ABSTRACT

WANG, ZHIWEI. Bra Underwire Customization by 3D Printing. (Under the direction of Dr. Minyoung Suh).

This research was initiated to enhance bra fit through underwire customization. The literature review showed that bra fit problems were a common phenomenon during wearing, and the primary reason was that no standard bra sizing system was widely accepted. More importantly, bra fit was largely affected by the shape and size of the underwire, so the underwire was one of the important factors to decide whether the bra would fit or not. Additionally, the underwire is a key component to provide support for the breast, while it is also one of the major causes of discomfort when wearing a bra. This research came up with the idea of bra underwire customization using 3D printing, aiming at investigating the benefit of the 3D printed underwire for bra fit customization.

A survey about bra purchase habits and wearing experience exposed several issues. Most people were barely familiar with their bra size, which might have been caused by the incorrect way to wear a bra and inconsistency bra sizing system and manufacturing standard in different brands and manufacturers. The survey also indicated that most people preferred a brick and mortar store because of its try-on convenience. In the aspect of bra wearing sensations, multiple problems existed, while the discomfort of the underwire is the most serious one. According to the survey responses, people showed high acceptance of the customized underwire, which provided the value of this research for underwear market.

In the experimental research, five 3D printed underwires, having different lengths and cross-sectional shapes, were developed through 3D body scanning, underwire modeling and 3D printing. Each wire was compared with a conventional underwire in wear trials, in terms of pressure measurement and the subjective rating. The subjective evaluation provided significant results: the customized underwires showed better comfort and support performance than the conventional underwire; in the pressure measurement, only the inner end of the customized underwire had significantly less pressure than the conventional underwire. Shorter underwires were rated for more supportable than longer underwires on outer underwire point, but no significant difference was found from the pressure data. Among underwires with different cross-sectional shapes, no significant difference was observed.

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Bra Underwire Customization by 3D Printing

By
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DEDICATION

To Mom and Dad

For always supporting me.

BIOGRAPHY

Zhiwei Wang was born in Qingdao, China on September 12, 1993. She received a Bachelor of Science in Fashion Design and Engineering from Donghua University, Shanghai, China. She enrolled at North Carolina State University in Raleigh, NC in the fall of 2015 as a graduate student in the Department of Textile and Apparel, Technology and Management. She is currently completing her graduate requirements for the M.S. degree in textiles and hopes to continue her work in the fashion industry.

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CHAPTER ONE: INTRUDUCTION

The bra underwire, as a backbone, plays an important role in breast support. However, it is also one of the major causes of discomfort while the bra is on.

An incorrect underwire design leads to bad bra wearing sensations since the patternmaking for bra bands and cups is based on the underwire shape, size and the center height (Shin, 2010). A series of problems are related to bra underwires in terms of discomfort, such as a too small underwire digging into the skin and poking out from the channeling, and health-related issues, such as breast diseases, metal allergies and mastitis (Marianne & Colman, 2009). Recently, a wireless bra was introduced into the market because of its better wearing sensations, but in order to support the mass of the breast, underwires are still regarded as necessary. Under this circumstance, wearers can benefit from an ergonomic underwire which conforms to the under-breast curve. The 3D scanning and printing technology could be employed to develop an ergonomic underwire since it is widely used in many different industries these days. In the fashion industry, this technology has been applied to customized products, develop prototypes, and achieve special design in haute couture (Vanderploeg et al., 2017), but no research has applied the 3D printing technology to underwire design.

This research came up with a concept of bra underwire customization, and the goal of this study was to investigate the benefit of the 3D printed underwire for the bra fit customization. A mixed-methods approach was used. For the survey research, participants' opinions related to bra purchase habits and wearing sensations were primarily collected using a questionnaire. Responses provided an understanding of bra consumption patterns. For the experimental research, a 3D body scanner, a modeling software, and a 3D printer were used to create customized underwires which were compared with the conventional underwire through a pressure measurement and a subjective evaluation. Pressure measurement provided the real-time pressure data, while subjective rating reflected real wearing sensation of underwires. In this research, five 3D printed underwires, having different lengths and cross-sectional shapes, were designed and compared with conventional underwires. The significant difference of comfort and support was analyzed through statistical models, and further discussions were followed.

CHAPTER TWO: REVIEW OF LITERATURE

2.1 Bra History and Design

2.1.1 Brief History of Bra

Vogue introduced the term *brassiere* for the first time in 1907, and it was listed in the Oxford English Dictionary in 1911 (Berry, 2007). In 1914, Mary Memphis Jacob was issued the first patent for the modern bra invention (Jacob, 1914). Then *brassiere* was gradually shortened to *bra* in the 1930s (Scribners & Sons, 2004). A bra or brassiere is defined as a type of undergarment designed to cover and support the breast. Originally, it was designed for female, but in recent years, undeniably, there are also some bra products for males in the market, which is beyond the scope of this research.

Before bras became the primary foundation garment, there were corsets. Corsets assisted the wearer in achieving the feminine body figure by emphasizing her waist. The first bras came from a corset that was split horizontally into two pieces (Yu, & Ng, 2006). This created two individual foundation garments: the waist cincher and the breast fastener. This shortened the length of corset, and then straps was attached to it to create more support and comfort for the breast (Cecil, 1986). A shortened corset became the starting point from which all modern bras came from. In France, Herminie Cadolle invented the first modern bra in 1889 (Yu, & Ng, 2006). This shortened corset, although better than a full corset, would still not be equivalent to bras of today.

The shortened corset went through many iterations of improvement and diverse styling. The advances have led to the multiple styles that are currently available in the lingerie industry. The first push-up bra was invented by Marie Tucek in 1893 (Tucek, 1893). Tucek's design influenced how the bra cups and paddings were developed in multiple styles. In 1904, Charles DeBeroise improved the demand of comfort to the existing bras lines by creating over 20 different styles of bras that were fashioned in silk and embroidered with lace (Yu, & Ng, 2006). These bras were light weight and provided the comfort that women wanted in their undergarments.

With an increased awareness of the need for the comfort, more advances were made to bras not only aesthetically, but also functionally. In 1913, Mary Phelps Jacob was tired of whale bone corsetry, so she took two handkerchiefs, some ribbon and cord to make a simpler bra (Cox, 2000; Yu, & Ng, 2006). Jacobs's bra had no support, and this type of bra would fall under the category of a bralette. Despite the increasing popularity of the bra, bras were still being produced in the form of shorter corsets. In the 1910s, bras looked just like corsets, being made with suppressing materials such as coutil and whale bone. Women have freed their abdomen from the tight lacings but were not necessarily doing so with their busts. It was not until 1911 when Madeline Gabeau patented the underwire that the restriction of the ribcage was lessened (Farrell-Beck, 2002). From 1930s, the underwire bra was produced commercially but it still did not receive an instant success (Farrell-Beck, 2002). After World War II, the underwire became a common practice in the lingerie industry (Farrell-Beck, 2002).

2.1.2 Bra Design

The bra might be one of the most complex and elaborate garments since breasts are complicated 3D shape. Some bras are comprised of up to 43 components; for all the components, the design elements need to meet the functional and structural demands of the garment (Chan, Yu, & Newton, 2001). The design options seemed endless but bra fit problems are extremely diverse in a practical sense. According to Shin (2007), bra designers need to consider five basic elements in order to achieve fit, which is the most important aspect of bra design: grain, set, line, balance and ease (negative ease/stretch).

Kristina Shin (2010) introduced diverse bra patternmaking methods that are widely used in industry in her book. In another book, Jennifer Lynne Matthews-Fairbanks (2016) introduced the process of sewing a bra, developing pattern modifications, pattern grading and drafting from body measurements. The foundation of bra design is well-presented in both books, including body measurement, materials and trims, and bra anatomy. However, Shin focused more on the industrial bra patternmaking process; direct pattern drafting methods for underwired bras were demonstrated step by step. In Fairbanks's book, the construction was the emphasis, and several methods were demonstrated. These two books provided practical guides to bra design and development, which were adopted in this research.

The anatomy of the basic bra is shown as Figure 1. Fabrics, elastic trims, and accessories such as connectors and fasteners are major materials. Fairbanks (2016) sorted six types of fabrics out that are commonly used in bras. Tricot is a type of knit fabrics which can be stretched in two directions, one direction, or no direction, and the 4-way stretch is the most frequent in bras. Jersey knit has high stretchability, so it is usually used on smaller bra cups because it would offer low support for the larger breast. Power net has a firm stretch with an excellent recovery and is used as the back band. Spandex knit is a kind of jersey knit with spandex or Lycra® that allows more stretch. Stabilizer is rigid and sheer material; it is used on the gore and the side panel. Lace fabrics can be produced into knit and woven constructions. Knit lace is recommended for the areas of high stretch such as shoulder straps or back band, while woven laces are used for cup construction.

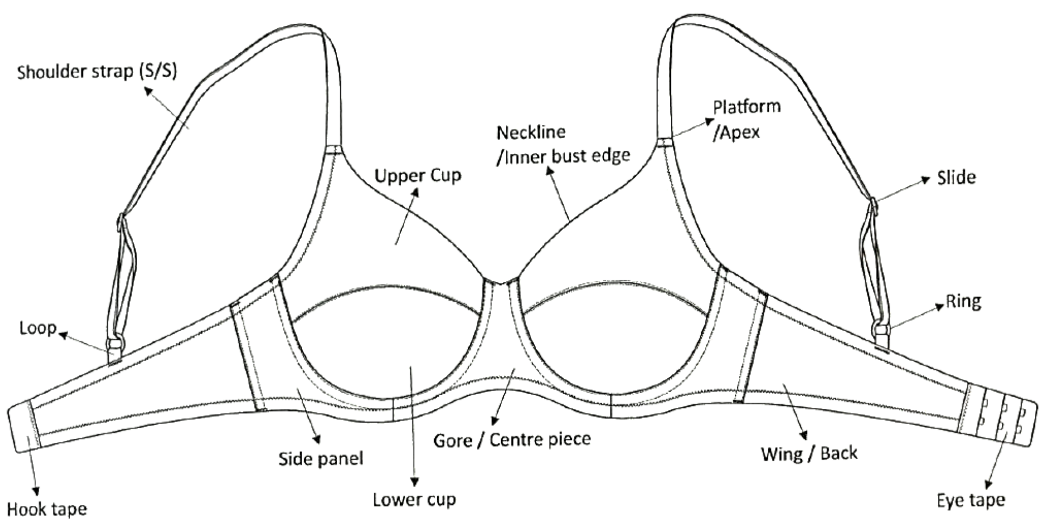


Figure 1. Basic bra anatomy (Shin, 2007)

Stretch and recovery factor of fabrics must be taken into consideration when designing bra patterns. Armstrong (2010) gave instructions for determining the stretch/recovery factor. The stretched length percentage over the original length (usually 5 inches) is calculated as the stretch factor. Releasing the fabric can yield the recovery factor, which is the recovered length percentage over the original length. Fairbanks (2016) listed the stretch reduction chart for different stretchy fabrics, shown in Table 1. According to the fabric stretch factor, the bra pattern should be shrunk down by 40 to 50% multiplier.

Table 1. Stretch reduction chart for fabrics

Stretched Length	Stretch Factor	40% Multiplier	45% Multiplier	50% Multiplier
5 1/4	5%	0.9800	0.9775	0.9750
5 1/2	10%	0.9600	0.9550	0.9500
5 3/4	15%	0.9400	0.9325	0.9250
6	20%	0.9200	0.9100	0.9000
6 1/4	25%	0.9000	0.8875	0.8750
6 1/2	30%	0.8800	0.8650	0.8500
6 3/4	35%	0.8600	0.8425	0.8250
7	40%	0.8400	0.8200	0.8000
7 1/4	45%	0.8200	0.7975	0.7750
7 1/2	50%	0.8000	0.7750	0.7500
7 3/4	55%	0.7800	0.7525	0.7250
8	60%	0.7600	0.7300	0.7000
8 1/4	65%	0.7400	0.7075	0.6750
8 1/2	70%	0.7200	0.6850	0.6500
8 3/4	75%	0.7000	0.6625	0.6250
9	80%	0.6800	0.6400	0.6000
9 1/4	85%	0.6600	0.6175	0.5750
9 1/2	90%	0.6400	0.5950	0.5500
9 3/4	95%	0.6200	0.5725	0.5250
10	100%	0.6000	0.5500	0.5000

Note: Table taken from Fairbanks, J. L. (2016).

Accessories are used to connect different bra parts or provide additional support. Bones are made of stainless steel or polymers which provide side support; rings and sliders are required to adjust the length of shoulder straps; hooks are used to connect the shoulder straps to the bra; hooks and eyes are used as back close; underwires provide support for breasts, which will be further discussed later in this chapter (Shin, 2007).

2.2 Bra Sizing System

2.2.1 Measurement methods

Considering mass production, a sizing system is important for all types of apparel, including bras. A scientific and effective bra sizing system can guide manufacturers to design and produce bras that fit their target market, and an individual women to be able to choose a more fitted bra (BareWeb Inc., 2011).

Currently, bra sizes usually consist of one or more letters to represent the breast cup size and a number to reflect the band size around the woman's torso. The term *cup* was first used to describe bras in 1916 when the *brassiere* patent was filed (Farrell-Beck & Gau, 2002). In 1928, Ida Rosenthal introduced cup sizes for bra ("Bra Drama", 2004). Later in 1932, the S.H. Camp and Company used the alphabet letters of A, B, C and D to describe how pendulous the breast was, and in 1937, Warner used the same alphabet letters to describe the types of breast shape, which A cups represented youthful, B cups represented average, C cups represented large and D cups represented heavy (Bressler, Newman & Proctor, 1998). Gradually, this alphabet cup sizing system became the basis of modern bra sizing system. As for band sizes, adjustable bands were achieved using multiple hook and eye closures in the 1930s, while the band sizing system was established just after the

World War II (Maharani, n.d.).

According to Pechter (1998), the most dominant bra sizing practices are based on measurements of the bust at the fullest part and under the bust at the narrowest part. The cup size is then determined by subtracting the under-bust measurement from the bust. This difference corresponds to a letter, which would become the cup measurement. However, this calculation depends on the brand or manufacturer. Each company may have a slightly different method on how to achieve this. No standard exists in industry and academia.

For band size, there are several possible methods to measure and calculate the size. For the method called as *Underbust +0*, a measuring tape is pulled around the torso, then pulled tight while keeping it horizontal and parallel to the floor, and the measurement is then rounded to the nearest even number in inches for the band size (“Bra Size Calculator”, n.d.). Another method, *Underbust +4*, which is used for Kohl’s online fitting guide, is similar to underbust +0, but if the measurement is an even number, 4 is added before naming the band size, and if the measurement is an odd number, 5 is added (“Bra Size Calculator”, n.d.). Currently, many large U.S. department stores rely on the combined method of *underbust +0* and *underbust +4* to determine the band size, where the measurement is taken underneath the bust. However, in the method that Victoria’s Secret uses, the measurement is taken above the bust instead of the under-bust area, where a measuring tape goes around the torso above the bust and under the armpit (“Your Angel Fit”, n.d.).

The cup size is calculated by subtracting the band size from the bust size, and the bust size is the girth measurement around the bust at its fullest point of the breasts while a fitted bra is on and a person stands straight (Zheng, Yu, & Fan, 2006). This method seems not clear enough since it assumes that a perfectly fitted bra is already there.

Based on the cup and band measurements, Yu, Fan, and Zheng (2006) defined two main bra sizing systems, based on the Imperial system and the metric system. Below are the calculation procedures and the comparison of these two systems.

In Imperial system, the measurement process is based on Underbust +4 method. Cup measurement is determined by subtracting the band size from the bust girth. The conversion from the length different to cup size follows Table 2. Applying this process, the Imperial bra sizing chart is formulated in Table 3. Following Underbust +0 method, in the metric system, the underbust girth directly becomes the band size. For example, a band size 80 corresponds to an underbust measurement of 80 cm and the cup size comes from the centimeter difference between the bust girth and the underbust girth. The sizing table is shown in Table 4.

Table 5 and Table 6 give a comparison of the Imperial system and the metric system, taking B cup and band size 34 as examples. The size intervals of both systems are similar, where 5 cm or 2” leads to one band size difference and 2.5 cm or 1” indicates one cup size difference. The metric bust girth (cm) and Imperial bust girth (cm) have a relationship which can be represented by the same linear regression equation $y = 0.9843x$, where x is the Imperial bust girth and y is the metric bust girth.

Table 2. Determination of bra cup size

Bust girth – ban size	-1”	0”	1”	2”	3”	4”	5”	6”	7”
Cup size	AA	A	B	C	D	DD	E	F	G

Note: Table created based on Yu, W., Fan, J., Harlock, S. C., & Ng, S. P. (2006).

Table 3. Imperial bra sizing system

Bra size	30B	34AA	32B	34A	34B	34C	36B	34D	34DD	38B	34E	34F	40B	42B	44B
Underbust girth (inches)	25-26	29-30	27-28	29-30	29-30	29-30	31-32	29-30	29-30	33-34	29-30	29-30	35-36	37-38	39-40
Bust girth (inches)	31	33	33	34	35	36	37	37	38	39	39	40	41	43	45

Note: Table created based on Yu, W., Fan, J., Harlock, S. C., & Ng, S. P. (2006).

Table 4. Metric bra sizing system

Bra size	65A	70A	75AA	75A	75B	75C	80B	75D	75DD	85B	75E	75F	90B	95B	100B
Underbust girth (cm)	65	70	75	75	75	75	80	75	75	85	75	75	90	95	100
Bust girth (cm)	75	80	82.5	85	87.5	90	92.5	92.5	95	97.5	97.5	100	102.5	107.5	112.5

Note: Table created based on Yu, W., Fan, J., Harlock, S. C., & Ng, S. P. (2006).

