Seamless knitted sports bra design: A responsive system design exploration

Adriana Carmen Gorea

Iowa State University

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Seamless knitted sports bra design: A responsive system design exploration

by

Adriana Carmen Gorea

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Apparel, Merchandising, and Design

Program of Study Committee:
Fatma Baytar, Co-major Professor
Eulanda A. Sanders, Co-major Professor
Sarah Bentil
Steven Herrnstadt
Chunhui Xiang

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2017

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ACKNOWLEDGEMENTS

To my beloved husband Sunil,
Without your constant support and love this dissertation would not have been possible.

To my dear children Valentina, Jaden and Taishan,
I will always support your dreams.

I would also like to express my endless gratitude to Dr. Eulanda Sanders and Dr. Fatma Baytar for encouraging me to pursue my research interests, and offering me constant mentorship and feedback during the research process.

Also, special thanks for the financial support provided by Dr. Eulanda Sanders through the Donna Danielson Endowment fund.

Among all who contributed to my research, many thanks to my committee members Dr. Chunhui Xiang, Dr. Sarah Bentil, and Prof. Steven Herrnstadt for their constructive feedback; to Xinao Textiles Ltd. for sponsoring this study with performance wool yarns; to Keith Sherrill at Seamless Knitting Solution for providing expertise; to Dr. Huantian Cao at University of Delaware for allowing me to use the equipment in the textile lab; and to the volunteering subjects who ran and sweated to support the sports bra science.
ABSTRACT

The transition of sports bras’ uses, from an active lifestyle to resting activities, requires dynamic and adaptable comfort properties of the design, as well as adequate breast support, fit, and comfort. Thus, the two-fold purpose of this study was to: (a) analyze the use of current materials and processes in the product development process of seamless sports bras, via industry interview and observation, and (b) propose a design solution for a seamless sports bra that offers variable breast support during running versus resting activities.

Using a case study approach, an in-depth interview with a Santoni seamless knitting technician provided data that led to mapping out the design and product development processes used for prototyping seamless sports bras. A seamless business model for a sports bra was created, and relationships among the over-arching themes of planning, marketing, product development, innovation, and production, which emerged from the grounded theory analysis, were discussed. Moreover, a detailed Product Development framework and a Tech Pack model were created and used to communicate the new design for a responsive seamless sports bra. Interactions between design, prototyping and functionality and how these themes relate to the components of the tech pack were discussed.

At the materials level, a biomimetic system framework was used to identify solutions to responsive interactions within wool/Nylon/spandex blended yarns and various knitting structures when actuated by moisture. Twenty pattern designs were knitted on a Santoni circular knitting machine, using two different yarn combinations: (a)
wool/spandex, and (b) wool/nylon/ spandex. Physical properties of the knit swatches were documented, as well as their thickness when dry versus three different moisture activation situations: (a) immediately after wetting, (b) after 30 minutes of air-drying, and (c) after 60 minutes of air-drying. Results showed that the Santoni circular knitting technology has capabilities to create a variety of texturally knit fabric designs that have a wide range of thicknesses, densities, and moisture responsiveness properties. Selections of knit patterns were made based on the textile testing results and used to design a responsive sports bra that incorporated female sweat maps and sports bra user needs. Sustainability considerations regarding the wet processing of the new responsive design were implemented, and the bra samples were not dyed, but only cold-washed and tumble-dried at low temperature.

Fifteen prototypes were developed via a Santoni circular seamless knitting machines and tested using human subjects and 3D body scanning technology. A convenience sample of fifteen semi-athlete female college students wore the new sports bra prototypes during three different moisture conditions: (a) before a run (dry), (b) after 30 minutes run on a treadmill (wet), and (c) after resting 30 minutes (starting to dry out). 3D body scans were collected in fully inhaled, as well as relaxed respiratory states after each condition. Questionnaires were used to evaluate comfort and responsiveness of the new design. The results revealed that the new responsive sports bra offers compression during the dry conditions, breathability and some level of breast support during running, and moisture management during the resting stage, all while offering high overall comfort and fabric softness. However, the length of the bra straps needs to be shortened,
and the breast support during running needs improvement, therefore further design iterations are needed.

The proposed integrative approach to the sports bra design offers a new framing for the systematic design process of a sports bra as a functional design garment and fills knowledge gaps within the seamless knitting process using performance wool blend yarns. The new biomimetic-inspired sports bra solution has a potential for commercial applications that can offer women a responsive, adaptable sports bra, to encourage healthier lifestyles, as well as to accommodate for the athleisure trend.
CHAPTER 1: INTRODUCTION

Background

According to Warner (2013), sportswear describes a very broad category of fashion-oriented comfortable clothing, based loosely on clothing developed for participation in sports. Sportswear as a fashion category consists of separate pieces that may be “mixed and matched,” a merchandising term meaning that articles of clothing are designed to be coordinated in different combinations: trousers or shorts or skirts with shirts and sweaters or jackets of a variety of sorts (Warner, 2013). “Active sportswear,” that later became activewear, was the term used to cover the clothing worn and designed for specific sports and exercise activities, such as football jerseys, yoga pants, sweatshirts, and sports bras to name just a few.

The benefits of exercise extend far beyond weight management. Research shows that regular physical activity can help reduce a person’s risk for many diseases and health conditions and improve the overall quality of life (Warburton et al., 2006). Increased consumer demand has prompted United States activewear sales to grow at double the rate of non-active apparel sales for several years, reaching $33 billion dollars in sales in 2014 (The NPD Group, 2014, para.1). According to a recent report by Morgan Stanley (2015), sales are expected to reach $83 billion in sales by 2020 (para.3).

With the increasing trend in well-being and healthy lifestyle, and particularly after the introduction of Title IX of Education Amendment in 1972, the increase of women participation in sports was significant (Carpenter & Acosta, 2000). Lopiano (2000) found that women count for more than 55% of all volleyball players, 43% of all runners, and 41% of all soccer players. A more active lifestyle demands adequate performance from
the clothing worn. Therefore, there has been a growth in the design of sports equipment and specialized apparel for active women, with a special emphasis on sports bras. Although it was Title IX, which prompted the invention of the sports bra (Schultz, 2004), today the sports bras represent a basic category of women activewear and a profitable market.

