ABSTRACT

LI, JIAYIN. The Evaluation of a 2D Measuring Garment for Accuracy in a Size Range and Customer Acceptance. (Under the direction of Dr. Andre J. West and Dr. Cynthia L. Istook).

Body measurement plays an important role in the apparel industry. It is wildly used in apparel pattern making, sizing, and fitting for manufacturers. As for the consumer, they need body measurements to find the right size clothing. However, measuring their own body is not easy. The traditional one-dimensional manual measuring method takes a long time and has a low accuracy for people without training. The three-dimensional body scanning method is fast and relatively accurate, but the price and size of the body scanners are not suitable for daily home use. In this case, the two-dimensional image measuring system that can be used on a smartphone or smart pads is considered as a convenient and affordable way for human body measuring.

The purpose of this research is to develop a series of garments that can be used as a measuring apparatus in a developed 2D image body measuring system. Base on the basic requirements of the 2D image body measuring system, a series of measuring garments, including three designs and five sizes, were developed for evaluation. To evaluate these developed measuring garments, a one-dimensional online survey was developed to collect basic demographic data for prediction model development as well as consumer preference and evaluation of the measuring apparatus to understand consumer acceptance of this kind of product. Two-dimensional image data and three-dimensional body scanning data were also collected to develop the prediction model, extract predicted body measurements through the 2D image body measuring system. The 1D, 2D, and 3D data were collected among 50 subjects for data analysis. The extracted prediction measurements were analyzed by comparing with the extracted three-dimensional body scanning data and among the three different designs to evaluate the impact of the fit and design of the measuring garments.
Four representative measurements as bust girth, waist girth, hip girth, and inseam length were selected to be compared between 3D vs. 3D, 2D vs. 2D, and 2D vs. 3D measurements. The 3D vs. 3D group compared extracted 3D body measurements among different fit of measuring garments on the same subject to evaluate the impact of garment fit. The paired t-test result suggested that the fit of measuring apparatuses has a statistically significant impact on body measurements but was acceptable in the apparel industry.

To extract the 2D measurements, the prediction models of these measurements were developed using the 2D images. Scikit-image, OpenCV-python, Scikit-learn, and TensorFlow application programming interface were referred. The least absolute shrinkage and selection operator (LASSO) method and Akaike information criterion (AIC) were used for model selection to narrow down the variable amount. The result of 2D vs. 3D measurements approved that having both arms above head would be an acceptable pose for better 2D image body outline detection. The 2D vs. 2D group compared the prediction measurements among the three different designs. The result suggested that the design does not have a significant impact on prediction measurements.

As for the consumer acceptance level, the participants were mostly college students, and they were interested in using these measuring apparatuses for body measuring. The feedback from these participants also showed that the measuring garments have some potential to be gym suits for future product development.

Overall, this research has successfully developed a series of garments that work with the developed 2D image measuring system as a measuring apparatus. Representative body measurements as inseam length predicted using this measuring apparatus and 2D image measuring system reached was acceptable in the apparel industry.
The Evaluation of a 2D Measuring Garment for Accuracy in a Size Range and Customer Acceptance

by
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DEDICATION

This dissertation is dedicated to my parents. Thank you for all of your support along the way.
BIOGRAPHY

Jiayin Li was born in Beijing, China. Jiayin received a bachelor’s degree in Fashion Design and Engineering from the Donghua University in Shanghai, China. She came to the United States in 2014 and received a Master of Science Degree in Textiles in 2016 from North Carolina State University. Her research interest includes 3D body scanning, sizing, and fit, as well as functional clothing design and product development.
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CHAPTER 1. INTRODUCTION

Clothing is a life necessity for human beings; it protects the human body, identifies job occupation, and represents the personal character. Sportswear, one of the most significant categories in the apparel industry, was first developed only for sports training and competition but has now become very common in daily life. In the past century, activewear has experienced revolutionary development, especially among women. From the cumbersome and inconvenient dresses to simple, lightweight sports bras and shorts, the development of women’s activewear reflects not only the changes among aesthetic and material technology but also the changes of female social status and the rise of women’s rights.

In modern society, sportswear has been widely accepted for casual/everyday use instead of limited to gyms and playgrounds (NPD Group, 2014; Rugolo, 2013). This change in consumer lifestyle has dramatically influenced the apparel market. Activewear has become a staple primarily for the U.S. apparel market over the past ten years, and women’s spending has dramatically contributed to the sales growth of the sportswear market (NPD Group, 2013; O’Sullivan, Hanlon, Spaaij, & Westerbeek, 2017). Meanwhile, e-commerce has proliferated since the beginning of the 21st century, and the online sales of sporting goods have reached 13.4 billion U.S. dollars, up from 9.3 billion U.S. dollars in 2014 (Statista, 2018).

The growth of online sales brought a great opportunity to the apparel industry, but it also brought challenges. Clothing returns are one of the biggest headaches for online apparel retailers as the return rates are significantly higher for e-retail fashion companies comparing to in-store sales. About twenty to fifty percent of online clothing sales are returned after purchase (Pulga, 2015). Apparel retailers are haunted by returns caused by sizing issues, with $62.4 billion in returns attributed to poor choices by the consumer (Cheng, 2015). However, over the next five
years, online sales of apparel, footwear, and accessories are predicted to continue to grow more than $40 billion, compounding the problem exponentially (Statista, 2018).

Combinations of strategic body measurements determine the size of clothing. Most consumers do not know their body measurements when attempting to determine the size of a garment they want to purchase when shopping online. Also, customers have significant difficulty in attempting to take their measurements. Many customers even buy a style in two sizes and return one adding to cost and waste. In 2015, $62.4 billion of returns were caused simply due to the wrong-size problem, occupying 0.5% of total sales (IHL Group, 2015). To cut costs and alleviate the headaches and frustrations of online shopping, a convenient, cost-efficient, and accurate body measuring tool is urgently needed for both consumers and apparel companies.

It is necessary to understand what to measure and how to measure the human body before developing this body measuring tool. Human body measurements are widely used in the apparel industry for designing, pattern making, sizing, grading, mass customization, 3D model recreation, and virtualization (Gupta, 2014; Lu, Wang, Chen, & Wu, 2010; Schofield & LaBat, 2005;). For apparel design and sizing system development, the most important human body measurements are summarized as primary and secondary measurements and listed in global and national standards (ASTM International, 2015; ISO, 2017c).

There are several different ways to collect human body measurement data. The most traditional method is manual measuring with a weight scale, camera, measuring tape, anthropometer, spreading caliper, and head spanner (Kouchi, 2014; Simmons, & Istook, 2003). Three-dimensional (3D) body scanning technology is a popular and modern method that is widely used in recent years. It collects human body measurements and creates digital data to generate the human form in point-cloud (a set of data points on an external surface) (ISO, 2017c).
Three-dimensional body scanning technology has promoted the development of 3D modeling and virtualization technology, which primarily benefit designers and manufacturers. Compared to the traditional manual measuring method, the measurement collected by 3D body scanning is more accurate and takes much less time. However, the cost of 3D whole-body scanners is usually too expensive for consumers to afford for daily use, which limited the use of 3D body scanning in academic research and industry only (Xia, Guo, & Li, 2018).

A 2D image body measuring method, in this case, is considered as a potential solution for low-cost and reliable human body measuring method. This human body measuring method uses 2D images collected by a standard camera or smartphone to rebuild the 3D model based on the silhouette information. To reduce the influencing factors and protect privacy for users, measuring garments are required for the 2D body measuring method (Grogan et al., 2017; Seo et al., 2006). With a potential market calling for a reliable and low-cost solution for human body measuring, it would be a valuable asset to develop an aesthetically acceptable measuring garment and 2D body measuring system for consumers to use in their daily life.

1.1. Purpose of Research

Based on the background information, there is an urgent demand for a convenient, accurate, and low-cost body measuring method. This method needs to be easy to use in daily life and adopted by society. A negative example is Google glasses. The privacy concern among consumers brought a negative perception on market acceptance. Thus, the adoption of the technology has not been realized (Rauschnabel et al., 2015). The purpose of this research was to develop a series of garments as a measuring apparatus for a human body measuring system using 2D images based on the research of the PrimeFit team. Close-fitting sportswear, as one of the
most popular categories in the apparel industry, was considered to be an appropriate option for this measuring apparatus as it tends to be a close fit and stretchy enough to fit more than one size. The measuring garments need to be aesthetically acceptable for consumers to wear and help locate the measuring area for body measurement collection. Primary and secondary measurements for most apparel categories, including gloves, hats, and socks, could be covered in the design. The color palette of the garment needs to be identifiable compared to the daily background environment for this method to work as the garment has to be an easily identifiable separate image.

1.2. Rationale of Research

The 2D image human body measurement system is a growing trend for home use body measuring methods. This could mostly benefit consumers and apparel retailers by helping conduct body measurements efficiently and accurately. Accurate body measurements could result in a lower return rate for online shopping. The 2D image measuring system used in this research has been tested and approved to be efficient and cost-effective for female body measurement, and it is easy to operate using a smartphone (Xia, 2018). The measuring garment will be used as a helpful tool to locate the measurement area and avoid the errors caused by loose fitted clothing during the 2D image measuring process. The sportswear style would also help consumers accept this type of garments and use them in their daily life for exercising rather than a new technology apparatus. Developing this measuring garment could help improve the 2D image measuring system and benefit consumers.
1.3. Research Questions

To guide the study, the following questions were developed to evaluate the measuring garment from accuracy and consumer acceptance level.

RQ1: Does the design and fit of the measuring garment affect the accuracy of measurements obtained from the 2D images of the human body?

1a. How does the design impact measuring results?
   1a1. What kinds of patterns, colors, and styles can be used to obtain accurate measurements?
   1a2. What are the appropriate color-design locations and sizes for landmarks on the human body?

1b. How does fit affect measurement results?

1c. What kind of accuracy can be achieved?

RQ2: Does the arm position impact the accuracy of measurements obtained from the 2D images of the human body?

RQ3: Does the fashion element of the measuring garment impact the attitude of the consumer to purchase the garments using the measuring app?

3a. Does the design relate to the consumer expectation for activewear?
   3a1: What are their expectations?
   3a2: Do they have any preferences on the fit or design?

RQ4: Would consumers adopt this new technology? How would they use it (simply as a measuring tool or wear it as an outfit)?
CHAPTER 2. LITERATURE REVIEW

The measuring garment development focused on two main features: consumer acceptance and measurement accuracy. To achieve this goal, it is important to find an existing apparel category to fit this new product so it can be easily accepted by consumers. In this research, activewear was selected as the design style for the measuring garments based on concerns of two levels: function level and market level. In this chapter, the history, function, and market analysis of female activewear were reviewed for further product design. On the other hand, human body measuring methods were also reviewed to define and locate the most important measurements.

2.1. Women Activewear Trends and Drivers

2.1.1. History of Women Sportswear in the U.S.

In the past, the definition of activewear was narrowly limited as clothing for sports or exercise. This definition has now been broadened as transition clothing from leisure to casual wear or even evening wear (O’Sullivan, Hanlon, Spaaij, & Westerbeek, 2017). From university gyms to the streets, women’s activewear has undergone a long and complicated process of evolution, together with the awakening of female consciousness and the rise of feminism.

The evolution of women’s activewear can be divided into four different stages: before the 1890s, 1890s to Second World War (1945), Second World War (1945) to the 1960s and 1960s until today.

2.1.1.1. Victorian period (1840-1900). Victorian Period was the embryonic stage of female sportswear. In the 19th century, women lived in an environment in which roles of men and women are strictly differentiated. The cult of “true womanhood” limited women into a pale and slim appearance, followed by the popularity of exquisite corsetry and dieting. The corsetry
covered the whole bodice part from the bust to the lower hip, emphasized the curve of the waist (Banner, 1983). Figure 1. shows a representative image of women in the Victorian period (Victorian-era.org, 2014), and Figure 2. shows the image of women wearing corsetry in 1831 (Tortora, & Eubank, 2015).

Figure 1. Victorian period attire for women (victorian-era.org, 2014)

Figure 2. The corsetry during the Victorian period in 1831 (Tortora, & Eubank, 2015, p332).
Under such morbid aesthetic, it would have been unlikely for women to participate in sports because the tight corsetry may have caused palpitations and swooning. The image of “true womanhood” also prohibited women from being seen under emotional excitement (Gerber, 1974; Kemper, 1977).

In the second half of the nineteenth century, the rise of women’s colleges brought more possibilities to women. These colleges bravely mixed traditional and experimental activities and offered women an education that comparable to their brothers. Entirely new educational environments encouraged the growth of women and brought evolutionary thoughts into their lives (Warner, 2006). These schools for women helped to increase the acceptance of higher education in women, including physical education. Elizabeth Blackwell, the first American woman, trained as a doctor, was an early advocate of the idea that men and women have equally balanced bodies, minds, hearts, and souls. She published several articles arguing the necessity of physical education and exercises among women (National Library of Medicine, 2000). In the 1860s, calisthenics was promoted by the famous physical advocate Dio Lewis in the U.S, and it became a popular form of female physical education. Figure 3. shows the image of a gymnastic dress developed by Dio Lewis in 1862 for female calisthenics (Lewis, 1862).

In the early 1880s, Senda Berenson from Smith College designed an indoor women’s basketball game based on existing men’s game. This new game was more interesting than calisthenics and attracted more women to participate in sports. In order to adapt more movements, a new style of clothing was demanded. A set of uniform style clothing called a gym suit was developed under this activity. This gym suit was a tremendous evolution and set up the foundation for modern women sportswear (Warner, 2006). Figure 4. shows the look of gym suits from Smith College in 1895.
Figure 3. Dio Lewis’s gymnastic dress in 1862 (Lewis, 1862).

Figure 4. Basketball gym suits from Smith College in 1895 (Warner, 2006).
Bicycling was another favorite sport for American people in the 1890s. It quickly eclipsed horseback riding. This activity became popular because it was considered a cheap and convenient means of transportation as well as exercise. The popularity of bicycling has also influenced the clothing women wear to go outdoors. The combination of long skirts and bicycle spokes were found inconvenient for safe riding, so women started to wear bloomers under skirts or to wear bloomer style bicycling outfits instead of skirts (Warner, 2006). Figure 5. shows the image of two ladies wearing bicycling outfits in 1894. This was an early attempt of women wearing trousers in the history of female activewear development.

![Bicycling Outfits in 1894](image)

2.1.1.2. The 1900s to the Second World War (1939). During the period from 1900 to 1960, the increasing number of women’s colleges help broadened literacy. Raising awareness of the equivalence between men and women became gradually accepted among educated people. Two significant breakthroughs happened during this period, and they significantly promoted the
evolution of women sportswear. The first breakthrough is that women started to participate in competitive sports in the Olympic games.

The first modern Olympic Games were held in Athens, Greece, in 1896. Over three hundred male athletes participated in this event. The second Olympic Games held in 1900 was the first time that women were allowed to participate. Among all athletes, only 2% of them were women, and they were not accorded any uniform or other possible recognition by the Olympic Committee (Welch & Costa, 1994). Female athletes were allowed to compete in only a few events, including tennis, golf, and archery. British tennis player Charlotte Cooper was the first female Olympic champion. As shown in Figure 6., she was wearing a stiff high collar shirt and a skirt that closely fitted on the hip and waist. Compared to male athletes wearing tank tops and above-knee shorts, her image was still limited by the elegant and pretty “womanhood” (BBC, 2017).

Figure 6. The first female Olympic champion Charlotte Cooper (BBC, 2017).
The second breakthrough is the uncovering of a women’s body. In the United States, before the mid-1920s, women were never seen swimming or bathing in public with their legs exposed. In many cities, the indecent exposure was considered a crime and may risk arrest. Stockings, in this case, were required for women who come to the public beach (Warner, 2006).

The reveal of women’s bodies stemmed from physical education in women’s colleges. Thus, the gym suit applied in physical education was the starting point for the female modern sportswear evolution. It allowed more freedom than outdoor sportswear because it was meant to be private clothing that should never be seen in public (Warner, 2006). By the 1920s, a new form of gym suit was needed to adapt to more competitive sports. As shown in Figure 7, a set of team uniforms, including a shirt and shorts, appeared in Rockford College in 1929, and it became popular in many schools in the 1930s.

Figure 7. The washable cotton romper suit from the 1930s (Warner, 2006).

Until the 1920s, women had worked assiduously to maintain their pale, freckle-free complexions. The original version of the swimsuit was called “bathing dress,” including a pair of
bloomers, stockings, and a skirt. Figure 8 shows the image of a bathing dress in 1871. Male swimsuits, in the meantime, were much more straightforward. Men wore a one-piece knitted garment with or without sleeves, and the shorts stopped above their knee. This close fit style was accepted among English women but was considered shocking in the United States (Alison, 1963).

The development of motor cars also helped promote the evolution of swimwear. The introduction of Henry Ford’s motor vehicle model T in 1908 made it easier for people to access public beaches and encouraged people to uncover under the sunshine. People outside the competitive sports gradually became accustomed to bared arms, legs, and backs. The popularity of movies also helped audiences accept swimsuits in newer, barer, and more daring styles (Godey’s, 1864).

Figure 8. Bathing suit in 1871 (Peterson’s Magazine, 1882).

2.1.1.3. Second World War and beyond (1939-1960s). During the war and post-war years, sportswear achieved the transition from sports use only to casual wear into people’s life (Skorich, 1997). World War II brought significant changes to both the U.S. society and the
apparel industry. The production capability of the apparel industry had significantly been honed during the war, allowing a much more full range of production activities and expanding women’s clothing options (Women’s Wear Daily, 1957). Many new synthetic blends were invented and improved during the war, which required less care than natural fiber made fabrics. Rayon was applied in many more categories of garments, and the color ranges were considerably broadened due to new design formulas (Women's Wear Daily, 1948).

At the social level, the booming middle class had optimistic expectations of their lives and were presenting a new positive attitude. Americans started moving to the newly developed suburbs to enjoy their family life instead of the hustle urban nightlife (Skorich,1997). From the year 1947 to 1953, over 1,200,000 Americans moved from cities to suburbs annually (Seldin,1976). Moving to the suburbs helped the middle class shape a new set of values and a new pattern in the American lifestyle. More and more people spent their spare time in outdoor travels and sports, which help raise the acceptance of sportswear (Richard, 1985). Sportswear was no longer limited to specific sports but accepted as an association with sports. Unlike high fashion dresses, sportswear presented a healthy and casual lifestyle. With very few significant social class elements, sportswear became the uniform of the American middle class (Skorich, 1997).

2.1.1.4. 1960s-now. Although gym suits persevered in the early 1960s in some parts of the United States, it finally naturally disappeared. The extinction of these gym suits was very likely because of the vanish of female athletics in college and high school. T-shirts and non-regulation shorts have taken over (Warner, 2006).

An important turning point was the issuance of Title IX. Title IX was passed in 1972 as part of the Education Amendments. This federal civil right law protects people from
discrimination based on sex in education programs or activities that receive Federal financial assistance. Title IX states that:

“No person in the United States shall, on the basis of sex,” be excluded from participation in, be denied the benefits of, or be subjected to discrimination under any education program or activity receiving Federal financial assistance” (ed.gov, 2019).

From 1972 to 1978, female athletic participation rates have highly increased in high school to comply with Title IX. In 2010, Stevenson and Betsey compared the outcomes in changes between pre- and post-cohorts across states. The result of their analysis reveals that at the state level, female sports participation raised by 10 percent, and female force participation raised by 1 to 2 percent. Thanks to Title IX, females had more opportunities to participate in athletic activities.

After decades of this development, sportswear has now been widely accepted as part of casual wear in American people’s lives, the idea of “activewear” has been expended as a combination of outdoor wear, performance wear, and sports-inspired wear (Shishoo, 2015). A survey in 1982 showed that around 60% of Americans wore running shoes and sweatsuits as their casual wear (Schwartz, 1986). The limitation from social classes and genders had been reduced while more attention had been put on the aesthetics and functions in the subsequent development of sportswear. Consumers are now expecting more possibilities for activewear beyond its original purposes as a combination of multifunctionality and fashion.

On an aesthetic level, the concept of fashion design has been gradually accepted into the sportswear field. Wearing activewear became a way for people to express their attitudes in fashion. Fashion design is believed to help add value and gain appeal for activewear. Famous fashion designers were also invited to design uniforms before official competitions such as the
Olympics. The uniform of the Italian national football team designed by Dolce Gabbana and the British uniforms designed by Giorgio Armani showed the influence of fashion in activewear (Cao & Wang, 2017).