Table 5. Comparison of Imperial system and metric system for B cups

Imperial size	30B	32B	34B	36B	38B	40B	42B	44B
Corresponding full bust (cm)	78.7	83.8	88.9	94.0	99.1	104.1	109.2	114.3
Metric size	65B	70B	75B	80B	85B	90B	95B	100B
Corresponding full bust (cm)	77.5	82.5	87.5	92.5	97.5	102.5	107.5	112.5

Note: Table taken from Yu, W., Fan, J., Harlock, S. C., & Ng, S. P. (2006).

Table 6. Comparison of Imperial system and metric system for Band Size 34

Imperial size	34AA	34A	34B	34C	34D	34DD	34E	34F
Corresponding full bust (cm)	83.8	86.4	88.9	91.4	94.0	96.5	99.1	101.6
Metric size	75AA	75A	75B	75C	75D	75DD	75E	75F
Corresponding full bust (cm)	82.5	85	87.5	90	92.5	95	97.5	100

Note: Table taken from Yu, W., Fan, J., Harlock, S. C., & Ng, S. P. (2006).

2.2.2 Labeling method

For commercial and marketing considerations, different manufacturers and brands have their own bra sizing standards. It is because the ground rule is based on their target market and the bra patterns are modified until it fits perfectly on their live fit models (Zheng, Yu, & Fan, 2006). Thus, a woman may find a better fitted bra from one brand but not from another brand, even though the size is the same. Additionally, although similar bra sizing systems are used in different brands, there are issues still that different countries have their own labeling standards.

The UK, the US and Canada use the same Imperial system, but they have different labeling methods. For example, UK standard band sizes are 28-30-32-34-36-38-40-42-44, and so on, while cup sizes are designated by AA-A-B-C-D-DD-E-F-FF-G-GG-H-HH-J-JJ-K-KK-L… (Brooks, 2015). The US and Canada use a same band size standard with the UK. However, cup sizes beyond a C cup are labeled as D-DD/E-DDD/F-G-H-I-J-K-L-M… (Brooks, 2015). In Australia and New Zealand, the cup size is same with the UK, but the band sizes are designated by 8-10-12-14-16-18-20-22-24… (Brooks, 2015). Italy uses small consecutive integers to express band size, and the size designations are often given in Roman numerals such as I, II, III, and IV ("Bra Size Converter", n.d.).

Continental European countries and Asian countries, including China, South Korea, and Japan, use the metric system. Band sizes are designated by 65-70-75-80-85-90-95… and these numbers are the underbust girth in centimeter. In South Korea, the cup sizes begin with "AAA", while in China and Japan, the cup sizes begin with "AA" (JIS L4006, 1998; KS K9404, 1999; FZ/T 73012-2008, 2008). Summarizing the bra sizes in different countries, an approximate sizes equivalents chart is shown in Table 7.

Table 7. Approximate band sizes equivalents chart

Underbust girth (cm)	58-62	63-67	68-72	73-77	78-82	83-87	88-92	92-97	98-102
EU/Asia	60	65	70	76	80	85	90	95	100
IT	0	1	2	3	4	5	6	7	8
US/CN/UK	28	30	32	34	36	38	40	42	44
AU/NZ	6	8	10	12	14	16	18	20	22

Note: Table created based on Brooks, K. (2015) and "Bra Size Converter", (n.d.).

2.2.3 Sister Size

Sister sizes are the bra sizes of the same cup volume (Bengtson, 2015). Figuring out a bra size's sister size requires one-size shifts in the numbers and letters in the opposite directions. *Sister size down* means one band size smaller than the current band size and one letter size larger than the current cup. For example, a 34C would become 32D after sister size down. Likewise, *sister size up* means one band size larger than the current band size and one letter size smaller than the current cup. For instance, a 34C bra would become 36B after sister size up. Therefore, it is possible that several sister sizes fit one person since the cup volume is kept same, while the band size can be adjusted to a smaller or larger level by arranging the multiple sets of hooks and eyes as the back close. Table 8 is the sister size chart where bra sizes in a row are sister sizes.

Table 8. Sister Size Chart (US and Canada)

Difference between underbust girth and bust girth	1"	2"	3"	4"	5"	6"	7"	8"
Bra sizes	32A	30B	28C	26D	24DD/E			
	34A	32B	30C	28D	26 DD/E	24DDD/F		
	36A	34B	32C	30D	28 DD/E	26 DDD/F	24G	
	38A	36B	34C	32D	30 DD/E	28 DDD/F	26G	24H
	40A	38B	36C	34D	32 DD/E	30 DDD/F	28G	26H
	42A	40B	38C	36D	34 DD/E	32 DDD/F	30G	28H

Note: Table taken from Bengtson, B. P. (2015).

However, this theory does not mean that every sister size bra satisfies a person since the band size is not taken into account. For example, a woman who perfectly fits into a 34B might not be as comfortable as in 36A. There is a possibility that the band would easily move around the body and when her arms raised, lifting the band up and displacing the cups. This movement in the band especially could be the reason for the bra not to fit properly.

In this research, a sister size was adopted to minimize the number of experimental bras. Each bra was designed to include enough band sizes variance. In this way, one 34B bra could be worn by multiple participants with bra sizes of 32C, 34B, and 36A.

2.2.4 Bra fit

According to Robson (2015), in the UK, 60% of over 2,000 women between the ages of 16 to 75 had bra fitting problems, and fit was the least important factor in 99% women when selecting a bra. About 80% to 85% women still wear the wrong bra size, and about 25% women have a difficult time finding a properly fitted bra (Wood, 2008). This phenomenon might have been caused by various reasons: there is not a standard system for bra size, which is different from country to country, even manufacturer to manufacturer; people might not know what a properly fitted bra is, and the preferred style might not be the most flattering or correct fit for them; the conventional bra may have incorrect design and construction methods.

Wood, Cameron, and Fitzgerald (2008) investigated the relationship between breast sizes, bra fit, and thoracic pain. They mentioned that larger-breasted women usually have difficulty in selecting a well-fitting bra. According to their research, buxom women were more likely to wear an incorrectly sized bra than smaller-breasted women. Overall, larger-breasted women tended to purchase bras that were too small, while smaller-breasted women tended to buy bras that are too large. Another study has found that the most common phenomenon when selecting a bra was to choose a too small cup and a too large band, for example, 38C instead of 34E, or 34B instead of 30D (Lantin, 2003). As breasts become larger, breast shape and the distribution of fat tissue changes, and the breasts become easy to sag. These changes make breast size measurements increasingly unreliable.

Following different standards, manufacturers develop the patterns and cut their bras differently, so, for instance, two 32B bras from two manufacturers may not fit one person (Diana, 2011). Customers are expected to know which sizing system and labeling method are used by each manufacturer. For those who buy bras from a certain brand all the time, they may be able to find the fitted bra easily. For example, Victoria's Secret has its own bra sizing system and measurement method, and the fitting guides in their retail stores are well prepared. Those guides can help consumers find out the correct bras. McGhee and Steele (2010) summarized a professional bra fitting criteria, shown in Figure 2. Avoiding the problems described in this table may help to select a well-fitting bra.

Band	☐	Too tight: flesh bulging over top of band: subjective discomfort "feels too tight"
	☐	Too loose band lifts when arms are moved above head, posterior band not level with inframammary fold
Cup	☐	Too big: wrinkles in cup fabric
	☐	Too small: breast tissue bulging above, below or at the sides
Underwire	☐	Incorrect shape: underwire sitting on breast tissue laterally (under armit) or anterior midline; subjective complaint of discomfort
Straps	☐	Too tight: digging in; subjective complaint of discomfort; carrying too much of the weight of the breast
	☐	Too loose: sliding down off shoulder with no ability to adjust the length
Front band	☐	Not all in contact with the sternum
Rating of bra fit	☐	Pass: no errors or if hooks or straps can be adjusted to allow correct fit
	☐	Fail: any other tricks

Figure 2. Professional bra fitting criteria (McGhee & Steele, 2010)

2.3 Underwire

2.3.1 Underwire Construction

The underwire concept can be traced back to 1893 when Marie Tucek patented her breast supporting device (Yu te al., 2006). It was a metallic or cardboard-rigid cradle, under the breasts for stability. The cradle curved around the front torso directly under the breasts, ended near the armpits, and was fastened by hook-and-eye closures at the back. The modern underwire bra started to develop in the 1930s and was widely spread by the 1950s (Napoleon, 2003).

A typical underwire is a U-shape flat wire and encased in the wire channeling (also called underwire casing) that supports the bottom and sides of each cup (Shin, 2010). One end of the underwire is close to the center front of the bra, and the other end is close to the armhole. Those two ends of the underwire are covered with plastic cushion tips, which are designed to keep the wire from penetrating the bra fabric (Figure 3). In 2002, S & S Industries issued a patent for a new underwire design which uses a spring-loaded plastic cushion tip to replace the traditional tips, shown in Figure 4. The spring was included to avoid the underwire penetrating the bra fabric, even under the heavy stress from laundering (Riordan, 2002).

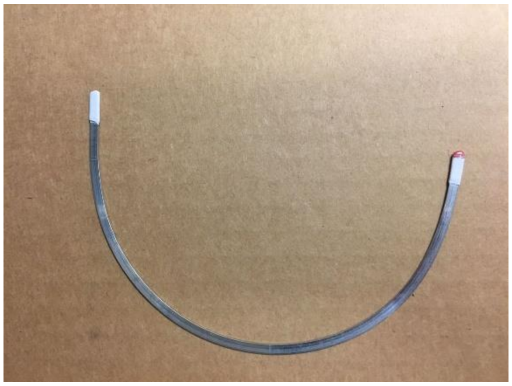


Figure 3. Underwire design

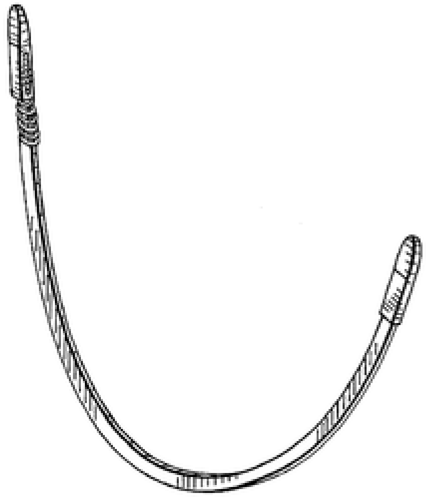


Figure 4. Underwire Design in S & S Industries' Patent (Underwire for brassiere,

2002)

Underwires can be made of metal, molded plastic or resin. Most are metallic, including steel and nickel titanium, and a shape-memory alloy is also possible (Sara Kehaulani Goo, 2004). According to S & S Industries, about 70 percent of women wear steel underwire bras. The reason why a plastic underwire has a very small percentage of the market share is that it cannot provide the same level of breast support and rigidity offered by metallic underwires. However, Richard Higgs (2000) pointed out that the traditional metallic underwire has tactile discomfort while wearing and detaching problem while washing. A new plastic-based bra was introduced, named Bioform bra, which not only offers better support and comfort but also overcomes traditional machine wash problems associated with the metallic underwire. During the process of plastic material selection, several requirements needed to be satisfied. The material had to be non-allergenic, odorless, in a target weight, able to withstand the high temperature in a washing machine and a dryer without degradation or deformation, and glass-reinforced polypropylene was finally selected.

Kristina Shin (2010) categorized underwires by three different center heights, including low, medium and high height. The underwire length and shape are related to the types of cup coverage. The high center height underwires are designed for full cup bras, strapless bras, and balcony bras (Figure 5), and the medium center height underwires are used in 3/4 cup bras (Figure 6), while the low center height underwires are suitable for plunge cup bras and 1/2 cup bras (Figure 7). However, there is another type of underwire called demi underwire available in market (Figure 8), whose length is much shorter than other underwires.

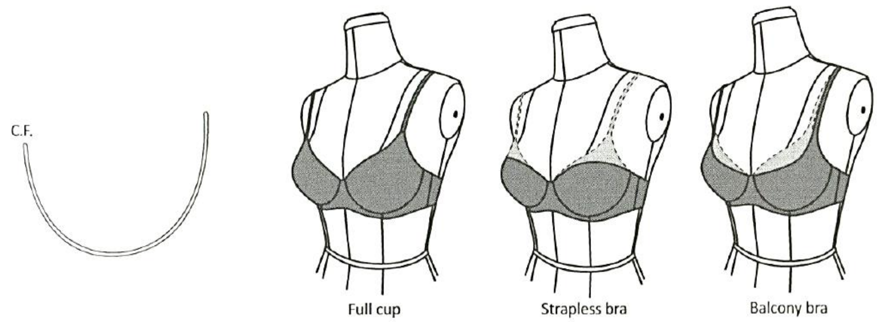


Figure 5. High center height underwires and cup coverages (Shin, 2010)

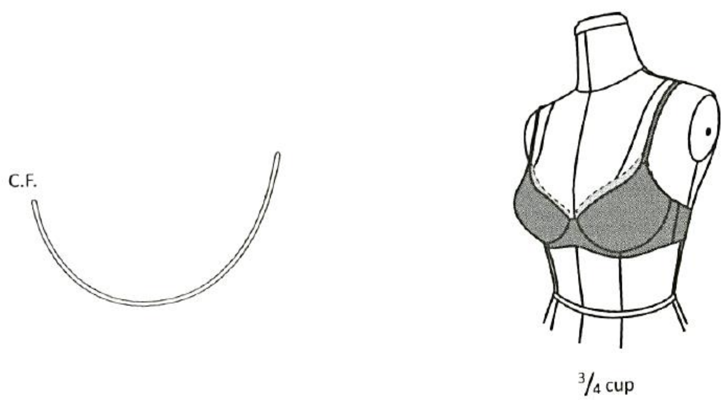


Figure 6. Medium c enter height underwires and cup coverages (Shin, 2010)

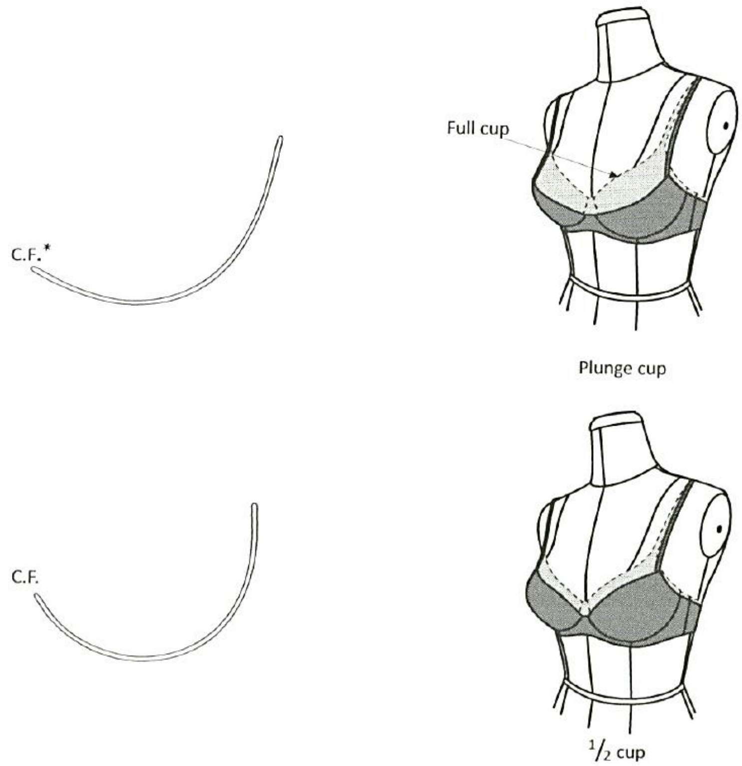


Figure 7. Low center height underwires and cup coverages (Shin, 2010)

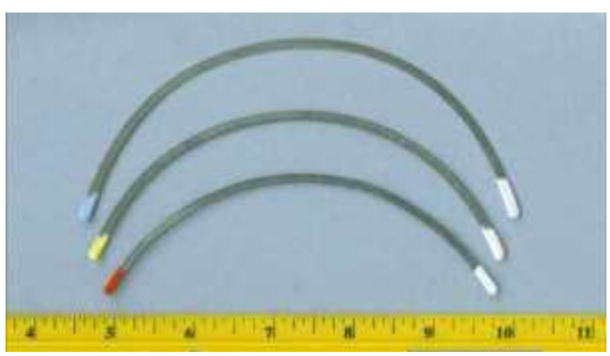


Figure 8. Demi underwire (Sew Sassy Fabrics, n.d.)

2.3.2 Discomfort and health-relevant issues

Patternmaking for bra bands and cups is based on the underwire shape, size and the center height (Shin, 2010). Thus, incorrect underwire design leads to bad bra wearing sensations. Andie Francese (n.d.) demonstrated a series of problems related to bra underwires. Ill-fitting is the biggest problem while the underwired bras is on. A too small underwire will result in the underwire digging into the skin badly and excessive breast tissues on the sides, while women who wear a too big underwire will find the gap between the wire and her rib cage. Poor underwired bras tend to have less padding and thinner channeling around the underwire, and it is easy to dig into the skin. To prevent the pain from an underwire, a more padding around the underwire is suggested since it will last longer and reduce pain. Poking out from the channeling is another significant problem (Figure 9). When being laundered in a washing machine and a dryer, bras are shuffled around very roughly, which will break down the channeling fabric around the underwire. After repeated wearing and washing, the underwire will eventually poke out from the channeling. When the underwire is revealed, it causes skin friction and may hurt the skin. Thus, hand-washing and natural drying are recommended to preserve the bra.

Figure 9. Underwire tears through the fabric (LinguistAtLarge, 2009)

Much more serious issue than discomfort is that underwire bra is related to health-related issues, such as breast diseases, metal allergies and mastitis (Marianne & Colman, 2009). Andie Francese (n.d.) mentioned that wearing underwired bras may increase the risk of breast cancer because a poorly fitted underwire can damage the breast tissue over time. For lactating women, an underwire may clogg her milk ducts (Littleton & Engebretson, 2002). Adisa and Mbanaso (2004) warned that a severe furuncular myiasis of the breast may happen if an underwired bra is worn in the tropics, especially in East Africa. Myiasis is caused by Tumbu flies when its eggs and larvae are deposited along the metal underwire, and they can only be killed by the heat of ironing.