Activewear, that traces its origins to the high-performance sportswear designed in the early 2000s for mountaineering, sailing, and hiking, is a clothing category defined by functionality, comfort, and safety (Quinn, 2010). In this category, garment specifications are developed and designed to construct products that fit the performance needs of the user when engaged in a certain type of sports activities (Manshahia & Das, 2014). To reconcile the demands of modern lifestyle, with women performing various daily activities while wearing the same clothing, the boundaries between street clothes, office attire, and sportswear are blurring (Warner-Campbell, 2010). Therefore, activewear has expanded into mainstream fashion, evolving into a new category, athleisure, that works for both athletic and leisure pursuits (Quinn, 2010). Due to this shift in the way the clothing is worn, the activewear marketplace has experienced a convergence of functionality, comfort, and fashion creating new complexities for the product developers and designers. According to Cotton Incorporated’s 2014 Sports Apparel Survey, more than nine in 10 consumers say they wear activewear for activities other than exercise (Cotton Incorporated’s Lifestyle Monitor, 2014, para.1). This consumer behavior shift led to a change in expected comfort and functionality of a sports bra.

Sports bras are functional garments designed to reduce repetitive movements of breasts during physical activity. Sports bras are not only a key product; they can also
serve as an entry point into sportswear as a whole since women do not wear their regular bras for participating in sports (Bowles et al., 2008). It has been found that independent breast movement occurs during physical activity due to limited intrinsic breast support (Burnett at al., 2015). Continuous and repetitive movements without breast tissue support can result in breast soreness, pain, and sagging (Zheng et al., 2006). A sports bra is defined as "a bra with built-up straps, coming over shoulders forming a crab-like back, secured by an elastic band around the body and worn for active sports" (Calasibetta, 1998, p. 63). A reduction in the magnitude of breast movement and a decrease in breast pain occurs during running when wearing a sports bra compared to an everyday bra (Mason et al., 1999).

The original sports bra, called a jogbra, was invented by Lisa Lindahl and Polly Smith in 1977 and was constructed from two jockstraps sewn together (Schuster, 1979). The invention of the commercial sports bra in 1977 was a significant advancement for physically active women (Schultz, 2004). While the sports bra design and innovation has evolved from the first general exercise bra, recent studies report that 75% of female marathon runners experience bra-related issues, such as tightness around the chest or straps slipping from the shoulders (Brown, 2014). Another study conducted by University of Portsmouth's Research Group in Breast Health found that 46% of 2,000 women surveyed said their breasts were a barrier to participating in sport (Burnett et al., 2015, p. 588). Moreover, sports bras are not only designed for maximum functionality; they are cultural objects, fashion objects, women associate clothing in general with body satisfaction (Littrell et al., 1990), and express disappointment with the fit as a reflection of the discontentment with their bodies (LaBat & Delong, 1990). In the same time, sports
bras have migrated from being worn for a short period, only to the gym or while exercising, to being worn most of the day (Schultz, 2004).

The various end uses of the sports bra, such as for comfort and leisure wear, for fashion or for active participation in sports activities, brought up functional design deficiencies of existing sports bras (Burnet et al., 2015). Correct mapping of the functional needs of the consumer is a key step for the design of sports bras as a category of functional apparel (Watkins & Dunne, 2015). Haycock (1978) found that, for women participating in exercise, breast support is crucial, and consumers regard this feature as the main function of a sports bra. The most common complaint is insufficient breast support, especially among the larger breast sizes, with some designs performing better than others (Dhanapala, 2016). The key performance variables that distinguish between levels of breast support during various sports activities are still unclear, and there is no industry standard to determine the performance of breast support garments such as sports bras (Risius et al., 2016). By trying to address these concerns, the manufacturers and designers of sports bras increased the range, complexity and style variety of their commercial sports bras offerings. Major developments in fiber and textile technologies, as well as garment construction and manufacturing methods, have been employed to improve sports bras design and functional properties (McCann, 2005).

Moreover, the current transition of sports bras’ uses, from an active lifestyle to resting activities, requires dynamic and adaptable comfort properties of the design as well as adequate breast support, fit and comfort. Despite the importance of external breast support, there has been a lack of research evidence upon which to design effective sports bras, until about a decade ago when the number of studies increased drastically. In the
current age of technological revolution, the sports bra industry has struggled in developing an adaptable and responsive sports bra, which supports the body during high impact sports while feeling soft and comfortable during rest (Hansman, 2017).

According to Onofrei et al. (2011), the most important characteristic of functional clothing in general is to create a stable microclimate close to the skin to support the body’s thermoregulatory system in any physical environment. Tactility and aesthetics are also considered important qualities of garments (Emirhanova & Kavusturan, 2008). Based on all these characteristics, knitted fabrics are commonly preferred not only for activewear in general but also particularly for sports bras (Mikucioniene & Milasiene, 2013). The latest generation of advanced knit structures have enabled controlled muscle tissue and compression, leading to increased oxygen and blood flow, and comfort (McCann, 2009). Axial loading that produces a squeezing or crushing effect is compression (Anderson, 2003). Current compression sports bras are categorized as ‘low support,’ ‘medium support,’ and ‘high support or high impact,’ but the compression level varies largely between different sports bra designs marketed with the same support level (Gorea & Baytar, 2016). Compression capabilities were also found to change after multiple cycles of wash and wear, as the mechanical properties of knitted fabrics can change over time based on the fiber type, yarn structure and fabric properties (Stankovic, 2006). Measuring and classifying compression levels also received generous attention from researchers, with methods varying from use of: (a) novel Pliance-X pressure sensors inserted between the bras and the body of the wearer (Zheng et al., 2009), (b) Textilpress device placed on cylinders mimicking body shape and skin texture (Maklewska et al., 2007), and (c) three-dimensional (3D) body scanning comparative
analyses of contours of the body while wearing the sports bras (Gorea & Baytar, 2016), to name a few. Seamless circular knitting machines have been the primary technology used for manufacturing compression sports bras, due to achieving uniform compression levels around the body (Tiwari et al., 2013). While compression itself is efficient in holding the breasts in place during movement, the chest flattening visual effect is one of the major customer complaints. Currently, sports bras are categorized as encapsulation, compression, and combination (Bowles et al., 2012). Encapsulation sports bras support each breast individually with the use of two distinct cups as part of the design. Compression bras compress both breasts simultaneously, holding them firmly against the body, reducing their movement but also flattening their shapes. Combination sports bras provide both compression and encapsulation, and they have the best customer reviews (Scurr et al., 2011). However, Zhou et al. (2013) found the compression type bra to be the most efficient at reducing breast movement.