On the functional level, technology development allowed more possibilities for material selection. Nowadays, the most commonly used fiber in activewear is polyester. Other fibers like acrylics, polyamide, polypropylene, and elastane are also applied in activewear (Shishoo, 2015). Knit fabric plays a vital role in the material competition; it makes activewear stretchy and fit closer to the human body. The invention of LYCRA® in 1958 brought a major leap in fiber evolution. This first human-made elastomeric yarn developed by DuPont® established a new generic fiber classification called elastane. Elastomeric yarns contributed greatly to all types of knit fabrics, including warp knits, circular knits, and flat knits on elastic properties. The most evident functions of elastomeric yarns are high recovery properties and controlled stretch that add freedom and comfort to close-fitting activewear like swimsuits, race suits, and gym suits (Hu, & Lu, 2015; Shishoo, 2015). An Australian swimwear company Speedo developed its first one-piece swimsuit in the 1950s. This new concept of close fit stretchy swimsuit brought a new trend of sleeker and tighter swimsuits and helped athletes to push their limits (Schmidt, 2008). In 1976, a variety of high function fabrics represented by GORE-TEX® with high breathability and lightweight were introduced to the market. Today, the research of materials has gone through the stages from conventional fibers to highly functional fibers, and now to high-performance fibers. By designing different fabric preparation and finishing processes, the high-performance fabrics now can satisfy different commercial requirements on fabric performances, including drape, stretchiness, thermal comfort, and moisture transfer. Other functions like reflective material and
wearable fitness trackers have also been introduced to activewear products. Consumers are now expecting more possibilities for activewear beyond its original purposes.

### 2.1.2. Sportswear Design and Fashion

The outline design of sportswear can be divided into five kinds of structures: tight type, H type, Y type, and X type. Tight type sportswear includes swimwear, gym suits, and other close fit styles. This type of sportswear could help minimize the resistance during exercise and emphasize the beauty of body curves. H type stands for loose fit sportswear such as basketball vests, tennis T-shirts, and shorts. The simple design and relatively loose fit could provide adequate space for physical activities. Y types extend the shoulder outline to protect human bodies from collisions. The typical Y type sportswear includes football and hockey clothing. X type sportswear is relatively rare, mainly used for figure skating and some other sports clothing (Jiang et al., 2008). Figure 9 showed some examples of these sportswear outlines.

![Figure 9. Examples of sportswear outline. (a) tight type, (b) H type, (c) Y type, (d) X type.](image)

When designing sportswear, colors also help deliver visual impact and emotional expression. The colors of sportswear are usually selected based on sports dynamics. For
activities that require strong explosive power like weightlifting and sprints, sportswear is typically designed in bright and light colors with a sharp contrast to make athletes feel excited and motivated. For activities like shooting and archery that require a calm psychological quality and a steady mindset, sportswear is usually cool colors like blue and white for steady performance. The combination of personalized and eye-catching color selection is also critical in tough conflict situations like boxing or wrestling (Bo, 2017; Li, 1999).

2.1.3. Sportswear Market Dynamics

The sportswear market is one of the most critical segments of the apparel market. In recent years, sales of sportswear continue to grow, which makes it a primary driver of the apparel industry (NPD Group, 2018). In the year 2014, U.S. consumers spent over $323 billion on apparel, footwear, and accessories products, a 1% increase compared to 2013. This 1% growth resulted in about $2 billion in additional sales, primarily driven by sportswear, bags, and athletic performance footwear (NPD Group, 2014). By 2017, the U.S. apparel sales declined about 2% compared to 2016 due to the slowed momentum and decrease in some other segment. However, the sales of activewear continued to grow in 2017, while non-activewear declined. The sales of activewear have grown by 2% to $48 billion, accounting for 22% of total industry sales (NPD Group, 2018). Figure 10 shows the projected sales trends of the sportswear market in the United States from 2015 to 2020.
Figure 10. Projected sales of sportswear market in the United States from 2015 to 2020 (in billion U.S. dollars) (Statista, 2018).

In these reports, it is suggested that females were the main contributors to the activewear sales growth. In the year 2012 to 2013, the U.S. women made up the 5% sales growth on August year-to-date figures (NPD Group, 2013). In 2014, the dollar sales of activewear among the U.S. female consumer increased by 8% compared to 2013. Sales among Sports bras, leggings, and sports jerseys also grew in line with the raised health and fitness consciousness and demand for comfort and versatility (NPD Group, 2014). In 2017, although the growth was not as steep as the growth in the past few years, women’s activewear sales still increased by about 4% compared to 2016, reaching $21.9 billion in sales (NPD Group, 2018). It is evident that in the U.S. activewear sales, the female consumer plays a significant role.

2.1.4. Consumer Decision Making in Sportswear Purchasing

Several articles have suggested that there are multiple factors influencing consumer decision making about sportswear purchases. In this study, female consumers will be selected as the main research subject since they are currently the primary driver of the sportswear market. For female consumers, generation and age, lifestyle, product quality, design, price, and store
services are the main factors influencing their decision making on sportswear purchases (O’Sullivan, Hanlon, Spaaij, & Westerbeek, 2017).

A series of research conducted by Rahulan, Troynikov, Watson, Janta, and Senner in 2013 and 2015 compared sportswear consumption between the generations Y and Baby Boomer and found that the baby boomer generation pays more attention to the quality and size range of sportswear products and prefer to go to physical sports stores to try the garments on for fit. Female consumers in the age range of baby boomers have a relatively stable income, so the price becomes less important for them while making a purchase decision.

As for Generation Y consumers, they look more into the comfort, style, and sports performance of the garment, and the price is a big factor for them while making purchase decisions. They also prefer shopping online much more than baby boomer consumers. Another big difference between consumers in these two age ranges is that baby boomers take less time reading the product details while generation Y consumers are tech-savvy and knowledge-hungry, they are usually more interested to know the details about the product. We could assume from this that generation Y consumers are more functional driven and style sensitive, they are willing to learn and experience advanced technologies when a new product comes to the market.

On the lifestyle level, it has been found that female consumers will increasingly be interested in flexible and non-organized physical activities instead of organized sports. Non-organized sports like walking, swimming, running, bike riding, and yoga tend to be more time-flexible and easy to start with compared to organized sports. It is predicted that this trend will keep increasing over the next 30 years (Hajkowicz et al., 2013; O’Sullivan, Hanlon, Spaaij, & Westerbeek, 2017).
2.2. Human Body Measurements

2.2.1. Application of Anthropometry in the Apparel Industry

Anthropometry, a branch of ergonomics, is defined as the study of human physical measurements and dimensions. Anthropometry focuses on analyzing the shape and size of human bodies and apply the result into product design to meet consumer demands (Gupta, 2014). In the apparel industry, anthropometry is applied in apparel design, pattern making, sizing, grading, mass customization, 3D model recreation, and virtualization (Gupta, 2014; Schofield & LaBat, 2005; Lu, Wang, Chen, & Wu, 2010).

2.2.1.1. Apparel design and pattern making. Clothing is a life necessity for human beings. It forms a close shell around the human body and creates an intimate environment with the body. Clothes move and interact with the human body every day and carry the responsibility for providing comfort and protection (Gupta, 2014).

Several factors influence the pleasantness of clothing, and the fit of clothing is arguably the most important. The fit of clothing may affect the comfort and performance of the user, and it could lead to discomfort or even harm under extreme conditions. For example, the Occupational Safety and Health Administration (OSHA) has issued safety guidelines to control the fitness of modern clothing and avoid accidents caused by loose-fitting clothing (OSHA, 1992). A research made by Anders et al. in 2005 has shown that wearing overly tight pants can result in hip movement and trunk muscle restriction. Research by Yoo and by Eungpinichpong supports that young workers wearing tight pants while participating in specific manual tasks may lead to the lumbar spine and low-back pain, and even disability (Yoo, & Yoo, 2012; Eungpinichpong et al., 2012).
2013). Therefore, it is essential to design apparel products using anthropometric data to find a good fit and eliminate hidden dangers.

Designers and pattern makers use anthropometric data for pattern drafting to develop basic patterns. The cardinal points on the patterns are matched to the body landmarks to extract the pattern based on body measurements. Landmarks are considered as the endpoints of measurements on the body (Schofield & LaBat, 2005; Tylor & Shoben, 1993). The effectiveness of anthropometric data collection and translation influences the quality of the drafted pattern. The evaluation of consumer fit preference is also required to match the market demands (Gill, 2015; Gupta, 2014).

In the 21st century, designers are looking for more efficient drafting methods. Research by Jin Kang & Min Kim focused on directly using CAD design software to generate body model and draft patterns from three-dimensional measurements collected by three-dimensional body scanners. A body model was first generated using the three-dimensional anthropometric data and later transformed into a dummy model in a convex shape. Next, a typical garment model is created by measuring the dummy model surface using stereoscopy. Finally, the optimum fit garment patterns are obtained by adjusting the garment model shape, considering the geometrical constraints the underlying body model (Jin Kang & Min Kim, 2000).

2.2.1.2. Sizing system development. Sizing and grading were one of the earliest commercial applications of anthropometry in the apparel industry (Gupta, 2014). Sizing refers to the process of setting up a size chart based on primary body measurements for a range of garment sizes. A sizing system is the set of size charts created for different body type categories of the population (Schofield & LaBat, 2005). Grading is the process that manufacturers used to
produce garments in a range of sizes in the apparel industry; it is a standard method of changing the pattern size by applying increases or decreases at certain points. The sizing specifications are derived from anthropometric surveys, and the grading systems are developed based on the sizing specifications (Moore, Mullet, & Young, 2001; Schofield & LaBat, 2005).

Large scale anthropometric surveys have been conducted to collect a large number of human body measurements to provide the basis for research and facilitate creating the sizing system for mass production apparel products and equipment for military personnel (Gupta, 2014). The anthropometric data are statistically analyzed to export the standard body measurements (SBM) size charts of the target population. To develop an acceptable and satisfying sizing system, it requires a good understanding of the target population and variation of body dimensions and accurate body dimensions taken from the scientific anthropometric survey.

**2.2.1.3. Mass customization.** Although the development of sizing system and grading methods have largely benefited mass production by reducing manufacturing time and cost, consumers still complain about the fit of garments, because the current body sizing system in the U.S. provides a standard data for each size, dismissing the unique body shapes and expecting all bodies to fit into the standard-sized garments (Bye, Labat, & Delong, 2006). During the past few decades, many fit problems have increased among consumers due to the loss of human shapes diversity caused by mass production. The older population (65 and older) is growing fast with the first wave of baby boomers turning 65 after 2011. Research has shown that for several decades female consumers in this population have reported complaints about the difficulty of finding well-fitting, comfortable clothing in stores (Lee, Damhorst, Lee, Kozar, & Martin, 2012).
Other consumers also complain that their perception of fit cannot be addressed and face confusion brought by the size differences between different brands (Bickle, Burnsed, & Edwards, 2015; Murray, 2016;). Therefore, mass customization could become an ideal solution to satisfy consumer demands.

Mass customization is a marketing and manufacturing technique that creates variety and customization through flexibility and quick response to the “voice of the consumer” (Little & Senanayake, 2010). Mass customization (MC) is characterized as a highly information sensitive way to maximize differentiation under a relatively low-cost level (Pine & Davis, 1993; Yeung & Ho-Ting, 2010). The process of apparel mass customization can be defined in five steps: collect anthropometric data, select fabric, and style, generate clothing patterns, cut the fabric, manufacture and conduct final adjustment (Lu, Wang, Chen, & Wu, 2010). Compared to traditional mass production, mass customization has advantages in innovative design and consumer-centric fit, which allow it to achieve a higher individual consumer satisfaction (Yang, Kincade, & Chen-Yu, 2015).

2.2.1.4. 3D model recreation and virtualization. Online shopping has been a growing trend in the 21st century. The internet has promoted the development of electronic retailing by reducing the inventory pressure of retailers and improve convenience for consumers. However, the convenience brought by the internet also changes consumers’ shopping experience. Without in-person visits, consumers have lost the chance of putting on the garment to assess fit and aesthetics. To improve the online shopping experience, many retailers have turned to advanced technologies like virtual-try-on, virtual-fit, and virtual reality to allow interaction with the products (Kim & Forsythe, 2008; Loker, Ashdown, & Carnrite, 2008).
The virtualization technologies help deliver product information that is close enough to real products. During the past few years, research has been focused on 3D model recreation, clothing fit evaluation, and fabric model performance improvement (Cichocka, Bruniaux, & Frydrych, 2014; Kim & Forsythe, 2008; Zhang, Lin, Pan, & Xiang, 2015). Three-dimensional body scanning technology has provided significant help for the anthropometric data collection and 3D model recreation using a set of point-cloud data.

Some commercial virtualization applications are now open to the market to allow consumers to predict garment fit. My Virtual Model website is one example, consumers can customize the body shape and some basic facial features to create a 3D avatar to get a preview of how they will look like wearing the garments (myvirtualmodel.com, 2018). Figure 11 shows the customized 3D avatar options on My Virtual Model website. Other virtualization applications like Marvelous Designer, Tri Mirror, Gerber 3D, Lectra 3D, EFI Optitex also help designers and apparel manufacturers in creating and adjusting patterns from 2D to 3D and from 3D to 2D (Figure 12).

Figure 11. Customize 3D Avatar on My Virtual Model (myvirtualmodel.com, 2018).
2.2.1.5. Other uses. Anthropometric data is also used in fields like health evaluation and product development. With the development of 3D body scanning technology, researchers have used 3D scanning data for shape and motion capturing in 3D printing and animation (Razzaq, Wu, Zhou, Ali, & Iqbal, 2015; Sturm, Bylow, Kahl, & Cremers, 2013).

2.2.2. Primary and Secondary Body Measurements

The primary measurements are defined as the basic dimensions that are used for clothing size designation, while the secondary measurements are the dimensions that may “additionally used in such size designation system” (ISO, 2017). These body dimensions are independent of different garment types. In this section, ISO and ASTM standards are covered as the most widely accepted standards in the U.S. market. ISO standards are developed by the International Standard Organization as a worldwide federation of national standards bodies (ISO member bodies). By the end of 2018, the International Standard Organization has published 22654 international
Standards, provided guidelines and specifications for different products and services (ISO, 2018).

In the apparel industry, ISO standards are universally accepted by designers, manufacturers, and researchers. On the other hand, the ASTM standards that are widely accepted in the United States were made by ASTM International, known as the American Society for Testing and Materials. This nonprofit organization has developed around 12,000 technical standards focusing on testing procedures and material classification (https://webstore.ansi.org/SDO/ASTM). To cover the national and international requirements on body measuring techniques, standard ISO 7250, ISO 8559, ASTM 5219 are selected for definition and landmark discussion. Standard ISO 20685 will also be covered, considering a discussion on 3D body scanning. Details of the standards are listed in Table 1.

Table 1

ISO And ASTM Standards on Body Measuring Technique

<table>
<thead>
<tr>
<th>Standard Name</th>
<th>Scope</th>
<th>Publication Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 7250-1 Basic human body measurements for technological design -- Part 1 Body measurement definitions and landmarks</td>
<td>Anthropometric Survey</td>
<td>2017-08</td>
</tr>
<tr>
<td>ISO 8559-1 Size designation of clothes -- Part 1 Anthropometric definitions for body measurement</td>
<td>Clothing</td>
<td>2017-03</td>
</tr>
<tr>
<td>ISO 8559-2 Size designation of clothes -- Part 2 Primary and secondary dimension indicators</td>
<td>Clothing</td>
<td>2017-03</td>
</tr>
<tr>
<td>ISO 20685-1 3-D scanning methodologies for internationally compatible anthropometric databases -- Part 1 Evaluation protocol for body dimensions extracted from 3-D body scans</td>
<td>Clothing</td>
<td>2018-10</td>
</tr>
</tbody>
</table>
Among the standards above, ASTM D5219-15 (ASTM International, 2015), ISO 8559-1 (ISO, 2017b), and ISO 8559-2 (ISO, 2017c) are specifically designed for apparel industry application. Measurements in ISO 7250-1 are developed for anthropometric database creation and population group comparison. Standard ISO 8559-2 will be discussed to understand primary and secondary measurements better. The definitions and illustrations of landmark locations of these primary and secondary measurements are listed below in Table 2.
### Table 2

*Primary and Secondary Measurements Based on ISO 8559 and ASTM 5219 (ISO, 2017c; ASTM, 2015)*

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Bust Girth</td>
<td>Jackets, Suits, Overcoats, Dresses, Knits (cardigans, sweaters, T-shirts), shirts/blouses, Full bodies (overalls, full swimwear, skiwear, and bibs); Undervest; nightwear, corsetry (bras; corsetry upper and full body)</td>
<td>Primary</td>
<td>The horizontal girth of torso measured at a bust point level</td>
<td>The horizontal circumference around the torso, taken under the arms and across the fullest part of the chest/bust apex including the lower portion of the shoulder blades.</td>
</tr>
<tr>
<td>2</td>
<td>Waist Girth</td>
<td>Jackets, Suits, overcoats, trousers/shorts, skirts, dresses, full bodies: (overalls, surf suits, full swimwear, skiwear, brace, and bibs); underpants, trunk, nightwear, corsetry upper and full body)</td>
<td>Secondary</td>
<td>The horizontal girth of the body measured at the waist level</td>
<td>The horizontal circumference around the torso taken at the waist.</td>
</tr>
<tr>
<td>3</td>
<td>Hip Girth</td>
<td>Jackets, overcoats, dresses, full bodies: (overalls, surf suits, wetsuits, bicycling gear, full swimwear, skiwear, brace, and bibs); undervest, nightwear, swimwear, corsetry upper and full body; panty girdle</td>
<td>Secondary</td>
<td>The horizontal girth of the body measured at the hip level</td>
<td>The maximum horizontal circumference around the torso taken at the greatest protrusion of the buttocks, as seen from the side.</td>
</tr>
<tr>
<td>4</td>
<td>Underbust Girth</td>
<td>Swimwear (with cups), bras, corsetry upper and full body (with cups)</td>
<td>Primary</td>
<td>The horizontal girth of the body at the underbust level</td>
<td>The horizontal circumference around the torso under the arms and bust.</td>
</tr>
</tbody>
</table>
Table 2

**Primary and Secondary Measurements Based on ISO 8559 and ASTM 5219 (ISO, 2017c; ASTM, 2015) Continued**

<table>
<thead>
<tr>
<th>#</th>
<th>Measurement</th>
<th>Garment Application</th>
<th>Measurement type</th>
<th>Measurement Definition from ISO 8559-1 (ISO, 2017b)</th>
<th>Measurement Definition from ASTM5219 (ASTM International, 2015)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The straight distance from the prominence of the back of the heel to the prominence of the longest toe, taken with the foot on a flat surface without shoes (use stable, flat ruler).</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>Foot Length</td>
<td>Socks, Stocking, knee-highs</td>
<td>Primary</td>
<td>Distance from rear of the heel to the tip of the longest (first or second) toe, measured parallel to the longitudinal axis of the foot.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The straight distance from the prominence of the back of the heel to the prominence of the longest toe, taken with the foot on a flat surface without shoes (use stable, flat ruler).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Hand Girth</td>
<td>Gloves</td>
<td>Primary</td>
<td>Maximum girth over the knuckles.</td>
<td>The maximum circumference of the hand around the knuckles excluding the thumb, taken with the fingers together.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Head Girth</td>
<td>Headwear</td>
<td>Primary</td>
<td>Maximum, approximately horizontal, the girth of the head measured above the centre point of brow ridge and crossing the rearmost point of the head. Hair shall be included in the measurement.</td>
<td>The maximum horizontal circumference of the head above the ears.</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Height</td>
<td>Jackets, Suits, overcoats, trousers/shorts, skirts, dresses, knits: (cardigans, sweaters, T-shirts); shirts/blouses, full bodies: (overalls, surf suits, full swimwear, skiwear and bibs); undervest, underpants, trunk, leggings, , swimwear; corsetry upper and full-body, corsetry lower body</td>
<td>Secondary</td>
<td>The vertical distance from the highest point of the head in the median line to the ground.</td>
<td>The vertical distance from the crown of the head to the floor, taken with subject standing and without shoes</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Weight</td>
<td>pantyhose</td>
<td>Secondary</td>
<td>The total mass of the body.</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 2

*Primary and Secondary Measurements Based on ISO 8559 and ASTM 5219 (ISO, 2017c; ASTM, 2015) Continued*

