additive manufacturing, Direct digital manufacturing, Fashion, Textile and apparel, Industry
	A Study on the Characteristics of 3D Printing Jewelry Design Utilizing with Fractal Geometry (2017)	Fractal geometry, 3D printing, Jewelry design
Education	Case study on 3D printing education in fashion design coursework (2017)	3D printing, 3D modeling, Fashion design education, Wearable products

programming has become blurred, and creation through convergence and collaboration with other fields has become an essential element in fashion, as in other fields. With the rise of 3D printing technology, the necessity of education related to 3D printing-based fashion design is also increasing (Kwon et al. 2017), and some have suggested that such technology should be applied to advance functional design and development goals (Lee & Koo 2018). Thus, in relation to the latest 3D printing technology, a wide range of 3D-printed fashion products are being developed and produced, including clothing, shoes, accessories, and bags (Chun 2017; Kim et al. 2019; Park & Yoo 2016; Sun and Valtas 2016). These 3D-printed products are motivating consumers to design and produce their own products, which can be a feasible means of meeting the complex needs of consumers with no extra costs related to manufacturing (Nyman et al. 2014) and the customization of designs (Sun & Zhao 2017). Particularly, implementing parametric designs with 3D printing technology conforms to the current fashion marketplace's rapidly changing needs, as doing so it can provide an array of customizable designs to consumers, increasing the potential to realize countless different designs with only one variable adjustment.

The geometric, organic, and atypical characteristics of parametric designs can be seen in fashion designs as well. For example, fashion designer Julia Davies presented a skirt that was inspired by shapes found in nature, such as snake skins and coral reefs, in her first collection in 2018 (Saunders 2019). Additionally, the fashion designer Iris Van Herpen, a notable pioneer in the area of parametric fashion designs using 3D printing technology, presented several collections that highlights parametric designs (Foreman 2018). Her collections display organic structures such as repetitions of geometric shapes and

patterns, water, cobwebs, and flexible curves, thus showing atypical structural characteristics that defy the natural shape of the body. In particular, her 2018 collection reveals the atypical nature of parametric designs by escaping or further maximizing the curvature of the human body. This has considerable significance as it not only proves fashion design and be infused with parametric design structures, but also it is possible to include all three characteristics of parametric structures in one garment. As such, modern fashion has been able to more easily suggest creative designs that have not been seen before through integration with various technologies.

Research questions

Despite ranging in several different structural characteristic, studies on parametric design were often limited to architecture and fine art. It is also implied that despite the increased interest on parametric design for fashion, as shown by major fashion designers, is not yet being reflected enough on the academic studies. Moreover, no literature was found regarding studies of parametric fashion design using the 3D printing technology. By addressing the research gaps, the aim of this study is to develop a wearable fashion product that has 3D printed parametric structural compositions. In order to achieve this, the following two research questions (RQs) were generated, reflecting the main stages of the design process: modeling and designing (RQ1), and developing apparel design (RQ2).

RQ1: What parametric design features can be simulated with 3D modeling and printing technology?

RQ2: What techniques can be used to produce fashion products using 3D printing technology, and what are the limitations?

Methods

This research was completed in multiple phases, each reflecting one of the above-mentioned research questions as illustrated in Fig. 1. First, in order to get a comprehensive view on the subject, a thorough review of the previous research on 3D printing technologies and fashion design was conducted. Then, we modeled and printed parametric design motifs inspired by architectural structures demonstrating the parametric forms. Subsequently, using the developed motifs, we designed 3 pieces of apparel and 2 pieces of accessories.
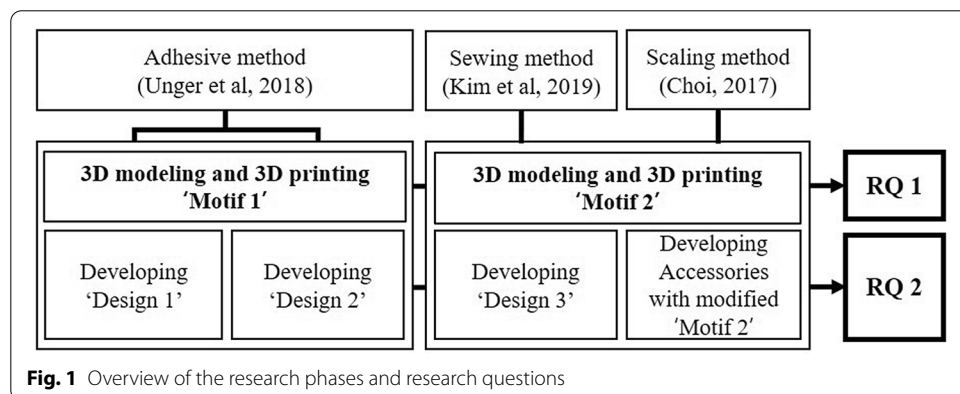
Fig. 1 Overview of the research phases and research questions

Parametric design process

The important requirement of parametric structural motif was its fluidity. However, because of the limited surface space of the 3D printer, in order to produce perfectly connected individual motifs that are seamlessly fluid next to each other, modeling tools and additional procedures were taken into consideration. The motifs were modeled using Rhinoceros 5, a commercial 3D computer graphics and computer-aided design application software, as well as Grasshopper, a visual programming language and tool that runs within the Rhinoceros 3D computer-aided design application. Converting program Cubicreator was adopted to produce the 3D CAD model to modify the dimensions of the printouts. Using these programs, motifs were accurately printed and performed parametric design directly on the human body contour while functioning as a wearable garment. As printing materials, flexible TPU filaments were used for design features that require supple and finer details, as well as ABS filaments for sturdy structural design details for its crisp and build-able characteristic. The 3D printer used in this study was a "Cubicon Single," an FDM-type 3D printer from HyVISION System.