Related to breast cancer, Luo, Yu and Chung (2006) gave a comprehensive review on both beneficial and detrimental health effects of the intimate apparel. Hsieh and Trichopoulos (1991) studied the possible risk factors which may cause breast cancer. It was reported that pre-menopausal women who wear bras had double risk of breast cancer, but the reason might have been smaller breast sizes, not the underwire itself.

2.4 3D Printing

3D printing, also known as additive manufacturing (AM) and rapid prototyping (RP), is a technology or process that creates a 3-dimensional product by depositing material layer-by-layer until the completed shape is formed (Atlantic Council, 2011; Mellor, Hao, & Zhang, 2014). ASTM Standard (2015) defined additive manufacturing as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining." 3D printing is an additive process opposite from traditional subtractive manufacturing, which cuts away material to create the desired shape (Atlantic Council, 2011; Berman, 2012).

The first patent was issued by Charles (Chuck) Hull for his invention of stereolithography apparatus (SLA) machine in 1983; in 1987, the first commercial RP system, the SLA-1, was introduced by 3D Systems in the US (Wohlers & Caffery, 2014). Since then, advanced 3D printing technology, materials and machines have continued to emerge. *The Economist* magazine forecasted that the 3D printing would be the third industrial revolution because of its prospects of succeeding in a new manufacturing industry (Chua & Leong, 2015).

2.4.1 Fundamentals and process

Chua and Leong (2015) drew an additive manufacturing wheel (Figure 10) to explain the four key aspects of 3D printing fundamental, including input, method, material, and applications. The input means the computer model or physical model which provides 3D object information, and the computer model is created by computer-aided design system, while, for the physical model, a coordinate measuring machine can be used to capture the data points. The initial state of 3D printing materials can be either solid, liquid, or powder, and depending on the materials, the different printing methods are employed such as cutting and joining, melting and solidifying or fusing, photo-curing, and joining or binding. 3D printing is widely applied in many walks of life, and they can be grouped into design, engineering, analysis and planning, and manufacturing and tooling.

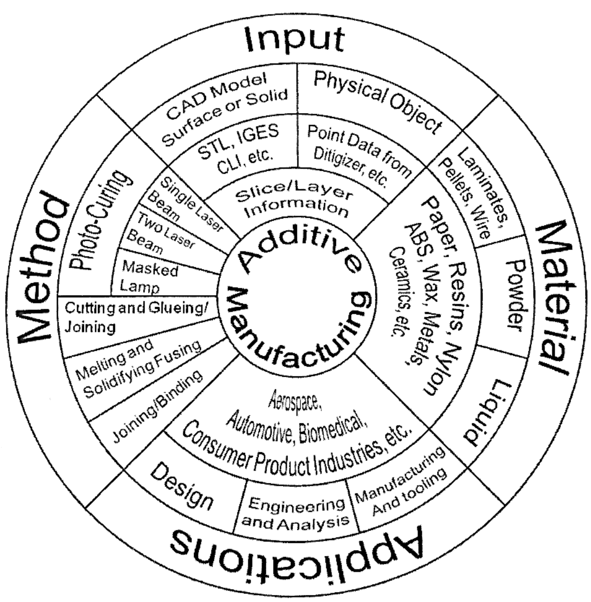


Figure 10. the 3D printing fundamental wheel (Chua & Leong, 2015)

Kochan and Chua (1994) summarized the process chain of 3D printing system (Figure 11). Five steps are included in the chain, which are 3D modelling, data convention and transmission, checking and preparing, building, and postprocessing. According to the quality of the model, the last three steps may be iterated in order to print out a satisfactory model.

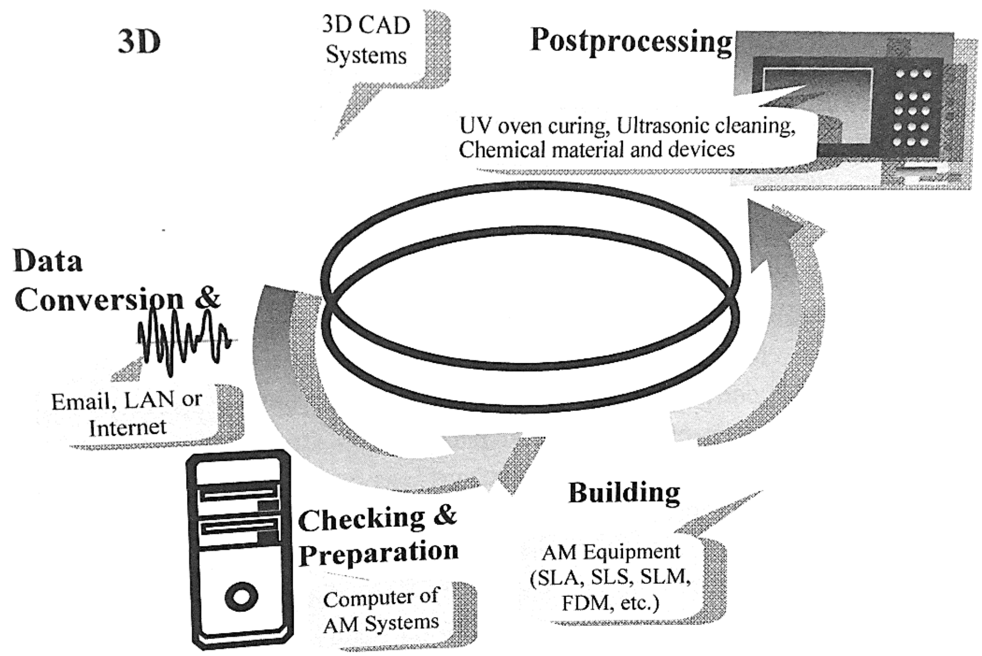


Figure 11. Process chain of 3D printing system (Kochan & Chua, 1994)

2.4.2 Technology

The 3D printing technologies or systems vary by the form of the materials, which can be categorized into liquid-based, solid-based, powder-based (Kruth et al., 1998).

For the 3D printers using liquid-based materials, the liquid is converted to the solid state through a curing process (Chua, & Leong, 2015). 3D Systems' Stereolithography Apparatus (SLA) and CMET's Solid Object Ultraviolet-Laser Printer (SOUP) use a photopolymer resin and an ultra-violet (UV) laser to cure and harden individual layers to build the final objects (Hoskins, 2013; Huang et al., 2013; Chua, & Leong, 2015). Stratasy's Polyjet and 3D Systems' Multijet Printing (MJP) use UV lamps for curing, and this technology allows multiple materials to be deposited in a single layer (Sclater, 2011; Chua, & Leong, 2015). EnvisionTEC's Bioplotter and RegenHU's 3D Bioprinting use the extrusion method to form objects (Chua, & Leong, 2015; Moroni et al., 2004). Rapid Freeze Prototyping makes 3D ice parts by freezing water droplets (Zhang et al., 1999).

The solid-based materials encompass all the materials in the solid state, including the form of wires, rolls, laminates and pellets (Chua, & Leong, 2015). *Melting and Solidifying or Fusing* method is used by Stratasys' Fused Deposition Modelling (FDM) and Solidscape's Benchtop System. The solid filament is fed into an extrusion head and heated to a semi-liquid state, then the semi-liquid material is deposited in ultra-thin layers and then quickly solidifies (Vanderploeg et al., 2017). MCOR Technologies' Selective Deposition Lamination (SDL), Cubic Technologies' Laminated Object Manufacturing (LOM), and Ultrasonic Consoliddation use the *Cutting and Joining* method, which is a process of the simple addition of sheets of paper. Tracing the edges of the object, the blade will cut every sheet at a time, and the final product is adhered by various sheets of papers (Chua, & Leong, 2015).

All the powder-based systems use the *Joining/Binding* method. A laser is employed to heat the powder to just below its boiling point to fuse the particles into a solid object (Huang et al., 2013; Sclater, 2011). Physical binder/glue could be used instead to join the particles. Eleven commercial systems are based on this method, including 3D Systems' Selective Laser Sintering (SLS), 3D Systems' ColorJet Printing (CJP), EOS's EOSINT Systems, Optomec's Laser Engineered Net Shaping (LENS), Arcam's Electron Beam Melting (EBM), Concept Laser GmbH's LaserCUSING®, SLM Solution GmbH's SLM®, 3D Systems' Phenix PXTM, 3D-Micromac AG'S MicroSTRUCT, The ExOne Company's ProMetal, and Voxeljet AG's VX System (Chua, & Leong, 2015).

2.4.3 Applications in fashion industry

3D printing is currently used in the fashion industry to customize products, develop prototypes, and achieve special design in haute couture (Vanderploeg et al., 2017). Incorporating special structures for breathable, light-weight, flexible, and fabric-like products, many fashion companies have introduced the 3D printing technology in their fabrics, dresses, accessories and other product lines (Brooke, 2013).

Catherine Wales, a London-based designer, displayed her Project DNA collection of 3D printed corsets, masks, and helmets on the exhibition at Design Museum (Zolfagharifard, 2013). These accessories were printed by 3D Systems' Selective Laser Sintering (SLS), and they can be customized according to the body measurements by using a 3D body scanner (Zolfagharifard, 2013). Continuum Fashion, a high-tech concept brand, used SLS to print the bathing suits, which gave the products a fabric-like feel with waterproof properties (Cuzella, 2015). It also sales ready-to-wear shoes and jewelries created by 3D printer (Fitzgerald, 2013). Iris van Herpen has also used SLS to develop a dress in her haute couture collection, VOLTAGE, shown at Paris Fashion Week in 2013. The dress made of flexible fabric-like material had a lace-like texture (Mendoza, 2014). Another application of SLS is Nike's Vapor Laser Talon football shoe. The Nike Vapor Laser Talon weighs only 5.6 oz. which helps athletes accelerate faster, and maintain their propulsion and acceleration speed longer and more efficiently (Nike, 2013)

Materialise's Mammoth Selective Laser printer increased the capability to create long, complex dresses by building the largest printing area, 210 cm in length, 70 cm in width, and 800 cm in height (Materialise, 2015). Iris van Herpen used this printer to build her dress in the Wilderness Embodied Collection. Lady Gaga's Anemone dress with incorporated bubble factory and Parametric Sculptured Dress were also created by this instrument. These two dresses were designed by London-based fashion technology company, Studio XO, in collaboration with Materialise (Sharma, 2013).

3D Systems' Spectrum Z510 is a binder jetting printer, and it is known as the only 3D printer in the market that can print products in multiple colors (Vanderploeg, 2017). The Timberland Company uses Spectrum Z510 to develop prototypes for the footwear in order to show a more realistic appearance of the end product (Burton Precision, 2016).

On the other hand, PolyJet allows multiple materials to be deposited in a single layer, which can give products different textures, structures and thicknesses, providing more movement and fit for people (Sclater, 2011). Iris van Herpen took the advantages of

PolyJet and designed a highly textured cape and skirt. These two pieces were printed with multiple materials, incorporating both hard and soft elements, giving the garments diverse flexibility and texture (Celaschi & Celi, 2015).

CHAPTER THREE: METHODOLOGY

The primary goal of this research was to investigate the benefit of 3D printed underwires for bra fit customization. A mixed-methods approach was used. The wearers' opinions related to bra purchase and wearing sensations were surveyed by the questionnaire, and after creating the experimental bras, 3D customized underwires were compared with a conventional 2D underwire through wear trials, in terms of pressure measurement and subjective evaluation. Design features of the underwire were also studied, including the cross-sectional shapes and lengths.

3.1 Research Questions

This study was framed by four research questions, and each was answered individually. The approaches to answer each of these questions were covered in detail in the experimental designs and measurement sections in this chapter.

1. What are consumer's purchase habits and wearing sensations towards a bra?
2. Comparing the 3D printed underwire with the conventional underwire, which one can provide better support and comfort?
3. Does the length of the 3D printed underwire influence bra comfort and support?
4. Does the cross-sectional shape of the 3D printed underwire influence bra comfort and support?

In order to answer the above four research questions, the first step of this study was to analyze consumer's purchase habits and wearing sensations for a bra. Covering the second research question, the second set of experiments focused on the comparison of the comfort and support level between the conventional underwire and the 3D printed underwires. In order to answer the last two research questions, the third and fourth experimental design investigated the comfort and support level among experimental bras with different lengths and different cross-sectional shapes.

3.2 Materials and Equipment

3.2.1 Experimental Bra

Every female has different breast shapes and anatomical structures around the breasts. To arrange bra wear trials with controlled size and fit, the design of experimental bras were limited by the following requirements. Firstly, it focuses on only the basic function of a bra, such as support and comfort. Functional bras, for instance, push-up bras, minimizer bras and sports bras, were not considered in this research. Secondly, the back closer needs to be designed gradually adjustable. Most of the bras in the market use hooks and eyes as a back closer, shown in Figure 12, which only allow three discrete adjustments. For the controlled size and fit, the pressure at the shoulder strap and underband was kept consistent while the bra is on, so hooks and eyes were replaced by a buckle closer, shown in Figure 13. Thirdly, the center front gore needs to be also adjustable because the distance between two busts varies from person to person, thus an adjustable center front gore was implemented. Fourthly, the underwire needs to be detachable. When doing pressure measurements, a participant needed to wear a one experimental bra throughout the experiment, so the bra had an opening at the outer position in order to put in and take out the underwire.

Only two experimental bras were used during wearing trials. One covered the bra sizes of 32C, 34B, and 36A, while another one was applied for the bra sizes of 32D, 34C, and 36B. Thus, the experimental bras must stay in same condition during the entire process of experiments, so the fabric was required to have high stretchability, durability and high elastic recovery. The Spandex knit produced by McMurray Fabrics, Inc. (Figure 14) was selected considering all the above needs. According to the testing method of stretchability (Fairbanks, 2016), this fabric has 50% stretch ratio in crosswise (cross-grain) and 65% stretch ratio in lengthwise (on-grain).

Figure 12. Hook & eye (mxinfa.com, 2010) Figure 13. Buckle (Buckleguy.com, n.d.)

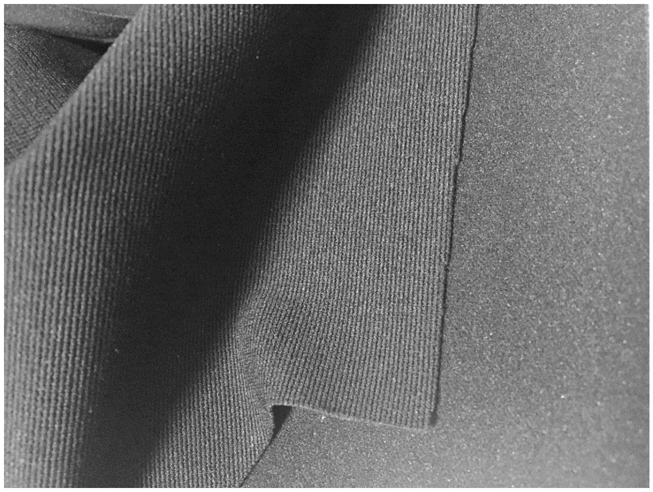


Figure 14. Fabric for Experimental Bras

Based on the above requirements, two experimental bras were developed, shown in Figure 15 and Figure 16. The bra cup was composed by two panels, and there was no pad in it. Two eyes were attached to each bra cup at the inner top and bottom (Figure 16) to engineer the center front gore length. Two polymer strings connected two cups at the top and bottom, and their length depended on the distance between two busts. A buckle was used as a back closer and the underwire was possible to put in and take out from the opening at the outer end, shown in Figure 17.

Figure 15. Experimental bra front **Figure 16. Experimental bra back**

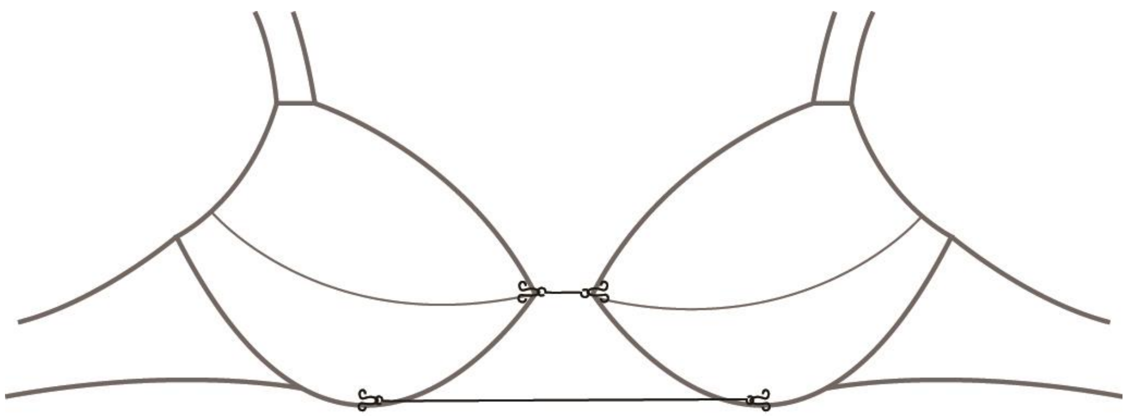


Figure 17. Cups connection

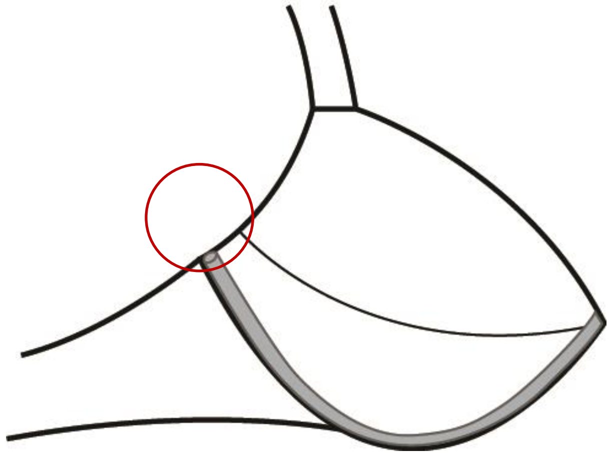


Figure 18. Opening for underwire

3.2.2 Conventional Underwire

Two conventional underwires purchased from Sewsassy.com are shown in Figure 19 and Figure 20. Figure 19 shows the size 34B, which covers its sister sizes of 32C and 36A, while Figure 20 shows the size 34C, which covers its sister sizes of 32D and 36B. Both underwires are flat metal wires with polymer-covered tips, where different colors marked at the inner end indicate their size.