<table>
<thead>
<tr>
<th>#</th>
<th>Measurement</th>
<th>Garment Application</th>
<th>Measurement type</th>
<th>Measurement Definition from ISO 8559-1 (ISO, 2017b)</th>
<th>Measurement Definition from ASTM5219 (ASTM International, 2015)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Inside Leg Length/ Crotch height</td>
<td>Suits (set of jacket and trouser together); trousers/shorts, leggings, longjohns;</td>
<td>Secondary</td>
<td>The vertical distance between the inside leg level and outer ankle point.</td>
<td>The vertical distance from the midpoint of the crotch to the floor, taken with the subject standing and without shoes.</td>
<td><img src="image1" alt="Figure" /></td>
</tr>
<tr>
<td>11</td>
<td>Neck Girth/ Mid-neck Girth</td>
<td>Shirts/blouses</td>
<td>Secondary</td>
<td>The girth of the neck at a point just below the bulge at the thyroid cartilage (Adam's apple) and measured perpendicular to the longitudinal axis of the neck.</td>
<td>The horizontal circumference of the neck, taken approximately 25 mm (1 inch) above the neck base level.</td>
<td><img src="image2" alt="Figure" /></td>
</tr>
<tr>
<td>12</td>
<td>Underarm Length</td>
<td>Shirts/blouses</td>
<td>Secondary</td>
<td>The distance between the armpit front fold point and palm side of the wrist at a level of the wrist point.</td>
<td>The distance from the mid-underarm point of the armpit to the inner wrist bone, taken with the arm down.</td>
<td><img src="image3" alt="Figure" /></td>
</tr>
<tr>
<td>13</td>
<td>Arm Length/ Outer Arm Length</td>
<td>Shirts/blouses</td>
<td>Secondary</td>
<td>Distance from shoulder point to wrist point.</td>
<td>The distance from the top of the shoulder joint along the outside of the arm over the elbow to the prominent wrist bone, taken with the arm bent (1.57 rad or 90°) and the hand placed on the hip.</td>
<td><img src="image4" alt="Figure" /></td>
</tr>
</tbody>
</table>
Table 2

**Primary and Secondary Measurements Based on ISO 8559 and ASTM 5219 (ISO, 2017c; ASTM, 2015) Continued**

<table>
<thead>
<tr>
<th>#</th>
<th>Measurement</th>
<th>Garment Application</th>
<th>Measurement type</th>
<th>Measurement Definition from ISO 8559-1 (ISO, 2017b)</th>
<th>Measurement Definition from ASTM5219 (ASTM International, 2015)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Back neck point (Cervicale) to wrist length</td>
<td>Shirts/blouses</td>
<td>Secondary</td>
<td>The distance across the shoulder and down the arm from the back neck point over the shoulder point and the elbow point to the wrist point.</td>
<td>The distance from the cervical over the top of the shoulder joint, along with the outside of the arm, over the elbow to the prominent wrist bone, taken with the arm bent 1.57 rad (90°) and the hand placed on the hip.</td>
<td><img src="image1.png" alt="Figure" /> <img src="image2.png" alt="Figure" /></td>
</tr>
<tr>
<td>15</td>
<td>Calf girth</td>
<td>Socks</td>
<td>Secondary</td>
<td>The maximum horizontal girth of the calf.</td>
<td>The maximum horizontal circumference of the lower leg, taken between the knee and the ankle.</td>
<td><img src="image3.png" alt="Figure" /> <img src="image4.png" alt="Figure" /></td>
</tr>
<tr>
<td>16</td>
<td>Ankle Girth</td>
<td>Socks</td>
<td>Secondary</td>
<td>The horizontal girth of the leg measured at the level of the outer ankle point.</td>
<td>The vertical distance from the prominence of the outer ankle bone to the floor, taken with subject standing and without shoes.</td>
<td><img src="image5.png" alt="Figure" /> <img src="image6.png" alt="Figure" /></td>
</tr>
<tr>
<td>17</td>
<td>Hand Length</td>
<td>Gloves</td>
<td>Secondary</td>
<td>Distance from the tip of the middle finger to the most distal wrist crease.</td>
<td>The straight distance from the prominence of the most extended finger to the inner wrist bone, taken across the palm with fingers together and palm flat (use a stable, flat ruler).</td>
<td><img src="image7.png" alt="Figure" /> <img src="image8.png" alt="Figure" /></td>
</tr>
</tbody>
</table>
2.2.3. Anthropometric Methods

The purpose of anthropometric methods is to ensure the comparability of human body measurements made by different operators and repeated measurements made by the same operator (Kouchi, 2014). The traditional anthropometric method can be traced back to more than one hundred years ago using simple tools like a tape measure and calipers to manually measure the human body. With the development of technology, three-dimensional body scanners became available as a new non-contact body measuring method.

2.2.3.1. Hand measure (1D method). The traditional anthropometric measurement uses simple, quick, non-invasive tools, including a weight scale, camera, measuring tape, anthropometer, spreading caliper, and sliding caliper (Kouchi, 2014; Simmons, & Istook, 2003). Figure 13 shows the primary tools used in traditional hand measure. The anthropometer is used for measuring the vertical distance from a specific landmark to the floor. The operator holds the rod vertical and slides the arm to the target landmark to get the measurements. The sliding caliper (Figure 13b & c) including one to two rods of the anthropometer and two arms, it can be used for breadth, depth, or other measurements between two landmarks. The spreading caliper, as shown in Figure 13 (d), is used for specific measurements like chest depth, mid-sagittal plane, and head length when the two tips of sliding caliper could not touch two landmarks at the same time. The tape measure is the most critical measurement tool for circumference and surface distance. It is also the measurement tool that most likely to cause measurement error if not operated correctly. The tape measure should not be stretched while measuring the object, and the zero points should overlap the scale on the tape measure, as shown in Figure 13 (e) (Kouchi, 2014).
Due to the low-cost measuring tools, the traditional hand measuring method became the most commonly used method for a long time in the apparel industry. However, this method has disadvantages as time-costing and relatively low comparability between different operators. Related studies have pointed out that 3D body scanning takes much less time than anthropometric methods. Full-body 3D scanning captures 3D data in about 12–15 seconds, creating a computer image in less than 1.5 minutes while traditional methods may take around 4 hours to conduct physical landmarks, measure, and record the data of one subject (Ashdown, Loker, Schoenfelder, & Lyman-Clarke, 2004; Simmons, & Istook, 2003). As for accuracy, the most troublesome problem using the traditional method is the observer error caused by
imprecision in a landmark location, subject positioning, and instrument applications (Simmons, & Istook, 2003). The result of measurement may vary from each measurer even when they are trained similarly.

2.2.3.2. 3D body scanning. According to the standard ISO 20685, the three-dimensional (3D) scanner is an instrument with a relatively new application to anthropometry. 3D body scanners include hardware and software that creates digital data representing a human form or a part of the human body in three dimensions; the digital data generates the human form into a 3D point cloud that can be applied in clothing, automotive design, engineering, and medical fields. Users are allowed to extract one-dimensional (1D) measurement data from the 3D point clouds and use this anthropometric data for design application. Several companies have been researching this technology for over 30 years; the most well-known ones are (TC’), Cyberware, SYMCAD, and Vitronic. Their 3D scanning products have been widely used in movies, games, and the apparel industry. Some well-known apparel companies like Nike, Wrangler, Kohl’s, and Levi’s are currently applying 3D body measurement and simulation technology in their product development process. This is used to evaluate product fitness, design new products, and cut the cost of time and money in designing and prototyping stage of product development (Song, & Ashdown, 2015).

Currently, there are several different methods used in 3D body scanning. They can be divided into four different methods: laser scanning, the projection of white light patterns, millimeter waves, and depth camera scanning.
2.2.3.2.1. 3D Laser scanning. Laser scanning technology use lasers to project onto the human body with one or more thin light stripes. The laser scanner unit, which is composed of the laser, the light sensor, and the optical system, is moved across the human body to digitize the surface. The number of laser sensors in the unit is usually determined by the body part to be scanned. The advantage of this scanning technology is the high accuracy, low measurement noise, and high resolution. However, the laser scanner is known to have a higher cost on hardware compared to other scanners, and it requires a longer time digitizing large surface (D'Apuzzo, 2007). The examples of these products are Cyberware’s WBX, WB4, and Voxelan.

![Example of a laser-based scanner](image)

Figure 14. Example of a laser-based scanner (Daanen, & Ter Haar, 2013).

2.2.3.2.2. Projection of white light patterns. This technology requires a grid plane, camera, white light source (usually referred to as Halogen lamp), and operating system. As shown in Figure 15, a light pattern (usually in the form of stripes) is projected onto the human body, one or more light sensors are used to acquire the scene, and the stripes captured on the surface of objects are measured singularly using triangulation. The advantage of white light scanning is that the scanning
process happens in a concise time frame, within one second, so that any uncontrollable body movement can be successfully avoided during scanning. The disadvantage is the limitation of the scanning area; usually, one device is not enough to scan the whole human body, so various equipment needs to be used serially, which may extend the time of scanning and increase the cost (D'Apuzzo, 2007). Companies like (TC2) and Vitronic have been developing the white light scanner and use them for whole body scanning.

Figure 15. (a): projection of light pattern as stripes. (b): scanning device. (c): a projected sequence of binary-coded stripes pattern (D'Apuzzo, 2007).

2.2.3.2.3. **Millimeter waves.** Active scanners use the reflection patterns of millimeter waves projected on the body, while passive scanners process the millimeter waves that are emitted by the human skin. A unique advantage of the millimeter wave scanning is that it can pass through most clothing but not the skin, which means the human body shape can be captured without undressing. Currently, this technology is mainly used in airport security checks, but the efficiency also brings up the ethical issue of privacy because private parts of the human body can be seen (Daanen, & Ter Haar, 2013).
2.2.3.2.4. **Depth sensor.** Depth sensors like Kinect and Time-of-Flight (ToF) cameras are considered to be a good choice of lower cost for body measurement currently. These sensors recover measure the time-of-flight of a light signal between the camera and the subject for each point of the image based on the known speed of light. The advantage of this new scanning technology is a much lower cost than other scanning sensors, but it comes with the price of high noise level, lower resolution, and significant systematic measurement bias. Recently several studies have pointed out that combining specific algorithms can help increase the resolution and accuracy of a depth camera in a limited range (Tong, Zhou, Liu, Pan, & Yan, 2012; Lee, Damhorst, Lee, Kozar, & Martin, 2012).

2.2.3.2.5. **Other input devices.** As mentioned above, due to the features of optical 3D body scanners like laser scanners and white light scanners, the limitation of the scanning area needs to be created by adding the number of sensors. To avoid extra cost, companies producing specific products like footwear, gloves, and helmets are looking into scanners dedicated to specific body parts. Foot scanners, hand scanners, head scanners, and whole-body scanners are developed to target specific products.

Foot scanners are mainly used for the footwear industry for customized footwear products and sports shoes comfort improvement. The measurement includes foot length, ball girth circumference, foot breadth, instep circumference, heel breadth, instep length, fibular instep length, the height of the top of ball girth, the height of instep, height of navicular, toe #1 angle, and toe #5 angle, arch length, and angle of heel bone using multiple laser beams (Park, 2012).

Hand scanners are used to develop good fitting customized gloves. Hand length, hand circumference, finger root circumference, interphalangeal joint circumference, finger length,
length of the root of thumb to the inner wrist, and length of the root of the little finger to the outer wrist are measured. To improve the accuracy, 3D hand scanning should be combined with 2D hand scanning to reduce the errors on edge. (Yu, Yick, Ng, & Yip, 2013)

Head scanners are mostly used to develop helmets for sports or scanning face data. In this case, the 3D scanner is mainly used to capture the head shape for digital output, and product developers can create landmarks on the 3D model to better analyze head measurement data and develop user-centered products accordingly (Mustafa, Pang, Perret-Ellena, & Subic, 2015).

Whole-body scanners are widely used to collect data from the whole body for apparel product development. White light scanners are more commonly used in this area to avoid unnecessary body movement by completing a scan in seconds.

2.2.3.3. Standard and measurement extraction for 3D scanning. Standard ISO 20685 is specifically designed to ensure the comparability of body measurement data collected through 3D body scanners. The definition of measurements is based on the definitions from ISO 7250-1. During the 3D scanning process, the position of the subject is crucial. Subjects should breathe normally, keep shoulders straight without being stiff, and keep muscles relaxed. Figure 16 shows the four recommended positions for 3D body scanning.

Definitions of body measurements in 3D body scanning are referred to standard ISO 7250-1 to be comparable with manual measurements. However, not all the measurements are extractable since the resolution of a 3D body scanner may not allow accurate measurement extraction from small body parts such as hands. Measurements that are most likely to produce accurate results are listed in Table 3.
To provide useful human body measurement data from 3D body scanning, specific algorithms also need to be developed to define the measuring content according to anthropometry. The details and methods of data processing may be different between algorithms, but they are following the same structures and principles to collect measurement data. The automatic body measurement process can be divided into three steps: (1) segment 3D body data; (2) identify landmarks on 3D body data; and (3) measure the human body (Lu & Wang, 2008; Han, & Nam, 2011). Following these three steps, the algorithm first segments the 3D model into five parts, including the head, torso, both arms, and both legs. Secondly, landmarks are identified on the 3D model. In general, anthropologists will place markers or stickers on the surface of the human body to highlight the position. For the marker-less human body, specific algorithms will be required to automatically build a coordinate system based on the standard of ISO and ASTM to identify the landmarks (Leong, Fang, & Tsai, 2007). Finally, based on the extracted landmarks, measurements can be made by placing a virtual measuring tape or caliper on the surface of the human body.
### Table 3

**ISO 7250-1 Measurements by a 3D Whole Body Scanner (ISO, 2018)**

<table>
<thead>
<tr>
<th>#</th>
<th>Measurement</th>
<th>Position Type</th>
<th>The definition in ISO 20685-1 (ISO 20685, 2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stature (body height)</td>
<td>B</td>
<td>The vertical distance from the floor to the highest point of the head (vertex)</td>
</tr>
<tr>
<td>2</td>
<td>Eye height</td>
<td>B (standing)/ D (sitting)</td>
<td>The vertical distance from the floor to the outer corner of the eye</td>
</tr>
<tr>
<td>3</td>
<td>Shoulder height</td>
<td>B (standing)/ D (sitting)</td>
<td>The vertical distance from the floor to the acromion</td>
</tr>
<tr>
<td>4</td>
<td>Iliac spine height, standing</td>
<td>C (standing)/ D (sitting)</td>
<td>The vertical distance from the floor to the anterosuperior iliac spine (the most downward-directed point of the iliac crest)</td>
</tr>
<tr>
<td>5</td>
<td>Crotch height</td>
<td>B</td>
<td>The vertical distance from the floor to the distal part of the inferior ramus of the pubic bone</td>
</tr>
<tr>
<td>6</td>
<td>Tibial height</td>
<td>B</td>
<td>The vertical distance from the floor to the tibiale</td>
</tr>
<tr>
<td>7</td>
<td>Chest depth, standing</td>
<td>A, B</td>
<td>The depth of the torso measured in the midsagittal plane at the mesosternal level</td>
</tr>
<tr>
<td>8</td>
<td>Body depth, standing</td>
<td>A, B</td>
<td>Maximum depth of the body</td>
</tr>
<tr>
<td>9</td>
<td>Chest breadth, standing</td>
<td>A</td>
<td>The breadth of the torso measured at the mesosternal level</td>
</tr>
<tr>
<td>10</td>
<td>Hip breadth, standing</td>
<td>A</td>
<td>The maximum horizontal distance across the hips</td>
</tr>
<tr>
<td>11</td>
<td>Sitting height (erect)</td>
<td>D</td>
<td>The vertical distance from a horizontal sitting surface to the highest point of the head (vertex)</td>
</tr>
<tr>
<td>12</td>
<td>Cervicale height, sitting</td>
<td>D</td>
<td>The vertical distance from a horizontal sitting surface to the cervicale.</td>
</tr>
<tr>
<td>13</td>
<td>Shoulder-elbow length</td>
<td>C</td>
<td>The vertical distance from acromion to the bottom of the elbow bent at a right angle with the forearm horizontal</td>
</tr>
<tr>
<td>14</td>
<td>Shoulder (biacromial) breadth</td>
<td>A, B</td>
<td>The distance along a straight line from acromion to the acromion</td>
</tr>
<tr>
<td>15</td>
<td>Shoulder (biacromial) breaching</td>
<td>A, B</td>
<td>The distance across the maximum lateral protrusions of the right and left deltoid muscles</td>
</tr>
<tr>
<td>16</td>
<td>Elbow-to-elbow breadth</td>
<td>D</td>
<td>The maximum horizontal distance between the lateral surfaces of the elbow region.</td>
</tr>
<tr>
<td>17</td>
<td>Hip breadth, sitting</td>
<td>D</td>
<td>The breadth of the body measured across the widest portion of the hips.</td>
</tr>
<tr>
<td>18</td>
<td>Thigh clearance</td>
<td>D</td>
<td>The vertical distance from the sitting surface to the highest point on the thigh.</td>
</tr>
<tr>
<td>19</td>
<td>Knee height, sitting</td>
<td>D</td>
<td>The vertical distance from the floor to the highest point of the superior border of the patella (suprapatella, sitting).</td>
</tr>
<tr>
<td>20</td>
<td>Abdominal depth, sitting</td>
<td>D</td>
<td>Maximum depth of the abdomen while sitting.</td>
</tr>
<tr>
<td>21</td>
<td>Buttock-abdomen depth, sitting</td>
<td>D</td>
<td>Projected maximum horizontal depth of the lower torso between the maximum anterior protrusion of the abdomen and the maximum posterior protrusion of the buttock.</td>
</tr>
<tr>
<td>22</td>
<td>Elbow-wrist length</td>
<td>C</td>
<td>The horizontal distance from the wall to wrist (ulnar styloid process)</td>
</tr>
<tr>
<td>23</td>
<td>Forearm-fingertip length</td>
<td>C</td>
<td>The horizontal distance from the back of the upper arm (at the elbow) to the fingertips, with the elbow, bent at right angles</td>
</tr>
<tr>
<td>24</td>
<td>Buttock-popliteal length (seat depth)</td>
<td>D</td>
<td>The horizontal distance from the hollow of the knee to the rearmost point of the buttock</td>
</tr>
<tr>
<td>25</td>
<td>Buttock-knee length</td>
<td>D</td>
<td>The horizontal distance from the foremost point of the knee-cap to the rearmost point of the buttock.</td>
</tr>
<tr>
<td>26</td>
<td>Neck circumference</td>
<td>A, B</td>
<td>The circumference of the neck at a point just below the bulge at the thyroid cartilage</td>
</tr>
<tr>
<td>27</td>
<td>Chest circumference</td>
<td>A</td>
<td>The circumference of the torso measured at nipple level</td>
</tr>
<tr>
<td>28</td>
<td>Waist circumference</td>
<td>A</td>
<td>The circumference of the trunk at a level midway between the lowest ribs and the upper iliac crest</td>
</tr>
<tr>
<td>29</td>
<td>Wrist circumference</td>
<td>A</td>
<td>The circumference of the wrist at the level of the styloid processes of the radius and ulna, with the hand outstretched</td>
</tr>
<tr>
<td>30</td>
<td>Thigh circumference</td>
<td>A</td>
<td>The maximum circumference of the thigh</td>
</tr>
<tr>
<td>31</td>
<td>Calf circumference</td>
<td>A</td>
<td>The maximum circumference of the calf</td>
</tr>
</tbody>
</table>
Currently, the most commonly used automatic body measurement extraction systems are the Size Stream and [TC]: scanners and software programs. These two programs have been referring to standard ISO 7250 and ISO 8559, which both offer more measurements than listed in ISO 20685 (Size Stream, 2017; ISO, 2010). The difference is that the [TC]: programs allow users to set customize parameters like bust, waist, and hips while Size Stream only allows the definition of waist parameter. Other customize parameters must be created as new parameters.

2.2.3.3. Concerns of 3D body scanning. Although 3D body scanning technology has proved to be efficient in measuring the human body in a short time and considerable accuracy, there are still several scanning issues that need to be addressed. First, the precision of the scanner should be evaluated and compared with other scanners before application in designing and manufacturing to avoid the error of landmarks. Secondly, consumer attitude should also be considered for customized product development. The development of 3D body scanning may bring a privacy concern for consumers as they need to wear underwear or close-fitting garments while scanning. Consumers may feel their privacy violated or feel unsatisfied with what their scan model projects look like and refuse to accept 3D body scanning technology. Another consumer concern is the cost of 3D body scanning services and related products. According to the survey, consumers with specific demands in fitness are willing to pay an extra sum within 30%-50% of the garment price for 3D body scanning services, in addition to the price of clothing (Lee, Damhorst, Lee, Kozar, & Martin, 2012).
2.2.3.4. Measure through 2D images. Two-dimensional (2D) imaging techniques have been explored as an alternative for body measuring in both academic research and commercial applications (H. A. Daanen & Ter Haar, 2013). Different from one-dimensional manual measurement methods and the relatively advanced three-dimensional body scanning technology, the two-dimensional body measuring method is commonly considered as a relatively low-cost substitute for three-dimensional body scanning. This method uses 2D images without depth information to rebuild three-dimensional models based on silhouette information. Usually, the front and side images will be used as references.