The parametric designs of this study were inspired by the architectural installation Bar Wall by Matsys and Aqua tower in Chicago, for its unique structural design. The Bar Wall was built by Matsys in 2013. The wall's fluid flow evokes the form of rolling hills while also making resonating with waves and wind. The configuration was inspired by Japanese screen paintings of cloudy mountain scenes and the existing vertical wood rib theme found elsewhere in the Bar, the new wall adds a distinct element to the Bar's main seating area. Similar to the Zero/Fold Screen completed in 2010, Matsys was interested in minimizing material waste in the fabrication of the wall by using parametric modeling to align adjacent ribs next to each other when cut. Amber Plywood was used for the wall as materials, and the parametric modeling was done with Rhinoceros and Grasshopper program. The Bar Wall was chosen as the main inspiration for its elaborate configuration of the panels, which shows all three distinguishing structural features: geometric, organic, and atypical characteristics of parametric designs.

The Aqua Tower was built by American architect Jeanne Gang in 2009. The skyscraper along Lake Michigan in Chicago in the US, distinguished by its curvy and rippled exterior. The building has a total of 82 floors and a 250-m-high residential-commercial complex (United News 2010). The towel features different floor plate outlines used as balconies where each floor was dependent on the impact of the wind. "The initial idea was to create hills and valleys, so to speak, on the facades of the building, so the occupants could see more of the views from the building.", says Gang, in her interview with Archdaily (Belogolobsky 2016). Gang prompted the idea of slicing the hills into horizontal layers of panels as a parametric model, with social and environmental purpose rather than iteration for form's sake. Two distinctive motifs were developed based on these inspirations. With these motifs, we produced three clothing items and two accessory pieces.

Apparel design process

This study developed wearable fashion products that reflect the characteristics of parametric designs. Four researchers worked in pairs to design the products. The main focus

of the apparel design process was to develop various types of apparel that can enhance the parametric structural features while also being wearable. Researchers designed two dresses, one jacket, a necklace and a bracelet using two different parametric motifs. When choosing the materials for the apparel, the practicality as well as the aesthetic of the design was considered. Specifically, it was significant to use the suitable fabric that will not only go seamlessly with the parametric theme, but also capable of holding the printouts in place without obscuring the silhouette. Another imperative part of the design process was to work out the right way to attach the printouts to the fabric. During the process, different methods for different fabrics were tested and examined thoroughly to find the best possible method.

Results

This section discusses the detailed process of developing fashion products that reflect the characteristics of parametric designs. The development of two motifs was inspired by certain parametric architectural structures, and they were modeled using Rhino 5's Grasshopper algorithm. Using 'Motif 1' and 'Motif 2', three pieces of garments ('Design 1', 'Design 2', and 'Design 3') as well as two accessories ('Design 4' and 'Design 5') were designed and produced. All photos and digital images of the design were provided by the researchers.

Stage 1: Garment design using 'Motif 1'

The inspiration for 'Motif 1' was derived from the Roka Akor SF Bar Wall, designed and produced by the design studio Matsys. This wall shows parametric structural characteristics through its repeated positioning of vertical wooden panels with atypical curves at regular intervals, with the parametric composition further maximized by the effective use of lighting. Inspired by the fluid curvilinear formation of the wood panels in the vertical direction, 'Motif 1' was developed. 'Motif 1' also calls back Iris Van Herpen's 2018 collection, with its many panels placed across the body moving fluidly with every movement. Using this motif, two dresses were designed ('Design 1', and 'Design 2').

3D modeling and 3D printing process

In order to model 'Motif 1', an algorithm was developed using Grasshopper, which is based on the Rhino 5 software from Rhinoceros (Table 2). During the modeling process, the overall shape of 'Motif 1' on Rhino 5 was modeled into a soft curve. Two different types of curved panels with different heights were connected using the Loft (A tool that creates a surface between two or more curves or polygons.) function (Table 2, "Surface modeling"). In order to transform the component Brep (Stands for "Boundary Representation". A way to produce combination of surfaces)' algorithm into a parametric form, the 'Component Geometry' algorithm designated a point to be the basis for an atypical deformation of the vertical panel. Once the preview of the surface showed split vertical panels successfully, as shown in Table 2 ("Applying algorithm"), the motif went into the baking process (Converting Rhinoceros model to a single object through Grasshopper program) as shown in Table 2 ("Final mesh").

For 3D printing materials, 'Motif 1' required great flexibility, and TPU filaments were used to maximize the smooth curves. During the 3D printing test phase, it was essential
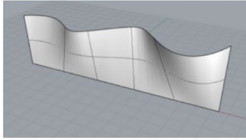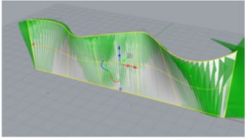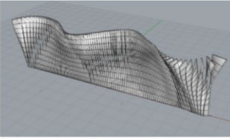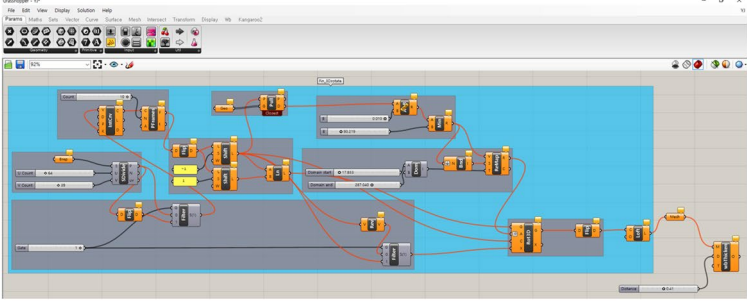
Table 2 Modeling process of 'Motif 1'
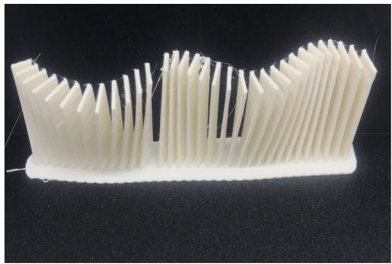
Modeling process	① Surface modeling	② Applying algorithm	③ Final mesh
Image			
Algorithm			