Textile and manufacturing technologies drive much innovation into the design at multiple stages in the process: fiber, textile, and garment construction (McCann, 2005). However, some recent research demonstrates that it is possible to achieve smart, defined as responsive functionality, by re-evaluating traditional materials and design processes (Hayes & Venkatraman, 2015). Improved functionality can be achieved by gaining a precise and thorough understanding of how these materials and textiles interact because of a systematic product design process rather than fast fashion design process (McCann, 2005; Krenzer et al., 2005). The fast evolution in the fiber and material technologies made activewear lighter, more breathable and improved its wicking, flexibility, fit, and strength, to name just a few developments. The use of high-tech materials, such as
microfibers, nanofibers, and technical textiles, requires extensive quality testing to achieve the performance required by activewear (Holme, 2007). Dhanapala (2015) argued that sports clothing is purchased predominantly with little consideration of the product’s intended active purpose, but rather for everyday use, further blurring the distinction between fashion and sportswear.

Few researchers have studied the responsive behavior for fibers and textiles (Eriksson et al., 2011; Heimdal, 2009; Pakchyan, 2008; Scott, 2015). There are two known conventional methods to integrate responsive function into textiles: (a) using the textile as a supporting layer or (b) integrating conductive yarns or smart materials into the textile structure during fabric production (Scott, 2015). However, both of these approaches focus on the integration of smart yarns or materials into the existing material of the garment, rather than considering the entire garment function. Kim Scheffler, Director of Product Development for Adidas Digital Sports, stated that,

For example, heart monitoring knitted sensors were designed separately, as fabric strips, that functioned well by themselves; but when inserted into the sports bra bands to create heart monitoring sport bras, the body movement distorted the signal leading to decreased efficiency. (K. Scheffler, personal communication, November 20, 2016)

According to the Biomimicry Institute in the United States, biomimicry (from the Greek words bios, meaning life, and mimesis, meaning to imitate) is a theoretical design framework “that seeks sustainable solutions by emulating nature’s time-tested patterns and strategies” (Frumkin et al., 2011, p.12). Biomimetics, a term created by Otto Schmitt in the 1950s to name the transfer process of knowledge from natural systems to technology, has produced significant and successful devices and concepts in the past half of the century but is still empirical (Vincent et al., 2006). The natural world provides excellent examples of responsive functional systems build with minimal use of energy
and using just a handful of materials (Eadie & Ghosh, 2011). Biological mechanisms can be actuated by their own material properties, which eventually leads to achieving higher responsiveness levels (Dompioti et al., 2010). Many of the innovations in textile and materials as related to enhancing activewear performance have been informed by biomimicry (Bar-Cohen, 2006; McCann, 2005; Vincent, 2006; Vincent et al., 2006). Shark skin has been mimicked for competitive swimwear by Speedo, insect shells served as models for helmets (McCann, 2008). As a theoretical framework, biomimicry focuses on the functional analysis of natural forms, processes, and systems, with the purpose of finding analogies and models of sustainable design solutions (Benyus, 1997). The resulting solution is only in very rare cases a true mimicry of natural structures or processes. Modern biomimetics is a systematical problem-solving approach that involves analysis and understanding of a biological model, followed by an abstraction and modification process to reach a technical solution that is more efficient than the already existing ones (Mihwich et al., 2006). The reason why biomimicry has been a successful model for textiles is due to textile fibers’ organic natures (Eadie & Ghosh, 2011). In addition, similar to many natural functional surfaces, the large surface area of fibrous textiles offers tremendous opportunities to functionalize them.

Vincent et al. (2006) observed that, while technology solves problems largely by using energy, biology problems are solved by the use of information and structure, two factors ignored by technology. Specifically, in nature, the biological structures of plants respond to a variety of stimuli, such as light, gravity, and touch. Plant materials are naturally hierarchical; each level is responsible for controlling and adapting certain functionalities (Gibson, 2012). The response of this biological system is not only a result
of the structuring of the material itself, but a result of the overall inter-relationships between all elements of the system, active and passive. A similar hierarchy can be seen in the specific case of a sports bra. The fibers make the yarns, that consequently make the fabric, and, via specific construction and design details, the fabric parts are assembled to make the sports bra. Each of these layers constitutes inter-related, hierarchical elements or subsystems, that react when the wearer moves, warms up, sweats and eventually dries out. The response of the entire bra system is a result of the overall mechanism, not just the functional result of a singled out part.

Therefore, the goal of this research is to find a biomimetic based design solution that will increase the responsive function of sports bras, offering high support during exercise and low comfortable support during resting activities, aiming to better serve the current lifestyle of women, stimulate their participation in sports and improve their overall health.

**Significance**

The importance of this study relays in its subject of the investigation that of improving sports bra design, in order to promote women participation in sports and healthier lifestyles. The consequence of a well-functioning sports bra goes beyond the regular womenswear market and affects breast cancer survivors. A recent online survey completed by 482 breast cancer survivors found that the top three barriers to exercise were procrastination, fatigue, and not being able to find a comfortable bra to wear for exercise (Gho et al., 2010).

Moreover, the proposed innovative approach to the sports bra design, integrating together all processes and materials of a hierarchical system as serving the same function,
that of offering responsive breast support, offers a new framing for the systematic design process of a sports bra as a functional design garment. Although garment manufacturers have attempted to capitalize on the sports bra market, not many bras currently marketed as sports bras have been designed using data from empirical studies (Lawson & Lorentzen, 1990). While engagement with sports bra use is high, sports bra design needs improvement to alleviate bra fit issues experienced by female runners (Brown et al., 2014). This research will add to the scientific and applied body of knowledge in the field of textiles and sports bra, breast support metrics.

As we begin the twenty-first century, sustainability of design processes and materials should be a major concern for the product development teams, not only at the garment construction level but also at the fiber and textile development level (McCann, 2009). This research documents the exploration of responsive properties for various natural and recycled fibers and yarns, and will add significant knowledge in this area of study. The use of current manufacturing technologies such as seamless knitting and 3D body scanning makes this study relevant for the development of commercial sports bras, leading to improved women health and well-being.

**Purpose**

The two-fold purpose of this study is to: (a) analyze the use of current materials and processes in the product development process of seamless sports bras, via industry interviews and observations, and (b) propose design solution for a seamless sports bra that offered variable breast support during running versus resting activities. A biomimetic system framework was used to identify solutions to responsive interactions within fibers, yarns and knitting structures when actuated by body moisture generated during running.
Prototypes were developed via circular seamless knitting machines and tested using 3D body scanning technology, and commercial applications were discussed.

Research Questions

This study considered the following research questions:

1. What are the current materials and processes used in the product development process of seamless sports bras?

2. What component materials and structures of a seamless sports bra system offer responsive behavior when actuated by body moisture? How are these materials and structures informed by the tenants of biomimicry?