To find the best solution for rebuilding the three-dimensional models and extract measurement results, research has been conducted. In 2006, Seo, Yeo, and Wohn released a method of mapping two-dimensional images to a parameterized deformable model based on 40 3D body scans. By 2012, Saito et al. developed a simple model to construct 3D shapes using a parameterized model. Additional research in 2013 made by Watson and Evans used a different method by partitioning the 2D images into segmentations and producing a probability map representing the subject. It then finds the closest 3D body model from a database based on the probability map and extracts body measurements from the 3D model. Other research explores the possibility of finding key points and measuring from the front and side image using extracted measurements to predict non-measurable measurements like circumferences using a simple linear model (Gazzuolo et al., 1992; Lin & Wang, 2011; Meunier & Yin, 2000).

The two-dimensional body measuring method provides a low-cost solution for non-contact human body measurement, and the measurement output is reliable for the apparel industry application. The main concern of using this method is that a clean background is needed to identify the outline of the human body. In the previous study, most researchers used pure
colors such as black or green. However, the backgrounds in daily life would be more complicated and more colorful, which could bring difficulty for silhouette identification (Lin & Wang, 2011; Seo et al., 2006). Another concern is privacy issues. Consumers must wear close-fitting garments or underwear while taking 2D images for two-dimensional body measurements to guarantee the accuracy, and this may bring a privacy discomfort (Grogan et al., 2017; Loker et al., 2004).

2.2.3.4.1. Measuring apparatus. As stated above, the privacy issue has been a concern for consumers while using non-contact body measuring technologies. The measuring apparatuses are developed to release these concerns and assist in measuring human bodies. The measuring apparatus can be divided into two types: pattern-based measuring apparatus and circuit-based measuring apparatus. The pattern-based apparatus was developed to help locate landmarks on the human body so that a traditional hand measuring method and two-dimensional measuring methods can be efficiently conducted. Figure 17 shows the stretch bodysuit for preparing custom-fitted clothing, invented by Liebermann in 2002. This bodysuit splits the surface into multiple parts to locate the landmarks. Figure 18 shows the measuring apparatus designed to work with imaging technologies. The circuit-based suit, as shown in Figure 19, could measure the human body by itself. This sample garment is made by Like A Glove Ltd., circuits and sensors were added to the predicted landmark location to collect human body measurements (Likeaglove, 2015).

These circuits-base body measuring apparatuses have some fatal limitations. First, they cannot be used in public, the designs were not acceptable for casual wear and sweating may become a threat to the service life of the product. Second, these apparatuses are not washable and
cannot change batteries, which further limited the application and reduced consumer desire to buy them.

![Diagram](image)

Figure 17. The stretch bodysuit developed for preparing custom-fitted clothing (US 2002/0166254 Al, 2002).

![Image](image)

Figure 18. The elastic measuring suit from elasizer (elasizer, 2017).

![Image](image)

Figure 19. The self-measuring garment using circuits (Likeaglove, 2015).
2.2.3.4.2. **Current 2D measuring products in the market.**

2.2.3.4.2.1. **ZOOSUIT.** ZOOSUIT was developed by Start Today Co., Ltd, the owner of the largest Japanese online apparel shopping website, “ZOOTOWN.” The latest version of ZOOSUIT is using a full-body marker recognition system which contains more than 350 different dot markers around the human body as fiducial markers for 3D model recreation. The garment itself is designed using thumb holes, foot straps, and a turtle neck to cover most of the human body (ZOZO, 2018). As shown below in Figure 20, the user is required to put on the ZOOSUIT correctly without wrinkles, put their cell phone on an approximately 30-inch tall table roughly six feet from the user, and then the user will follow the voice command from the ZOOSUIT application to take 12 photos clockwise. The dot markers on the 12 photos will be captured and used for 3D model recreation. In the end, the application produces 16 measurements, including chest, upper waist, lower waist, hip, arm length, inseam, and circumferences of the neck, upper arm, thigh, calf, and ankle.

![Image of ZOOSUIT measuring process](image_url)

Figure 20. ZOZO suit measuring process (ZOZO Application, 2018).
According to the information from ZOZO.com, Start Today is planning to deliver 6-10 million ZOZOSUITS for free by the end of 2018. Their brand ZOZO is now developing their customized fitted clothing line by collecting consumer measurements and promoting machine learning of relationships between consumer measurements and apparel items (ZOZO, 2018). Consumers will be able to use the ZOZOSUITS to collect their body measurements, directly order the styles they prefer, and get their customized fitted garments within a few weeks.

2.2.3.4.2.2. 3Dlook. 3DLook is a body measuring application developed by a company called 3DLOOK Inc. This application allows users to measure themselves using a front view and a side view photo; the photo could be a “selfie” in front of a mirror, or a photo taken by another person, as shown in Figure 21. Without landmarks, 3DLook uses computer vision to analyze the photos. First, the front and side view photos were taken by a smartphone are used to detect human body outline in computer vision. The detected outline is then transferred to 3DLook’s neural network. Secondly, the neural network processes the outline and detects key points for body measurements and produces a set of possible maps for each key point. The maps are then combined and processed with predetermined filters in each stage. In the third step, the key points are used for 2D contour matching as initialization. Next, a virtual camera builds 2D contour models into a parameterized 3D human body model and projects it onto an image plane. Finally, the virtual 2D models are matched with real 3D human body models to reduce errors while scanning the human body and processing the measurements. The 3D matching process is also applied for 3D human model recreation (3DLook.me, 2018).
Compared to measuring apparatuses with circuits design, these methods seem more acceptable in daily home use. However, the costume design of ZOZO cut off the possibility of public use, and the accuracy of the 3DLOOK application highly depends on the fit of the user's clothing. Therefore, measuring garments with reliable accuracy and acceptable design aesthetic could be an ideal solution for the 2D body measuring method.
CHAPTER 3. METHODOLOGY

The goal of this research is to develop a series of garments that can be used as a measuring apparatus in the 2D image body measuring system developed by the PrimeFit research team. Figure 23 shows the process of this existing two-dimensional image body measuring system. In this measuring system, a smartphone is used as the data collection tool to capture two-dimensional (2D) images. Basic demographics (1D) data, including height, weight, age, gender, and ethnicity, are collected as references. This body measuring system can predict human body measurements based on the collected 2D images and existing three-dimensional (3D) anthropometric databases. The developed system has reached a satisfying result being within the tolerance of hip girth prediction for online shopping, but the accuracy of waist girth and inseam length predictions still have room to be improved, with an increased dataset, this could be accomplished.

To assist this two-dimensional image body measuring system, the measuring garments need to fit the human body closely and can be distinguished from the background. The research questions to guide the evaluation of the measuring garments are listed below:

RQ1: Does the design and fit of the measuring garment affect the accuracy of measurements obtained from the 2D images of the human body?

1a. How does the design impact measuring results?

1a1. What kinds of patterns, colors, and styles can be used to obtain accurate measurements?

1a2. What are the appropriate color-design locations and sizes for landmarks on the human body?

1b. How does fit affect measurement results?
1c What kind of accuracy can be achieved?

RQ2: Does the arm position impact the accuracy of measurements obtained from the 2D images of the human body?

RQ3: Does the fashion element of the measuring garment impact the attitude of the consumer to purchase the garments using the measuring app?

3a. Does the design relate to the consumer expectation for activewear?

3a1: What are their expectations?

3a2: Do they have any preferences on the fit or design?

RQ4: Would consumers adopt this new technology? How would they use it (simply as a measuring tool or wear it as an outfit)?

The main target of this research was to find out how the design and fit of the measuring garments impact human body measurement data collection and extraction from 2D images. To achieve this target, the whole research process was split into three main steps: prototype design, data collection, and measurement extraction, and data analysis. The tools and research methods used in each step are listed in Figure 24. The first step was to design several prototypes of measuring garments, including different colors and patterns as landmarks. Research questions 1a1 and 1a2 were answered during this development process. The second step collected 1D, 2D, and 3D data. The data types and contents are listed in Figure 22. The 2D side view images were collected in two poses, one with arms beside the body and one with arms above head. This design was to collect 2D image data in different arm locations to compare the impact made by side view poses. Research question 2 is answered by comparing the 2D prediction results of these two poses.
After collecting all data needed, the PrimeFit two-dimensional image measuring system was used to extract five representative human body measurements from 2D images for further analysis and comparison. The third step analyzed all collected 1D data from the survey to answer research questions 2 and 3 as consumer demands and expectations on the measuring garments. The measurements extracted from 2D and 3D data were used to answer research questions 1b and 1c regarding finding out how the design and fit of the measuring garments impact the measurement results, which is the main target of this research.

Figure 22. 1D, 2D, and 3D data content.
Figure 23. Schematic of the developed body measuring system (Xia, 2018).
<table>
<thead>
<tr>
<th>Purpose</th>
<th>Data</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prototype Making</strong></td>
<td><strong>Data Collection</strong></td>
<td>Qualitative</td>
</tr>
<tr>
<td>Determine measurements to be considered</td>
<td>Collect 1D demographic, 2D image, and 3D body scanning data</td>
<td>ISO standards, ASTM standards</td>
</tr>
<tr>
<td>Make a prototype RQ 1a1 1a2</td>
<td><strong>2D and 3D data extraction</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1D, 2D, and 3D data for a group of female students with sample size of 50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Collected 2D images and 3D body scanning measurements</td>
<td>1D: Survey including demographic information and preference questions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2D: A smartphone and measuring garments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3D: Size Stream body scanner</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OpenCV-Python, Size Stream Studio, Scikit-image</td>
</tr>
<tr>
<td><strong>Data Analyze</strong></td>
<td>Collect survey data</td>
<td></td>
</tr>
<tr>
<td>Analyze collected survey data</td>
<td>Extracted measurements from 2D and 3D dataset</td>
<td>1D: Survey including demographic information and preference questions</td>
</tr>
<tr>
<td>Analyze consumer lifestyle and expectation on activewear RQ 3a, RQ 3a1.</td>
<td></td>
<td>2D: A smartphone and measuring garments</td>
</tr>
<tr>
<td>Analyze consumer attitude towards the measuring garment and the measuring system RQ4.</td>
<td></td>
<td>3D: Size Stream body scanner</td>
</tr>
<tr>
<td>Analyze collected measurement data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Compare 3D body scanning data with extracted 2D measurements RQ 1c and 2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Compare 3D data between wearing same design but different size measuring garments RQ 1b.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Compare extracted 2D data wearing same size but different design measuring garments RQ 1a.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 24. Summary of methodology.
3.1. Step One: Prototype Design

Stage one focused on developing a series of prototype measuring garments for data collection and user evaluation. The purpose of this stage was to explore possible design solutions and appropriate locations for landmarks. Standard ISO 8559-2 and ASTM 5219-15 were used as references. According to the definitions in Table 2, bust girth, waist girth, hip girth, and inseam length were selected as the most basic measurements to extract from 2D images because they are the most important measurements for the majority of apparel products. Other measurements like arm length, crotch height could be added into the designs for future research.

After selecting the representative measurements, research questions 1a1 and 1a2 were answered to locate the representative measurements on the measuring garments. This design was necessary to allow the measuring system to detect the measuring area. The standards and definitions mentioned above were considered while designing the measuring garments.

During the design process, color palettes and textile patterns were carefully selected for aesthetic evaluation. The color palettes and textile patterns were decided based on the most common styles and colors in the current female activewear market and fashion reports. Multiple attempts were required to get relatively satisfying design options based on consumer preferences. In this stage, three different designs were developed, presenting three levels of design elements contained. The three levels were: highly functional focused with very few design elements; a moderate combination of function and fashion; and a highly fashionable design that was very close to existing products in the market. This result supported answers to research questions 1a1 and 3a2.

Finally, after finishing the functional design and fashion design process, a sizing system was developed for grading and sizing. Different from the commercial activewear products in the
market, the measuring garments developed in this research were developed to cover more than one commercial size and fit a variety of body shapes. The garment pattern and sizing system were developed considering the stretchiness of fabric and the distribution of American female sizes. Standard ISO 8559-2 and ASTM D5585-11e1 were used to instruct the sizing system development, and the SizeUSA 3D body scanning dataset from TC\textsuperscript{2} was used as references. The new sizing system of the measuring garment will be from size XS to size XL, covering standard adult female missy figure type size range 0-18 based on standard ASTM D5585-11e1.

### 3.2. Step Two: Data Collection and Measurements Extraction

To evaluate the developed measuring garments and the two-dimensional body measuring system, 1D demographic and activewear preference data, 2D image data, and 3D body scanning data are collected for analysis. A request for IRB approval is submitted and approved for data collection, and the document is attached in Appendix A.

The 1D data was collected through an online survey. The survey contained three main sections. The first section was basic demographic data, including age, ethnicity, height, and weight. The second section included lifestyle and activewear shopping preference questions to understand how recruited participants exercise and use activewear in their daily life. The third section was answered after participants tried the measuring garments, participants were asked to evaluate the garments based on fit, comfort, design, and application of the garments they put on during the research process.

The 2D image data and 3D body scanning data were collected during the body measuring process. Participants were required to put on 4-5 sets of measuring garments, including three different designs and 2-3 different sizes: one that fits the best, one smaller size, and one larger
size. Participants in Size XS or XL did not have a smaller/larger size, so they only put on two different sizes. The best-fitting size for each subject was selected based on the height and weight information and feedback of fit and comfort. The subject was then required to put on a one-size-smaller garment and a one-size-bigger garment in the same design to collect the data of the same subject wearing measuring garments in a different fit. After trying different sizes, the subject was required to put on two other designs in the best-fitting size.

For each set of measuring garments, participants were firstly scanned in the Size Stream body scanner to collect 3D body scanning data, then stood under a 34.8” x 85.3” door frame to collect 2D image data using a smartphone. When taking 2D photos, participants were asked to stand in 3 poses: front view with both hands separated from body sides, side view with both hands close to the side seam of the legging, and side view with both hands above the head. The three poses are shown in Figure 25. The side view pose with both arms beside the body was considered the best side view pose because it is the same as the standard 3D body scan pose. The reason for having the third pose, side view with both hands above the head, was because some of the subjects have their arms covering their back when taking a side view photo (shown in Figure 25 b), which added bias for bust, waist, and hip girth predictions from the 2D images. Having both hands above the head may slightly change the bust measurements but helped predict the shape of the covered region in the side view image.
Figure 25. Example of 3 poses for 2D image data collection. (a) front view, (b) side view with arms down, (c) side view with arms above head.

To compare the measurements of 2D and 3D measuring methods, the four main measurements are bust girth, waist girth, hip girth, and inseam length need to be extracted from 3D body scanning files. It is important to define the four representative measurements because they must be extractable from the Size Stream Studio for further comparison between 2D and 3D measurements.

To extract representative measurements from a 2D image and evaluate the effect of measuring apparatus design, the LASSO (least absolute shrinkage and selection operator) regression model was trained using the Akaike information criterion (AIC) for model selection. The LASSO regression model is a linear model that tends to prefer solutions with fewer parameters. Using AIC criteria can discourage the model from being overfitting by considering the goodness of fit (residual errors) as well as the complexity of the model (number of selected
features). The extracted 3D measurements of sample group subjects used as an independent variable for model training.

To train the prediction models and evaluate their performance, subjects were separated into a sample group (40%) and a test group (60%). The images of sample group subjects wearing measuring apparatus were used to generate prediction models from the three different designs. The images of the test group were used to test the performance of the regression models.

3.3. Step Three: Data Analysis

In this step, data collected through the 1D survey was analyzed to understand consumer lifestyle regarding exercising and activewear purchasing preferences. To improve the prototype of measuring garments, it was crucial for the researcher to find out what consumers use activewear for in their daily life and what kinds of expectations they have when purchasing an activewear product. This result answered research questions three and 3a1. The feedback from participants about their evaluation of measuring garment’s fit and design was also valuable. This information indicated their preferences on the garment’s fit and design, and their acceptance of this new body measuring method. This result answered research questions 3a2 and 4.

The analysis of extracted 2D and 3D measurements was split into three sections: 3D vs. 3D, 2D vs. 3D, and 2D vs. 2D. First, 3D vs. 3D compared the extracted 3D measurements of the same subject wearing different sizes to find out if the fit of the measuring garments made any difference in the 3D body scanning measurement results. These two sections answered the research question 1. The second section, 2D vs. 3D, compared 2D measurements with 3D measurements to evaluate the accuracy of the two image labeling methods and two side view poses (arms beside the body and arms above head). Finally, 2D vs. 2D compared the extracted
2D measurements between 3 different designs of the same subject and the performance of prediction models to find out if different patterns and colors could make any difference in 2D measurement prediction.
CHAPTER 4. RESULTS AND DISCUSSION

4.1. Results and Discussions on Stage One

4.1.1. Generation 1 and 2 of Measuring Garment Prototype

To develop a measuring garment for the PrimeFit 2D image body measuring system, the first step was to locate important color-design locations for landmarks on the human body. According to the measurements listed in Table 2, section 2.2.2, and extractable 3D measurements listed in Table 3, section 2.2.3.3, bust girth, waist girth, hip girth, and inseam length were selected as representative measurements for further data extraction and comparison. Among these representative measurements, bust, waist, and hip girth were selected because they are the primary measurements for most of the existing apparel product categories like shirt, skirt, pants, and jackets. The inseam length was selected because it was the most important length measurement for pants and leggings, and it was the only length measurement in these four representative measurements. The selected representative measurements and their definitions are listed below in Table 4.

Table 4


<table>
<thead>
<tr>
<th>Measurement</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bust girth</td>
<td>The horizontal girth of torso measured at a bust point level (ISO, 2017b)</td>
</tr>
<tr>
<td>Waist girth</td>
<td>The horizontal girth of the body measured at the waist level (ISO, 2017b)</td>
</tr>
<tr>
<td>Hip girth</td>
<td>The maximum horizontal circumference around the torso taken at the greatest protrusion of the buttocks as seen from the side (ASTM International, 2015)</td>
</tr>
<tr>
<td>Inseam leg length</td>
<td>The vertical distance from the midpoint of the crotch to the floor, taken with the subject standing and without shoes (ASTM International, 2015)</td>
</tr>
</tbody>
</table>
After selecting the four representative measurements, the first generation of the measuring garment prototype was developed using multiple color bands to indicate where the selected representative measurements were located. Some extra measurements, such as upper arm girth, wrist girth, and knee girth, were added for future potential data extraction. Figure 26 shows the location of all measurements coded with colored bands.

The first generation of measuring garment was developed using a 290 gsm two-way stretch knit fabric with bright colored bands to locate measurement locations. As shown in Figure 27 a, based on the feedback from the model and researcher’s visual evaluation, this measuring garment fits well on the legs but not on the torso area. The fabric was also too heavy and too thick, which may have added more bias to the measurement results because it may have
applied more pressure or created more empty spaces when subjects wore a smaller/larger size of measuring garment. The landmark locations also needed to be expanded to cover the areas of the targeted measurements.

The second generation of measuring garments was improved by solving the problems found in generation one. The measurement color bands were expanded, removing the gap between bust, waist, and hip color bands. The number of color codes was also reduced by removing unhelpful bands and using the same color for measuring areas that were not close to each other. For example, the same red was used in the bust and wrist area, and the same blue was used in both the waist and knee area. This improvement created more possibilities for future designs. To improve the fit of the garments, the second generation used 220 gsm extra light four-way stretch knit fabric.

Figure 27. The first generation (a) and second-generation (b) of measuring garment prototypes.
The second generation of measuring garments were used in Dr. Xia’s research for the PrimeFit 2D image measuring system development. The second generation was made in 3 sizes: small, medium, and large. The highly stretchy fabric covered a wide range of body shapes within these three sizes. During the research process, the participants gave positive feedback on the comfort and fit of the garments. However, some participants pointed out that the fabric was too thin and could be seen through while wearing dark-colored underwear, which made them feel less comfortable to wear the garment in public. Another problem was that the sleeves and leggings were not long enough for taller body shapes, and it may lead to the displacement of the wrist, thigh, and knee girth color band locations.

4.1.2. Final Prototype Design

Comprehensively considering the feedback from the first two generations, the final prototype for this research had the following improvements: fabric, pattern design, style design, and size control. This final product used a medium weight four-way stretch knit material with 83% polyester and 17% spandex in 260 gsm. The medium weight could ensure that this material was less translucent to help protect user privacy without being too heavy and bring extra bias to the body measuring results. The four-way stretch material could satisfy the needs of fit for more variable body shapes.