Table 3 Printing material tests for 'Motif 1'

	ABS	TPU
Printing test		

to take into account that the characteristics of parametric designs may vary in shape depending on the settings of the variables. As shown in Table 3, when the motifs were printed with ABS material, the printouts proved to be too brittle and unusable. After several modeling and printing processes, we were able to find the optimal conditions for successful printing.

Test 1 was conducted on panels with a thickness of 0.10 mm and length of approximately 150.00 mm. When printed, the wavy arrangement of the layout was combined with thin panels erected in the vertical direction, which decreased the dispensing accuracy of the filament from the 3D printer nozzle and resulted in breaks in the middle of the panels as they were being printed. Finally, it was concluded that the height of the model should be lowered and the thickness of the panel should be adjusted accordingly.

In Test 2, the model with a maximum height of 100.00 mm and thickness of 0.30 mm was printed. Upon an examination of the results, it revealed that it is possible to print sturdier panels than in Test 1, but the top right side of the model was not printed properly. After assessing the printing process, it was concluded that the panels were wiggling out of place as the nozzle moved back and forth in order to fill in the panel edges, with the results showing a poor outcome. Up to this point, the Raft function as a base for
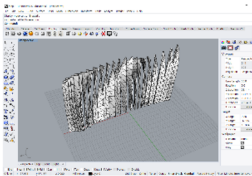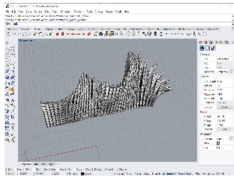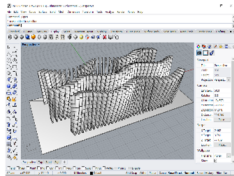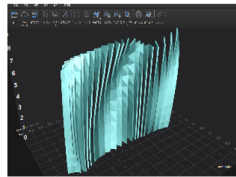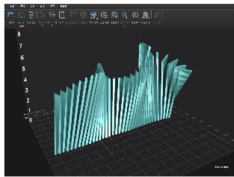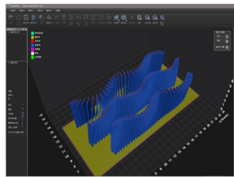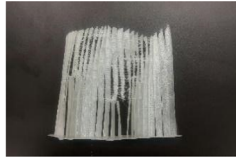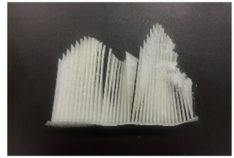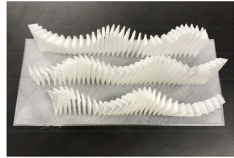
the models were utilized. The Raft function operates within the Cubicreator printer and automatically lays out the base layer without any additional floor modeling. However, as this function was deemed insufficient to hold down the model securely and to prevent it from moving out of place, we added a floor mesh to Rhino 5 with a depth of approximately 0.05 mm.

Looking at the results, in Test 3 each panel was printed robustly and with clean edges, showing optimum results, and we used the models of Test 3 in the final fashion product development process (Table 4). The printing time of 'Motif 1' was 7 h and 24 min, and the material consumption was calculated to be 35.79 g.

Stage 2: Garment design using 'Motif 2'

'Motif 2' was inspired by the Aqua Tower. The most notable characteristic of this building is that its appearance can change dramatically depending on the angle of view, making it is an atypical structural characteristic of a parametric design. In addition, the wave-like patterns of the building's cladding demonstrate organic liquidity, which can be referred to as an organic structural characteristic of this parametric design. Therefore, 'Design 3' was intended to reflect the organic and atypical characteristics of the Aqua building.

Table 4 Printing test of 'Motif 1'

Printing test	Test 1	Test 2	Test 3
Rhino 5			
Cubicreator			
Results			
Thickness	0.1mm	0.3mm	0.3mm
Length	15.0mm	10.0mm	10.0mm
Depth of floor	Not applied	Not applied	0.05mm

3D modeling and 3D printing process

In order to assemble the 3D model of 'Motif 2', researchers developed an algorithm using Grasshopper based on the Rhinoceros 5 software from Rhinoceros.

First, the model needed to divide into sections in order to ensure that it would fit the 3D printer's bed. As shown in Table 5, 2D clothing patterns was scanned into Adobe Illustration files and uploaded to Rhino 5. Using the T-spline function, which allowed to model free-form surfaces, researchers drew the clothing patterns in the Illustration files and then divided each pattern into sections. To implement 'Motif 2', the garment patterns were set to the surface, and the S-shaped curve was set using Grasshopper. The width and the height of the surface and the curve of the model were adjusted using Rhino 5. This step was necessary because the motif generated by Grasshopper was only a modeling form, and the printable file had to be created by adding extra width before the baking step. Subsequently, each pattern was split into several pieces. With the intention of sewing 'Design 3' onto the garment, the amount of the seam allowance for each model was elongated by extending the floor size by 1 cm or more. The bottom surface was extended to 0.05—0.10 mm to match the thin fabric. Finally, split pattern models were each given different numbers so that they could be accurately sewn into the proper position.