3. How can a sports bra be designed to function as a responsive system using wearer’s body moisture as system actuator?

Objectives

An analysis of qualitative data gathered via industry interviews, notes and observations identified variables that were used for the experimental part of this study. Empirical testing determined responsive design components for a sports bra prototypes, and the development of prototypes will be documented in a process flow chart. Quantitative and qualitative testing of the prototypes were analyzed. The following research objectives have been identified:

1. Analyze the current design process practices for seamless knitted sports bras and identify design process components and interactions by one manufacturer.

2. Identify feasible materials and processes for biomimetic inspired responsive sports bra design.

3. Create prototypes for responsive seamless sports bra designs.

A diagram of the overall research project and how the stated objectives relate to the overall goal is shown in Figure 1.1. Future explanation of the research design is detailed in Chapter 3 (Methods).

Assumptions

As a functional design study, the pre-identified user-needs are key to the final solution. Not having the customer feedback on an existing model for such a responsive system, the main assumption is that a bra that changes functionality from high breast support to low breast support serves the need of an active lifestyle woman. Another assumption is that natural fibers and biological systems offer the best responsive analogies to the adaptable function problem of the sports bras.

Seamless knitting technology offers a more efficient and sustainable alternative to the cut and sew manufacturing option existing at the current time. There is less yarn wasted when knitting rather than by cutting patterns out of a knitted fabric. However, another assumption is that a more efficient manufacturing process will lead to a better product quality.
Figure 1.1. Overall research project.

Scope and Limitations

This study focused on women sports bras as a category of activewear. Moreover, only seamless compression sports bras made via Santoni seamless technology investigated. Current standards for body and garment dimensions include those established by the Association of Standards and Testing Materials (ASTM) and the International Standards Organization (ISO). Multiple factors involved in bra sizing and
fitting as well as the variety of body shapes, exercise types, diet types and sweating add complexity and limitation to such study.

Although other knitting technologies are currently available for manufacturing seamless sports bras, the prototypes were made on seamless Santoni technology available at the time of the study in a location convenient to the researcher. Other limitations derive from using the biomimetic model for the design development, although other responsive systems suitable for apparel design might exist. Fiber and yarn selection, based on testing made with technology and knowledge available at the time of the study, was another limitation. It should be also mentioned that among several 3D body scanner types that are currently available, significant variance exists in how each one of them captures specific body measurements (Istook & Hwang, 2001). Although the same 3D body scanner was consistently used for all the trial testing, the 3D body scanning equipment itself has shortcomings regarding the accuracy of capturing the data. The 3D body scanner model that was used for testing the prototypes, a Textile/Clothing Technology Corporation [TC]² NX-16 model, constitutes another limitation, as its calibration was made following the manufacturer’s instructions.

**Definitions of Terms**

*Design process*  
“the translation of information in the form of requirements, constraints, and experience into potential solutions which are considered by the designer to meet required performance characteristics” (Luckman, 1984, p.84).

*Biomimetics* 
also known as “bionics,” “biognosis,” “biomimesis,” or “biomimicry,” is the “study of the formation, structure, or function
of biologically produced substances and materials and biological mechanisms and processes especially for the purpose of synthesizing similar products by artificial mechanisms that mimic natural ones” (Vincent et al., 2006, p.471).

**Functional clothing** a generic term that “includes all types of clothing or assemblies that are specifically engineered to deliver a pre-defined performance or functionality to the user, over and above its normal functions” (Gupta, 2011, p.331).

**Sports bra** "a bra with built-up straps, coming over shoulders forming a crab-like back, secured by an elastic band around the body and worn for active sports” (Calasibetta,1998, p. 63).

**Seamless knitting** “creates one entire complete garment with minimal or no cutting and sewing process” (Choi &Powell, 2005, p.1).

**Comfort** "the sensation of contented well-being and the absence of unpleasant feelings" (Fuzek & Ammons, 1977, p. 121).

**Jersey fabric** a “loose term used to describe weft knitted piece goods” (Brackenbury, 1992, p.180).

**Textile** "a term (…) generally applied to fibers, yams, fabrics, or products made of fibers. yams, or fabrics" (Kadolph & Langford, 1998, p. 5).

**Wicking** "the ability of clothing structures to transport liquid water by capillary action” (Fourt & Houies, 1970, p. 126).
*Sports apparel* “clothing designed for, or that which can be used in active sports” (Fowler, 1999, p 81).

*Activewear* apparel purchased with the intent that it will be used in active sports” (Grant et al., 2017, p.4).

*Athleisure* “a hybrid of sportswear and the rest of your wardrobe” (Cochrane, 2015, p. 2).
CHAPTER 2: REVIEW OF LITERATURE

The first section of this chapter presents literature findings regarding women’s participation in sports/athletics, focusing on the impact of Title IX. The second section concerns the evolution of athletic apparel for women, introducing the consumer shift to athleisure. The third section describes the sports bras as functional apparel and the literature overview of their functional shortcomings. The fourth section introduces design approaches to improving the functionality of sports bras. The fourth section also highlights seamless knitting technology, new fibers, and materials used, as well as the biomimetic framework as a new design approach to functional apparel.

Women’s Participation in Sports/Athletics

A growing body of literature supports the conclusion that a physically active lifestyle lowers the risk for heart disease, certain cancers, obesity, osteoporosis, and Alzheimer’s disease. The environment for the participation of females in sports has drastically changed after the enactment Title IX portion of the Education Amendments of 1972 Public Law No. 92-318, 86 Stat. 235 (generally referred to as “Title Nine”), which prohibited sex discrimination in educational programs that receive federal funds (Carpenter and Acosta, 2000). While in 1972, only one of 27 high school girls played varsity sports, in 1998, that figure was one in three. The increase in the participation of women in sports following Title IX has been undoubtful and well documented. Lopiano (2000) found that more than 55 million women participate in recreational sports and fitness activities regularly (p. 163).

It is almost inarguable that the Title IX had a greater impact on American women’s sports than any other development in American history, and not only in
collegiate sports, although the legislation primarily targeted at colleges and universities. This legislation stated 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” (Kuhn, 1976, p. 49). The law did not mention sports, but it led to profound changes in women’s athletics.