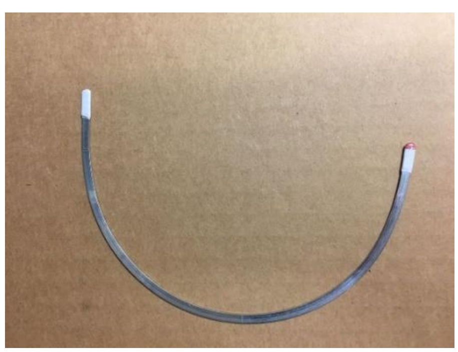


Figure 19. 34B Conventional Underwire

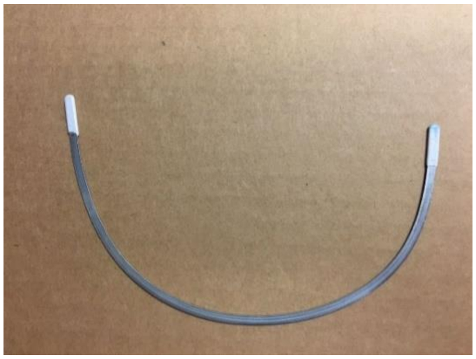


Figure 20. 34C Conventional Underwire

Cross-sectional dimension is 1mm thick and 3mm wide for both underwires. Figure 21 is the schematic diagram for the underwire dimension. The 34B underwire has inner width of 123.8mm, inner depth of 73mm and outer length of 225.4mm. Correspondently, the 34C underwire has those sizes of 133.4mm, 76.2mm and 235mm, respectively.

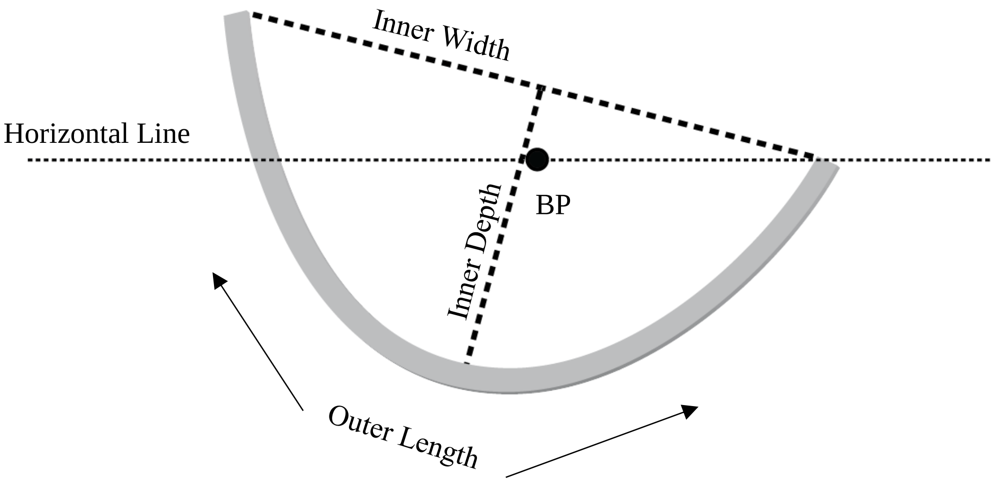


Figure 21. Schematic diagram of conventional underwire

3.2.3 Custom Underwire Model

To customize an underwire, the first step was to acquire the breast shape data using a 3D body scanner. Size Stream (Size Stream, LLC, Cary, NC) is the body scanner used in this research. It is a full body measurement system which could capture thousands of data points to create a 3D body contour that allows detailed measurement of a subject body, shown as Figure 3.22. It only takes six seconds to get one person scanned and less than thirty seconds for body mesh creation and measurement extraction. The scanning space is highly private, shown as Figure 3.23, and does not catch the visual appearance of the body to protect the privacy of participants.

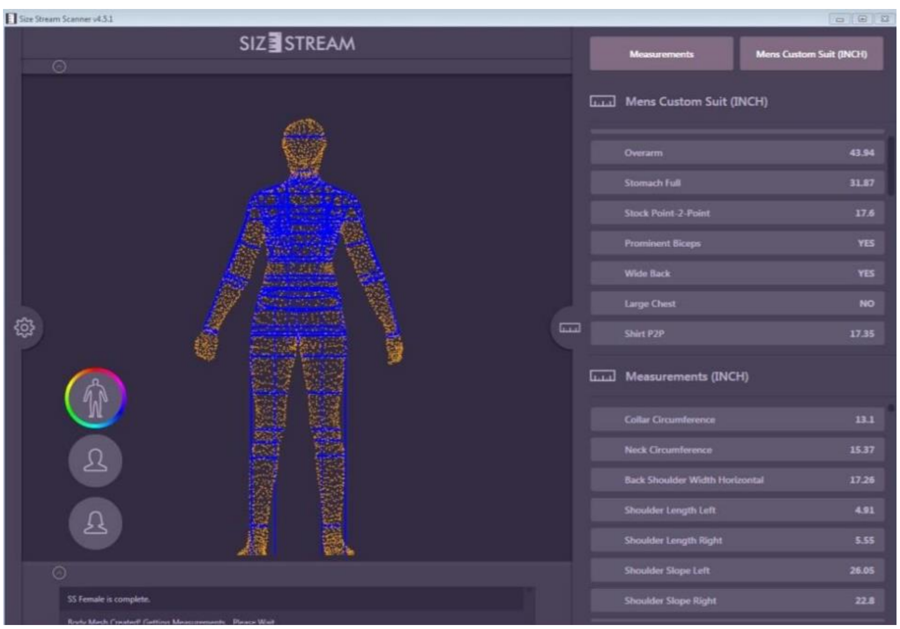


Figure 22. Size Stream system

Figure 23. Scanner booth (SS14 3D Body Scanner, 2016)

In order to expose the breast root, a self-adhesive tape was attached to the skin to lift the breast up slightly, shown in Figure 24. Keeping away from the breast root, the tape was stuck on the lower part of the breast. The breast would be lifted up by lifting two ends of the tape. When the breast root was completely exposed, attaching the tape to the skin, the breast could be kept as lifted.

Figure 24. Lift up breast

After creating the body mesh model, the scan file was opened in Geomagic Design X (3D Systems, Inc., Rock Hill, SC), a 3D image analysis software, to establish 3D underwire models (Figure 25). First of all, a horizontal reference plane was set at the position of bust point. The intersection points of the horizontal reference plane and breast root are the inner point and outer point of the customized underwire. Secondly, a 3D-shaped line, starting from the inner point and ending at the outer point, was drawn along the breast root on the body surface. Thirdly, according to the required dimension of the underwire, the width and thickness were further created. Besides, extending the length of 3D-shaped line from the outer position, three different underwires were developed; low, medium, and high. The outer end point moved up by 25.4 mm (1 inch) and 50.8 mm (2 inches) for the medium outer position underwire and high outer position underwire, respectively.

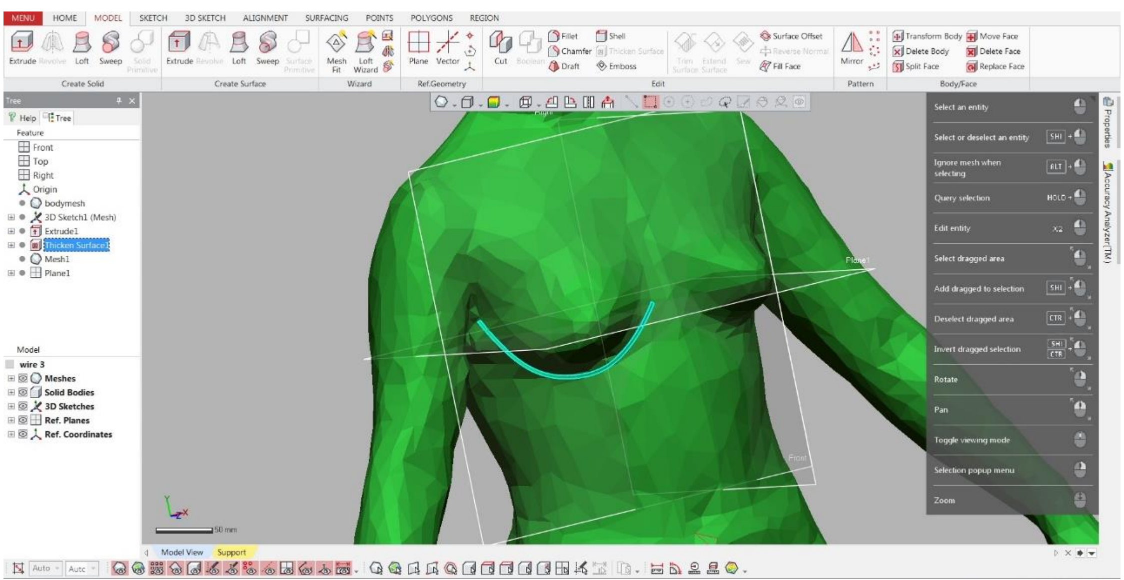
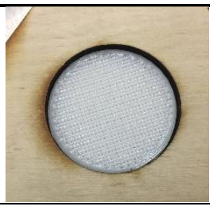


Figure 25. Geomagic Design X operation interface

3.2.4 3D Printed Underwire

Acrylonitrile Butadiene Styrene plus (ABSplus) was selected as a thermoplastic resin due to its relatively high flexibility and stability ("ABSplus", n.d.). Stratasys UPrint SE Plus (Stratasys Ltd., Eden Prairie, MN) was used for Fused Deposition Modeling, which is known for fast turnaround time. Printing density was another important decision to affect flexibility and stability of the printed wires. Three different levels of printing densities (solid, spare high, and sparse low) are summarized in Table 9.

Table 9. Printing Structures

Sample			
Density	Solid	Sparse high density	Sparse low density
flexibility	Low	Medium	High
stability	High	Medium	Low

The solid structure generally has high stability which could provide a long lifetime for an underwire, but its flexibility is limited, and this could result in a rigid touch. On the contrary, sparse low density has high flexibility, but might not be stable enough. Sparse high density structure could provide reasonable stability and flexibility. Considering that the underwire is fairly thin, the solid structure was still expected to provide good flexibility, while other two structures might have been too flexible to support breasts.

Therefore, the solid printing structure was chosen in this research.

3.2.5 Pressure measurement device

Pliance-x system (Novel, Munich Germany) is the pressure measurement device used in this research. It measures a dynamic pressure distribution based on capacitive sensors. Figure 3.26 shows the user interface for pressure measurement. Four colored squares at the left of the screen represent four pressure sensors each. Their colors represent the amount of peak pressure observed. Three diagrams at the right side show dynamic pressure changes over time, including peak pressure (kpa), force (N) and area (cm^2) from top to bottom.

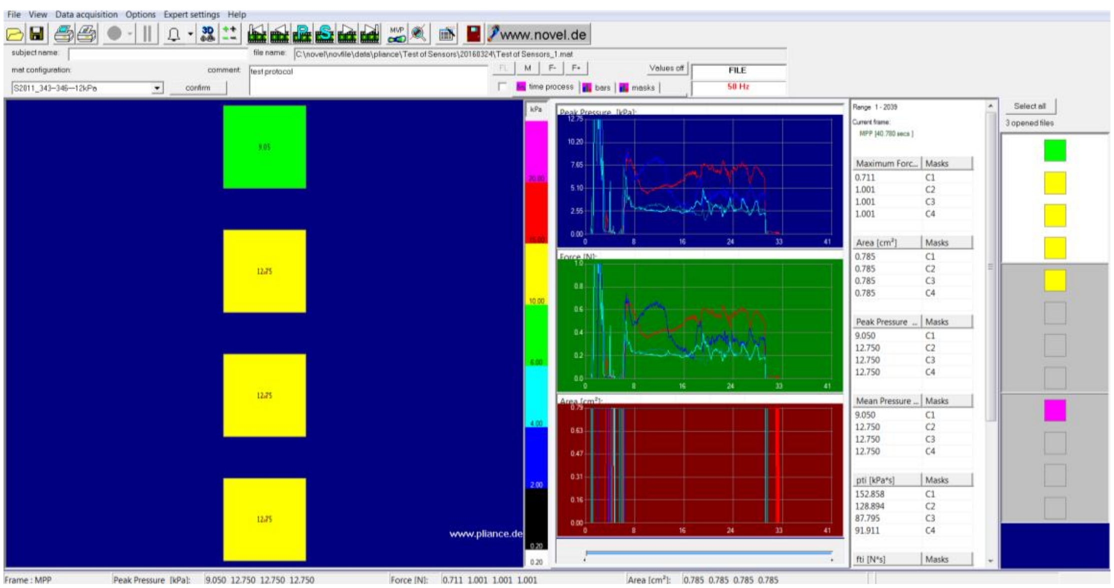


Figure 26. Novel pliance-x system

3.3 Experimental Design

3.3.1 Participants

This research invited twenty participants to do the body measurements and wear trials. In order to collect more representative and reliable results, participants were narrowed down to 18-25 year old females with the bra size of 34B or 34C, including their sister sizes, such as 36A, 32C, 36B or 32D.

Before a wear trial was administered, the use of human subjects in this research was approved by the Institutional Review Board (IRB) through North Carolina State University. Offline flyers were posted in college buildings and students apartments at the beginning of January 2017 to recruit participants. People who were willing to participate were encouraged to contact the researcher by email. All participants had to come twice; the first visit for body scanning and the second visit for wear trials. All participants were requested to sign the informed consent form before the experiments. A specific ID number was given to each participant to anonymize the participant information. During the entire research processes, only the ID number was used to recognize the participants.

3.3.2 Experimental Design I

Covering the first research question, the first step of this study was to analyze consumer's purchase habits and wearing sensations for a bra. A questionnaire was established and participants' responses were analyzed to answer the first research question.

There were two sections in the questionnaire. The first section was about the demographic information of participants, while the second section covered bra purchase habits and wearing sensations. Questions in both two sections were filled by participants.

3.3.3 Experimental Design II

Covering the second research question, the second set of experiments focused on the comparison of the comfort and support level between the conventional and the 3D printed underwires. As shown in Figure 3.9, the conventional underwire had its inner end at the same level to the bust point, and was 225.4mm long. In order to be consistent, the 3D printed underwire was intended to have the same inner end position and outer end position with the conventional underwire, and the cross-sectional shape was kept in 1mm in thickness and 3mm in width. The only difference between the conventional and 3D printed wires was the overall shape. However, according to the preliminary underwire samples, the 1mm thick underwire was too soft to be used as an underwire, so the thickness was increased to 2mm. The conventional underwire is a 2D flat wire in the pre-shaped curvature, while the 3D printed underwire is a three-dimensional, which conforms to the unique breast root shape of each individual.

3.3.4 Experimental Design III

In order to answer the third research questions, the third experimental design investigated the comfort and support level among experimental bras with different underwire length. Three kinds of underwire lengths were selected with low, medium and high outer end points. As shown in Figure 27, the short underwire has its outer end at the same horizontal level to the inner end, the medium length underwire is 25.4mm longer than the short one, and the longest underwire is 25.4mm longer than the medium length. Applying this length definition to the conventional underwire, it could be classified as a medium length underwire. The cross-sectional shape of these wires was kept to be 3mm thick and 3mm wide.

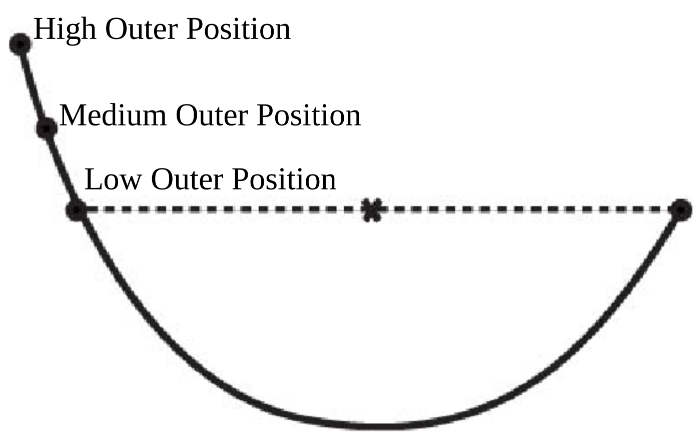


Figure 27. Three different underwire lengths

3.3.5 Experimental Design IV

In order to answer the fourth research questions, the fourth experimental design compared the comfort and support level among the experimental bras with different cross-sectional shapes. Two kinds of cross-sectional shapes were compared; the sagittal underwire is 2mm thick and 3mm wide (Figure 3.28) and the vertical underwire is 3mm thick and 2mm wide (Figure 29).

Figure 28. Sagittal underwire

Figure 29. Vertical underwire

Gathering the underwire demonstrated in experimental design II, III and IV, there are overall 6 underwires to be evaluated, including one conventional underwire and five customized underwires. Those five customized underwires were a 3 by 2 vertical underwire, a 2 by 3 sagittal underwire, a 3 by 3 low outer position underwire, a 3 by 3 medium outer position underwire, and a 3 by 3 high outer position underwire. Different types of experimental underwires are summarized in Figure 30.