As demonstrated by printing the first motif, ABS material was too fragile when printed in thin panels. The printing material test with varying TPU panels turned out to be successful as shown in Table 6. 'Design 3' underwent some trial and error due to the thickness of the floor surface, as the base layer had to be thin enough, at 0.10 mm, for sewing with fabric on a sewing machine. The process of these tests are shown in Table 7. In Test 1, the intended atypical parametric design form was successfully printed. However, the thickness of the base layer was modeled to be 1.00 mm, and this proved to be too thick for sewing. Therefore, for Test 2, the floor surface was adjusted to be 0.05 mm thinner

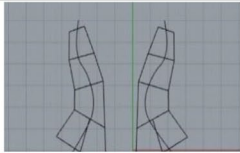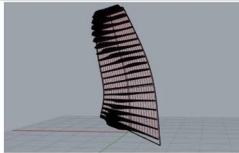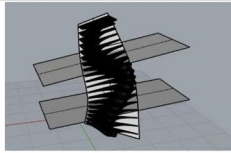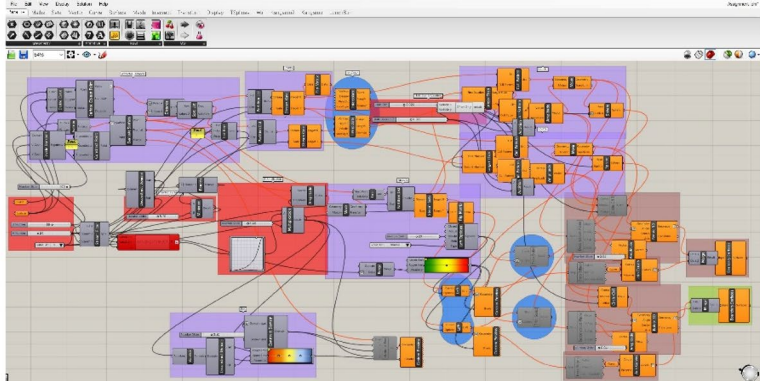**Table 5** Modeling process of 'Motif 2'

Table 6 Printing material tests for 'Motif 2'
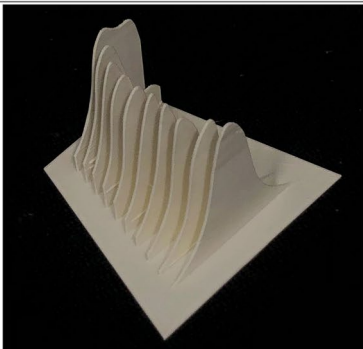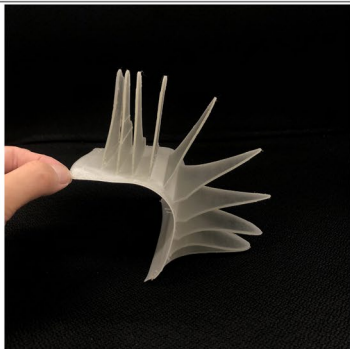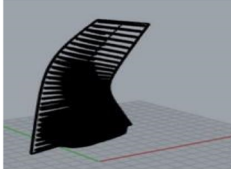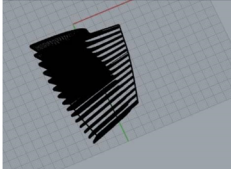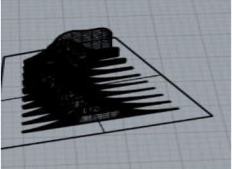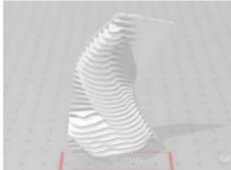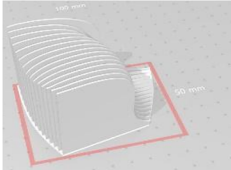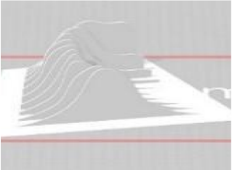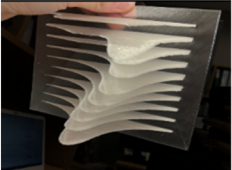
ABS	TPU
Printing test	

Table 7 Printing test of 'Motif 2'

Printing Test	Test 1	Test 2	Test 3
Rhino5			
Cubicreator			
Results			
Thickness	1mm	0.2mm	0.2mm
Length	40.0mm	70.0mm	60.0mm
Depth of floor	1mm	0.05mm	0.05mm

than in the first test, and the height of the panels was set to 70.00 mm, more than twice that in the first test. When printed, the base layer appeared to be adequate for sewing, but the panels were too long and the tips easily broke. To solve this problem, researchers extended the surface level by 0.05 mm and adjusted the panel height to 60.00 mm after surface extrusion to implement the final model, as shown in Test 3. It took 6 h and 33 min to print the final product, requiring 65.94 g of TPU filament.

As shown above, RQ 1 was demonstrated. Geometric, Organic, and Atypical parametric design features can be simulated with 3D modeling and printing technology.

'Design 1' developing process

As the fabric material for 'Design 1', researchers selected a specific material with less flexibility or stiffness in order to support the weight of the printouts. This was done because 'Design 1' had to support the weight of multiple printouts which were to be attached to ensure the parametric shapes. The selected fabric for 'Design 1' was a coarse-surface material that complemented the texture of the 3D-printed 'Motif 1'. For sewing threads, it required some durability in order to sew through the thick fabric. The finalized product was sewn with 150-denier synthetic fiber sewing thread. The number of stitches per inch was 10 to 11 stitches.