In 1977, James Fixx wrote what became a very popular book, *The Complete Book of Running* (Fixx, 1977). This book started a running and fitness trend among both genders, and the increased popularity of sports among women exposed the limitations of conventional bras for athletic use. Some of the listed shortcomings were: (a) straps slipping off the shoulders, (b) friction and chafed skin, (c) hooks or other metallic elements poked into the skin, and (d) breast soreness caused by movement (Keen, 2015). The introduction of the sports bra did more than improving women athletes’ performances: it represented a revolution in ready to wear clothing, and for many women, the bra actually made practicing sports possible. The sports bra became the cloth symbol of Title IX’s success. It is emblematic of the athletic industry targeting women as consumers that one of the leading retail stores noted for its sports bras bears the name of Title Nine Retail (Ladd, 2014). In 2004, one of the global sportswear giants Nike, Inc. acknowledged the trend and increased its focus on the women’s market, launching its first female-targeted catalogue. More recently, O’Sullivan et al. (2017) found that women are a significant and partially untapped segment in the activewear marketplace.

In any sporting activity, many factors are considered to perform at the optimum level. Three main attributes in the success or failure of a sport relate to: (a) the athlete’s
ability, (b) equipment and facilities, and (c) engineered clothing (Chowdhury et al., 2012). The clothing needs of females participating in sport and physical activities have changed in the past decade and trends of participation in non-organized physical activity more than organized sports have been observed (Bramel, 2005, p. 26). As a result, the demands for multifunctional sports clothing that incorporate both comfort and performance have increased, leading to an evolution of clothing shapes as well as its design elements (O’Sullivan et al., 2017).

**Evolution of Athletic Apparel for Women**

The aesthetics of sports clothing has been a constant area of controversy and resistance to women’s participation in sport. In 1931, Lili de Álvarez from Spain, shocked social norms by playing tennis at Wimbledon in shorts instead of the long dresses that women tennis players were expected to wear (Beutler, 2008). Unfortunately, incalculable numbers of women were too discouraged to participate in impact sports, such as running or aerobics, because of the discomfort or embarrassment of excessive breast motion.

Today, sports bras are acknowledged as an essential piece of sporting equipment, not just a fashion accessory or lingerie (McGhee et al., 2008). Interestingly, however; sports bras are a relatively new invention, with the first commercially available sports bra only being available as recently as the late 1970s. In 1975, Glamorise Foundations Inc. introduced the "Free Swing Tennis Bra," the first commercially available ‘sports bra,’ which offered more support than regular bras, reducing breast movement and discomfort, but its design was not much different from that of a regular bra. (Figure 2.1)
The credits for the original sports bra, called a jogbra, specifically designed for jogging, are given to Lisa Lindahl and Polly Smith in 1977, who invented a bra constructed from two jockstraps sewn together and submitted a patent for their design (Schuster, 1979). As soon as the jogbra was selling on the market, initially distributed via mail order in 1978, new designs were created by various competitor businesses (Bastone, 2013).

LaJean Lawson, an exercise scientist who has been conducting sports bra research at Oregon State University's biomechanics lab for nearly 20 years, noted that early on, there was a big push away from conventional bra construction, with some designs having turned the cups upside-down and quite a heavy construction (Bastone, n.d.). In the 1980s, the aerobics trend promoted by movie stars such as Jane Fonda spurred women to wear fashionable sweatbands, bodysuits, and legwarmers outside of the fitness classes, starting a fundamental shift on how sportswear was used. The iconic image of soccer player Brandi Chastain ripping her shirt off at the 1999 Women's Soccer World Cup solidified the sports bra as an acceptable standalone piece of clothing, as well as a fashion statement (Bowles, 2012). According to the Cotton Incorporated 2014 Sports Apparel Survey, 91%
of women say they wear active apparel for purposes other than exercise and 47% of women say they are more likely to dress in activewear all weekend than they were a few years ago (Cotton Incorporated’s Lifestyle Monitor, 2015, para. 4). Moreover, this preference for a weekend spent wearing activewear crosses all age groups and athletic abilities: the millennial women wear it the most (49%), followed by Gen X (48%) and Baby Boomers (44%) (Cotton Incorporated’s Lifestyle Monitor, 2015, para. 5). The athletic clothing worn for leisure created a new garment category, athleisure. The athleisure trend has become so popular; it has carved out a niche for itself in the clothing industry and has won an entry into the online Merriam-Webster dictionary, which defines it as “casual clothing meant to be worn both for exercising and for general use” (Athleisure, n. d.). Athleisure clothing is worn on the streets, in restaurants, when shopping, at social occasions and on the catwalk. Spring/Summer 2016 collections from Chloe and Valentino featured tracksuits are examples of this trend. The consumer attraction of athleisure lies in the combining of trendy fashion with active silhouettes and fabrications, allowing women to use the garment items in various ways. Fowler (1999) identified three distinct types among women: (a) the serious athlete, (b) the weekend athlete, and (c) the woman seeking comfortable apparel. One of the reasons for the massive popularity of the athleisure trend is that it filled a gap in the market place, where clothing that was functional was not particularly stylish. This relaxed standard of clothing has been largely driven by the millennials, the largest demographic in the United States comprising 28% of the population. Their increased health consciousness and a cultural shift in the workplace has made it more acceptable to wear sneakers and sweatpants to the office (Kasriel-Alexander, 2015). Since athleisure reflects a lifestyle shift, it is
unlikely it will disappear soon, despite the market being over-stretched. The retailers will have to keep adapting, and this will mean using different materials, new features such as odorless fabrics, antimicrobial, wicking and other cutting-edge fiber technologies, and keeping up to pace with the changing fashion trends (Trefis, 2016, para. 1).

Lululemon was the first company to see and seize this shift in activewear in a major way. The company went public in 2007, raising $327.6 million and reaching $1.4 billion in sales in the 2012 fiscal year (Edgar Online, n. d.). A big part of Lululemon's product strategy is to change the way it markets its products, tapping into the activewear consumer’s mindset, and swaying away from standard sizing labels. Rather than traditional sizing, Lululemon will sell its new pants in categories such as hugged, naked, relaxed, tight, and held in. Each one serves a specific purpose in the customer's life, whether its fitness practitioners looking for the supportive fits or those looking for the fashionable, comfortable, looser fits for more casual settings (Petro, 2015). Lululemon was far from the only company to target the activewear category. Sweaty Betty, the United Kingdom’s first fashionable take on fitness gear, was also launched in 1998, as was Athleta (which was acquired by Gap Inc. in 2008). In 1999, a group of former Nike executives launched women’s activewear company Lucy, which was acquired by VF Corporation in 2007. Nike made a big impact in the women's market with its "#BetterForIt" digital marketing campaign, featuring everyday women rather than the supermodels and professional athletes commonly seen in advertising for athletic wear.