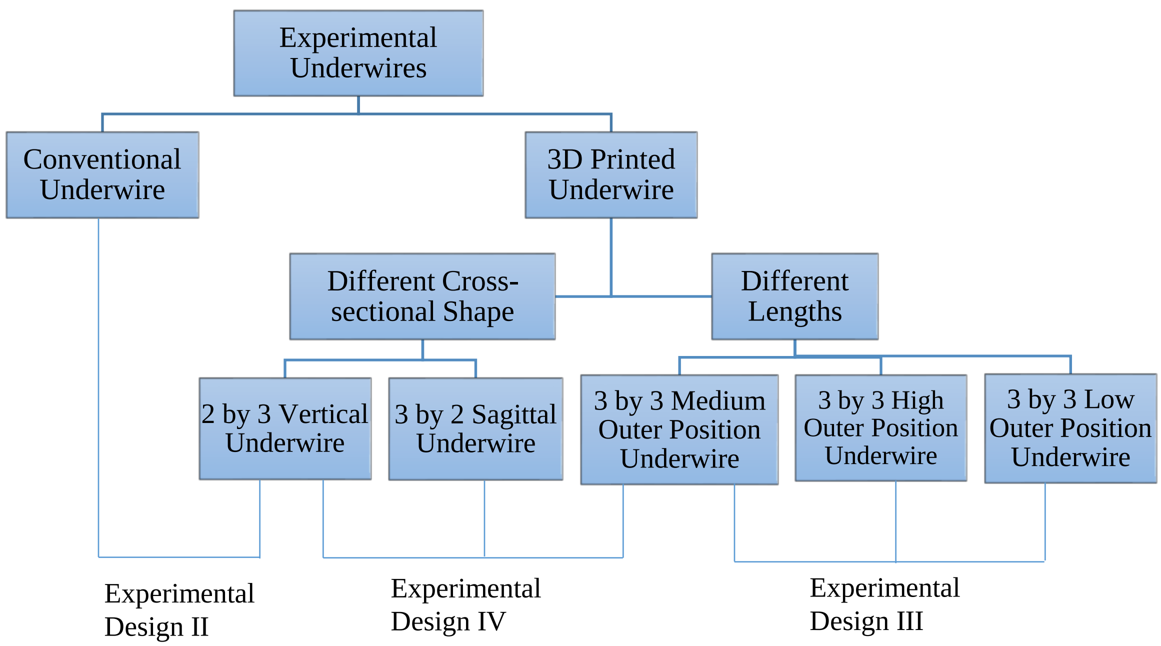


Figure 30. Experimental underwires category

3.4 Measurement

3.4.1 Questionnaire

Demographic information was asked, including age and ethnicity. Participants' answers reflected their preference for bra size, bra wearing habit and consumption pattern among people of different ages and ethnicities. The experiences of giving birth to a baby and breast-feeding were included because they might have influenced the breast shape and size.

The question about bra size reflected participants' knowledge of their bra size. The purchase channel of a bra, to some extent, showed consumer's cognition of bra size as well. Brand preference was measured by asking 3 brands to buy bras from most frequently. Bra purchasing frequency, lifetime and quantity were also investigated. The question of the most important influence factors when buying a bra reflected the key element when a designer develops a bra, including esthetics, comfort, support, shaping, fabrics, and other elements. Bra cup, strap, bands and underwire were compared by asking the main problems of a bra when throwing it away. The question of rating the comfort and support level with the underwire that participant wear aimed to investigate the main uncomfortable and unsupportable parts of the conventional underwire. An open-ended question of redesigning a bra was set to include more ideas and solve the existing problems. Consumer's acceptance level of customized underwire was also asked in the questionnaire.

In this research, a 5 Likert scale was adopted to analyze the comfort and support level of the experimental underwires. Scale 1 represents very uncomfortable or very low support and scale 5 represents very comfortable or very high support. The questionnaire was attached as an appendix.

3.4.2 Wear Trial

Pressure observation and subject evaluation are two methods used during the wear trials to measure the comfort and support level of experimental underwires. Pressure is the most quantified parameter to be measured and controlled when evaluating the comfort level. For accurate and precise measurements, it was necessary to restrict how the experimental bras were put on by each participant. In this research, participants were asked to rate the comfort and support level of each underwire, so the lengths of shoulder straps and underbands were adjusted to the participants' most comfortable status.

After adjusting the bra, four pressure sensors were inserted inside the experimental bra along the underwire to measure the pressure by the underwire. During the whole process of wear trial, in order to keep the bra under the same conditions, the experimental bra was only allowed to be adjusted at the beginning of the experiment. Four sensor positions were shown in Figure 31.

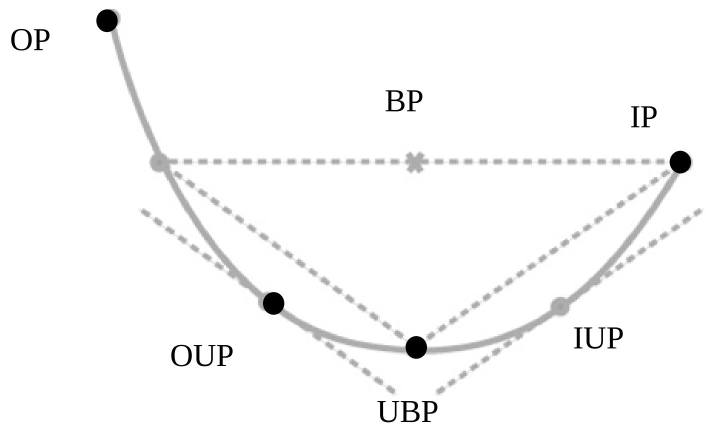


Figure 31. Pressure sensors position

The position IP was selected as an inner point, which was on the same horizontal line as bust point. The position OP was at the outermost point which varied depending on underwire lengths. Under breast point (UBP) was the lowest point of the underwire while the bra is on. After connecting IP and UBP with a straight line, the tangent line parallel to this line was found, and the point of contact was defined to be an inner underbust point (IUP). In the same way, the outer underbust point (OUP) was located at the lateral side. Since only four sensors were available, only IP, OP, UBP, and OUP were selected to measure the pressure (Figure 32).

Figure 32. Pressure measurement

Subjective evaluation is another method to score the comfort and support level of experimental underwires. While the experimental bra was on, the participant was asked to follow the predetermined actions to evaluate each underwire. These actions included raising arms to the chest (Figure 33), lifting arms over head (Figure 34), rotating upper body (Figure 35) and expanding the chest (Figure 36). When doing the pressure measurement and the subjective evaluation, the sequence of six experimental underwires were random. Researcher recorded the sequence of the underwires for each participants without letting them know. This design would minimized the influence from participants' subjective impression of each underwire.

Figure 33. Raise arm to chest

Figure 34. Lift arm over head

Figure 35.Rotate upper body

Figure 36. Expand chest

3.5 Data Analysis

For experimental design I, descriptive analysis such as means, mediums and modes were done. Means and mode were used to analyze bra purchase frequency, lifetime and quantity. A scatter plot can identify the type of correlation, if any, between two variables. For example, age and purchase habit, ethnicity and purchase habit, age and wearing experience, and ethnicity and wearing experience were compared using scatter plots. For the experimental design II, III, and IV, statistical models were developed to judge statistical significance. The one-way ANOVA and paired T-test were used to determine if significant difference would exist among six types of underwires.

CHAPTER IV: RESULT

4.1 Questionnaire results

4.1.1 Demographic information

Twenty female participants were included in this research. Their ages were from 18 to 25, while most of the participants were 22 years old and the average age was 21.4. Nine were Caucasian and eleven were Asian. None of them had ever given a birth to a baby or had breasting-feeding experience.

4.1.2 Bra size

Participants were asked to inform of their bra sizes, which was compared with their actual bra sizes acquired from the body scans. 95% of the participants believed that they knew their bra sizes, while only one participant reported that she had no idea about her size. However, there were obvious differences between the bra sizes reported by the participants and their actual bra sizes. Table 10 shows that none of the participants reported the actual size. 75% of the participants had smaller band sizes and larger cup sizes. 40% of the participants were wearing bras that were the sister size of their actual sizes.

4.1.3 Bra purchase habits

There was a significant ethnic difference about bra quantity that each participant owns. The Caucasian tended to own 3 to 5 bras while most of the Asian own 6 to 8 bras, shown in Table 11. Generally, a relatively high percentage of participants reported 6 to 8 bras. Regarding bra purchase channels, most people bought bras in offline stores due to its try-on convenience, while only 20% of the participants preferred online stores. As for bra purchase frequency and bra life time, the most common frequency to buy bras was every 6 to 12 months and 15 out of 20 participants used a bra for 1 to 2 years before throwing it away. The response distributions are shown in Figure 37 and 38.

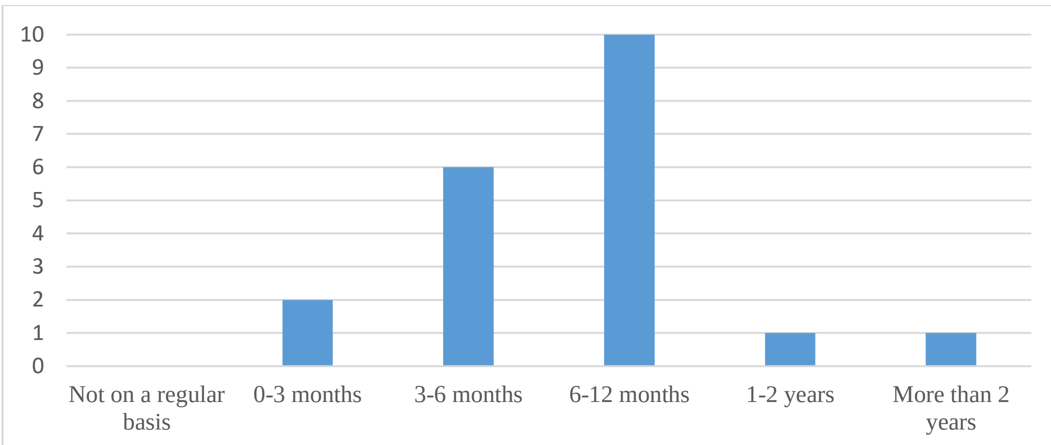


Figure 37. Bra purchase frequency

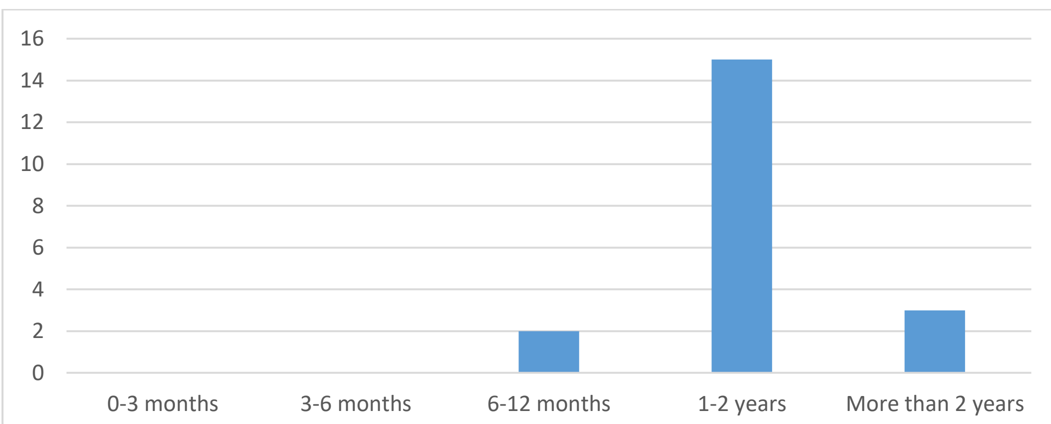


Figure 38. Bra life time

Table 10. Participants' reported bra sizes and actual bra sizes

Reported sizes	34B	34B	34C	34C	34B	32D	34B	32B	34C	34B	34C	34B	32C	34B	32D	32C	32B	34B	34B	N/A
Actual sizes	36A	38A	34B	34B	34A	34B	36B	38A	36B	34A	36B	36B	34B	36A	36B	34B	34B	36B	36A	34B

Table 11. Bra quantity by ethnicity

Bra Quantity / Ethnicity	Less than 3	3 - 5	6 - 8	More than 8	Total
Caucasian	0	5	2	2	9
Asian	0	1	7	3	11
Total	0	6	9	5	20

Comfort was chosen as the most important consideration when buying a bra, and appearance was ranked as the second important factor (Figure 39). What is worth mentioning that price was another factor which was not included on the list.

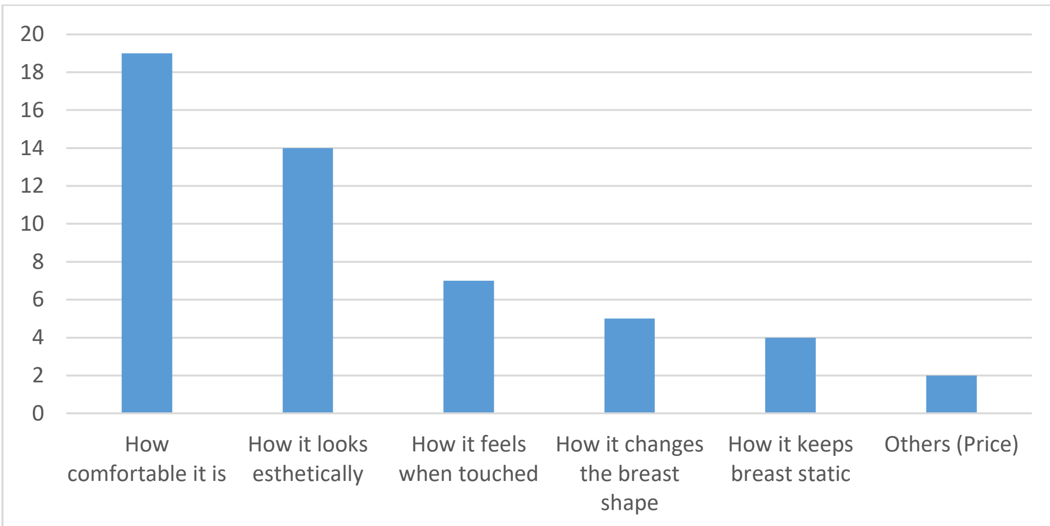


Figure 39. The most important factors when buying a bra

4.1.4 Brand preference

Overall seventeen brand names were mentioned for the preferred bra manufacturers, including Victoria's Secret, Macy's, Target, Candies, Wacoal, Jockey, Hanes, Triumph, Eve's Temptation, Aerie, Walmart, 6ixty8ight, Aimer, Calvin Klein, Costco, Imi's, and Embry's Form. A scoring system was employed to analyze the overall brand preference. For every participant, the brand listed for the first rank got three points, the brand for the second rank got two points, and the last brand got only one point. The total score of each brand from each participant was added up. The brand of the highest score was interpreted as the most preferred manufacturer. Using this method, Victoria's Secret got the obviously highest score of 32, which meant it is the most popular brand for these twenty participants (Figure 40).

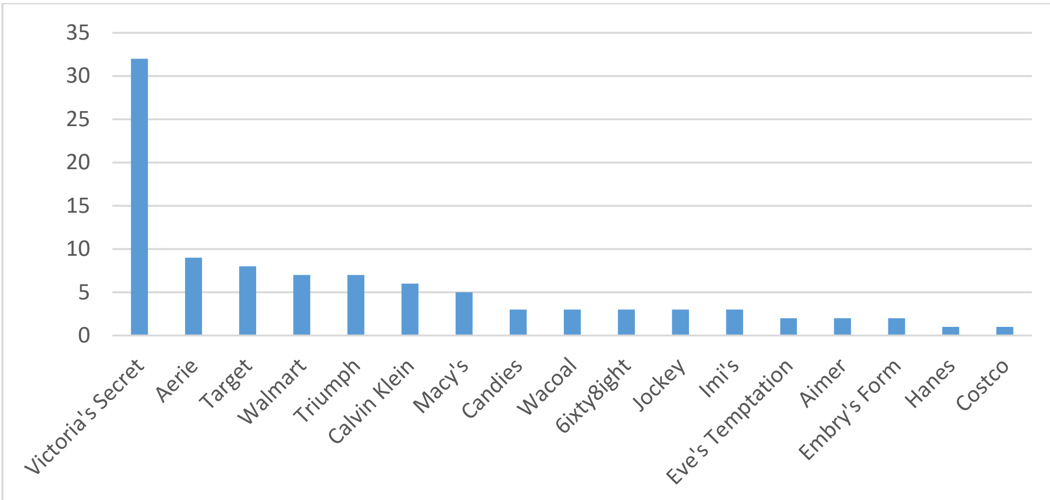


Figure 40. Brand preference

4.1.5 Bra wearing sensations

The main complaints against bras were straps becoming loose and sliding down and underwire becoming distorted; both problems received 70% of the votes. Nearly half of the participants answered that bra cups becoming loose were another defect of the bras. Bands becoming loose were problematic but not common, which only received 30% of the votes.

Table 12 and 13 described the subjective comfort and support ratings towards participants' own bra underwires. For comfort sensation, participants tended to show negative evaluation on IP and neutral attitude on the other measurement points. Their feeling of underwire support level was better than the comfort and the average rating was close to 4.0, which represented slightly high support. In general, participants felt worse comfort and support sensations on IP than the other points.