The printouts were attached to the fabric by a glue gun. According to Unger et al. (2018), the adhesion between a 3D printing polymer and a textile fabric can be increased by coating the fabric with an appropriate polymer. Although their study used cotton fabrics to coat different polymers in order to attach the printouts, we found the method was also possible on polyester fabric as well. The glue gun worked as a heating element to melt the adhesive that increased the tackiness of the polymer, which then solidified after being in contact with the printouts. Moreover, the melted polymer clung on to the rough and course texture of the polyester fabric, resulting in better adhesion.

The overall look of the dress has several futuristic elements in its design, with the seamless blending of the 3D printouts. The silhouette of the dress was designed to appear as if the dress was on its own gravitational pull, defying the natural curve of the human body, which came from its crisp fabric texture. The front side of the dress consisted of five columns of 'Motif 1'. The fluid and organic curves of the structure were amplified by linking the printouts such that they were next to each other. Because 'Motif 1' was positioned along the dress length, the dynamic heights of the panels and corresponding varying directions were further emphasized, demonstrating rhythmicity. On the waistline, the printouts were attached to form a line that accentuated the curve by narrowing the gap between the motif columns. The 3D printouts attached on the front of the dress were positioned such that they climbed up the body, moved over the shoulders, and then went back down to the waistline, forming a V-shape on the back of the dress. Furthermore, additional printouts were attached on the back, directly above the scapula, in two columns that formed the same arch as the lumbar curve. Just as lighting was used on the Roka Akor Wall to emphasize the curved shapes of the panels, LED lights were added to the dress here as well, and they were positioned linearly with the 3D printouts to emphasize further the parametric formation of the curved surface of the panels.

The final product can be seen in Fig. 2. The 3D printout placement emphasized the silhouette of the dress as well as the stiff fabric that deviated from the curves of the human body, giving the dress a futuristic undertone. In addition, the LED light bulbs, an unconventional detail on clothing products, were seamlessly blended into the 3D-printed materials, successfully showing the possibility of creative designs created from the incorporation of new materials.

'Design 2' developing process

For 'Design 2', polyester was selected, which has a smooth texture and a flowing silhouette to ensure that the developed structure could also be utilized not only on a stiff surface but also on the natural curves of the human body. For sewing threads, 100-denier

Fig. 2 Final product of 'Design 1'

Fig. 3 Final product of 'Design 2'

synthetic fiber was used which is suitable for thin material, such as chiffon and silk. The number of stitches per inch was 10 to 11 stitches. Using a glue gun, 'Motif 1' was attached to the fabric such that it would form organically connected rows along the curves of the upper body. The skirt half of 'Design 2' consisted of two layers, with stiff interfacing added to the layers in order to reflect the structural characteristics of the material. To emphasize the shape of 'Motif 1', several layers of the Organza fabric were also draped along the armhole. The hemline of the skirt was also designed in an asymmetric form, as 'Motif 1' had an atypical feature, showing a one-sided flowing structure. To prevent the zippers from obstructing the printout flow, they were added in two parts, on the back and the right side-line. These results are shown in Fig. 3. With 'Design 2', the design focused on displaying the fluidity of the panels of 'Motif 1' along with the curves of the body. The two rows of panels were positioned such that they had a half inch gap between them, allowing the lower row naturally to drape along with the curved surface of the garment.

'Design 3' developing process

'Design 3' is a jacket that reflects the atypical structural characteristics of parametric designs. To reflect the fluidity and the organic curves of the parametric design, the jacket

was designed with curves on the flat patterns themselves. Therefore, the chest, waist, and pelvic lines were made to show an exaggerated body shape.

Before making the actual product, researchers needed to ensure that the size of the 3D-printed motif of 'Design 3' was identical to that of an actual clothing pattern. Therefore, it was inspected whether there was at least 1 cm of seam allowance relative to the fabric pattern so as neatly to seal the two layers. The size of the printed models was individually checked before sewing with chiffon fabric. For the jacket, sturdy leather fabric appeared to be sufficient to support the weight of the printouts while maintaining the artificially curvy silhouette.

When making 'Design 3', attaching the printouts with the fabric was challenging. The plastic TPU material was found to be difficult to sew through. The sewing threads needed to sew through the TPU material along with the leather fabric. According to Kim et al. (2019), 0.16 mm transparent nylon thread was optimal for firm connections of the ornate TPU printouts. The finalized product was sewn with 150-denier Nylon sewing thread. The number of stitches per inch was 11 to 12 stitches. However, when sewn with industrial sewing thread, the plastic did not always properly hold the sewn thread inside it. Therefore, for future production, we suggest that a special type of sewing machine-such as one specialized for leather-to be used. The sewing process was especially strenuous in areas such as the armhole line and the princess line, and required some delicate touches when working with the sewing machine.

The highest point of the panels was 60.00 mm, and it was difficult to move freely within the regular sewing machine. In addition, there was a risk that the panels could break during the sewing process, especially on the sections where the printouts overlapped. 'Design 3' also used LED lights to show the amorphous curves more effectively. During the sewing process of the motifs and the leather fabric, we considered putting the bulbs between the fabric and the printouts so that the lights would be secured between the two layers. However, this process was eventually revealed to be too complicated. In the end, we decided to attach the LED lights onto the printouts themselves. The final product can be seen in Fig. 4. The beige leather jacket was styled with a bluish gray chiffon skirt.