Aiming to bring more trendy as well as eco-friendly fashion into its athletic wear, in 2004, Adidas started a sportswear collaboration with Stella McCartney. Ten years later, the collaboration became a full brand available at 790 points of sale, worldwide,
with a product range aimed at surfers, runners, and practitioners of yoga (Bryer et al., 2015, p.772). Moreover, in 2016, Adidas took a direct competitive action to Nike’s expansion on the athleisure market, by launching Adidas Athletics. It is a minimal and stylish line designed with advanced fabric, and bridges between style and performance (Green, 2016).

The shift in consumer preference to athleisure brought a flurry of innovations and fashionable designs into sports bra products, at the expense of the regular intimate bra market that saw a decline in sales. Women now prefer to wear a sports bra instead of a regular bra (Bowles, 2012).

**Sports Bras as Functional Apparel**

In the design of functional apparel, the evidence-based methods and processes of engineering are combined with the creative processes of art and fashion, in a user-centered approach (Watkins & Dunne, 2015). Correct mapping of the functional needs of the consumer is a key step for the design of sports bras as a category of functional apparel. Haycock (1978) found that, for women participating in exercise, breast support is crucial, and this feature is regarded by consumers as the main function of a sports bra. Unlike conventional bras that hold breasts up and away from the body, sports bras and tops are designed to hold breasts close to the chest to minimize bouncing, prevent stretched ligaments, and decrease pain from exaggerated breast movement (Leavitt, 1990). A sports bra is defined as "a bra with built-up straps, coming over shoulders forming a crab-like back, secured by an elastic band around the body and worn for active sports" (Calasibetta, 1998, p. 63).

A reduction in the magnitude of breast movement and a decrease in breast pain have been found during running when wearing a sports bra compared to an everyday bra.
A sports bra that provides adequate support by restricting breast motion and increasing comfort may increase motivation to remain in a fitness program. Literature studies using human subjects suggests that appropriate breast support should increase willingness to exercise (Haake et al., 2012; McGhee & Steele, 2010) and reduce embarrassment (Scurr et al., 2011). Furthermore, ill-fitting bras are a serious medical issue as they can contribute to numerous negative health outcomes, such as upper limb neural symptoms and deep bra furrows caused by excessive strap pressure; neck and back pain (Ryan, 2000; Greenbaum et al., 2003), as well as poor posture and exercise-induced breast discomfort (Lorentzen & Lawson, 1987; McGhee et al., 2007). The shoulder straps cutting into the shoulders, straps slipping off the shoulders, and perceived tightness of sports bra around the chest was found to be common deterrents for use of sports bras (Bowles et al., 2012). Continuous and repetitive movements wearing clothing that has inadequate properties can result in soreness, pain and irreversible tissue sagging (Zheng et al., 2007).

The importance of a well-functioning sports bra goes beyond the regular womenswear market and affects breast cancer survivors. A recent online survey completed by 482 breast cancer survivors found that the top three barriers to exercise were procrastination, fatigue, and not being able to find a comfortable bra to exercise in (Gho et al., 2014, p. 722). Although well-designed sports bras have been found to be effective in decreasing breast motion during physical activity, a sports bra can only comfortably provide support if it fits a woman properly, irrespective of how beautifully designed it is (Page & Steele, 1999). White & Scurr (2012) summarized that 70 to 100% of women have been found to be wearing the wrong size bra (p. 705) The bra sizing
system has shortcomings due to its limited reference measurements used as well as to its inability to cover a broad range of unique anatomical breast shapes. Zheng et al (2007) found that, since 1935, the bra sizing system used only two measurements (bust girth and underbust girth), despite the 3D geometric complexity of women’s breasts, suggesting that the existing sizing system may be inappropriate. A good sizing system should be built based on appropriate anthropometric data to assign an appropriate sized garment to an individual (Paal, 1997).

According to the breast curve side view, Martin (1957) classified the breast shape into four types, including flat, hemisphere, conic and goat shapes. Morris et al. (2002) proposed a method for calibrating 3D female breast sizes by modeling the breast in its ideal position and shape on the chest wall. They developed a range of 18 standard cup shapes based on 50 subjects’ breast root shapes and dimensions. Lau (2014) created an extensive illustration categorizing the breast sizes, separation, projection and height and creating a scale to help with the complex bra fit new sizing system design. However, the above studies on breast measurements, shape classification and sizing have significant limitations due to relatively small number of body measurements used as well as small population size. The geometrical complexity of the anatomical structure of women breasts makes designing bras with effective breast support and creating accurate bra sizing very difficult. The respiratory state has also been found to affect bra size determinations (Bowles et al., 2005; McGhee & Steele, 2006). As average breast sizes are getting bigger, there is a need to investigate 3D breast movements and performance of sports bras (Zhou et al., 2011).
Despite the importance of external breast support, particularly for active women, there has been a lack of research evidence upon which to design effective sports bras, until about a decade ago when the number of studies increased drastically. Typically, sports bra performance has been investigated through reductions in breast displacement, breast pain, velocity and acceleration (Scurr et al., 2011). The initial release of sports bras onto the market stimulated the first scientific evaluations of sports bra designs, published in the 1980s (Steele, 2013). These initial studies included biomechanical analyses of the effectiveness of various breast support options in reducing breast motion and enhancing breast comfort (Gehlsen & Albohm, 1980; Lawson & Lorentzen, 1990). There have also been investigations examining how breast biomechanics and discomfort are influenced by external breast support (Bowles et al., 2005; Bowles & Steele, 2013, Starr et al., 2005) or the mode of activity (Campbell et al., 2007; McGhee et al., 2007; Scurr et al., 2011; White et al., 2011). A comprehensive review paper on studies that have investigated breast motion and sports bra design, including breast biomechanics studies is provided by Zhou et al. (2011) and found that various studies have generated inconsistent findings. While most of the breast movement occurs vertically, some studies found that the different sizes and shapes of breasts do not follow the same distribution of displacement. White et al. (2015) suggested that the reduction of breast motion in the anteroposterior direction should be considered by the sports bra designers, in order to help reduce breast pain for female runners with larger breasts.

The types of exercises considered in the breast motion studies are mainly walking, running, jogging, and aerobics. The breast displacement was found to be the highest in running and the lowest in walking due to the different intensities. Therefore, women
should wear sports bras to limit their breast movements and hence reduce breast pain, but different support levels of sports bras are needed for different activities (Okabe & Kurokawa, 2006). Results suggest that different cup size groups may have different support and design requirements (Lawson & Lorenzen, 1990).