Table 12. Comfort rating description

	N	Minimum	Maximum	Average	Std. Deviation	Std. Error Mean
IP Comfort	19	1.00	5.00	2.6316	1.11607	1.246
UBP Comfort	19	2.00	5.00	3.3684	0.89508	0.801
OUP Comfort	19	1.00	5.00	3.4737	0.84119	0.708
OP Comfort	19	2.00	4.00	3.4737	0.61178	0.374
Overall Comfort	19	2.00	5.00	3.3158	0.74927	0.561

Table 13. Support rating description

	N	Minimum	Maximum	Average	Std. Deviation	Std. Error Mean
IP Support	19	1.00	5.00	3.5789	1.16980	1.368
UBP Support	19	2.00	5.00	4.1579	0.83421	0.696
OUP Support	19	3.00	5.00	4.2632	0.56195	0.316
OP Support	19	3.00	5.00	4.1053	0.56713	0.322
Overall Support	19	3.00	5.00	3.9474	0.62126	0.386

Regarding the suggestions to improve bras, 60% of the participants hoped to have a more comfortable bra in the aspects of underwires, fabrics and overall design. 45% of them emphasized that underwires should have been more comfortable and fitted. Under this circumstances, 90% of the participants indicated that they would like to have a customized underwire for bras, among which 83.3% were very likely to buy it.

4.2 Comparison between the conventional and customized underwire

A paired T-test was employed to test whether there is a significant difference in the support rating between the conventional underwire and the 3 by 2 vertical underwire. Between the conventional underwire and the 3 by 2 vertical underwire, the descriptive analysis (Table 14) indicated that participants gave higher support ratings for the 3 by 2 vertical underwire than the conventional underwire on all the measurement points. The conventional underwire was rated for about 3.5, while the rating of 3 by 3 vertical underwire was more than 4. The T-test results showed (Table 15) that there was a statistically significant difference in the support rating at all the measurement points, including IP (p=0.019), UBP (p=0.009), OUP (p<0.000), OP (p=0.031), and the overall comfort (p=0.002).

Table 14. Support rating of the conventional and the 3 by 2 vertical underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Support	Conventional	20	3.3500	1.2680	0.2835
	3 by 2 Vertical	20	4.0000	1.1239	0.2513
UBP Support	Conventional	20	3.8500	0.9333	0.2087
	3 by 2 Vertical	20	4.5500	0.6863	0.1535
OUP Support	Conventional	20	3.4500	1.0501	0.2348
	3 by 2 Vertical	20	4.3000	0.8645	0.1933
OP Support	Conventional	20	3.7500	0.8507	0.1902
	3 by 2 Vertical	20	4.1000	0.8522	0.1906
Overall Support	Conventional	20	3.6500	0.8751	0.1957
	3 by 2 Vertical	20	4.1500	0.7452	0.1666

Table 15. Paired T-test of support rating between the conventional and the 3 by 2 vertical underwires

Pair	Paired Differences					t	df	Sig.(2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
IP1 - IP2	-0.650	1.136	0.254	-1.182	-0.118	-2.557	19	**0.019***
UBP1 - UBP2	-0.700	1.080	0.241	-1.205	-0.194	-2.896	19	**0.009***
OUP1 - OUP2	-0.850	0.745	0.166	-1.198	-0.501	-5.101	19	**0.000***
OP1 - OP2	-0.350	0.670	0.150	-0.663	-0.036	-2.333	19	**0.031***
Overall1 - Overall2	-0.500	0.606	0.135	-0.784	-0.215	-3.684	19	**0.002***

Note: 1 and 2 in the first column represent the conventional underwire and the 3 by 2 vertical underwire respectively. * indicates the difference is significant at 0.05.

The comfort rating of IP, UBP, OUP, OP, and the overall comfort between the conventional underwire and the 3 by 2 vertical underwire was also analyzed by the paired T-test. The descriptive analysis (Table 16) showed that the rating of the 3 by 3 vertical underwire was higher than the conventional underwire for more than 0.6, which indicated that bra comfort could be dramatically improved by the customized underwire. The paired T-test results showed (Table 17) that there was a statistically significant difference in the comfort rating of all the measurement points, including IP (p=0.0081), UBP (p=0.0002), OUP (p=0.0033), OP (p=0.0089), and the overall comfort (p=0.0011).

Table 16. Comfort rating of the conventional and the 3 by 2 vertical underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Comfort	Conventional	20	3.6000	0.8208	0.1835
	3 by 2 Vertical	20	4.3500	0.8751	0.1957
UBP Comfort	Conventional	20	3.3500	0.7452	0.1666
	3 by 2 Vertical	20	4.3000	0.7327	0.1638
OUP Comfort	Conventional	20	3.7000	0.7327	0.1638
	3 by 2 Vertical	20	4.4000	0.6806	0.1522

Table 16 Continued

OP Comfort	Conventional	20	3.8000	0.7678	0.1717
	3 by 2 Vertical	20	4.4000	0.5982	0.1338
Overall Comfort	Conventional	20	3.7000	0.5712	0.1277
	3 by 2 Vertical	20	4.3500	0.5871	0.1313

Table 17. Paired T-test of comfort rating between the conventional and the 3 by 2 vertical underwires

Pair	Paired Differences					t	df	Sig.(2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
IP1 - IP2	-0.75	1.0195	0.2279	-1.2271	-0.2728	-3.29	19	**0.004***
UBP1 - UBP2	-0.95	1.0500	0.2348	-1.4414	-0.4585	-4.05	19	**0.001***
OUP1 - OUP2	-0.7	0.9787	0.2188	-1.1580	-0.2419	-3.20	19	**0.005***
OP1 - OP2	-0.6	0.8207	0.1835	-0.9841	-0.2158	-3.27	19	**0.004***
Overall1 -	-0.7	0.9233	0.2064	-1.1321	-0.2678	-3.39	19	**0.003***

Note: 1 and 2 in the first column represent the conventional underwire and the 3 by 2 vertical underwire respectively. * indicates the difference is significant at 0.05.

Pressure measurements were also analyzed by the paired T-test in testing whether there was a significant difference in IP, UBP, OUP, OP, and the total pressure between the conventional underwire and the 3 by 2 vertical underwire. The descriptive analysis (Table 18) indicated that lower pressure was observed on IP and UBP of the 3 by 2 vertical underwire, but on OUP and OP, the pressure of the conventional underwire was lower. As shown in Table 19, there was a significant pressure difference only on IP ($p = 0.001$), UBP ($p = 0.009$), and the total pressure ($p = 0.003$). However, no significant difference was found on the measurement points of OUP and OP.

Table 18. Pressure on the conventional and the 3 by 2 vertical underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Pressure	Conventional	20	1.5550	0.9297	0.2079
	3 by 2 Vertical	20	0.8150	0.8349	0.1867
UBP Pressure	Conventional	20	6.8450	3.2250	0.7211
	3 by 2 Vertical	20	5.5017	2.7361	0.6118
OUP Pressure	Conventional	20	4.4517	2.7214	0.6085
	3 by 2 Vertical	20	3.5517	2.3945	0.5354
OP Pressure	Conventional	20	1.7233	0.9383	0.2098
	3 by 2 Vertical	20	2.0233	2.6234	0.5866
Total Pressure	Conventional	20	14.5750	4.4590	0.9971
	3 by 2 Vertical	20	11.8917	5.3938	1.2061

Table 19. Paired T-test of pressure measurement between the conventional and the 3 by 2 vertical underwires

Pair	Paired Differences					t	df	Sig.(2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
IP1 - IP2	0.740	0.861	0.192	0.337	1.143	3.843	19	**0.001***
UBP1 - UBP2	1.343	2.078	0.464	0.370	2.315	2.891	19	**0.009***
OUP1 - OUP2	0.900	2.272	0.508	-0.163	1.963	1.771	19	0.093
OP1 - OP2	-0.300	2.630	0.588	-1.531	0.931	-0.510	19	0.616
Total1 - Total2	2.683	3.473	0.776	1.057	4.309	3.455	19	**0.003***

Note: 1 and 2 in the first column represent the conventional underwire and the 3 by 2 vertical underwire respectively. * indicates the difference is significant at 0.05.

Pressure distribution was another evaluation factor which was based on the pressure measurement. Each points had the pressure percentage of the total pressure, and this reflected that how the pressure was distributed along the underwire. The conventional wire had higher load on IP and OUP than the 3 by 2 vertical wire, but lower load on UBP and OP (Table 20). In general, there was about 46% of total pressure loaded on UBP, and 29% on OUP. Only 9% and 14% of total pressure was measured on IP and OP. The data were analyzed by paired T-test, and the result (Table 21) showed that no significant different existed between the conventional underwire and the 3 by 2 vertical underwire.

Table 20. Pressure distribution between the conventional and the 3 by 2 vertical underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP	Conventional	20	0.116	0.080	0.018
	3 by 2 Vertical	20	0.078	0.085	0.019
UBP	Conventional	20	0.458	0.153	0.034
	3 by 2 Vertical	20	0.479	0.133	0.030
OUP	Conventional	20	0.295	0.120	0.027
	3 by 2 Vertical	20	0.289	0.099	0.022
OP	Conventional	20	0.133	0.089	0.020
	3 by 2 Vertical	20	0.153	0.114	0.026

Table 21. Paired T-test of pressure distribution between the conventional and the 3 by 2 vertical underwires

Pair	Paired Differences					t	df	Sig.(2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
IP[1] - IP[2]	0.037	0.082	0.018	-0.001	0.076	2.011	19	0.059
UBP1 - UBP2	-0.020	0.141	0.031	-0.087	0.045	-0.657	19	0.519
OUP1 - OUP2	0.006	0.124	0.027	-0.052	0.064	0.225	19	0.824
OP1 - OP2	-0.020	0.134	0.030	-0.083	0.042	-0.687	19	0.500

Note: 1 and 2 in the first column represent the conventional underwire and the 3 by 2 vertical underwire respectively.

4.3 Comparison between underwires of different underwire lengths

Customized underwires with three different lengths were compared in this research. As described in Figure 27, the shortest wire had an outer point as low as the level of bust point, and this outer point was extended by 25.4mm and 50.8mm to acquire medium and high outer points. Descriptive analysis (Table 22) show that IP had the lowest support rating among all the measurement points, and UBP had the highest rating. Adopting the one-way ANOVA, a statistically significant difference on support sensation was proven only on OUP ($p = 0.0359$) (Table 23), and the post hoc test are shown in Table 24. For OUP, participants felt the most support with the 3 by 3 high outer end underwire and least support with the 3 by 3 medium outer end underwire. However, significant difference was found only between the longest wire and the medium length one. No significant difference was found between different wire lengths on the other measurement points.

Table 22. Support rating of the 3 by 3 low, medium, and high outer end underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Support	Low outer end	20	3.7000	1.0311	0.2306
	Medium outer end	20	3.8000	1.1517	0.2575
	High outer end	20	3.6500	1.1367	0.2542
	Total	60	3.7167	1.0907	0.1408
UBP Support	Low outer end	20	4.5500	0.5104	0.1141
	Medium outer end	20	4.2000	1.0563	0.2362
	High outer end	20	4.6000	0.5026	0.1124
	Total	60	4.4500	0.7462	0.0963
OUP Support	Low outer end	20	4.3500	0.4894	0.1094
	Medium outer end	20	4.0000	1.0260	0.2294
	High outer end	20	4.6000	0.5026	0.1124
	Total	60	4.3167	0.7477	0.0965
OP Support	Low outer end	20	4.0000	0.7255	0.1622
	Medium outer end	20	4.0500	0.7592	0.1698

Table 22 Continued

	High outer end	20	4.1000	1.0208	0.2283
	Total	60	4.0500	0.8321	0.1074
Overall Support	Low outer end	20	4.1000	0.5525	0.1235
	Medium outer end	20	3.9500	0.8256	0.1846
	High outer end	20	4.3500	0.7452	0.1666
	Total	60	4.1333	0.7241	0.0935

Table 23. One-way ANOVA of support rating among the 3 by 3 low, medium, and high outer end underwires

		Sum of squares	df	Mean square	F	Sig.
IP Support	Between groups	0.2333	2.0000	0.1167	0.0951	0.9095
	Within groups	69.9500	57.0000	1.2272		
	Total	70.1833	59.0000			
UBP Support	Between groups	1.9000	2.0000	0.9500	1.7496	0.1831
	Within groups	30.9500	57.0000	0.5430		
	Total	32.8500	59.0000			
OUP Support	Between groups	3.6333	2.0000	1.8167	3.5281	**0.0359***
	Within groups	29.3500	57.0000	0.5149		
	Total	32.9833	59.0000			
OP Support	Between groups	0.1000	2.0000	0.0500	0.0699	0.9325
	Within groups	40.7500	57.0000	0.7149		
	Total	40.8500	59.0000			
Overall Support	Between groups	1.6333	2.0000	0.8167	1.5887	0.2131
	Within groups	29.3000	57.0000	0.5140		
	Total	30.9333	59.0000			

Note: * indicates the difference is significant at 0.05.

Table 24. Post Hoc Test of the support rating among the 3 by 3 low, medium, and high outer end underwires

	Underwire (I)	Underwire (J)	Mean Difference (I-J)	Std. Error	Sig.
OUP Support	Low	Medium	0.3500	0.2269	0.1285
	Low	High	-0.2500	0.2269	0.2752
	Medium	High	**-0.60000**	0.2269	**0.0106***

Note: * indicates the difference is significant at 0.05.

The comfort rating of the three different lengths underwires were analyzed by one-way ANOVA. The descriptive analysis (table 25) showed that the comfort rating seemed increased as the length of the underwire became shorter. However, according to the ANOVA results (Table 26), no significant difference was found on all measurement points. Therefore, there was no significant difference among different lengths underwires in terms of comfort.

Table 25. Comfort rating of the 3 by 3 low, medium, and high outer end underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Comfort	Low outer end	20	4.4000	0.7539	0.1686
	Medium outer end	20	4.2500	0.8507	0.1902
	High outer end	20	4.0500	0.9445	0.2112
	Total	60	4.2333	0.8511	0.1099
UBP Comfort	Low outer end	20	4.4500	0.6048	0.1352
	Medium outer end	20	4.1500	0.7452	0.1666
	High outer end	20	3.9500	0.7592	0.1698
	Total	60	4.1833	0.7247	0.0936
OUP Comfort	Low outer end	20	4.4000	0.5982	0.1338
	Medium outer end	20	4.0000	0.9177	0.2052
	High outer end	20	4.0500	0.7592	0.1698
	Total	60	4.1500	0.7773	0.1004
OP Comfort	Low outer end	20	4.3000	0.9234	0.2065
	Medium outer end	20	4.1000	0.7182	0.1606
	High outer end	20	3.7000	0.8645	0.1933
	Total	60	4.0333	0.8629	0.1114
Overall Comfort	Low outer end	20	4.3500	0.5871	0.1313
	Medium outer end	20	3.9500	0.6863	0.1535
	High outer end	20	3.9500	0.6048	0.1352
	Total	60	4.0833	0.6455	0.0833

Table 26. One-way ANOVA of comfort rating among the 3 by 3 low, medium, and high outer end underwires

		Sum of squares	df	Mean square	F	Sig.
IP Comfort	Between groups	1.2333	2.0000	0.6167	0.8470	0.4340
	Within groups	41.5000	57.0000	0.7281		
	Total	42.7333	59.0000			
UBP Comfort	Between groups	2.5333	2.0000	1.2667	2.5378	0.0879
	Within groups	28.4500	57.0000	0.4991		
	Total	30.9833	59.0000			
OUP Comfort	Between groups	1.9000	2.0000	0.9500	1.6044	0.2099
	Within groups	33.7500	57.0000	0.5921		
	Total	35.6500	59.0000			
OP Comfort	Between groups	3.7333	2.0000	1.8667	2.6468	0.0796
	Within groups	40.2000	57.0000	0.7053		
	Total	43.9333	59.0000			
Overall Comfort	Between groups	2.1333	2.0000	1.0667	2.7082	0.0752
	Within groups	22.4500	57.0000	0.3939		
	Total	24.5833	59.0000			

Regarding the pressure, there was less than 1 kPa measured on IP and slightly more pressure was on OP. Most pressure was being loaded on UBP as high as 7 kPa (Table 27). One-way ANOVA of pressure measurement (Table 28) showed that only OP (p=0.0066) had significant difference among different underwires. Post Hoc Test (Table 29) demonstrated that the pressure on OP gradually increased as the underwire length became longer. The low outer end underwire and the medium outer end underwire had significantly lower pressure than the long underwie.

Table 27. Pressure on the 3 by 3 low, medium, and high outer end underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Pressure	Low outer end	20	0.8333	0.7676	0.1716
	Medium outer end	20	0.7867	0.8441	0.1888
	High outer end	20	0.8200	0.8064	0.1803

Table 27 Continued

	Total	60	0.8133	0.7931	0.1024
UBP Pressure	Low outer end	20	6.9267	3.5053	0.7838
	Medium outer end	20	7.2100	2.9656	0.6631
	High outer end	20	7.7217	3.8325	0.8570
	Total	60	7.2861	3.4102	0.4402
OUP Pressure	Low outer end	20	3.7633	1.9622	0.4388
	Medium outer end	20	3.6667	2.2897	0.5120
	High outer end	20	3.8433	1.8296	0.4091
	Total	60	3.7578	2.0029	0.2586
OP Pressure	Low outer end	20	1.2567	0.6957	0.1556
	Medium outer end	20	1.4333	0.9056	0.2025
	High outer end	20	2.5133	1.9358	0.4329
	Total	60	1.7344	1.3930	0.1798
Total Pressure	Low outer end	20	12.7800	4.9423	1.1051
	Medium outer end	20	13.0967	3.8146	0.8530
	High outer end	20	14.8983	5.8131	1.2999
	Total	60	13.5917	4.9315	0.6367

Table 28.One-way ANOVA of pressure measurement among the 3 by 3 low, medium, and high outer end underwires

		Sum of squares	df	Mean square	F	Sig.
IP Pressure	Between groups	0.0231	2.0000	0.0116	0.0178	0.9824
	Within groups	37.0884	57.0000	0.6507		
	Total	37.1116	59.0000			
UBP Pressure	Between groups	6.4940	2.0000	3.2470	0.2723	0.7626
	Within groups	679.6288	57.0000	11.9233		
	Total	686.1229	59.0000			
OUP Pressure	Between groups	0.3130	2.0000	0.1565	0.0377	0.9630
	Within groups	236.3644	57.0000	4.1467		
	Total	236.6775	59.0000			
OP Pressure	Between groups	18.5121	2.0000	9.2561	5.4970	**0.0066***
	Within groups	95.9789	57.0000	1.6838		
	Total	114.4910	59.0000			
Total Pressure	Between groups	52.2241	2.0000	26.1121	1.0765	0.3476
	Within groups	1382.6328	57.0000	24.2567		
	Total	1434.8569	59.0000			

Note: * indicates the difference is significant at 0.05.