Fig. 4 Final product of 'Design 3'

Stage 3: Accessory design using modified 'Motif 2'

Based on the previous utilization of 'Motif 2,' we were also able to create a necklace ('Design 4') and a bracelet ('Design 5') using variations of 'Motif 2.' 'Motif 2' was split into panels and applied to designs for the production of accessories with parametric characteristics.
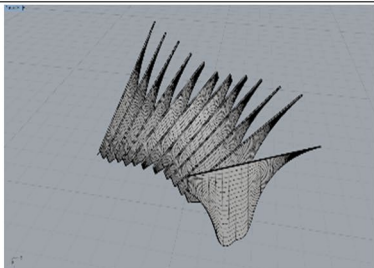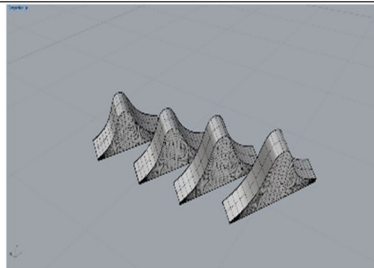
Modification of 'Motif 2'

Choi (2017) demonstrated the key characteristics of 3D printed geometric fractal can be categorized into three different characteristics: continuity, geometric, and exaggeration. Continuity creates a new and self-assigned new space through a recursive structure through a cyclic structure that is formed along a single directional basis. Geometric form organizes a three-dimensional and constructive structure under the mathematical order of fractals. Exaggeration demonstrates the informal beauty and the maximization of the shape by expanding the scales or distorting of the units. For the modification of 'Motif 2,' the distinction of the motifs comes from how the individual panels were used and whether the changed scale is exclusively facing one direction, utilizing the fractal characteristics of continuity and scaling.

Rhino 5 was used to modify 'Motif 2' and to model 'Design 4' and 'Design 5.' In the variation of 'Motif 2' for 'Design 4,' the separated panels of 'Motif 2' were regrouped in a repetitive structure while varying the sizes and angles to impart some rhythm (Table 8). After the combination of the panel clusters, 'Motif 2' was modeled into three different necklaces (Prototypes A, B, and C). Finally, Prototype C was chosen for further development because it best demonstrated the organic curves and geometric fluid structure of the parametric design. During the modification process of 'Motif 2' for 'Design 5,' 'Motif 2,' which consisted of several panels with its own parametric characteristics, was dismantled, split and reduced into single units, which were positioned to form a new design.

'Design 4' and 'Design 5' developing process

Regarding 'Design 4,' a typical circular shape of a necklace was used to outline the body, and the modified version of 'Motif 2' was used to depict fluidity and geometric characteristics of the parametric design. Instead of adjusting the motif in a certain direction, it was repeatedly resized and placed to add rhythm, and to emphasize its atypical structure. As shown in Table 8, due to the fact that the motifs were attached

Table 8 Variation of 'Motif 2'

Modeling variation	Variation 1	Variation 2
Image		

to 'Design 4', pointing downwards, the printing process had to be taken into account. Thus, extra support columns for each motif were established while the necklace was flipped on its back. During the printing process, it was found that if the width of the motif panels was less than 0.20 mm, the support columns would be too weak to be fixed onto the bed. Therefore, the product was finalized by adjusting the width of each motif so that it was at least 0.20 mm, and the printing process was they conducted by careful removing of the support columns. It took 10 h and 33 min to print 'Design 4', and the cost was 40.18 m (100.51 g) of filament. Black ABS filament was used for the final product, as it was light and simultaneously retained the effect of looking dense.

Regarding 'Design 5', a bracelet that had the geometric and amorphous characteristics of a parametric design was developed. As shown in Table 9, the body of the bracelet was constructed in a four-step hexagonal shape consisting of 12 sides on the outer part of the bracelet to form a geometric shape. However, as in the case of 'Design 4', the panel size was not varied in both directions, but rather in one direction, and only panels of the same size could be repeatedly used. Therefore, individual motifs of different sizes were placed together in different sections to show an atypical structure. During the printing process, it was necessary to consider if additional support columns would be required as the panels floated in mid-air while hanging on the side of the bracelet. However, after some readjustment of the proper sizing and after running the model through Cubicreator, products with smooth surfaces without support columns could be printed. It took a total of 5 h and 4 min to print 'Design 5' at a cost of 20.31 m (50.81 g) of filament. White ABS was used to ensure a light and bright finish.

As shown above, RQ 2 was effectively demonstrated. As shown by 'Design 1', 'Design 2', and 'Design 3', challenges found in integrating 3D printing technology with apparel fashion products mainly concerned the methods of attaching the 3D print-outs to the fabric. On the other hand, with 'Design 4' and 'Design 5', which required no attachments, the motifs were printed using ABS filament in order to appeal the design intention. This was to produce light yet rigid and portable accessories. However, because the size of the accessories was not adjustable due to the rigid and inflexible nature of the ABS material used, it was necessary to determine the true required size of the accessories and to make a device that could enable the detach-ability of accessories. Regarding the ABS material used in the design, we suggest that those conducting future studies broaden this idea further. The design materials and the attachment methods are shown in Table 10.
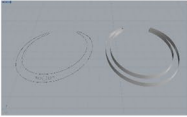
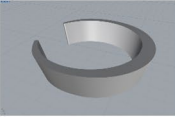**Table 9** Modeling process of 'Design 4' & 'Design 5'
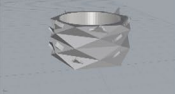
Modeling process	Modeling process 1	Modeling process 2	Modeling process 3	Final product of Design
Design 4				
Design 5				