Breast position within a bra (i.e., breast compression and elevation) has also been linked to breast discomfort during exercise (McGhee & Steele, 2010). Currently, sports bras are classified into two main types: compression and encapsulation bras (McGhee & Steele, 2010). A combination of compression and encapsulation is considered as a third type. Compression bras do not have cups and evenly press breasts close to the body, thus minimizing motion. This creates an unflattering and uncomfortable look. As an alternative, encapsulation bras have cups to support the breast tissue, resulting in a more feminine shape (Krenzer et al., 2005). Both strategies aim to restrict the breast movements in all directions and to limit the internal forces within the breasts, to reduce the exercise-associated pain, discomfort, and embarrassment (Zhou et al, 2011). A combination type sports bra provides both compression and encapsulation; providing better support and aesthetics in the same time (Chang et al., 2009). White et al. (2009) found no significant differences between the two types of sports bras, encapsulating and compression, in controlling breast movement.

Regarding the design features of sports bras, Zhou et al. (2012) concluded that the most effective sports bras had the following features: (a) compression type, (b) short above waist style, (c) high neckline, (d) cross back design, (e) bound neckline edging, (f) no gore panel at center front, (g) no under breast wire, (h) no cradle, (i) no pad, and (j) non-adjustable wide straps. As for the functional properties of a sports bra, Krenzer et al.
(2000) found that a sports bra should provide good upward support, limit breast motion, and be constructed from primarily non-elastic materials that are non-allergenic, non-abrasive, and have good moisture management properties. McGhee and Steele (2010) proposed the inclusion of thick foam pads inside the bra cups to elevate and compress the breasts in an encapsulation sports bra to reduce vertical breast displacement and exercise-induced bra discomfort. In industrial practice, inelastic, thin fabrics in the bottom cup and side sling fabric connected to wide shoulder straps are commonly used to elevate the breasts and distribute the gravitational force from the breasts to the back of the wearer.

According to Onofrei et al. (2011), the most important characteristic of functional clothing is to create a stable microclimate close to the skin to support the body’s thermoregulatory system in any physical environment. Tactility and aesthetics are also considered important qualities of garments (Emirhanova & Kavusturan, 2008). Based on all these characteristics, knitted fabrics are commonly preferred not only for activewear in general but also particularly for sport bras (Mikucioniene & Milasiene, 2013).

The latest generation of advanced knit structures have enabled controlled muscle tissue and compression, leading to increased oxygen and blood flow, and comfort. (McCann, 2009). Axial loading that produces a squeezing or crushing effect is called compression (Anderson, 2003). Some studies classified clothing compression, or pressure, as static and dynamic (Zheng et al., 2009). Static pressure was imposed on one local area of the body when standing still. By contrast, the dynamic pressure was exerted on a local body area during constant motion. In the case of sports bras, compression needs to be considered in both stages, static and dynamic, as the women need adequate yet comfortable breast support while still, as well as while performing physical activities.
Evaluating compression using pressure sensors, motion capture cameras, and 3D body scanning technology generates high amounts of data. However, the accuracy of breast measurements, in the case of 3D body scanning, as well as accuracy of movement data, in the case of motion capture technology, could be affected by the quality of the equipment, the number of study points on the breasts, the location and number of reference points, and the reference systems (Tong et al., 2012). Therefore, it has been proven difficult to translate compression measurements into breast support efficiency. Current compression sports bras are categorized as ‘low support,’ ‘medium support,’ and ‘high support or high impact,’ but the compression level varies largely between different sports bra designs marketed with the same support level (Gorea & Baytar, 2016). Compression was found to change after multiple cycles of wash and wear, as the mechanical properties of knitted fabrics can change over time based on the fiber type, yarn structure and fabric properties (Stankovic, 2006).

Seamless circular knitting technology has been the primary technology used for manufacturing compression sports bras, due to achieving uniform compression levels around the body (Tiwari et al., 2013). While compression itself is efficient in holding the breasts in place during movement, the chest flattening visual effect is one of the major customers complains. Welded and molded parts also replace some stitched seams, which are too often the source of chafing and discomfort.

**Design Approaches to Improving Sports Bra Functionality**

The understanding of design criteria is very important when developing products as specific as functional apparel. Users have an intimate relationship with their clothing
and need them to fulfill both function and form requirements (Borcherding & Bubonia, 2011). Therefore, user feedback is valuable to stimulate, validate, and authenticate design ideas. However, designers need to create activewear product concepts by sorting user input to highlight only the useful information (Morris & Ashdown, 2015). Orlando-DeJonge (1984) also stated that designers have to address issues beyond the apparent request of the customer, toward a more general picture of the problem. The designer’s role is to interpret and transform information from users to valuable knowledge. Many times during surveys or interviews, users will not be able to clearly identify the fit problem and might suggest the wrong solution.

Sports bras, as a major category of activewear with specific functional design features, have become increasingly complex in styling and details. The new designs reflect not only the continuous changes of user profile and needs but also the major developments in fiber and textile technologies, garment construction methods and fashion trends (McCann, 2005).

**Seamless Knitting Technology**

The rise and popularity of knitted fabrics in sportswear apparel is credited to their ability to better lend themselves to casual activities as well as extreme performance sports (Hayes & Venkatraman, 2016). Knitted fabrics were once thought of as inferior to woven fabrics due to their relative instability, however; innovations in both yarn and manufacturing technologies have elevated knitted fabrics to have qualities that far outweigh those offered by woven fabrics (McCann, 2008).

Knitting is defined as “the process of forming a fabric by the intermeshing of loops of yarn” (McIntyres & Daniels, 1997, p. 190) and knitting accounts for more than
30% of total current fabric production (Millington, 1996). A yarn is defined as “an assembly of substantial length and relatively small cross-section, of fibres or filaments, with or without twist” (Spencer, 2001, p. 3). The end use of knitted fabrics, created either in tubular or flat form, can be apparel and other products including sweaters, underwear, hosiery, socks, and stockings. Knitted fabrics are commonly categorized into two main groups: warp and weft knitted, based on the direction of the way they are knitted (vertically or horizontally) (Tiwari et al., 2013). Both types can be made using single yarns or multiple yarns and create complex pattern designs. The formation of knitted loops and properties of the resulting fabrics can differ significantly between each group and knitting pattern (McCann, 2008). The knit structure is differentiated from other textile architectures (weaving, braiding, stitching, etc.) by its unique unit cells – the knit and purl loops, cells combined in orthogonal rows (courses) and columns (wales), shown in Figure 2.2, which lead to specific fabric properties (Abel, 2014).