To take full advantage of the four-way stretch fabric, the style design of the final prototype was also improved. Figure 28 shows the improvement of the sleeves and leggings. A cuff with a thumbhole was added to the sleeves to make sure that the wrist area was fully covered and make the sleeve fit better around the forearm. The new design for the leggings was a
foot strap, which allowed the leggings to cover the whole leg, helping avoid the displacement of thigh and knee color bands and ensure the consistency of inseam length measurements.

Figure 28. Sleeve and legging design improvement (a) sleeve with new thumbhole design, (b) legging with new foot strap design.

Besides the style of the garments, the textile patterns and colors used on the final prototypes were also enriched to discover the influence of design elements on 2D image predicted human body measurements. In this research, three designs are developed for the final prototypes. The three designs contained three levels of color distinction and three levels of pattern regularity, from low to high, the three design schemes represent different aesthetic levels, from highly functional design with no fashion elements to lower functionality with more fashion elements. Based on general research of the current sportswear market, black, white, blue, and dark green were selected as color elements for the more fashionable designs, and the textile patterns selected were geometric patterns and irregular abstract patterns. Figure 29 shows some examples of the popular activewear patterns in the current market.
Figure 29. Examples of popular activewear color and pattern designs in the current market. (a,b) leggings from Adidas, (c) leggings from Nike, (d,e) leggings from Fabletics. (Adidas.com, 2019; Nike.com, 2019; Fabletics, 2019)

Figure 30 shows the elements used in the three designs, and Figure 31 shows the technical drawing and final products of these three designs. It is shown in design 1, highly distinguishable color blocks without any designed textile patterns were used for each measurement area. The colors used in this design were carefully selected as in relatively high saturation levels and were not commonly seen in normal backgrounds such as bedrooms and hallways. Seven different colors are used in this design. In design 2, a geometric-style textile pattern was added to the legging area. Five main colors, black, white, grey, navy blue, and sky blue, were used in this design. In design 3, an irregular abstract textile pattern was applied to the legging and shoulder area. To make this design more fashionable, the straight color bands on leggings were replaced with curvy color blocks. Only three main colors, black, dark green, and olive green were used in this design. Textile patterns applied in design 2, and design three were downloaded from Fashion Snoops, a global fashion trend forecast organization.
Figure 30. Three different textile patterns used in the final prototype design. (a) simple color blocks, (b) geometric-style pattern, (c) irregular abstract pattern.

Finally, to fit a variety of different body shapes and commercial sizes, the measuring garments were made in 5 sizes, namely X-Small, Small, Medium, Large, and X-Large. As shown in Table 5, these five sizes ranged from size 0 to size 18 based on the ASTM D5585-11e1 standard body measurements of adult female misses (ASTM, 2012). With the four-way stretch of the fabric, each size could fit more than intended, which helped evaluate the influence of measuring garment fit by asking research participants to try on a smaller and a larger size in addition to their best-fitting size and compare the measurement results by analyzing if the pressure or loose fit significantly changed the 2D and 3D measurements.
Table 5

**Final Prototype Sizes and Corresponding Standard Body Measurements**

<table>
<thead>
<tr>
<th>Size</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-Small</td>
<td>Small</td>
<td>Medium</td>
<td>Large</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chest/Bust Girth</td>
<td>31 3/4</td>
<td>33</td>
<td>34 1/8</td>
<td>35 1/4</td>
<td>36 1/4</td>
<td>37 1/4</td>
<td>38 3/4</td>
<td>40 3/8</td>
<td>42 1/8</td>
<td>44</td>
</tr>
<tr>
<td>Waist Girth</td>
<td>26 1/8</td>
<td>26 3/8</td>
<td>27 5/8</td>
<td>28 1/2</td>
<td>29 1/2</td>
<td>30 1/2</td>
<td>32 1/4</td>
<td>34</td>
<td>36</td>
<td>38 1/4</td>
</tr>
<tr>
<td>Hip/Seat Girth</td>
<td>33 7/8</td>
<td>35 1/8</td>
<td>36 3/8</td>
<td>37 1/2</td>
<td>38 1/2</td>
<td>39 1/2</td>
<td>41</td>
<td>42 1/2</td>
<td>44 1/4</td>
<td>46</td>
</tr>
<tr>
<td>Crotch Height</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
<td>30 1/2</td>
</tr>
</tbody>
</table>

Note. Taken from ASTM D5585-11e1, size 0-18 (ASTM, 2012).

### 4.2. Data Collection and Measurements Extraction

#### 4.2.1. Data Collection

In step two, 1D survey data, 2D image data, and 3D body scanning data were collected from 50 female subjects recruited from NC State University. It took about 25-30 minutes to collect all three types of data from each subject. First, the participants answered the demographic, lifestyle, and activewear shopping preference questions in the online survey. After finishing the first two sections of the survey, the researcher used the height and weight information as a reference, combined with visual observation, to find the best-fitting sizes for the participants to try on. The researcher then used visual evaluation and the feedback from the participant to determine the best-fitting size for the participant. If the participant felt the measuring garment too tight or too loose, and the same result could be gathered through observation, the researcher would consider the first size as the smaller or larger size. Based on this decision, the participant would try on 4-5 sets of measuring garments in total, including a best-fitting size, a smaller size, and a larger size apparatus made in design 2, and two best-fitting size apparatuses made in design 1 and design 3. Participants whose best size was X-Small or X-Large did not have a smaller or larger size. In that case, they only tried on four sets of garments in total. For each set of measuring garments, participants were required to be 3D body scanned in
the Size Stream body scanner for 3D data collection and stood under 34.8” x 85.3” doorframe for 2D image data collection using a smartphone. After collecting the 2D and 3D data, participants were asked to complete the last section of the online survey, evaluate the garments they tried, and give comments if they had any. More details of the collected data are described and analyzed in section 4.3.

4.2.2. 3D Measurements Extraction

As stated in section 4.1.1, Table 4, the representative measurements were selected as bust girth, waist girth, hip girth, and inseam length. In the Size Stream Studio program, bust girth, hip girth, and inseam length can be directly extracted using the definition of “Chest/Bust Circum Tape Measure,” “Seat Circum Tape Measure,” and “Inseam Right.” However, the waist girth extraction needed to be decided upon because there are multiple methods to find the waist level in the computer program. Table 6, made by Dr. Xia in 2018, presented these four methods to find a waist level in a computer program. Dr. Xia compared these four methods using a randomly selected data sample from the SizeUSA data. The dataset contained 125 scans with 30 (24%) in age 18-25, 28 (22.4%) in age 26-35, 26 (20.8%) in age 36-45, 22 (17.6%) in age 46-55, 12 (9.6%) in age 56-65, and 7 (5.6%) in age 66+. The four methods were conducted on all sample scans, and the method that resulted in the closest level were counted (Figure 31 (Xia, 2018)).
Table 6

*Methods of Finding A Waist Level in A Computer Program*

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waist level: <em>small-of-back</em></td>
<td>The point where the spine had the largest indent when viewed from the side (Han, Nam, &amp; Hwang Shin, 2010).</td>
</tr>
<tr>
<td>Waist level: <em>narrowest-front</em></td>
<td>The narrowest part of the torso between the hips and the bust.</td>
</tr>
<tr>
<td>Waist level: <em>center-b/w-bust-hips</em></td>
<td>The centerline between the levels at the most protruding point at the front (bust level) and back (hips level) from the side view of a body.</td>
</tr>
<tr>
<td>Waist level: <em>proportion-waist</em></td>
<td>The center of the central waist region with a proportional length (such as small of back height minus 4 cm) being the lower limit and the narrowest front point on the torso being the upper limit (Gill et al., 2014)</td>
</tr>
</tbody>
</table>

Note. Taken from Xia, 2018.

Figure 32. Results of the best method of finding a waist level. (Xia, 2018)

Based on Xia’s research, there is no significantly accurate method for waist level detection; the best method should be selected base on the age of subjects. The participants recruited in this research were mostly college students from NC State University, mostly in the age range 18-25. For this research, the center-b/w-bust-hips was the best method to find the waist level in 3D scanning data. The waist level was detected as the mid-level between the bust and
hip level in the 3D body scanning data. The four representative measurement locations are shown below in Figure 33.

Figure 33. Representative measurement locations in the Size Stream Studio program.

Because the Size Stream whole-body scanner was used in this research for 3D data collection, the scanning file could only be extracted into 3D measurements using the Size Stream Studio. This computer program only contains two methods to find the waist level as Small-of-back and proportion-waist method, the mid-level between bust and hip location of each subject needed to be redefined before extraction. This research used the proportion-waist method but redefined the upper and lower limit of each subject to reduce the search area to make the computer program measure the exact mid-level location between bust and hip.

The first step of extracting the waist measurement was to extract the height of the bust level, hip level, and the original optimal small of back level of all subjects. The second step was to redefine the upper and lower limit of the waist level search area in the Size Stream Studio program. Equation (1) presents the method to calculate the waist height. The upper and lower
limit of the waist level search area was edited in the “OptimizedMeasurements.mg” file. All four
limits as the FrontUpperLimit, FrontLowerLimit, BackUpperLimit, and BackLowerLimit were
edited into the same amount calculated in (2). The OptimizedMeasurements.mg files of each
subject were independently edited and saved as a new .mg file. Finally, the researcher loaded
each single 3D body scanning file with their corresponding .mg file into the Size Stream Studio
program and exported their waist girth measurements.

\[
\text{WaistHeight} = \frac{\text{BustHeight} - \text{HipHeight}}{2} + \text{HipHeight} \quad (1)
\]
\[
\text{NewLimit} = \text{Waist Height} - \text{OptSmallofBack Height} \quad (2)
\]

4.2.3 2D Measurements Extraction

To extract the 2D measurements from 2D images using the PrimeFit 2D image body
measuring system, 17 subjects were selected as the training group, and 30 subjects were selected
as the test group. All images in these two groups were compressed into low-resolution images to
reduce the training time and test image loading time.

After compressing the image size, the training group images were marked using Mask R-
CNN implemented in TensorFlow to mark the apparatus and separate it from the background of
the image (Abdulla, 2018; He et al., 2017,). To make sure each design had the same number of
images for prediction model training, the images of the training group wearing different fit
apparatus in design 2 were not used, only the images of subjects wearing design 1, 2, and 3 in the
best fitting size were used for image training. Finally, 351 images were used for prediction
model training.

In this research, two different labeling methods were used to compare, to determine
which might be better for image training. Method 1 marked the torso part of the body from the
neck level to the thigh level. Arms and legs below the thigh girth level were not included.
Method 2 included torso and legs in the label and arms were not included. On all training images, the measuring apparatus regions were highlighted and labeled with the design code and pose code. The highlighted measurement detection areas of these two methods are shown in Figure 34.

The training images labeled with highlighted apparatus regions were used to train the Mask R-CNN model in the PrimeFit 2D image measuring system for measurement area detection. The three designs were trained separately to compare the influence made by pattern and color design. The trained models were able to detect the contour of the measuring regions in test images. The resulting images for apparatus detection are shown in Figure 35.
Figure 34. Examples of training images marked with Mask R-CNN for apparatus detection. (a) Method 1 only torso part marked, (b) method 2 torso and legs marked.
Figure 35. Examples of resulting images marked for apparatus detection. (a) Method 1 only torso part marked, (b) method 2 torso and legs marked.
4.3. Data Analysis

4.3.1. 1D Data

The 1D data was collected through an online survey. The survey contained three main sections: demographic data, lifestyle, and activewear shopping preference questions, and an evaluation of the apparatus. The first two sections were answered before trying the measuring apparatuses, and the last section was answered after trying the measuring apparatuses to collect the evaluation from users. A detailed analysis of the collected data is described in the following sections.

4.3.1.1. Demographic Data. Age, ethnicity, height, and weight are collected in the first section of the online survey from the 50 participants. The height and weight were measured using a physician scale with electronic height and weight outputs. The distributions of the collected demographic data are presented in Figure 36 – Figure 39. Most of the recruited subjects were college students. The ethnicity distribution, as shown in Figure 35, was composed of 60% Asian, 38% White, and 2% African American. Although the ethnicity data were converted into dummy variables for 2D prediction model analysis, this information is still kept for future research. The mean height was 64.55 inches, and the mean weight was 127.28 lbs. The height and weight measurements were used as main references for 2D measurement extraction in the PrimeFit 2D image measuring system.
Figure 36. Age distribution of the collected data.

Figure 37. The Ethnicity of the collected data.

Figure 38. Height distribution of the collected data.
Figure 39. Weight distribution of the collected data.

4.3.1.2. **Lifestyle and activewear shopping preference.** The second section of 1D data is lifestyle and activewear shopping preference information. Data collected in this section was used to understand what kinds of sports were popular among the participants, how they use activewear in their daily life, and what elements were important for them while making the purchasing decisions.

Figure 40 and Figure 41 present the exercise lifestyle of participants, including their exercise frequency and favorite exercise types. It can be seen that about 80% of the participants exercise more than once a month, while 22% of them exercise more than four times a week. Similar to the phenomenon presented in the article written by O’Sullivan, Hanlon, Spaaij, and Westerbeek in 2017, flexible and non-organized sports are far more popular than team sports among the participants. The top 5 non-organized sports were fitness/gym (60%), followed by walking (58%), running (38%), yoga (38%), and hiking (18%). Only 18% of the participants joined team sports for exercise.
Figure 40. Exercise frequency of participants.

Figure 41. Popular exercise types among participants.

Figure 42 – Figure 47 present the activewear shopping preference of participants. The questions in this section included the frequency of purchasing activewear, favorite activewear brands, how activewear is used, elements that matter the most while making purchasing decisions, and the acceptable price range for activewear products. Participants were mostly recruited from NC State University, which represented the population of college students to some extent. The frequency of purchasing a new activewear product was mostly less than once a quarter, 36% of participants get new activewear once a year or less and only 10% of participants
would do it several times a month. When purchasing a new activewear product, the top 3 favorite sportswear brands were Nike (86%), Adidas (76%), and Under Armour (50%).

Figure 42. Frequency of purchasing activewear.

Figure 43. The popularity of activewear brands in the market.

Figure 44 shows the result of participants selecting common applications for using activewear in their daily life (choose all that apply). The most common application was exercise (96%), followed by everyday wear (48%) and lounging at home (42%). Most of the participants
only expected using activewear for exercising or as casual wear; fashion ability was not
commonly considered. Only 14% of the participants would use their activewear as a fashion
statement. This phenomenon also appeared when selecting the top 3 elements when making
activewear purchasing decisions. The top 3 elements were comfort (74%), fit of clothes (62%),
and quality and breathability (52%) (Figure 45). Fit, comfort, and quality of the garments were
more valued than fashion aspects for most college students since they expect to use the
activewear more for exercising and as casual wear rather than expressing their fashion aesthetic.

Figure 44. Activewear application.

Figure 45. Elements that matter when making activewear purchasing decisions.
Because most of the participants were college students with a limited income, the acceptable price range for activewear products was relevantly low. None of the participants would like to pay more than $100 for an activewear product. However, participants seemed willing to pay slightly more for an activewear bottom than the top. As shown in Figure 46, approximately 62% of the participants thought $30 - $60 was acceptable for an activewear top. As for activewear bottoms, 52% of participants thought $30 - $60 is acceptable for an activewear bottom.

Figure 46. The acceptable price range for an activewear top.

Figure 47. The acceptable price range for an activewear bottom.
4.3.2. Evaluation of Measuring Garments Prototypes

The results of the participant’s evaluation of the measuring garments based on color, pattern, and style are shown in Figure 48. The general evaluation required participants to grade the three designs from 1 to 5, with 1 being the lowest score and five being the highest. The mean score of design 1 was 3.02, significantly lower than design 2 (mean score 3.96) and design 3 (mean score 3.88).

![Graph showing evaluation scores for designs 1, 2, and 3.]

Figure 48. General evaluation of 3 designs.

Figure 49 – Figure 51 presents the participant’s attitudes to wearing the three designs on different occasions. Participants expressed a relatively positive attitude for using these apparatuses for body measuring. For design 1, 30% of the participants were somewhat likely, and 30% were very likely to use it for body measuring (Figure 49). Participants felt somewhat likely (44%) or very likely (30%) to use design 2 for body measuring. The attitude towards design 3 is similar to design 2, 36% of participants felt likely, and 38% felt very likely to use design 3 for body measuring.

For applications on public occasions, the attitude towards the three designs became very different. It was very unacceptable for most of the participants to use design 1 outside the home.
for exercising. Approximately 44% of the participants selected very unlikely, and 18% selected unlikely to wear design 1 apparatus to the gym. Compared to design 1, designs 2 and 3 had more potential to be accepted for exercising. About half of the participants selected somewhat likely or very likely to wear design 2 to the gym. More than half of the participants expressed a positive attitude to wear design 3 for exercising in public occasions. None of the designs were accepted as casual wear by most of the participants. 60% of participants felt very unlikely to wear design 1 as casual wear. 38% felt very unlikely for design 2, and 30% very unlikely for design 3.

Figure 49. How likely participants would be to use the apparatus for body measuring.

Figure 50. How likely participants would wear the designs in the gym.
At the end of the survey, some of the participants left comments on what they liked and disliked about the three designs. The comments mostly focused on color, textile pattern, and the general design of the apparatuses. Table 7 – Table 10 are the selected comments from participants. The comments on design 1 are mostly negative about the color. Participants said that they did not like this design because there are too many vivid colors in one look, which made the design very bold and would make them feel self-conscious wearing it in a public setting. The attitudes toward design 2 were more positive. The color palette used in this design was commonly accepted, the negative comments are focused on the stripe patterns on the legging area. Design 3 was highly evaluated on general design but received polarized comments on the textile pattern. Participants who gave negative comments on the pattern all mentioned that they do not want the monkey as an element of the pattern. The feedback to all three designs focused on the fit around the waist and neck. For participants whose body shape was more similar to the hourglass, the apparatuses were somewhat loose around the waist area. Participants also complained that the high neck of the apparatuses was uncomfortable, and lower neck design would be preferred.
Table 7

Comments on Design 1

<table>
<thead>
<tr>
<th>Color</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I did not like the colors together, I would not use it because of the colors.</td>
<td></td>
</tr>
<tr>
<td>Too vivid and many colors, reduce the number of colors to 2-3.</td>
<td></td>
</tr>
<tr>
<td>I liked the black fill but didn't love the more garish colors.</td>
<td></td>
</tr>
<tr>
<td>I would prefer neutral colors instead; I would feel self-conscious at the gym in this.</td>
<td></td>
</tr>
<tr>
<td>Too many different colors on one garment, it can be extreme fashion or ugly.</td>
<td></td>
</tr>
<tr>
<td>Very bright colors that would remind me of wearing it to grab attention when outdoors.</td>
<td></td>
</tr>
<tr>
<td>The colors are not really my taste.</td>
<td></td>
</tr>
<tr>
<td>I like the amount of color on the garment.</td>
<td></td>
</tr>
<tr>
<td>Too many colors in one look.</td>
<td></td>
</tr>
<tr>
<td>I like the colors.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pattern</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I wish the coloring were less block-like.</td>
<td></td>
</tr>
<tr>
<td>I think it would look better as striping instead of blocks.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>General Design</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>This design is cool, but it’s a bit bold. The design kind of looks like a warrior/ soldier.</td>
<td></td>
</tr>
<tr>
<td>The design is bold, but not for me</td>
<td></td>
</tr>
</tbody>
</table>

Table 8

Comments on Design 2

<table>
<thead>
<tr>
<th>Color</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I like the colors a lot.</td>
<td></td>
</tr>
<tr>
<td>I love the color combo.</td>
<td></td>
</tr>
<tr>
<td>Like the color palette.</td>
<td></td>
</tr>
<tr>
<td>I love the colors.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pattern</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I am not a fan of the horizontal all-over stripes.</td>
<td></td>
</tr>
<tr>
<td>Like the pattern design.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>General Design</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>The legging print is nice; I would wear the leggings on their own if I were going to the gym.</td>
<td></td>
</tr>
<tr>
<td>I love this design. I would definitely wear this! The leggings go really well with the top.</td>
<td></td>
</tr>
<tr>
<td>I love the top, but I wasn't a huge fan of the design for the bottoms.</td>
<td></td>
</tr>
<tr>
<td>This reminded me of an Olympic uniform, definitely liked this one the most</td>
<td></td>
</tr>
<tr>
<td>Neat and clean, like it.</td>
<td></td>
</tr>
<tr>
<td>I really like this one!</td>
<td></td>
</tr>
<tr>
<td>It reminds me of something to wear when sailing and being near the ocean and needing full-body coverage.</td>
<td></td>
</tr>
</tbody>
</table>
Table 9

Comments on Design 3

<table>
<thead>
<tr>
<th>Color</th>
<th>I loved the color choice! The color is too dark, maybe it can be brighter?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
<td>I like the cute monkey. I just personally don't like characters, i.e., the monkeys on my clothing. The tropical floral is cute, but the monkeys make it look a little youthful. This would be great for kids, but for adults, I would take out the monkeys. I think that the monkeys are a bit juvenile. If it didn't have the monkeys, I would be more likely to wear it!</td>
</tr>
<tr>
<td>General Design</td>
<td>I think the green with the monkeys is the best design. I really like how fun and cute it looks. I would be most likely to wear this design in particular. I loved this design! I really liked this garment as a whole but probably would not wear it because my personal preference is not something so tight fitting. Special design, like it. I really like this for the gym. It might be a little bold for me for everyday wear. Very cute but not for a public occasion. Good design for a statement.</td>
</tr>
</tbody>
</table>

Table 10

Comments About the Fit of The Apparatus

<table>
<thead>
<tr>
<th>Waist</th>
<th>Waist is loose. The waist was the largest part. The belly part is a little bit loose for all three.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck</td>
<td>The neckline is too high. I found the neck area too tight. The neck is too tight. If the neck were lower, I would definitely wear it. It is better to be a flat collar.</td>
</tr>
<tr>
<td>General</td>
<td>The legs fit perfectly, and so did the top. All the garments are not very easy to wear. Somewhat tight during putting on. I would probably not wear the leggings at all.</td>
</tr>
</tbody>
</table>
4.3.3. 3D Body Scanning Data

During the research process, each subject was asked to put on 4-5 measuring apparatuses covering three designs (design 1, design 2, and design 3) and three fit levels (a smaller size, a best-fitting size, and a larger size made in design 2). A total of 237 scans were collected with 50 best-fitting size in design 1, 50 best-fitting size in design 2, 50 best-fitting size in design 3, 39 smaller size in design 2, and 48 larger size in design 2. The representative measurements, including bust girth, waist girth, hip girth, right leg inseam length, and right leg girth, were extracted from 3D body scan data.