Table 29. Post Hoc Test of the pressure measurement among the 3 by 3 low, medium, and high outer end underwires

	Underwire (I)	Underwire (J)	Mean Difference (I-J)	Std. Error	Sig.
OP Pressure	Low	Medium	-0.17667	0.41035	0.668
	Low	High	**-1.25667**	0.41035	**0.003***
	Medium	High	**-1.08000**	0.41035	**0.011***

Note: * indicates the difference is significant at 0.05.

In terms of pressure distribution, IP still had the lowest load while UBP had the highest load (Table 30). One-way ANOVA (Table 31) showed that only OP (p=0.036) had significant difference in pressure distribution among underwires with different lengths. The Post Hoc Test (Table 32) demonstrated that the pressure percentage distributed on OP was lower on the short and medium underwire than the long one. On the other measurement points, the pressure was distributed more on the shorter underwire, but it was not significantly different.

Table 30. Pressure distribution of the 3 by 3 low, medium, and high outer end underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP	Low outer end	20	0.069	0.063	0.014
	Medium outer end	20	0.068	0.078	0.017
	High outer end	20	0.051	0.048	0.011
	Total	60	0.062	0.064	0.008
UBP	Low outer end	20	0.535	0.137	0.031
	Medium outer end	20	0.548	0.141	0.032
	High outer end	20	0.502	0.132	0.029
	Total	60	0.528	0.136	0.018
OUP	Low outer end	20	0.289	0.116	0.026
	Medium outer end	20	0.271	0.120	0.027
	High outer end	20	0.267	0.106	0.024
	Total	60	0.276	0.113	0.015
OP	Low outer end	20	0.107	0.061	0.014

Table 30 Continued

	Medium outer end	20	0.113	0.069	0.016
	High outer end	20	0.180	0.139	0.031
	Total	60	0.133	0.100	0.013

Table 31. One-way ANOVA of pressure distribution among the 3 by 3 low, medium, and high outer end underwires

		Sum of squares	df	Mean square	F	Sig.
IP	Between groups	0.004	2.000	0.002	0.474	0.625
	Within groups	0.236	57.000	0.004		
	Total	0.240	59.000			
UBP	Between groups	0.023	2.000	0.011	0.606	0.549
	Within groups	1.064	57.000	0.019		
	Total	1.086	59.000			
OUP	Between groups	0.006	2.000	0.003	0.220	0.803
	Within groups	0.742	57.000	0.013		
	Total	0.748	59.000			
OP	Between groups	0.065	2.000	0.033	3.521	**0.036***
	Within groups	0.530	57.000	0.009		
	Total	0.595	59.000			

Note: * indicates the difference is significant at 0.05.

Table 32. Post Hoc Test of the pressure distribution among the 3 by 3 low, medium, and high outer end underwires

	Underwire (I)	Underwire (J)	Mean Difference (I-J)	Std. Error	Sig.
OP Pressure	Low	Medium	-0.006	0.030	0.852
	Low	High	**-0.073**	0.030	**0.020***
	Medium	High	**-0.067**	0.030	**0.032***

Note: * indicates the difference is significant at 0.05.

4.4 Comparison between underwires of different cross-sectional shapes

The underwires with different cross-sectional shapes were compared in this research, which were a vertical (3 by 2) underwire, and a sagittal (2 by 3) underwire. A square (3 by 3) underwire was also included to help the comparison. The vertical underwire tended to get higher rating regarding support and the sagittal underwire received obviously higher rate than the other two types of underwires (Table 33). However, statistical analysis showed that no significant difference existed in terms of support rating (Table 34 and 35), comfort rating (Table 36 and 37), pressure measurement (Table 38 and 39), and pressure distribution (Table 40) on every measurement points.

Table 33. Support rating of the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Support	Vertical	20	4.0000	1.1239	0.2513
	Sagittal	20	3.7000	0.9234	0.2065
	Square	20	3.7000	1.0311	0.2306
	Total	60	3.8000	1.0218	0.1319
UBP Support	Vertical	20	4.5500	0.6863	0.1535
	Sagittal	20	4.3500	0.7452	0.1666
	Square	20	4.5500	0.5104	0.1141
	Total	60	4.4833	0.6507	0.0840
OUP Support	Vertical	20	4.3000	0.8645	0.1933
	Sagittal	20	4.2000	0.6156	0.1376
	Square	20	4.3500	0.4894	0.1094
	Total	60	4.2833	0.6662	0.0860
OP Support	Vertical	20	4.1000	0.8522	0.1906
	Sagittal	20	3.9500	0.9445	0.2112
	Square	20	4.0000	0.7255	0.1622
	Total	60	4.0167	0.8334	0.1076
Overall Support	Vertical	20	4.1500	0.7452	0.1666
	Sagittal	20	4.0000	0.6489	0.1451
	Square	20	4.1000	0.5525	0.1235
	Total	60	4.0833	0.6455	0.0833

Table 34. One-way ANOVA of support rating among the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

		Sum of squares	df	Mean square	F	Sig.
IP Support	Between groups	1.2000	2.0000	0.6000	0.5662	0.5708
	Within groups	60.4000	57.0000	1.0596		
	Total	61.6000	59.0000			
UBP Support	Between groups	0.5333	2.0000	0.2667	0.6217	0.5406
	Within groups	24.4500	57.0000	0.4289		
	Total	24.9833	59.0000			
OUP Support	Between groups	0.2333	2.0000	0.1167	0.2563	0.7748
	Within groups	25.9500	57.0000	0.4553		
	Total	26.1833	59.0000			
OP Support	Between groups	0.2333	2.0000	0.1167	0.1632	0.8498
	Within groups	40.7500	57.0000	0.7149		
	Total	40.9833	59.0000			
Overall Support	Between groups	0.2333	2.0000	0.1167	0.2731	0.7620
	Within groups	24.3500	57.0000	0.4272		
	Total	24.5833	59.0000			

Table 35. Comfort rating of the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Comfort	Vertical	20	4.3500	0.8751	0.1957
	Sagittal	20	4.6000	0.6806	0.1522
	Square	20	4.4000	0.7539	0.1686
	Total	60	4.4500	0.7686	0.0992
UBP Comfort	Vertical	20	4.3000	0.7327	0.1638
	Sagittal	20	4.5500	0.8256	0.1846
	Square	20	4.4500	0.6048	0.1352
	Total	60	4.4333	0.7217	0.0932
OUP Comfort	Vertical	20	4.4000	0.6806	0.1522
	Sagittal	20	4.5500	0.6863	0.1535
	Square	20	4.4000	0.5982	0.1338
	Total	60	4.4500	0.6490	0.0838
OP Comfort	Vertical	20	4.4000	0.5982	0.1338
	Sagittal	20	4.6000	0.5982	0.1338
	Square	20	4.3000	0.9234	0.2065
	Total	60	4.4333	0.7217	0.0932

Table 35 Continued

Overall Comfort	Vertical	20	4.3500	0.5871	0.1313
	Sagittal	20	4.5500	0.6863	0.1535
	Square	20	4.3500	0.5871	0.1313
	Total	60	4.4167	0.6187	0.0799

Table 36. One-way ANOVA of comfort rating among the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

		Sum of squares	df	Mean square	F	Sig.
IP Comfort	Between groups	0.7000	2.0000	0.3500	0.5842	0.5609
	Within groups	34.1500	57.0000	0.5991		
	Total	34.8500	59.0000			
UBP Comfort	Between groups	0.6333	2.0000	0.3167	0.5997	0.5524
	Within groups	30.1000	57.0000	0.5281		
	Total	30.7333	59.0000			
OUP Comfort	Between groups	0.3000	2.0000	0.1500	0.3483	0.7074
	Within groups	24.5500	57.0000	0.4307		
	Total	24.8500	59.0000			
OP Comfort	Between groups	0.9333	2.0000	0.4667	0.8926	0.4152
	Within groups	29.8000	57.0000	0.5228		
	Total	30.7333	59.0000			
Overall Comfort	Between groups	0.5333	2.0000	0.2667	0.6893	0.5060
	Within groups	22.0500	57.0000	0.3868		
	Total	22.5833	59.0000			

Table 37. Pressure measurement of the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP Pressure	Vertical	20	0.8150	0.8349	0.1867
	Sagittal	20	0.6317	0.8418	0.1882
	Square	20	0.8333	0.7676	0.1716
	Total	60	0.7600	0.8068	0.1042
UBP Pressure	Vertical	20	5.5017	2.7361	0.6118
	Sagittal	20	5.8667	3.3228	0.7430
	Square	20	6.9267	3.5053	0.7838
	Total	60	6.0983	3.2086	0.4142

Table 37 Continued

OUP Pressure	Vertical	20	3.5517	2.3945	0.5354
	Sagittal	20	3.7333	3.0391	0.6796
	Square	20	3.7633	1.9622	0.4388
	Total	60	3.6828	2.4636	0.3181
OP Pressure	Vertical	20	2.0233	2.6234	0.5866
	Sagittal	20	1.7900	2.0580	0.4602
	Square	20	1.2567	0.6957	0.1556
	Total	60	1.6900	1.9598	0.2530
Total Pressure	Vertical	20	11.8917	5.3938	1.2061
	Sagittal	20	12.0217	6.4609	1.4447
	Square	20	12.7800	4.9423	1.1051
	Total	60	12.2311	5.5528	0.7169

Table 38. One-way ANOVA of the pressure measurement among the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

		Sum of squares	df	Mean square	F	Sig.
IP Pressure	Between groups	0.4974	2.0000	0.2487	0.3740	0.6896
	Within groups	37.9043	57.0000	0.6650		
	Total	38.4018	59.0000			
UBP Pressure	Between groups	21.9163	2.0000	10.9582	1.0668	0.3509
	Within groups	585.4846	57.0000	10.2717		
	Total	607.4009	59.0000			
OUP Pressure	Between groups	0.5247	2.0000	0.2624	0.0418	0.9591
	Within groups	357.5764	57.0000	6.2733		
	Total	358.1011	59.0000			
OP Pressure	Between groups	6.1778	2.0000	3.0889	0.7988	0.4549
	Within groups	220.4229	57.0000	3.8671		
	Total	226.6007	59.0000			
Total Pressure	Between groups	9.2074	2.0000	4.6037	0.1450	0.8654
	Within groups	1809.9990	57.0000	31.7544		
	Total	1819.2064	59.0000			

Table 39. Pressure distribution of the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

	Underwire	N	Mean	Std. Deviation	Std. Error Mean
IP	Vertical	20	0.078	0.085	0.019
	Sagittal	20	0.054	0.073	0.016
	Square	20	0.069	0.063	0.014
	Total	60	0.067	0.074	0.010
UBP	Vertical	20	0.479	0.133	0.030
	Sagittal	20	0.510	0.138	0.031
	Square	20	0.535	0.137	0.031
	Total	60	0.508	0.136	0.017
OUP	Vertical	20	0.289	0.099	0.022
	Sagittal	20	0.295	0.109	0.024
	Square	20	0.289	0.116	0.026
	Total	60	0.291	0.106	0.014
OP	Vertical	20	0.153	0.114	0.026
	Sagittal	20	0.141	0.080	0.018
	Square	20	0.107	0.061	0.014
	Total	60	0.134	0.089	0.011

Table 40. One-way ANOVA of the pressure measurement among the vertical (3 by 2), and the sagittal (2 by 3), and the square (3 by 3) underwires

		Sum of squares	df	Mean square	F	Sig.
IP	Between groups	0.006	2.000	0.003	0.547	0.582
	Within groups	0.315	57.000	0.006		
	Total	0.321	59.000			
UBP	Between groups	0.031	2.000	0.015	0.836	0.439
	Within groups	1.053	57.000	0.018		
	Total	1.084	59.000			
OUP	Between groups	0.000	2.000	0.000	0.017	0.983
	Within groups	0.666	57.000	0.012		
	Total	0.667	59.000			
OP	Between groups	0.023	2.000	0.011	1.461	0.240
	Within groups	0.440	57.000	0.008		
	Total	0.463	59.000			

CHAPTER V: DISCUSSTION AND CONCLUSION, LIMITATION AND FUTURE STUDY

A bra underwire plays an important role in breast support, especially for large breasts. However, it is also one of the major causes of discomfort while the bra is on. This research came up with the idea to customize bra underwires using 3D scanning and printing technology, aiming at solving the discomfort problem and improving breast support. Questionnaires and wear trials were done to answer four research questions. A survey was designed to investigate the bra purchase habits and wearing experience. Five 3D printed underwires, covering different lengths and cross-sectional shapes, were produced and compared with the conventional underwire through wear trials, in terms of the pressure measurement and the subjective rating. Statistical models were employed to analyze the significant difference of comfort and support. The result of the study was discussed in this chapter.

5.1 Questionnaires

Survey results showed that none of the participants reported the actual size, which brought about negative responses regarding bra wearing sensations. As a consumer, participants had a rare knowledge of bra size. Since the breast is individually shaped, most participants preferred off-line stores in order to try on the bras. According to the literature (Manning, 2014), because of the wrong method to wear a bra, they could not buy a bra with the correct size. In fact, many underwear brands provide bra size measurement services. Fitting guides help to measure the breast size and give bra size suggestions and the instructional flyer is often posted on the wall in the fitting room, so consumers should follow the instruction to find the correct size. However, the primary causes of the underwire discomfort comes from the bra sizing and the underwire design. Form the aspect of the bra, demonstrated in the literature review, no bra sizing system or manufacturing standard is agreed by different brands and manufacturers, so consumers may wear bras with different sizes and an underwire with wrong size may cause discomfort. Additionally, from the aspect of underwire itself, the structure or material may be unscientific. Breast root shape and position vary from person to person, while underwires are only categorized into limited sizes. An unfitted underwire will result in severe discomfort, which is reflected in the survey result. The 3D printed underwire is customized based on the breast root shape, which is supposed to provide comfort to the maximum extent. Its market acceptance is reflected in the survey result.

5.2 Differences between the conventional underwire and the customized underwire

A 3 by 2 vertical underwire was designed to be compared with the conventional underwire since they had the same length and comparable cross-sectional shape. The conventional underwire was a 2D underwire made of steel which was relatively rigid, while the customized underwire was 3D-printed according to the individual breast root shapes and made of ABSplus, which was more flexible.

The experimental data proved that the 3 by 2 vertical underwire performed better than the conventional wire in a few aspects. From the aspect of pressure, the customized underwire put significantly less pressure on IP and UBP than the conventional underwire, and total pressure was also significantly low with customized underwire. As for OUP, the pressure was less on the customized underwire than the conventional one even though the difference was not significant. Only OP got more pressure from the customized underwire than the conventional underwire. It could be concluded that the shape of customized underwire was improved to fit the inner breast root, but still the improvement was not significant for the outer breast root.

From the aspects of the comfort and support, their ratings were measured significantly higher with the customized underwire than the conventional underwire on all measurement points. Participants felt more comfort and more breast support while the bra with the customized underwire was on, and this was reflected on all measurement points. The customized underwire was flexible and fitted the shape of the breast root, so the participants could feel more support from the customized underwire even though the pressure was less than the conventional underwire. The comfort sensation was observed better for the same reason as well. Overall, the research finding supported the assumption that the 3D printed underwire would be preferred over the conventional underwire.

5.3 Influence of underwire length

Three customized underwires were compared to see the effect of underwaire lengths with the low outer position, the medium outer position and the high outer position. Initially, it was assumed that the short underwire would show more comfort but less support, and the experimental result partially supported this assumption.

OP of low and medium outer end underwires had less pressure than the high outer end underwire, but for other measurement points, there was no pressure measurement difference among the three underwires. The result of pressure distribution was same as the pressure data. The possible reason might be that the measurement points of IP, UBP and OUP were same on underwires with different lengths, but the location of OP was adjusted as the length of the underwire was changed. Therefore, the pressure on IP, UBP and OUP was kept as similar, while the pressure on OP was measured to be different.

For comfort sensation, participants did not felt any significant difference among different lengths of underwires. This result indicated that the length of the underwire might not influence the comfort level of the underwire. The possible reason for the result might be that these three underwires with different lengths were customized, so they fitted the breast root shape in the similar way. However, the statistical analysis showed that participants felt more comfortable as the length of the underwire became shorter, so there might be a trend that shorter underwire is more comfortable.

For support, the difference was only significant between the high outer end underwire and the medium outer end underwire on OUP. For other measurement points, IP, UBP, and OP, got similar levels of support rating for all types of underwires and there was no significant difference of the support rating on those points. The possible reason might be that the support sensation comes from the bottom part of the underwire. For underwires with different lengths, the structure of the bottom part was same, so the support sensation was supposed to be same as well.

5.4 Influence of the underwire's cross-sectional shape

Three customized underwires with different cross-sectional shapes were compared with each other; they were 3 by 2 (vertical), 2 by 3 (sagittal), and 3 by 3 (square) underwires. The hypothesis on this experimental design was that breast support and comfort might vary depending on underwire dimensions and the vertical underwire might provide breast more support than the vertical underwire, and the sagittal underwire might be more comfortable. Through the experiment, the result did not favor the hypothesis. However, the vertical underwire got relatively high rating from the support evaluation on all measurement points and the sagittal underwire got relatively high rating from the comfort evaluation on all measurement point, which agreed to the hypothesis. One of the possible reasons why the result was not significant might be that the difference of the three cross-sectional shapes were not large enough. When the bra was sewn, the underwire was encased by channeling, and this might have weakened the impact of the cross-sectional shapes.