Table 10 Developing process of motifs and designs

	3D modeling and 3D printing 'Motif 1'		3D modeling and 3D printing 'Motif 2'	
	Developing 'Design 1'	Developing 'Design 2'	Developing 'Design 3'	Accessory design using modified 'Motif 2'
Fabric Material	Stiff, polyester fabric	Thin, polyester fabric	Leather	-
Print Material	TPU Thickness: 0.30 mm Length:10.00 mm Depth of floor: 0.05 mm		TPU Thickness: 0.20 mm Length:60.00 mm Depth of floor: 0.05 mm	ABS Width: 20.00 mm
Attachment method	Adhesive glue gun		Sewed on printouts	-

Discussion

Two types of motifs were developed using the Grasshopper algorithm of Rhino 5 to create fashion products that reflect the characteristics of parametric designs. The contribution of this study is that has successfully created 3D printed fashion designs, and also made it possible to embrace parametric designs on garments. Moreover, researchers were also able to select printing materials most suitable for wearable garments and examined their limitations. In the process of this study, we discovered the followings:

3D modeling and the 3D printing phase

This study expanded the possibility of 3D printing fashion found in prior research. In their study, Chun (2017) has demonstrated the broadening potential of 3D-printed fashion products being developed and produced as not only commercial products, but also as artistic expressions. By incorporating parametric design characteristics into fashion products, this study confirmed that they can also have aesthetic aspects. 3D modeling was done reflecting the characteristics of the parametric structure mentioned in prior studies such as geometric structural characteristics (Casale et al. 2013), organic structural characteristics (Pottmann 2010), and atypical structural characteristics (Park 2017). By applying parametric design to fashion using the 3D printing technology, this study demonstrated that 3D printing technology can not only contribute to the technical aspect of fashion design, but also has the potential of produce innovative and creative designs as well. Based on these results, parametric fashion designs can create countless ornate designs and is able to easily produce a variety of configurations.

This paper enlightened the necessity of developing a 3D printing converter program that could more accurately simulate actual printing results. The algorithms developed on Grasshopper allowed 'Motif 1' and 'Motif 2' to be easily manipulated. However, printing tests were essential to be executed alongside with the modeling test, because it was not possible to evaluate the stability of the 3D model if only examined on the virtual modeling process screen of Rhino 5. Although researchers were able to simulate the printing process and calculate the success rate by analyzing the printing path before the actual process with the Cubicreator's view mode function, some failed to print successfully despite showing no problems in the simulation phase.

Other contribution of this study is recording complications and resolutions found during the modeling and printing process. For 'Motif 1', the continuous printing of smooth

and narrow vertical panels was essential to produce stable results. The printing test results showed that stable printing of the motif was possible only when the appropriate height and width of the vertical panel was found. Also, finding the appropriate thickness of the floor layer was imperative to prevent the whole model from shaking out of place during the long printing process. However, for 'Motif 2', because the floor layer had to be thin enough to be sewn onto the fabric of 'Design 3', it was challenging to find the perfect width. Also, the motif had to be adjusted to an appropriate height to prevent it from wilting down towards the ground, tugging the fabric down with it.

During the printing phase of a parametric design, choosing the best possible printing materials proved to be another challenge. 'Motif 1' and 'Motif 2' were printed with the flexible TPU filament, and it complemented the light and delicate fabric. However, due to TPU's high viscosity, when printed, the curved panels came out with rough surfaces instead of being smooth, which was not suitable for expressing the atypical and organic form of the parametric characteristics. Moreover, because the FDM method was less accurate in precision than other 3D printer types, such as the SLA and DLP (digital light projector) types, the surfaces of the printouts were often rough and unclean, which was especially challenging to print narrow panels repeatedly with fine details. In addition, it was difficult to print continuous motifs organically, due to the limited bed size of the printer. Therefore, to achieve high-quality parametric design products, using 3D printing methods other than FDM type should be considered. In terms of fashion products, the development of 3D printing materials with different textures is worth evaluating.

Applying 3D printing technology to fashion products

In sum, this study utilized TPU and ABS filament in order to create a wide range of fashion product that includes apparel and accessories. This was in response to further the findings of prior researches successfully producing clothing, shoes, and bags (Chun 2017; Kim et al. 2019; Park & Yoo 2016; Sun & Valtas 2019). As demonstrated by previous studies, the TPU material was flexible and had the advantage of bending along the body curve (de Leon et al. 2019). Therefore, this study also utilized the TPU filament for the apparel portion of the design process. Although the attached printouts were flexible enough to effectively convey organic fluidity of parametric design, the high density of the filament resulted in weighing down the garment significantly. Thus, a lighter and more flexible 3D printing material for greater practicality of fashion products should be available for future designs. When it comes to attaching the 3D printouts on the fabric, this study utilized the previously demonstrated adhesion technique, as well as the direct sewing method (Kim et al. 2019; Unger et al. 2018).

The accessories were made using the modified version of 'motif 2' which conveys characteristics of distorted and continuous fractal design formation. Two pieces of accessories ('Design 4' and 'Design 5') were printed with the ABS filament, which was much lighter in weight and more solid in textile than the TPU. The finished accessories have demonstrated to be easier to produce than the garments of 'Design 1', 'Design 2', and 'Design 3' due to the smooth finish and the low viscosity of the material. In addition, during the printing phase, ABS material was more stable than that of the TPU material and resulted in producing quality pieces. This difference in two materials will be a

crucial choice in future study, as not only choosing the right material can potentially change the result of the final product very drastically, but also knowing the two materials can be suggested as possible customizability, as suggested by Sun and Zhao (2017).