4.3.3.1. 3D vs. 3D: compare measurements extracted from a different fit. The best-fitting size, smaller size, and larger size apparatus measurement results were compared using paired t-test to evaluate the effects of different measuring garment fit level on body measuring results. The subjects whose best-fitting size was X-Small did not have a smaller size and subjects whose best-fitting size was X-Large did not have a larger size, the sample size for subjects who tried a smaller size and subjects who tried a larger size was different. Paired t-tests were conducted separately for comparing smaller size versus best-fitting size and larger size versus best-fitting size. The results are presented in Tables 11 and 12.

The number of subjects who tried both a smaller size and best-fitting size was 39. Paired t-tests demonstrated that the bust and waist girth measurements of subjects wearing a smaller size garment were significantly smaller than the same measurements of subjects wearing the best-fitting size garment. The measurement results of hip girth and right inseam girth did not have significant differences between the two different fits.
The number of subjects who tried both a larger size and a best fitting size was 48. The paired t-test result showed that the waist girth, hip girth, and right inseam length of subjects wearing larger size garment were significantly larger than the measurement results of subjects wearing the best-fitting size garment. The measurement results for bust girth were not significantly different between the two fits.

Table 11

*Results of The Paired T-Tests (Smaller Size Vs. Best-Fitting Size)*

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Smaller size Mean</th>
<th>Best-fitting size Mean</th>
<th>p (small vs. best)</th>
<th>Flag (small vs. best) *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bust girth</td>
<td>36.46</td>
<td>36.7</td>
<td>0.0019</td>
<td>&lt;</td>
</tr>
<tr>
<td>Waist girth</td>
<td>31.15</td>
<td>31.47</td>
<td>0.0003</td>
<td>&lt;</td>
</tr>
<tr>
<td>Hip girth</td>
<td>38.77</td>
<td>38.85</td>
<td>0.1281</td>
<td>-</td>
</tr>
<tr>
<td>R-Inseam length</td>
<td>29.33</td>
<td>29.26</td>
<td>0.7677</td>
<td>-</td>
</tr>
</tbody>
</table>

*: Flag is labeled based on p values when \( \alpha = 0.05 \) for one side tests; < means the smaller size mean is significantly smaller than the best size mean, - means the difference is not significant.

Table 12

*Results of the paired t-tests (larger size vs. best fitting size)*

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Larger size Mean</th>
<th>Best-fitting size Mean</th>
<th>p (large vs. best)</th>
<th>Flag (large vs. best) *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bust girth</td>
<td>35.76</td>
<td>35.65</td>
<td>0.072</td>
<td>-</td>
</tr>
<tr>
<td>Waist girth</td>
<td>30.79</td>
<td>30.37</td>
<td>0.0001</td>
<td>&gt;</td>
</tr>
<tr>
<td>Hip girth</td>
<td>38.12</td>
<td>37.91</td>
<td>0.0007</td>
<td>&gt;</td>
</tr>
<tr>
<td>R-Inseam length</td>
<td>29.29</td>
<td>29.09</td>
<td>0.0183</td>
<td>&gt;</td>
</tr>
</tbody>
</table>

Note. *: Flag is labeled based on p values when \( \alpha = 0.05 \) for one side tests; > means the larger size mean is significantly larger than the best size mean, - means the difference is not significant.

**4.3.4. 3D Vs. 2D: Compare 2D Measurements with 3D**

The measurements predicted by the 2D image measuring system (2D auto) were compared to the measurements extracted from 3D scans (3D auto) to evaluate the general accuracy of the 2D measuring method. Histograms and Q-Q plots were created to demonstrate
the difference between 2D and 3D measurements (Appendix C). The distributions of differences were generally normal. Therefore, paired t-tests were conducted to compare the two labeling methods and two poses for side view images. The results of the paired t-tests are presented in Table 13. There is no significantly better labeling method or pose for the 2D image measuring system. The measurements with the largest difference were the bust girth, regardless of labeling method or pose. The 2D predicted measurements were significantly different from the extracted 3D measurements. The inseam length is another measurement that has significant differences between the 2D and 3D measurements. It can be observed that when labeling the whole body, the 2D prediction measurements were significantly larger than the 3D measurements with arms beside the bodies. If only the torso was labeled, the 2D prediction measurements were significantly larger than the 3D measurements when hands were above heads.

Table 13

Results of The Paired T-Tests On 2D Images Vs. 3D Scan

<table>
<thead>
<tr>
<th>Measurement</th>
<th>3D auto mean</th>
<th>Labeling</th>
<th>Pose</th>
<th>2D auto mean</th>
<th>p</th>
<th>Flag *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bust girth</td>
<td>35.71</td>
<td>Whole-body</td>
<td>arms up</td>
<td>36.1</td>
<td>0.0001</td>
<td>&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>arms down</td>
<td>36.1</td>
<td>0.0001</td>
<td>&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torso</td>
<td>arms up</td>
<td>36.09</td>
<td>0</td>
<td>&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>arms down</td>
<td>30.57</td>
<td>0.8737</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole-body</td>
<td>arms up</td>
<td>30.41</td>
<td>0.051</td>
<td>-</td>
</tr>
<tr>
<td>Waist girth</td>
<td>30.56</td>
<td>Whole-body</td>
<td>arms up</td>
<td>30.6</td>
<td>0.5867</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>arms down</td>
<td>30.6</td>
<td>0.6288</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torso</td>
<td>arms up</td>
<td>37.94</td>
<td>0.1197</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>arms down</td>
<td>38</td>
<td>0.3068</td>
<td>-</td>
</tr>
<tr>
<td>Hip girth</td>
<td>38.09</td>
<td>Whole-body</td>
<td>arms up</td>
<td>37.95</td>
<td>0.1159</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>arms down</td>
<td>37.97</td>
<td>0.1809</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torso</td>
<td>arms up</td>
<td>29.27</td>
<td>0.4367</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>arms down</td>
<td>29.35</td>
<td>0.0411</td>
<td>&gt;</td>
</tr>
<tr>
<td>Inseam length</td>
<td>29.22</td>
<td>Whole-body</td>
<td>arms up</td>
<td>29.36</td>
<td>0.0221</td>
<td>&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>arms down</td>
<td>29.29</td>
<td>0.2141</td>
<td>-</td>
</tr>
</tbody>
</table>

Note. *: Flag is labeled based on p values when α = 0.05 for one side tests; > means the 2D auto mean is significantly larger than the 3D auto mean, - means the difference is not significant.
The result of the paired t-test between 3D measurements and 2D prediction measurements suggests that there is no significant difference between the two labeling methods. Therefore, in the following sections, only the prediction models of the whole-body labeling method are presented. The prediction model of torso labeled images can be found in Appendix D.

### 4.3.5. 2D vs. 2D: Comparison of Measurements Extracted from Different Designs

To find out if the color and pattern of the measuring apparatus would make any impact on the 2D image predicted measurements, the LASSO (least absolute shrinkage and selection operator) regression models were trained on the 2D images collected from the participants. Akaike Information Criterion (AIC) was used for model selection, and the scikit-learn API was used for model training. The data was collected from 50 participants wearing three different designs, 47 of which were useable after primary checking. The final dataset contains 207 sets of images, including 47 in design 1, 135 in design 2, and 46 in design 3. The design 2 image data set has more photos because it included the images of participants wearing other sizes of garments in design 2. The subjects were then randomly split into training (40%) and testing datasets (60%).

Two groups of Lasso models with AIC model selection were trained using the extracted 3D measurements and 2D images. The first group used the front view with the arms-down image for 2D measurement extraction, and the second group used the front view with arms-up images for 2D measurement extraction.

Besides the 2D images, demographic information of height, weight, age, and ethnicity were also included as candidate dependent variables for prediction model training. Age and
ethnicity variables were converted to dummy variables to be processed through the machine learning models in scikit-learn API.

A general format of the resulting LASSO model is shown in (3) based on Xia’s (2018) research, in which (a) $\beta_0$ is the intercept, (b) $\beta_1...\beta_n$ are coefficients for the $n$ dependent variables, (c) $x_1...x_n$ are the dependent variables, (d) $\bar{x}_1...\bar{x}_n$ are means for the dependent variables, (e) $\sigma_1...\sigma_n$ are standard deviations for the $n$ dependent variables and (f) $\hat{y}$ is the predicted value.

$$\hat{y} = \beta_0 + \beta_1 \frac{(x_1-\bar{x}_1)}{\sigma_1} + ... + \beta_n \frac{(x_n-\bar{x}_n)}{\sigma_n}$$ (3)

In the prediction model, the four representative measurements of bust girth, waist girth (center-b/w-bust-hips), hip girth, and inseam length were used as the independent variables. Bust width, bust depth, bust height, waist width (center-b/w-bust-hips), waist depth (center-b/w-bust-hips), waist height (center-b/w-bust-hips), hip width, hip depth, hips height, and crotch height were selected as predictor measurements and used as dependent variables and extracted from 2D images. All dependent variables were standardized by removing the mean and scaling to unit variance. The missing values were imputed by the mean of the variable before training the models.

Generally, the performance of prediction models in the arms-up group was slightly better than the arms-down group. This is because the outline of side-view images with an arms-up pose was less covered and easier to detect. Among all three designs, design 2 was significantly better than the two other designs in the bust girth prediction model which had the highest $R^2$ value. The performance of design 3 bust girth prediction model was significantly worse than two other
designs and had the lowest $R^2$ value. The impact of design is not significant in other representative measurements.

### 4.3.5.1 Bust girth prediction.

The prediction model for the bust girth measurement in design 1, the arms-down pose, is presented in (4). Dependent variables were narrowed down to weight and BMI. The $R^2$ value of the prediction model was 0.573. Figure 52(a) shows the difference between the predicted bust girth and the bust girth measurement extracted from 3D scans, in 20 out of 33 subjects (60.61%), the difference between predicted bust girth measurements and 3D bust girth measurements were more than 1 inch.

\[
BustGirth\text{\_ArmsDown1} = 35.911 + 0.904 \times \frac{(\text{Weight} - 130.194)}{\sqrt{405.130}} + 0.673 \times \frac{(\text{BMI} - 21.213)}{\sqrt{6.027}}
\]  

(4)

The prediction model for the bust girth measurement in design 1, the arms-up pose, is presented in (5). Dependent variables were narrowed down to weight, BMI, and hip depth. The $R^2$ value of the prediction model was 0.576. Figure 52(b) shows the difference between the predicted bust girth and the bust girth measurement extracted from 3D scans, in 18 out of 33 subjects (54.55%), the difference between predicted bust girth measurements and 3D bust girth measurements were more than 1 inch.

\[
BustGirth\text{\_ArmsUp1} = 35.911 + 0.402 \times \frac{(\text{Weight} - 130.194)}{\sqrt{405.130}} + 0.605 \times \frac{(\text{BMI} - 21.213)}{\sqrt{6.027}} + 0.917 \times \frac{(\text{HipDepth} - 8.488)}{\sqrt{0.521}}
\]  

(5)
Figure 52. Bust girth model prediction results of design 1. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

The prediction model for the bust girth measurement in design 2, the arms-down pose, is presented in (6). Dependent variables were narrowed down to bust width, bust depth, waist width, and waist depth. The $R^2$ value of the prediction model was 0.653. Figure 53(a) shows the difference between the predicted bust girth and the bust girth measurement extracted from 3D scans, in 45 out of 113 subjects (39.82%), the difference between predicted bust girth measurements and 3D bust girth measurements were more than 1 inch.

\[
\text{BustGirthArmsDown2} = 35.951 + 0.255 \times \frac{(\text{BustWidth} - 11.653)}{\sqrt{0.915}} + 0.933 \times \frac{(\text{BustDepth} - 8.841)}{\sqrt{0.417}} + 0.470 \times \frac{(\text{WaistWidth} - 11.024)}{\sqrt{0.917}} + 0.403 \times \frac{(\text{WaistDepth} - 7.976)}{\sqrt{0.569}}
\]

The prediction model for the bust girth measurement in design 2, the arms-up pose, is presented in (7). Dependent variables were narrowed down to weight, bust width, bust depth, waist width, and waist depth. The $R^2$ value of the prediction model was 0.739. Figure 53(b) shows the difference between the predicted bust girth and the bust girth measurement extracted from 3D scans,
in 51 out of 113 subjects (45.13%), the difference between predicted bust girth measurements and 3D bust girth measurements were more than 1 inch.

**BustGirthArmsUp2**

\[
\begin{align*}
    &= 35.951 + 0.408 \frac{(\text{Weight} - 130.194)}{\sqrt{405.130}} + 0.171 \frac{(\text{BustWidth} - 11.441)}{\sqrt{1.178}} \\
    &+ 0.470 \frac{(\text{BustDepth} - 8.259)}{\sqrt{0.394}} + 0.497 \frac{(\text{WaistWidth} - 10.935)}{\sqrt{0.959}} \\
    &+ 0.573 \frac{(\text{WaistDepth} - 7.618)}{\sqrt{0.432}}
\end{align*}
\]  

(7)

Figure 53. Bust girth model prediction results of design 2. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

The prediction model for the bust girth measurement in design 3, the arms-down pose, is presented in (8). Dependent variables were narrowed down to bust depth. The R² value of the prediction model was 0.492. Figure 54(a) shows the difference between the predicted bust girth and the bust girth measurement extracted from 3D scans, in 15 out of 32 subjects (46.88%), the difference between predicted bust girth measurements and 3D bust girth measurements were more than 1 inch.

**BustGirthArmsDown3**

\[
BustGirthArmsDown3 = 35.642 + 0.820 \frac{(\text{BustDepth} - 8.875)}{\sqrt{0.538}}
\]  

(8)
The prediction model for the bust girth measurement in design 3, the arms-up pose, is presented in (9). Dependent variables were narrowed down to waist width, waist depth, and hip depth. The R² value of the prediction model was 0.739. Figure 54(b) shows the difference between the predicted bust girth and the bust girth measurement extracted from 3D scans, in 16 out of 32 subjects (50%), the difference between predicted bust girth measurements and 3D bust girth measurements were more than 1 inch.

\[
\text{BustGirth}_{\text{ArmsUp3}} = 35.642 + 0.181 \frac{(\text{WaistWidth} - 11.506)}{\sqrt{0.729}} + 0.430 \frac{(\text{WaistDepth} - 7.588)}{\sqrt{1.095}} + 0.665 \frac{(\text{HipDepth} - 8.756)}{\sqrt{0.742}}
\] (9)

Figure 54. Bust girth model prediction results of design 3. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

**4.3.5.2 Waist girth prediction.** The prediction model for the waist girth measurement in design 1, the arms-down pose, is presented in (10). Dependent variables were narrowed down to weight and BMI. The R² value of the prediction model was 0.649. Figure 55(a) shows the difference between the predicted waist girth and the waist girth measurement extracted from 3D
scans, in 12 out of 33 subjects (36.36%), the difference between predicted waist girth measurements and 3D waist girth measurements were more than 1 inch.

\[
WaistGirth ArmsDown1
\]

\[
= 30.298 + 1.249 \frac{(Weight - 130.194)}{\sqrt{405.130}} + 0.660 \frac{(BMI - 21.213)}{\sqrt{6.027}}
\]  

(10)

The prediction model for the waist girth measurement in design 1, the arms-up pose, is presented in (11). Dependent variables were narrowed down to weight, BMI, waist depth, and hip depth. The R² value of the prediction model was 0.726. Figure 55(b) shows the difference between the predicted waist girth and the waist girth measurement extracted from 3D scans, in 16 out of 33 subjects (48.48%), the difference between predicted waist girth measurements and 3D waist girth measurements were more than 1 inch.

\[
WaistGirth ArmsUp1
\]

\[
= 30.298 + 0.406 \frac{(Weight - 130.194)}{\sqrt{405.130}} + 0.751 \frac{(BMI - 21.213)}{\sqrt{6.027}}
\]

\[
+ 0.787 \frac{(WaistDepth - 7.224)}{\sqrt{0.639}} + 0.652 \frac{(HipDepth - 8.488)}{\sqrt{0.521}}
\]

(11)

Figure 55. Waist girth model prediction results of design 1. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.
The prediction model for the waist girth measurement in design 2, the arms-down pose, is presented in (12). Dependent variables were narrowed down to weight, waist depth, hip width, and hip depth. The R² value of the prediction model was 0.737. Figure 56(a) shows the difference between the predicted waist girth and the waist girth measurement extracted from 3D scans, in 46 out of 113 subjects (40.71%), the difference between predicted waist girth measurements and 3D waist girth measurements were more than 1 inch.

\[
WaistGirth_{ArmsDown2} = 30.372 + 0.723 \frac{(Weight - 130.194)}{\sqrt{405.130}} + 0.587 \frac{(WaistDepth - 7.976)}{\sqrt{0.569}}
+ 0.739 \frac{(HipWidth - 13.271)}{\sqrt{0.828}} + 0.623 \frac{(HipDepth - 9.194)}{\sqrt{0.830}}
\]  

(12)

The prediction model for the waist girth measurement in design 2, the arms-up pose, is presented in (13). Dependent variables were narrowed down to weight, BMI, hip width, and hip depth. The R² value of the prediction model was 0.787. Figure 56(b) shows the difference between the predicted waist girth and the waist girth measurement extracted from 3D scans, in 43 out of 113 subjects (38.05%), the difference between predicted waist girth measurements and 3D waist girth measurements were more than 1 inch.

\[
WaistGirth_{ArmsUp2} = 30.372 + 0.819 \frac{(Weight - 130.194)}{\sqrt{405.130}} + 0.176 \frac{(BMI - 21.213)}{\sqrt{6.027}}
+ 0.547 \frac{(HipWidth - 13.235)}{\sqrt{0.785}} + 0.917 \frac{(HipDepth - 8.847)}{\sqrt{0.473}}
\]  

(13)
Figure 56. Waist girth model prediction results of design 2. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

The prediction model for the waist girth measurement in design 3, the arms-down pose, is presented in (14). Dependent variables were narrowed down to BMI and waist depth. The $R^2$ value of the prediction model was 0.768. Figure 57(a) shows the difference between the predicted waist girth and the waist girth measurement extracted from 3D scans, in 12 out of 32 subjects (37.5%), the difference between predicted waist girth measurements and 3D waist girth measurements were more than 1 inch.

\[
\text{WaistGirthArmsDown3} \quad = \quad 30.273 + 0.470 \frac{(\text{BMI} - 21.046)}{\sqrt{5.928}} + 1.684 \frac{(\text{WaistDepth} - 8.175)}{\sqrt{0.531}} \quad (14)
\]