5.5 Conclusion

This study came up with an idea of bra underwire customization and aimed to investigate the benefit of the 3D printed underwire for bra fit customization. Four research questions were formulated for this study. The first research question was consumer's purchase habits and wearing sensations towards bras. Most people wore wrong size bras, which might be caused by the incorrect way to put bras on and the inconsistent bra sizing system and manufacturing standard in different brands and manufacturers. Therefore, most people preferred the offline stores because of its try-on convenience and they had significant brand preference which might be caused by the limited choices of the brands. In the aspect of bra wearing sensations, the discomfort from the underwire was the most common. People showed the willingness to accept customized underwires.

The second research question was designed to compare the customized underwire with the conventional underwire in the aspects of comfort and support. The customized underwire showed better comfort and support performance than the conventional underwire in terms of the subjective evaluation. In the pressure measurement, only the inner part of the customized underwire had significantly less pressure than the conventional underwire.

The length and the cross-sectional shape of the underwire were investigated as the last two research questions. In the aspect of length, the pressure measurement and pressure distribution of the OP underwire was lower with the low and medium outer end underwires than the high outer end underwire. The support level of OUP on the high outer end underwire was better than the medium outer end underwire. No significant difference was observed among the underwires with different cross-sectional shapes, but the sagittal underwire tended to be more comfortable and the vertical underwire tended to provide more support. In conclusion, the 3D printed underwires performed better than the conventional underwire, especially the 3 by 2 vertical underwire and the 2 by 3 sagittal underwire.

5.6 Implication

Theoretically, this research provided an effective method to design and develop underwires, which might be applied in other bra unerwires researches. In practical terms, first of all, the survey result showed the main problem of bra discomfort, which could be the reference of new bra design and development. Secondly, participants provided many brands or stores when buying bras, so the launch of the 3D printed underwire will increase consumer's loyalty to the brand since the customized underwire is more comfortable. Additionally, the brand will collect a huge amount of body scanned data, which will help to analyze the breast shape, and develop the more fitted bras for their target market.

5.7 Limitation

There were several limitations in this study. The first limitation came from the small sample size in this research. Because of the limitation of time, only twenty participants were invited to this research, so the result might not represent the entire population. Also, the participant recruitment was only for the specific size of breast, and therefore, the experimental result cannot be applied to the larger or smaller breasts. Secondly, the wear trials were only based on the right side breast, and during the measurements, no underwire was worn on the left side breast. Thus, it is possible that the condition of left breast might have influenced the underwire on the right side. Thirdly, there is a possibility that the definition of support was not understood clearly enough by the participants, which might have influenced the result of the subjective evaluation. Lastly, the pressure measurement process had the room for improvement. The experimental bras were adjusted to the most comfortable status for each participant, while different people might have different preference in a way to wear the bra.

5.8 Suggestions for Future study

3D printing technology is widely applied in diverse fields recently, and more people care about the comfort and function of the apparel. 3D printing will give a huge benefit in the fashion industry. Based on the results of this study, the following future research areas are proposed:

- Only one type of material was used in this research, so the results of the experiment were based on the selected material. More diverse materials could be tested in order to find out the best material to develop underwires. Additionally, the 3D printing material investigated in this research is easily damaged, which will have a very short lifespan. The underwire could be used in the experiment since participants only wear it in a short time, but it cannot be used as a daily underwire. A more durable material should be employed in order to produce the commercial customized underwire.

- The industry application of the 3D printing underwire has a lot of potential for future investigations. The material cost, time cost and all the relative feasibility need to be evaluated to assess its market value. Additionally, sorting the breast shape into limited types rather than customize for individuals could be another possible method to produce bras, which might have higher cost performance.

- Further research could focus on other areas of bra components, such as band, shoulder straps, and cups. It could be another meaningful topic that how to standardize the bra sizing system and bra manufacturing process.

REFERENCES

ABSplus. (n.d.). Retrieved from http://www.stratasys.com/materials/fdm/absplus

Alyson Vanderploeg, Seung-Eun Lee & Michael Mamp. (2017). The application of 3D printing technology in the fashion industry, *International Journal of Fashion Design, Technology and Education, 10*(2), 170-179.

American Cancer Society. (2017, March 24). Disproven or Controversial Breast Cancer Risk Factors. Retrieved from https://www.cancer.org/cancer/breast-cancer/risk-and-prevention/disproven-or-controversial-breast-cancer-risk-factors.html

Armstrong, H. J. (2010). Patternmaking for fashion design. New Jersey: Pearson Education, Inc.

ASTM F2792-12a: Standard Terminology for Additive Manufacturing Technologies. (2015). West Conshohocken: ASTM International.

Atlantic Council. (2011). Could 3D printing change the world? *Strategic Foresight Report*. Retrieved from https://info.aiaa.org/SC/ETC/MS%20SubCommittee/Alice%20Chow_3D%20Printing%20Change%20the%20World_April%202012.pdf

Bengtson, B. P. (2015). The standardization of bra cup measurements: Redefining bra sizing language. *Clinics in Plastic Surgery*, *42*(4), 405.

Australian bra sizes. (2017). Retrieved from https://www.berlei.com.au/size-charts

Berman, B. (2012). 3-D printing: The new industrial revolution. *Business Horizons*, 55, 155–162.

Berry, C. (2007, Dec 10). Boom and busts. *New York*, *40*, 74-75. Retrieved from http://proxying.lib.ncsu.edu/index.php?url=http://search.proquest.com/docview/205129318?accountid=12725

Bra drama and the calendar girls. (2004, January 5). Retrieved from http://www.bbc.co.uk/insideout/northeast/series5/bras_calendar_girls.shtml

Bra Size Calculator. (n.d.). Retrieved from http://www.brasizecalculator.tk/faq.html

Bra Size Converter. (n.d.). Retrieved from http://www.brasize.com/au-to-us-uk-eu-fr-it.html

Bressler, K., Newman, K., & Proctor, G. (1998). *A century of style: lingerie*. London: Quarto Publishing Plc.

Brooke, E. (2013). Why 3D printing will work in fashion. *Tech Crunch*. Retrieved from http://techcrunch.com/2013/07/20/ why-3d-printing-will-work-in-fashion/

Brooks, K. (2015, February 25). How to REALLY Measure your bra size. Retrieved from http://thebraguide.com/how-to-measure-your-bra-size/#uksizing

Buckle. (n.d.). Buckleguy.com. Retrieved from https://www.buckleguy.com/5000-5001-

1-mojave-plastic-side-release-buckle/

Burton Precision. (2016). Timberland saves time and money, finds the right style with 3D printing. Retrieved from http://www.burtonprecision.com/2014/11/timberland/

Cecil, S. L. (1986). *The Great Book of Lingerie*. New York: Vendome Press.

Celaschi, F., & Celi, M. (2015). Advanced design as reframing practice: Ethical challenges and anticipation in design issues. *Futures*, *71*, 159–167.

Chan, C. Y. C., Yu, W. W. M., & Newton, E. (2001). Evaluation and analysis of bra design. *The Design Journal*, *4*(3), 33-40.

Chua, C. K., & Leong, K. F. (2015). *3D printing and additive manufacturing principles and applications*. Singapore : World Scientific Publishing Company Pte Limited.

Clovia.com. (n.d.). Retrieved from Bra Size Calculator website: https://www.clovia.com/bra-size-calculator/

Cox, C. (2000). *Lingerie: A lexicon of style*. New York: St. Martin's Press.

Cuzella, J. (2015). Fast fashion: A proposal for copyright protection of 3D-printed apparel. *Colorado Technology Law Journal*, *13*(2), 369–393.

Fairbanks, J. L. (2016). *Bare essentials: bras construction and pattern drafting for lingerie design*. Los Angeles: Los Angeles Fashion Resource, Fairbanks Publishing, LLC.

Farrell-Beck, J., & Gau, C. (2002). *Uplift : the bra in America*. Philadelphia: University of Pennsylvania Press.

Fetters, A. (2011). How to measure bra size. *Women's Health Magazine*. Retrieved from https://web.archive.org/web/20110225011832/http://www.womenshealthmag.com:80/beauty-and-style/bra-size

Find Your Bra Size. (2011, January 30). Retrieved from https://www.barenecessities.com/feature.aspx?pagename=fit_sizing

Francese, A. (n.d.). Underwire Bra Problems. Retrieved from https://www.leaf.tv/articles/underwire-bra-problems/

FZ/T 73012-2008: Brassiere. (2008). China Textile Industry Association.

Heish, C. C., & Trichopoulos, D. (1991). Breast size, handedness and breast cancer risk. *Eur J Cancer*, *27*(2), 131–135.

Higgs, R. (2000). *Plastics seeking to usurp the underwire*. Plastics News, 12(40), 9.

Hook. (2010). Shantou Xinfa Co., ltd. Retrieved from http://mxinfa.com/index.php/product/H&K%206.html

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: A literature review. *International Journal of Advanced Manufacturing Technology*, *67*, 1191–1203.

ISO 4416 : Size designation of clothes−Women's and girls' underwear, nightwear, foundation garments and shirts. (1998). International Organization for Standardization.

Jacob, M. P. (1914). "Brassiere" US Patent No. 1. *USPTO Patent Full Text and Image* Database.

Kehaulani, S. (2004, December 10). Functional Fashion Helps Some Through Airport Checkpoints. *The Washington Post*. Retrieved from http://www.washingtonpost.com/wp-dyn/content/article/2004/12/10/AR2005033112495_pf.html

Kochan, D., & Chua, C. K. (1994). Solid Freeform Manufacturing - Assessments and Improvements at the Entire Process Chain. *27th International Symposium, Automotive Technology and Automation, 9*.

Kruth, J. P., Leu, M. C., & Nakagawa, T. (1998). Progress in additive manufacturing and rapid prototyping. CIRP Annals – Manufacturing Technology, 47(2), 525–540.

KS K 9404: Sizing systems for foundation garments. (1999). Korean Standards Association.

Lantin, B. P. (2003, April). A weight off my shoulders. The Daily Telegraph. Retrieved from http://www.telegraph.co.uk/women/womens-health/3301186/A-weight-off-my-shoulders.html

Littleton, L. Y., & Engebretson, J. (2002). *Maternal, Neonatal, and Women's Health Nursing*. Delmar Thomson Learning.

Manning, C. (2014, May). 7 Ways to Tell You're Wearing the Wrong Size Bra. *Cosmopolitan*. Retrieved from http://www.cosmopolitan.com/style-beauty/fashion/advice/a6792/bra-fit-tips-and-tricks/

Maharani. (n.d.). Bra sizes. Retrieved from http://www.cupmysize.com/bra-sizes/

Marianne, L., & Colman, C. (2009). *What Women Need to Know*. E-reads.

Materialise. (2015). Mammoth stereolithography: Technical specifications. Retrieved from http://manufacturing.materialise.com/mammoth-stereolithography-technicalspecifications-0

McGhee, D. E., & Steele, J. R. (2010). Optimising breast support in female patients through correct bra fit. A cross-sectional study. *Journal of Science and Medicine in Sport*, *13*(6), 568-572.

Mellor, S., Hao, L., & Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, 149, 194–201.

Mendoza, H. R. (2014). 3D printed fashion presents dresses which are actually comfortable. Retrieved from http:// 3dprint.com/16385/3d-printed-fashion/

Moroni, L., de Wijn, J. K., & van Blitterswijk, C. A. (2004). 3D Plotted Scaffolds for Tissue Engineering: Dynamical Mechanical Analysis. *European Cells and*

Materials, *7*(1), 68.

Napoleon, A. (2003). *Awakening Beauty: An Illustrated Look at Mankind's Love and Hatred of Beauty*. U.S.: Virtualbookworm.com Pbulishing Inc.

Nike. (2013). Nike debuts first-ever football cleat built using 3D printing technology. Retrieved from http://news.nike.com/news/nike-debuts-first-ever-football-cleat-built-using- 3d-printing-technology

Riordan, T. (2002, October 28). Patents; in bra technology, an incremental improvement can translate into comfort. Retrieved from http://www.nytimes.com/2002/10/28/business/patents-in-bra-technology-an-incremental-improvement-can-translate-into-comfort.html?sec=technology&spon=&pagewanted=all

Robson, S. (2015, September 11). Britain's average bra size has grown as region with the biggest boobs is revealed. Retrieved from http://www.mirror.co.uk/news/uk-news/britains-average-bra-size-grown-6423192

Sclater, N. (2011). Mechanisms and mechanical devices sourcebook. New York, NY: McGraw-Hill

Scribners, C., & Sons. (2004). *Encyclopedia of Clothing and Fashion*. Cengage Gale.

Sharma, R. (2013). Lady Gaga goes gaga over 3D printing. Forbes. Retrieved from http://www.forbes.com/sites/rakeshsharma/2013/12/06/lady-gaga-goes-gaga-over-

3dprinting/

Shin, K. (2010). *Patternmaking for Underwear Design*. U.S.

SS14 3D Body Scanner. (2016). Cary, NC: Size Stream LLC.

Tucek, M. (1893). “Breast Supporter” US Patent No. 494,397. *USPTO Patent Full Text and Image Database*.

Underwire for brassiere - US6468130 (B1). (2002, October 22). Retrieved from https://worldwide.espacenet.com/publicationDetails/biblio?CC=US&NR=6468130&KC=&FT=E&locale=en_EP

Wohlers, T., & Caffery, T. (2014). History of additive manufacturing. *Wohlers Report 2014*, 15–17.

Wood, K., Cameron, M., & Fitzgerald, K. (2008). Breast size, bra fit and thoracic pain in young women: a correlational study. *Chiropractic & Osteopathy*, 16, 1. http://doi.org/10.1186/1746-1340-16-1

Your Angel Fit. (n.d.). Retrieved from https://www.victoriassecret.com/popups/how-to-measure-overlay

Yu, W., Fan, J., Harlock, S. C., & Ng, S. P. (2006). *Innovation and technology of women’s intimate apparel*. England: Woodhead Publishing Limited.

Zhang, W., Leu, M. C., Ji, Z., & Yan, Y. (1999). Rapid Freezing Prototyping with

Water. *Materials and Design*, *20*, 139–145.

Zolfagharifard, E. (2013). When science is stylish: Designer uses 3D printing to create a range of accessories that is taking the fashion world by storm. *Daily Mail*. Retrieved from http://www.dailymail.co.uk/sciencetech/article- 2384802/Catherine-Wales-uses-3D-printing-create-rangeaccessories-taking-fashion-world-storm.html

APPENDIX

Questionnaire for Bra Underwire Customization Research

Participant ID: ________________________

Part 1: Basic Information

1. Your age? __________ years old
2. Your ethnicity? _______

   A. Caucasian B. Asian/Pacific Islander C. Black or African American

   D. Hispanic or Latino E. Native American or American Indian F. Other ______________
3. Have you ever given a birth to a baby? A. Yes B. No
4. Do you have breasting-feeding experience? A. Yes B. No

Part 2: Bra Consumption

5. Do you know your bra size? A. Yes, it's ________. (eg. 34B, 32C) B. No.
6. Which purchase channel do you usually use to buy bras?

   A. Offline store B. Online store
7. List 3 brands which you usually buy bras from according to frequency.

   1.________________ 2.___________________ 3._____________________
8. If you shop bras regularly, how often do you buy a bra?

   A. No, I do NOT buy a bra on a regular basis.

   B. Less than 3 months C. 3 – 6 months D. 6 – 12 months

E. 1 – 2 years F. More than 2 years

9. How long do you use a new bra until you throw it away?

   A. Less than 3 months B. 3 – 6 months C. 6 – 12 months

   D. 1 – 2 years E. More than 2 years

10. How many bra do you have?

   A. Less than 3 B. 3 – 5 C. 6 – 8 D. More than 8

11. When buying a bra, what are the most important influence factors? Select ALL appropriate options.

   A. How it looks esthetically B. how comfortable it is C. how it keeps breast static

   D. how it changes the breast shape E. how it feels when touched

   F. Others __________________________

12. What are the main problems of the bra when you throw it away? Select ALL appropriate options.

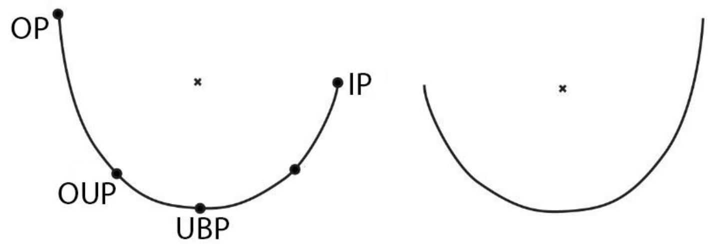
   A. Bra cup becomes loose B. Strap becomes loose and slide down

   C. Bands become loose. D. Underwire become distorted

   E. Others ____

13. Please rate the comfort level with the underwire that you wear.

	1: Very Uncomfortable	**2: Slightly Uncomfortable**	**3: Neither comfortable nor uncomfortable**	**4: Slightly Comfortable**	**5: Very Comfortable**
IP					
UBP					
OUP					
OP					
Overall					



Underwire structure

14. Please rate the support level with the underwire that you wear.

	1: Very low support	2: Slightly low support	3: Neither high support nor low support	4: Slightly high support	5: Very high support
IP					
UBP					
OUP					
OP					
Overall					

15. What are your expectations of a bra if it could be redesigned?

____
____

16. If there is an underwear brand who produces a customized underwire based on your own breast shape, how much likely will you buy it?

A. Extremely Unlikely B. Unlikely C. Neutral D. Likely E. Extremely likely