The fashion products developed in this study could be largely classified into women's wear ('Design 1', 'Design 2', and 'Design 3') and accessories ('Design 4', and 'Design 5'). When designing fashion products using 3D printing technology, choosing the right fabric showed some complication. 'Design 1' and 'Design 2' both made out of polyester fabric, but with different thickness and texture. While both used the printouts, 'Motif 1'. The fabric of 'Design 1' was stiffer than that of 'Design 2' and therefore had less flexibility and less room to move. In 'Design 1', 'Design 2', and 'Design 3', the main consideration when applying the 3D printouts to clothes was attaching the printed motifs onto the fabric. In 'Design 1' and 'Design 2', the printouts were attached to the fabric using a glue gun. The advantage of this method was that it was quick and simple, preventing the fabric from absorbing the glue, which what happened when tested with liquid glue. However, this approach lacked with practicality. With the glued motif, it is impossible to wash the clothes. Also, the glued motif was not sturdy enough to stay on fabric so that it was hard to put on and off the dress. Therefore, in 'Design 3', we attempted to sew the 3D printouts onto the fabric itself. Although this required an extra modeling procedure to measure and accurately model the seam allowance onto the motifs themselves, this showed better results than in 'Design 1' and 'Design 2'.

Conclusions

Fusing the craftsmanship of fashion design and the structural characteristics of parametric design allows not only artistic but also technological designs (Yap & Yeong 2014). This is especially effective when combined with 3D printing technology, as shown by a variety of studies utilizing the synergy between these technologies in designing and producing apparels (Boz et al. 2019; Chun 2017). Two main research questions of this study were 1) What parametric design features can be simulated with 3D modeling and printing technology? and 2) What techniques can be used to produce fashion products using 3D printing technology, and what are the limitations? After developing two different 3D-printed parametric motifs using an FDM-type 3D printer, this study produced three sets of fashion products and two pieces of accessories. The implications of this study are as follows:

First, this study proved the three main structural features of parametric design can be simulated with 3D printed motifs. This study successfully developed two motifs that enabled various artistic expressions of parametric designs. In particular, 'Motif 1' and 'Motif 2' show the geometric and organic structural features of parametric design with their continues panels, all individually existing, but creating a fluid motion of movement when put together. Also, with 'Design 4' and 'Design 5', the scattered pattern of 'Motif 2''s parametric panels successfully demonstrate the atypical structural characteristics of parametric design. In addition, this study has thoroughly demonstrated that these parametric motifs could be easily modified depending on the design and type of fashion products desired. 'Motif 1' was applied to 'Design 1' and 'Design 2' to create women's wear, and 'Motif 2' was applied to 'Design 3' to create a jacket. In addition, 'Motif 2' was modified and applied to make accessories of 'Design 4' and 'Design 5'.

Second, we were able to recreate techniques used in developing 3D printing fashion. For 'Design 3', we successfully recreated Kim et al. (2019)'s sewing method to put fabric and 3D printout together. For 'Design 1' and 'Design 2', we not only successfully regenerate the polymer coating technique, but also demonstrated the procedure could be done on the Polyester fabric as well, something the previous wasn't able to conclude. We also recorded every limitations and challenges emerged during the course of development process. The main issue was finding the correct material, size, length and depth of the motif that coordinates to the garment, while not risking the fluidity of the parametric features. This challenge was resolved after multiple print tests and garment tests. Other issue includes the process of attaching the printed motifs onto the garment itself. We used different methods, and concluded that using a glue gun is fast and effect for both thick and thin fabric, while not risking of staining the garment. Better alternative was to sew the printouts onto the garment itself using a commercial grade sewing machine. However, this turned out to be another set of challenges, for it mostly worked for woven fabrics, but for tougher textiles such as leather, it required leather sewing machine or hand-sewing.

This study embraces the potential that parametric designs can be utilized for fashion products. In particular, when working with the TPU material, it was possible to produce multiple motifs in one printing session without any modeling adjustments thus saving time and energy. In addition, the development of various products, such as dresses, jackets, and accessories, demonstrated the possibility of developing a full collection of fashion products using 3D printed parametric designs. This also suggests the possibility of producing customized fashion product that can meet the needs of the wearer, especially if the 3D modeling process is tailored to the size of the human body.

This study supports the possibility of producing full sized fashion products with a low-end 3D FDM-type printer. While, a common limitation showed in prior studies was that the 3D printer was only able to print small-sized accessories or has been used for textiles due to its small bed size. The 3D modeling techniques tested in this study reinforced the possibility that creators could bring forward their ideas into tangible products in an easy and quick manner. Furthermore, this study uncovered some limitations and difficulties with regard to wearing and washing the clothes produced and provided some suggestions in relation to these for those undertaking future studies.

Despite many challenges, this study has proved that it was not only possible to produce parametric fashion design using 3D printing technology, but it also has unlimited potentials. Technology is advancing faster than ever. Embracing and utilizing more technical approaches to fashion design has never been more important. The study poses some suggestions and perspective for existing researches. The contribution of this study was that we developed fashion products that embodied parametric designs on the human body using 3D printing technology, reinforcing the aforementioned possibility of wearing parametric designs as fashion products and the technical possibilities associated with 3D printers. For the future research, we suggest continuing these attempts to utilize 3D printers (other than the FDM type) or to use different materials for the integration of parametric designs and fashion designs. Furthermore, as established in this study, when attaching 3D printouts to the fabric, using the glue gun and sewing have demonstrated to be useful techniques. However, future studies may develop new methods to incorporate

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3D printing on various garments. Given a sufficient level of significant endeavor, someday establishing a constructive system to commercialize 3D-printed fashion products may be possible. We hope the findings of this study can be helpful to those engaged in future studies to integrate parametric fashion designs with 3D printing technology and further advances in related technologies to improve the function of printers and speed up the work process.

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