The prediction model for the waist girth measurement in design 3, the arms-up pose, is presented in (15). Dependent variables were narrowed down to BMI, waist width, waist depth, and hip height. The $R^2$ value of the prediction model was 0.802. Figure 57(b) shows the difference between the predicted waist girth and the waist girth measurement extracted from 3D scans, in 7 out of 32 subjects (21.88%), the difference between predicted waist girth
measurements and 3D waist girth measurements were more than 1 inch. The performance of the arms-up model is slightly better than the arms-down model.

\[
\text{WaistGirthArmsUp3} = 30.273 + 0.880 \left( \frac{\text{BMI} - 21.046}{\sqrt{5.928}} \right) + 0.572 \left( \frac{\text{WaistWidth} - 11.506}{\sqrt{0.729}} \right)
\]

\[
+ 1.246 \left( \frac{\text{WaistDepth} - 7.588}{\sqrt{1.095}} \right) + 0.004 \left( \frac{\text{HipHeight} - 32.856}{\sqrt{3.102}} \right)
\]

(15)

Figure 57. Waist girth model prediction results of design 3. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

4.3.5.3 Hip girth prediction. The prediction model for the hip girth measurement in design 1, the arms-down pose, is presented in (16). Dependent variables were narrowed down to weight and BMI. The \( R^2 \) value of the prediction model was 0.508. Figure 58(a) shows the difference between the predicted hip girth and the hip girth measurement extracted from 3D scans, in 16 out of 33 subjects (48.48%), the difference between predicted hip girth measurements and 3D hip girth measurements were more than 1 inch.

\[
\text{HipGirthArmsDown1} = 37.823 + 0.683 \left( \frac{\text{Weight} - 130.194}{\sqrt{405.130}} \right) + 1.706 \left( \frac{\text{BMI} - 21.213}{\sqrt{6.027}} \right)
\]

(16)
The prediction model for the hip girth measurement in design 1, the arms-up pose, is presented in (17). Dependent variables were narrowed down to weight, BMI, and hip depth. The $R^2$ value of the prediction model was 0.562. Figure 58(b) shows the difference between the predicted hip girth and the hip girth measurement extracted from 3D scans, in 15 out of 33 subjects (45.45%), the difference between predicted hip girth measurements and 3D hip girth measurements were more than 1 inch.

$$HipGirth_{ArmsUp1} = 37.823 + 0.426 * \frac{(Weight - 130.194)}{\sqrt{405.130}} + 1.617 * \frac{(BMI - 21.213)}{\sqrt{6.027}} + 0.358 * \frac{(HipDepth - 8.488)}{\sqrt{0.521}}$$  (17)

Figure 58. Hip girth model prediction results of design 1. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

The prediction model for the hip girth measurement in design 2, the arms-down pose, is presented in (18). Dependent variables were narrowed down to BMI, waist width, and waist depth. The $R^2$ value of the prediction model was 0.607. Figure 59(a) shows the difference between the predicted hip girth and the hip girth measurement extracted from 3D scans, in 60 out
of 113 subjects (53.10%), the difference between predicted hip girth measurements and 3D hip girth measurements were more than 1 inch.

\[
\hat{HipGirth}_{\text{ArmsDown2}} = 37.741 + 1.196 \frac{(BMI - 21.213)}{\sqrt{6.027}} + 0.181 \frac{(WaistWidth - 11.024)}{\sqrt{0.917}} \\
+ 0.241 \frac{(WaistDepth - 7.976)}{\sqrt{0.569}}
\]  \hspace{1cm} (18)

The prediction model for the hip girth measurement in design 2, the arms-up pose, is presented in (19). Dependent variables were narrowed down to BMI. The \( R^2 \) value of the prediction model was 0.535. Figure 59(b) shows the difference between the predicted hip girth and the hip girth measurement extracted from 3D scans, in 64 out of 113 subjects (56.64%), the difference between predicted hip girth measurements and 3D hip girth measurements were more than 1 inch.

\[
\hat{HipGirth}_{\text{ArmsUp2}} = 37.741 + 1.241 \frac{(BMI - 21.213)}{\sqrt{6.027}}
\]  \hspace{1cm} (19)

Figure 59. Hip girth model prediction results of design 2. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.
The prediction model for the hip girth measurement in design 3, the arms-down pose, is presented in (20). Dependent variables were narrowed down to BMI, waist width, and waist depth. The $R^2$ value of the prediction model was 0.455. Figure 60(a) shows the difference between the predicted hip girth and the hip girth measurement extracted from 3D scans, in 22 out of 32 subjects (68.75%), the difference between predicted hip girth measurements and 3D hip girth measurements were more than 1 inch.

$$\text{HipGirthArmsDown3} = 37.723 + 1.381 \times \frac{(\text{BMI} - 21.046)}{\sqrt{5.928}} + 0.429 \times \frac{(\text{WaistWidth} - 11.556)}{\sqrt{0.581}} + 0.718 \times \frac{(\text{WaistDepth} - 8.175)}{\sqrt{0.531}}$$  \hspace{1cm} (20)

The prediction model for the hip girth measurement in design 3, the arms-up pose, is presented in (21). Dependent variables were narrowed down to BMI. The $R^2$ value of the prediction model was 0.478. Figure 60(b) shows the difference between the predicted hip girth and the hip girth measurement extracted from 3D scans, in 14 out of 32 subjects (43.75%), the difference between predicted hip girth measurements and 3D hip girth measurements were more than 1 inch.

$$\text{HipGirthArmsUp3} = 37.722 + 1.255 \times \frac{(\text{BMI} - 21.046)}{\sqrt{5.928}}$$  \hspace{1cm} (21)
Figure 60. Hip girth model prediction results of design 3. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

4.3.5.4 Inseam length prediction. The prediction model for the inseam length measurement in design 1, the arms-down pose, is presented in (22). Dependent variables were narrowed down to weight, bust height, and hip depth. The $R^2$ value of the prediction model was 0.553. Figure 61(a) shows the difference between the predicted inseam length and the inseam length measurement extracted from 3D scans, in 9 out of 33 subjects (27.27%) the difference between predicted inseam length measurements and 3D inseam length measurements were more than 1 inch.

\[
\text{InseamLengthArmsDown1} = 29.771 + 0.219 \frac{(\text{Weight} - 130.194)}{\sqrt{405.130}} + 0.999 \frac{(\text{BustHeight} - 46.665)}{\sqrt{4.578}} + 0.174 \frac{(\text{HipDepth} - 8.312)}{\sqrt{2.358}} \tag{22}
\]

The prediction model for the inseam length measurement in design 1, the arms-up pose, is presented in (23). Dependent variables were narrowed down to weight and hip height. The $R^2$ value of the prediction model was 0.472. Figure 61(b) shows the difference between the
predicted inseam length and the inseam length measurement extracted from 3D scans, in 10 out of 33 subjects (30.30%), the difference between predicted inseam length measurements and 3D inseam length measurements were more than 1 inch.

\[ \hat{\text{InseamLength}}_{\text{ArmsUp}} = 29.771 + 0.233 \frac{(\text{Weight} - 130.194)}{\sqrt{405.130}} + 0.799 \frac{(\text{HipHeight} - 32.635)}{\sqrt{3.332}} \]  

(23)

Figure 61. Inseam length model prediction results of design 1. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

The prediction model for the inseam length measurement in design 2, the arms-down pose, is presented in (24). Dependent variables were narrowed down to waist height and hip height. The \( R^2 \) value of the prediction model was 0.524. Figure 62(a) shows the difference between the predicted inseam length and the inseam length measurement extracted from 3D scans, in 19 out of 113 subjects (16.81%), the difference between predicted inseam length measurements and 3D inseam length measurements were more than 1 inch.

\[ \hat{\text{InseamLength}}_{\text{ArmsDown}} = 29.546 + 0.849 \frac{(\text{WaistHeight} - 39.562)}{\sqrt{2.772}} + 0.281 \frac{(\text{HipHeight} - 32.429)}{\sqrt{2.070}} \]  

(24)
The prediction model for the inseam length measurement in design 2, the arms-up pose, is presented in (25). Dependent variables were narrowed down to height, waist height, and hip height. The $R^2$ value of the prediction model was 0.679. Figure 62(b) shows the difference between the predicted inseam length and the inseam length measurement extracted from 3D scans, in 18 out of 113 subjects (15.93%), the difference between predicted inseam length measurements and 3D inseam length measurements were more than 1 inch.

$$InseamLengthArmsUp_2 = 29.546 + 0.270 \frac{(Height - 65.559)}{\sqrt{4.320}} + 0.714 \frac{(WaistHeight - 39.271)}{\sqrt{3.853}} + 0.216 \frac{(HipHeight - 32.494)}{\sqrt{3.042}}$$

(25)

Figure 62. Inseam length model prediction results of design 2. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.

The prediction model for the inseam length measurement in design 3, the arms-down pose, is presented in (26). Dependent variables were narrowed down to height and hip height. The $R^2$ value of the prediction model was 0.530. Figure 63(a) shows the difference between the predicted inseam length and the inseam length measurement extracted from 3D scans, in 10 out
of 32 subjects (31.25%) the difference between predicted inseam length measurements and 3D inseam length measurements were more than 1 inch.

\[
InseamLengthArmsDown3
\]

\[
= 19.716 + 0.529 \frac{(Height - 65.531)}{\sqrt{4.577}} + 0.324 \frac{(WaistHeight - 0.324)}{\sqrt{2.772}}
\] (26)

The prediction model for the inseam length measurement in design 3, the arms-up pose, is presented in (27). Dependent variables were narrowed down to height and hip height. The \( R^2 \) value of the prediction model was 0.588. Figure 63(b) shows the difference between the predicted inseam length and the inseam length measurement extracted from 3D scans, in 10 out of 32 subjects (31.25%) the difference between predicted inseam length measurements and 3D inseam length measurements were more than 1 inch.

\[
InseamLengthArmsUp3
\]

\[
= 29.716 + 0.592 \frac{(Height - 65.531)}{\sqrt{4.577}} + 0.486 \frac{(HipHeight - 32.856)}{\sqrt{3.102}}
\] (27)

Figure 63. Inseam length model prediction results of design 3. (a). Prediction results in the arms-down pose. (b). Predicted results in the arms-up pose.
CHAPTER 5. CONCLUSIONS AND FUTURE STUDIES

5.1 Conclusions

The purpose of this research was to develop a series of garments that could be used as a measuring apparatus in the 2D image body measuring system developed by the PrimeFit research team to assist online shopping and customize clothing. In the past few decades, sportswear has gone through a long process of revolution and is now widely accepted for daily wearing and exercises. On the other hand, the awakening of female consciousness and the rise of feminism also allowed women to come out from home and participate in all kinds of sports and work. In the 21st century, women want to pair technology with clothing to make their life more efficient. These measuring garments could be an efficient product that can measure the human body for online shopping size recommendation and also as sportswear or casual wear.

To achieve this goal, four research questions were developed in section 1.2, and three stages of prototype development, data collection, and data analysis were designed to find the answer to those questions.

Stage one focused on developing the measuring apparatus. Before designing the apparatus, ISO and ASTM standards were viewed to find out the most used measurements in apparel products and their locations on the human body. Bust girth, waist girth, hip girth, and inseam length were selected as representative measurements for apparatus design and data extraction. To explore possible design solutions, three designs were developed with three levels of color distinction and three levels of pattern regularity. Five sizes developed from ASTM D5585-11e1 were also assigned to each design to test the impact of apparatus fit on human body measuring.
Stage two focused on testing the apparatuses, collect data, and extract data from 3D scan files and 2D images. In the data collection process, 1D demographic and sportswear preference data, 2D image data, and 3D scan data were collected from 50 female college students. 1D data was collected through an online survey, 2D image data was taken by a smartphone with participants wearing apparatuses inside a standard doorframe, and 3D scan data was taken by Size Stream whole-body scanner with participants wearing the apparatuses. Participants were required to put on 2-3 different sizes including a best fitting size, a slightly smaller size, and a slightly larger size in the same design, and the best fitting size apparatus in the other two designs for 2D and 3D data collection. The 2D image includes one front view image and two side-view images. Two poses as arms beside the body (arms down) and arms above head (arms up) were used for side view images. This process collected data of the same subject wearing a different fit and different designs of measuring apparatus for further comparison. The second section of step two focused on data extraction from 2D image and 3D scan files. The four representative measurements, namely bust girth, waist girth, hip girth, and inseam length, were extracted from 3D scans as independent variables for 2D prediction model training. The waist girth level was defined as the center between bust and hip girth. The 2D images were labeled using Mask R-CNN to highlight the outline of measurement regions for data extraction.

Stage three focused on analyzing the collected 1D, 2D, and 3D data. The 1D data collected from the online survey were separated into three sections: basic demographic data, sportswear preference data, and measuring garments evaluation data. It is found that among college student participants, they prefer flexible and non-organized sports like fitness in the gym, walking, running, and yoga. The participants were only willing to pay less than 60 dollars for a sportswear product, and they value the quality more than fashion ability. After trying the three
designs of measuring apparatus, the participants evaluated the garments based on the style, color, and pattern. Generally, participants were interested in using all three designs for body measuring, but they tended not want to use these apparatuses in the public area or as casual wear.

The extracted 2D and 3D measurements were used to evaluate the effect of measuring apparatus design and fit. The 3D measurements of the same subject wearing different sizes were compared to analyze the effect of garment fit. The results suggested that when wearing a smaller size of the garment, the bust girth and waist girth were significantly smaller than the best fitting size measurements. When wearing a larger size, the waist girth, hip girth, and inseam length were significantly larger than the best fitting size measurements. It should be noticed that all differences of the mean were smaller than 0.5 inches. However, when making patterns for apparel products, the basic ease for bodice around bust is 4 inches, and 2.5 inches around waist (Gill, 2011). Although these differences were significant at the statistical level, they are very acceptable in the apparel industry.

The 2D representative measurements were extracted by training LASSO regression models with AIC for model selection. The measurements extracted using the prediction models of two labeling methods and poses were compared with 3D extracted measurements, and there was no significant difference. The resulting prediction model of three designs in two poses was further compared, and the results showed that the bust girth is significantly better in design 2 and significantly worse in design3, but the waist girth, hip girth, and inseam length prediction measurements did not have a significant difference among the three designs. The prediction model trained with arms-up pose images were slightly better than the prediction models trained with arms-down images.
5.1.1. Research Question 1

Research questions 1 and 1b asked about the impact of the fit and design of the measuring garments. It can be concluded that the fit of measuring apparatuses has a statistically significant impact on 2D prediction measurements but was acceptable in the apparel industry. The impact of measuring apparatus design was not significant. Research questions 1a and 1a1 wanted to know how the design might impact the measuring results and what kinds of patterns, colors, and styles can be used to obtain accurate measurements. Based on the prediction model, it seems that design has a limited impact on 2D prediction measurements, which means the design and color used in measuring garments designs have more possibilities. As for the style of measuring garments, after three generations of development, researchers determined that a foot strap and thumbhole would be necessary to cover arms and legs for multiple body shapes. For research question 1c, the current designs have achieved satisfying predictions in inseam length, but for hip girth, waist girth, and bust girth, there still has some room for improvement.

5.1.2. Research Question 2

Research question 2 explored the impact of side view pose in 2D image data. The comparison between the two poses approved that there is no significant difference between the two poses, and their regression models tend to be similar. This result approved that the arms-up pose can also be used for 2D image measure, which could make it easier for model training in future studies.
5.1.3. Research Question 3

Research question 3 focused on consumer attitude towards the measuring garments. The evaluation of 3 designs in different aesthetic level suggested that fashion elements could impact consumer attitude to use the measuring garments. Based on the online survey answered by 50 college students, it can be concluded that these consumers tend to participate in flexible and non-organized sports. They are more interested in the medium- or low-price sportswear products with relatively high quality and comfort. Fashion ability was not valued as much as the other two elements. However, designs with basic aesthetics were still preferred, as they showed more interested in designs with fashion elements and textile patterns compared to the color block design with poor fashion aesthetics. In the comments towards three designs, some of the participants mentioned that they did not like the turtleneck design and would prefer a flat collar, and some design elements like the monkey in the textile pattern for design 3 might be considered negatively by some consumers.

5.1.4. Research Question 4

Research question 4 asked about consumer acceptance of the new technology. After trying the apparatus and the 2D measuring method, most of the participants were interested in using the apparatus for body measuring. The measuring garments have some potential to be gym suits for the participants, but wearing the measuring garments as casual wear was not acceptable for the majority of them.

Overall, the developed measuring apparatuses can be used with the developed 2D measuring system for body measuring at home, and the conclusion that the design does not have
a significant impact on prediction measurements provided more possibility for future design and development.

5.2. Limitations and Further Studies

This research was limited by the size of the population and the limited age range. Most of the participants were a convenience sample of college students and as such, were more sensitive and curious about this kind of new technology and potentially more willing to try it. The accuracy of this 2D measuring method could also be improved with a larger population covering more age ranges, ethnicities, and body shapes to enrich the dataset for machine learning. Other objects, such as labels or tags, could be used as a reference unit instead of a door frame. More light conditions and backgrounds could be tested to improve the accuracy of 2D prediction measurements.
REFERENCES

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APPENDICES
Appendix A

NORTH CAROLINA STATE UNIVERSITY
INSTITUTIONAL REVIEW BOARD FOR THE USE OF HUMAN SUBJECTS IN RESEARCH
SUBMISSION FOR NEW STUDIES

Protocol Number 14281

Project Title
"Measuring Garment" Consumer Evaluation

IRB File Number:

Original Approval Date:

Approval Period

Source of funding (if externally funded, enter PINS or RADAR number of funding proposal via ‘Add New Sponsored Project Record’ button below):
None

NCSU Faculty point of contact for this protocol: NB: only this person has authority to submit the protocol
West, Andre J; Textile & Apparel, Technology & Management

Does any investigator associated with this project have a significant financial interest in, or other conflict of interest involving, the sponsor of this project? (Answer No if this project is not sponsored)
No

Is this conflict managed with a written management plan, and is the management plan being properly followed?
No

Preliminary Review Determination

Category:

In lay language, provide a brief synopsis of the study (limit text to 1500 characters)
Predicting body measurements from 2D images has been newly developed as an easy and affordable way for consumers to measure themselves. As the core measurement tool of this method, the measuring garments need to be developed as a set of socially acceptable garments without influencing the measurement result. To support the development of the measuring garments, body measuring data and participants' aesthetic preference will be collected. To decrease the variance and increase the significance of the analysis, the data collection will mainly be focused on college female students between 18 and 30.

50-100 participants will be invited to collect the following information:
1) a survey includes a) basic information (age, sex, ethnicity, weight measured by a weight scale and height measured through a wall-mounted ruler); b) sports-related lifestyle preference; c) evaluation of the provided measuring garments.
2) body measurement data in the format of a 3D point cloud models wearing the provided measuring garments collected through the Size Stream Body scanner.
3) and 2D images of the participants wearing a provided mask and scan garments taken with a cell phone provided by the researcher. The participants will put on up to 3 different sets of measuring garments and two 2D images will be taken while wearing each set. An eight-digit code will be generated and linked to the data. The whole process takes around 30 minutes.

Briefly describe in lay language the purpose of the proposed research and why it is important.
The purpose of this research is to develop a series of measuring garments that are socially acceptable and can be used as a measuring tool for body measurement prediction. Body measurements are used when deciding a size of clothing to purchase. However, most customers have trouble measuring themselves accurately and correctly. Predicting body measurements from 2D images has been newly developed as an easy and affordable way for consumers to measure themselves. As the core measurement tool of this method, the measuring garments need to be developed as a set of socially acceptable garments without influencing the measurement result. The attitude of potential consumers will be used to make sure that the developed measuring garments are acceptable to them, which indicates that they will be more likely to use the garments and wear them in their daily life. The collection of 2D images and 3D body scanning
data will be used to analyze the predicted measurement of human body and make comparison to make sure the measurement collected from the measuring garments are accurate.

My research qualifies for Exemption. Exempt research is minimal risk and must fit into the categories b.1 - b.6 found here: http://www.hhs.gov/ohrp/humansubjects/guidance/45cr46.html

0

Is this research being conducted by a student?
Yes

Is this research for a thesis?
No

Is this research for a dissertation?
Yes

Is this independent research?
Yes

Is this research for a course?
No

Do you currently intend to use the data for any purpose beyond the fulfillment of the class assignment?
No

Please explain

If so, please explain

If you anticipate additional NCSU-affiliated Investigators (other than those listed on the Title tab) may be involved in this research, list them here indicating their name and department.
N/A

Will the Investigators be collaborating with researchers at any institutions or organizations outside of NC State?
No

List collaborating Institutions and describe the nature of the collaboration

What is NCSU's role in this research?

Describe funding flow, if any (e.g. subcontractors)

Is this international research?
No

Identify the countries involved in this research

An IRB equivalent review for local and cultural context may be necessary for this study. Can you recommend consultants with cultural expertise who may be willing to provide this review?

Adults 18 - 54 in the general population?
Yes

NCSU students, faculty or staff?
Yes

Adults age 55 and older?
No

Minors (under age 18—be sure to include provision for parental consent and/or child assent)?
No

List ages or age range:

Could any of the children be "Wards of the State" (a child whose welfare is the responsibility of the state or other agency, institution, or entity)?
No

Please explain:
Prisoners (any individual involuntarily confined or detained in a penal institution -- can be detained pending arraignment, trial or sentencing)?
No

Pregnant women?
No

Are pregnant women the primary population or focus for this research?
No

Provide rationale for why they are the focus population and describe the risks associated with their involvement as participants

Fetuses?
No

Students?
Yes

Does the research involve normal educational practices?
No

Is the research being conducted in an accepted educational setting?
No

Are participants in a class taught by the principal investigator?
No

Are the research activities part of the required course requirements?
No

Will course credit be offered to participants?
No

Amount of credit?
No

If course credit will be given, list the amount and alternative ways to earn the same amount of credit. Note: the time it takes to gain the same amount of credit by the alternate means should be commensurate with the study task(s)

How will permission to conduct research be obtained from the school or district?
N/A

Will you utilize private academic records?
No

Explain the procedures and document permission for accessing these records.

Employees?
No

Describe where (in the workplace, out of the workplace) activities will be conducted.

From whom and how will permission to conduct research on the employees be obtained?

How will potential participants be approached and informed about the research so as to reduce any perceived coercion to participate?

Is the employer involved in the research activities in any way?
No

Please explain:

Will the employer receive any results from the research activities (i.e. reports, recommendations, etc.)?
No

Please explain. How will employee identities be protected in reports provided to employers?

Impaired decision making capacity/Legally incompetent?
No

How will competency be assessed and from whom will you obtain consent?
Mental/emotional/developmental/psychiatric challenges?
No
Identify the challenge and explain the unique risks for this population.

Describe any special provisions necessary for consent and other study activities (e.g., legal guardian for those unable to consent).

People with physical challenges?
No
Identify the challenge and explain the unique risks for this population.

Describe any special provisions necessary for working with this population (e.g., witnesses for the visually impaired).

Economically or educationally disadvantaged?
No

Racial, ethnic, religious and/or other minorities?
No
Describe the procedures used to overcome any language barrier.

Will a translator be used?
No
Provide information about the translator (who they are, relation to the community, why you have selected them for use, confidentiality measures being utilized).

Explain the necessity for the use of the vulnerable populations listed.
The student age group is selected as the target participant group because 1) students are easy to recruit; 2) they share similar body shapes and measurements which reduces the total variance and the required sample size, and 3) they share similar clothing interests.

State how, where, when, and by whom consent will be obtained from each participant group. Identify the type of consent (e.g., written, verbal, electronic, etc.). Label and submit all consent forms.

Recruiting emails will be sent to potential participants through researcher's NCSU email account (see attachment, Li 14281 recruiting email content.docx).

The email explains basic information about the project and types of data that will be collected. A link to a digital copy of the consent form is included. A link to booking appointments through Google calendar is also included. Once participants have decided to join the research, they can use the Google calendar link to book appointments.

Participants will come to the scanning location based on appointment time they sign up for. The scanning location is in room 3412 at College of Textiles, NC State University. Upon their arrival, they will be presented with the attached consent form in paper by the researcher. The research will then explain the consent form and participants will be asked to read it carefully before signing. Participants have the right to reject and leave if they are not conformed of participating in the research at any point.

There is no direct immediate/direct benefit to the participant.

Attachment
1. Li 14281 informed consent form.docx
2. Li 14281 recruiting email content.docx

If any participants are minors, describe the process for obtaining parental consent and minor's assent (minor's agreement to participate).
N/A

Are you applying for a waiver of the requirement for consent (no consent information of any kind provided to participants) for any participant group(s) in your study?
No
Describe the procedures and/or participant group for which you are applying for a waiver, and justify why this waiver is needed and consent is not
Are you applying for an alteration (exclusion of one or more of the specific required elements) of consent for any participant group(s) in your study?
No.
Identify which required elements of consent you are altering, describe the participant group(s) for which this waiver will apply, and justify why this waiver is needed.

Are you applying for a waiver of signed consent (consent information is provided, but participant signatures are not collected)? A waiver of signed consent may be granted only if: the research involves no more than minimal risk; the research involves no procedures for which consent is normally required outside of the research context.
No.
Would a signed consent document be the only document or record linking the participant to the research?
No.
Is there any deception of the human subjects involved in this study?
No.
Describe why deception is necessary and describe the debriefing procedures. Does the deception require a waiver or alteration of informed consent information? Describe debriefing and/or disclosure procedures and submit materials for review. Are participants given the option to destroy their data if they do not want to be a part the study after disclosure?

For each participant group please indicate how many individuals from that group will be involved in the research. Estimates or ranges of the numbers of participants are acceptable. Please be aware that participant numbers may affect study risk. If your participation totals differ by 10% from what was originally approved, notify the IRB.

50-100 females

How will potential participants be found and selected for inclusion in the study?
By sending out advertisement emails in NC State email list. By contacting faculties in the College of Textiles and kindly ask them to spread the information to their students. The recruiting email includes the information that we are looking for female college students. Will also include our blurb on Facebook and the Prime Fit Website (www.theprimefit.com) and will encourage women to share with their friends for a snowball effect.

Attachment: Li 14281 recruiting email content.docx

For each participant group, how will potential participants be approached about the research and invited to participate? Please upload necessary scripts, templates, talking points, flyers, blurbs, and announcements.
By spreading out advertisement emails in NC State email list. By contacting faculties in the College of Textiles and kindly ask them to spread the information to their students.

Attachment: Li 14281 recruiting email content.docx

Describe any exclusion criteria for your participants and describe why those criteria are necessary (if your study concentrates on a particular population, you do not need to repeat your description of that population here.)
Participants are required to be female college students, age 18 through 30. This is applied to reduce variance in the sample data.

Is there any relationship between researcher and participants - such as teacher/student; employer/employee?
No.
What is the justification for using this participant group instead of an unrelated participant group? Please outline the steps taken to mitigate this relationship.

Describe any risks associated with conducting your research with a related participant group.

Describe how this relationship will be managed to reduce risk during the research.

How will risks to confidentiality be managed?

Address any concerns regarding data quality (e.g. non-candid responses) that could result from this relationship.
In the following questions describe in lay terms all study procedures that will be experienced by each group of participants in this study. For each group of participants in your study, provide a step-by-step description of what they will experience from beginning to end of the study activities.

1. Potential participants will first receive an email regarding basic information of the research and a link that they can use to book scan appointments.
2. Once they agree to participate, they will come to the scan location (room 3412 during their appointment time).
3. Upon the arrival of the participants, they will first be asked to read and sign consent forms.
4. After that, they will be asked to fill in the first section of the survey (basic information part), the survey is attached.
5. They will then they will be body scanned wearing the provided scan garments, there is a private changing area protected with a booth for participants to put on measuring garments next to the body scanner.
6. Immediately after the scan, we will take the bust and waist measurement manually in order to validate the scanned measure output.
7. Finally, 2D images of the participants wearing a provided mask and scan garments will be taken with a cell phone provided by the researcher (the cell phone will be a personal phone belong to researcher). The participants will put on up to 3 different set of measuring garments (closed fitting space will be provided) and two 2D images will be taken while wearing each set. Images from the cell phone will be permanently removed and stored in a locked Google drive (images will be transferred through a code protected computer using USB), accessible only by the researchers. The cell phone is also locked with an access code. The cell phone will not be connected to Wi-Fi throughout the research process.

The measuring garments are designed to be covering most of the human body. The garments will be washed every day after being used.

Attachment:
1. Li 14281 survey.docx

Describe how, where, when, and by whom data will be collected.
All data will be collected in room 3412 at College of Textiles by the researcher during participants’ assigned appointment time.

Social?
Yes
Psychological?
No
Financial/Employability?
No
Legal?
No
Physical?
Yes
Academic?
No
Employment?
No
Financial?
No
Medical?
No
Private Behavior?
No
Economic Status?
No
Sexual Issues?
No
Religious Issues/ Beliefs?
No
Describe the nature and degree of risk that this study poses. Describe the steps taken to minimize these risks. You CANNOT leave this blank, say
'NA', none or no risks’. You can say “There is minimal risk associated with this research.”
There is minimal risk associated with this research since subjects will not be scanned in their undergarments. There will be a private space for participants to get changed in the 3D body scanner booth (there is no camera in the changing room).

If you are accessing private records, describe how you are gaining access to these records, what information you need from the records, and how you will receive/record data.

N/A

Are you asking participants to disclose information about other individuals (e.g., friends, family, co-workers, etc.)?

No

You have indicated that you will ask participants to disclose information about other individuals (see Populations tab). Describe the data you will collect and discuss how you will protect confidentiality and the privacy of these third-party individuals.

If you are collecting information that participants might consider personal or sensitive or that if revealed might cause embarrassment, harm to reputation or could reasonably place the subjects at risk of criminal or civil liability, what measures will you take to protect participants from those risks?

Participants have the right to be a part of this study, to choose not to participate, or to stop participating at any time without penalty.

When 2D images are taken, participants are wearing provided scan garments that cover most part of a body. They will also be asked to wear a mask that protects their faces from being captured.

When doing 3D body scanning, participants will change their clothing in a closed space to protect their privacy.

If any of the study procedures could be considered risky in and of themselves (e.g., study procedures involving upsetting questions, stressful situations, physical risks, etc.) what measures will you take to protect participants from those risks?

The study procedures are minimal risks. Participants have the right to be a part of this study, to choose not to participate, or to stop participating at any time without penalty.

Describe the anticipated direct benefits to be gained by each group of participants in this study (compensation is not a direct benefit).

There is no direct immediate/direct benefit to the participant.

Participants will get printouts with their body measurements. The body measurements can be used for size determination and clothing customization.

If no direct benefit is expected for participants describe any indirect benefits that may be expected, such as to the scientific community or to society. The measurement sheet can help participants better understand their body shapes It may also motivate them to maintain good health. It can also help them choose clothing size when they go shopping. The purpose of the study is to develop a body measurement system for daily use. This is beneficial for users who want to measure their body in an easy and cheap way.

Will you be receiving already existing data without identifiers for this study?

No

Will you be receiving already existing data which includes identifiers for this study?

No

Describe how the benefits balance out the risks of this study.

Will data be collected anonymously (meaning that you do not ever collect data in a way that would allow you to link any identifying information to a participant)?

No

Will any identifying information be recorded with the data (ex: name, phone number, IDs, e-mails, etc.)?

No

Will you use a master list, crosswalk, or other means of linking a participant’s identity to the data?

No

Will it be possible to identify a participant indirectly from the data collected (i.e. indirect identification from demographic information)?

No

Audio recordings?

No

Video recordings?

No

Images?
Yes
Digital/electronic files?
Yes
Paper documents (including notes and journals)?
Yes
Physiological Responses?
No
Online survey?
Yes
Restricted Computer?
Yes
Password Protected files?
Yes
Firewall System?
Yes
Locked Private Office?
Yes
Locked Filing Cabinets?
No
Encrypted Files?
Yes

Describe all participant identifiers that will be collected (whether they will be retained or not) and explain why they are necessary.

Participants’ email addresses are required when they sign up for the appointment time. This is required by Google Calendar. However, this information will not be linked to their body data.

Data obtained from body scanners, in the form of 3D point clouds, is generally unidentifiable. Participants will wear a mask when their pictures are taken. File encryption using Microsoft Encrypting File System will be used to protect the confidential data. The data will be put in a secure hard drive and kept in a locked office in Wilson College of Textiles.

If any links between data and participants are to be retained, how will you protect the confidentiality of the data?

While appointments will be managed through a Google calendar, there will be no direct link from the data to the participants.

Participants will complete and sign a paper consent form that has a randomly generated code attached. The code can be used to validate that each participant consented to be involved in the study and linked to participants’ research data. The paper consent forms will be filed in a locked office away from any other data.

Images will be taken with a cell-phone because that is how consumers will ultimately use the application. The cell phone can be connected directly to a password-protected computer to download the images using the normal USB cable.

If you are collecting data electronically, what (if any) identifiable information will be collected by the host site (such as email and/or IP address) and will this information be reported to you?

No identifiable information will be collected by the host site. All body-related data is collected through a specific computer and a specific cell phone. These electronic devices are password protected. Participant’s data will be represented in an eight digit code instead of their names. Therefore, no link will be created between data and subjects. Besides the listed body data and basic information, no other data will be collected.

Describe any ways that participants themselves or third parties discussed by participants could be identified indirectly from the data collected, and describe measures taken to protect identities.

The third party can’t identify the participants indirectly from the data collected.

For all recordings of any type: Describe the type of recording(s) to be made Describe the safe storage of recordings Who will have access to the recordings? Will recordings be used in publications or data reporting? Will images be altered to de-identify? Will recordings be transcribed and by whom?

The data that will be collected from participants include:
1) demographic data (age, sex, ethnicity, weight, height) collected through a questionnaire, a weight scale, and a wall-mounted ruler;
2) body measurement data in the format of 3D point cloud models (wearing the provided scan garments) collected through the Size Stream body scanner;
3) Manual measurements of the bust and waist taken with a tape measure
4) and two 2D images of the participant wearing a provided mask and scan garments taken with a cell phone provided by the researcher.

An eight digital code will be generated and linked to the data. All body-related data is collected through a specific computer and a specific cell phone. These electronic devices are password protected. Questionnaires will be locked in researcher's office. The office is code protected.

Currently, only the listed researchers (Jiayin Li, Cynthia Istock, and Andre West) in the consent form will have access to the recordings. Potentially, the collected data may be used for future research as an existing database. Since no identification will be saved, neither currently researchers or future researchers will be able to identify any participants.

The analysis result will be used for publication purpose; however, the original recordings will not be published.

Images are for the purpose of measurement collection. No de-identification process will be included.

Describe how data will be reported (aggregate, individual responses, use of direct quotes) and describe how identities will be protected in study reports.

Collected data will be analyzed to test the accuracy of measurement prediction. The result will be published. However, the original recordings will not be published. Therefore, no identities will be reported.

Will anyone besides the PI or the research team have access to the data (including completed surveys) from the moment they are collected until they are destroyed?

The collected data may be used for future research as an existing database. Since no identification will be saved, neither currently researchers or future researchers will be able to identify any participants.

Describe any compensation that participants will be eligible to receive, including what the compensation is, any eligibility requirements, and how it will be delivered.

The subject will be offered with a printout of their body measurements and a short sleeve t-shirt as compensation.

Explain compensation provisions if the participant withdraws prior to completion of the study.

If a participant withdraws prior to completion of the study, she will still get a short sleeve t-shirt, however, she may or may not get a measurement printout depending on how far she goes. This is because measurement printout is generated from the collected body point cloud.
Appendix B

"Measuring Garment" Consumer Evaluation Survey

Section 1: Basic Information
1. Age: _____________
2. Gender: ☐ FEMALE ☐ MALE
3. Ethnicity: ☐ White ☐ African American ☐ Hispanic ☐ Asian ☐ Native American
   ☐ Multiracial _____________________ (please list all ethnicities that apply)
   ☐ Other _____________________ (please write the ethnicity that applies to you)

4. Are you currently enrolled as a college student? ☐ YES ☐ NO

Following is filled by the researcher:
Participant’s ID number: __________________________
Weight: _____________________ lbs. Height: ___________________ inches
Section 2: Sports-related Lifestyle and Preferences

1. How often do you engage in active exercise?
☐ Less than once a month ☐ 1-3 times a month ☐ Once a week
☐ 2-4 times a week ☐ more than 4 times a week

2. What do you most often do for exercise? (Choose all that apply)
☐ Fitness/Gym ☐ Walking ☐ Running ☐ Swimming ☐ Hiking ☐ Dancing ☐ Bike Riding
☐ Yoga ☐ Aerobics ☐ Pilates ☐ Team Sports ☐ Other (Please specify)

3. How often do you buy new activewear (either a top, a bottom, or any other item of activewear)
☐ Less than once a year ☐ Once a year ☐ Once a quarter ☐ Once a month ☐ Several times a month

4. What are your favorite activewear brands? Select the top 3 you like.
☐ Nike ☐ Adidas ☐ Puma ☐ Under Armour ☐ Lululemon ☐ Fabletics ☐ Other (Please specify)

5. What do you mainly use activewear for? (Choose all that apply)
☐ Exercise ☐ Lounging at home ☐ As everyday wear ☐ As a fashion statement

6. What're the top 3 things you care about while shopping activewear?
☐ Fit of clothes ☐ Comfort ☐ Quality and breathability of the material
☐ Design and fashion aspect ☐ Versatility, ability to wear outside the gym
☐ Durability, ability to wash easily ☐ Price ☐ Other (Please Specify)

7. How much are you willing to pay for an activewear top?
☐ Less than $30 ☐ $30-$60 ☐ $60-$100 ☐ $100-$200 ☐ More than $200

8. How much are you willing to pay for an activewear bottom?
☐ Less than $30 ☐ $30-$60 ☐ $60-$100 ☐ $100-$200 ☐ More than $200
Section 3: Evaluation of Designed Measuring Garments

A. Please answer the following questions after trying 3 Measuring Garments.

1. Select your evaluation of the fit from 1-5

1: very tight  
2: slightly tight  
3: fits perfectly  
4: slightly loose  
5: very loose

Garment 1: 1 2 3 4 5
Garment 2: 1 2 3 4 5
Garment 3: 1 2 3 4 5

2. Select your evaluation of the comfort from 1-5

1: very uncomfortable  
2: slightly uncomfortable  
3: neither  
4: comfortable  
5: very comfortable

Garment 1: 1 2 3 4 5
Garment 2: 1 2 3 4 5
Garment 3: 1 2 3 4 5

B. Please answer the following questions base on the 5 designs below (the 5 designs will be attached):

1. Select your evaluation of each set of measuring garments from 1-5 (1 is lowest and 5 is highest)

Design1: 1 2 3 4 5
Design2: 1 2 3 4 5
Design3: 1 2 3 4 5
2. How likely would you use this garment for body measuring?

1: very unlikely 2: somewhat unlikely 3: neither likely nor unlikely 4: somewhat likely 5: very likely

<table>
<thead>
<tr>
<th>Design1:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>Design2:</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Design3:</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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</tbody>
</table>

3. How likely would you wear this garment to the gym?

1: very unlikely 2: somewhat unlikely 3: neither likely nor unlikely 4: somewhat likely 5: very likely

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<th>Design1:</th>
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<tr>
<td>Design3:</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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</tbody>
</table>

4. How likely would you wear this garment as casual wear?

1: very unlikely 2: somewhat unlikely 3: neither likely nor unlikely 4: somewhat likely 5: very likely

<table>
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<tr>
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<td>1</td>
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5. Please add your suggestions or comments below for each design if you have any.

Design1:

Design2:

Design3:
Appendix C. Histograms Q-Q plots of Difference between the 2D and 3D Measurements

Whole body label:
Torso label:
Appendix D. Performance of Prediction Models Trained with Torso-labeled Images

Design 1:
Design 2:
Design 3:

blu_3d_seat_girth prediction results_down

\[ |y^* - y| > 1\text{"} \text{cnts} \\
|y^* - y| < 1\text{"} \text{cnts} \]

Sample index

blu_3d_seat_girth prediction results_up

\[ |y^* - y| > 1\text{"} \text{cnts} \\
|y^* - y| < 1\text{"} \text{cnts} \]

Sample index

blu_3d_inseam prediction results_up

\[ |y^* - y| > 1\text{"} \text{cnts} \\
|y^* - y| < 1\text{"} \text{cnts} \]

Sample index

blu_3d_inseam prediction results_down

\[ |y^* - y| > 1\text{"} \text{cnts} \\
|y^* - y| < 1\text{"} \text{cnts} \]

Sample index

jun_3d_bust_girth prediction results_down

\[ |y^* - y| > 1\text{"} \text{cnts} \\
|y^* - y| < 1\text{"} \text{cnts} \]

Sample index

jun_3d_bust_girth prediction results_up

\[ |y^* - y| > 1\text{"} \text{cnts} \\
|y^* - y| < 1\text{"} \text{cnts} \]

Sample index