*Figure 2.2. Weft knitting, course and wale directions (Brackenbury, 1992, p.23).*

Warp knitted fabrics have vertical interloping of yarns, making them less likely to unravel while also providing less stretch. By contrast, the weft knitted structure, commonly associated with horizontal hand knitting, provides the greatest stretch, is pliable, soft and the fabric has good drape properties (Gao, 2009; Chen, 2013). However,
weft-knitted fabrics often have problems with dimensional stability, and the washing process can distort the fabric. Application of surface finishes is currently used by industry to minimize this behavior (McCann, 2009).

The use of weft knitted fabrics in activewear has increased due to the demand of stretchable, wrinkle-resistant and tight-fitting garments. (McCann & Bryson, 2009). Circular weft knitting machinery is traditionally used for hosiery (Brackenbury, 1992) Developments came from the Italian machine builder Lonati in 1988, which were aiming to extend their market and capabilities of the machinery to knit seamless underwear (Spencer, 2001). This led to the creation of a new company, Santoni, which was promoted as a specialist producer of machines with the capability to knit what was claimed to be seamless garments (McCann, 2009). The seamless property refers to the main garment parts, going circularly around the body, without having a front and back panel as separate parts; small seams are still needed to assemble other garment parts, such as shoulder seams, armhole, and neckline bindings (Power, 2012). Figure 2.3 shows a typical commercial seamless sports bra, with the following features: underbust band, breast encapsulation via center front material rouching, racer back straps, and elastic binding at armholes and neckline edges. Most seamless sports bras have variations of these features.
Compared to flat weft knitting machines, circular weft knitting machines provide higher productivity, lower costs, faster production times and produce more comfortable fabrics, among many others (Millington, 1996). In the global environment, seamless garment knitting puts less stress on the environment by minimizing waste disposal and reducing the need to grow as much as cotton, wool and other natural raw materials (Mowbray, 2004). Seamless knitting is forecasted to continue growing and could be one of the largest next-generation knitting technologies. A diagram of the knitting classifications is shown in Figure 2.4. Circular knitting machines are highly productive and efficient, and the capability of producing fine gauge knitwear that is soft and comfortable made it a great choice for manufacturing seamless sports bras. The circular knitting pattern tends to show superior mechanical properties when compared to a warp-knitting pattern, but it also has shortcomings resulted from the twisting of the knitting material. Among compression fabrics, there currently seems to be no specific effects on moisture management properties when different knitting densities of the fabrics are compared (Tiwari et al., 2013).
In recent years, several companies have developed seamless or complete garment machines such as Santoni, Sangiacomo, and Orizio (Choi & Powell, 2005). Santoni is generally acknowledged to be the leader in seamless knitting apparel manufactured on circular knitting machinery (McCann, 2009; Semnani, 2011). For seamless flatbed knitting machines, two suppliers, Shima Seiki (from Japan) and Stoll (from Germany), are the leaders in machine manufacturing. They offer solutions for the knitting of complete garments on computerized V-bed knitting machines. In the 1960s, the Shima Seiki company explored the tubular-type knitting principle commercially to produce gloves, but only in 1995, at the International Textile Machinery Association fair, seamless entire garment knitting was introduced by showing the innovative WholeGarment® system. Today, Shima Seiki produces five versions of the innovative WholeGarment® machine that can produce a one-piece three-dimensional complete garment with no stitching, linking or sewing processes (Hunter, 2004). The WholeGarment® knitting system does not offer major advantages to the manufacturing of a seamless sports bra since the bra does not have sleeves or additional parts besides
the circular tube of the body. Similarly, Stoll company has manufactured flat V-Bed knitting machines for more than 130 years and has today more Stoll, 2017). The Stoll machine also markets complete garment knitting machines called “Knit and Wear®,” that offers slightly different stitch patterns and capabilities that Shima Seiki, based on machine structure as well as their CAD systems.

Many factors influence the size and fitting of seamless sports bras. They include the type of yarns used, loop density, yarn tension (controlled by the machine), knitting structure, production environment (temperature & humidity) and finishing processes (Zheng et al, 2008). The interface between the knitwear designers and the knit technicians is critical to the success of new sample development. The designer’s concept sketch must be realized through the capabilities of the machine governed by the technical expertise of the technician (Choi & Powell, 2005).

**New Fibers and Materials**

Along with the type of garment construction approach, fiber content and fabric structure affect the design and performance of sports bras. The degree of stretch, thermal insulation, absorbency, wicking properties, drying rate, washability, and durability are a few of these factors (Watkins, 1984). The amount of moisture which textile fibers are capable of absorbing affects their use in activewear. Hyun (1989) found that moisture influences: (a) the perceived comfort of the wearer, (b) the fabric shrinkage during laundering, (c) the rate of drying after laundering, and (d) static electricity development.

The first high-support sports bra, introduced in 2003 by Champion, Jogbra’s current owner, combined nylon fabric with seamless design for friction-free performance. However, according to the Cotton Incorporated 2014 Sports Survey, among women,
although 46% recount comfort as the most important property in activewear, around 70% said they prefer cotton and cotton blends, and 81% associate better quality with all-natural fibers (Cotton Incorporated’s Lifestyle Monitor, 2015, para.10).

Currently, commercial seamless sports bras typically contain elastane, polyamide, or polyester fibers. These are lightweight with good strength and resistance to abrasion; they are easy to wash, are dimensionally stable, and dry quickly (Zhou, 2016). The properties of these fibers along with cotton, the fiber preferred by customers, are shown in Figure 2.5.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Cotton</th>
<th>Spandex (Lycra)</th>
<th>Polyamide (Nylon)</th>
<th>Polyester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Stretchability</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Recovery</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Strength</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Comfort</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

*Figure 2.5. Properties of basic fibers used in sports bras (adapted from Shishoo, 2005, p. 48).*

Knit fabric is interconnected with loops of yarns, which is composed of fibers and filaments (Brackenbury, 1992). The overall knitted fabric behavior is affected by the fiber blends and their fineness (McGreggor & Naebe, 2013). Moreover, yarn count (quality) is crucial in producing a uniform fabric structure. Other yarn properties such as yarn twist, number of folds and yarn count determine the fabric properties (Spencer, 2010).

There is a very generous literature studying properties of knitted fabrics made of various fibers and yarns as applied to activewear (Reza, 2012; Stegmaier et al., 2005; Tiwari et al., 2013). An earlier study done by Nutting and Leaf (1963), showed experimentally that the loop shape (geometry) of weft-knitted fabrics is controlled by the
loop length, fiber type, and properties and method of relaxation (Nutting & Leaf, 1963). As the knitting technology evolved, combined with knowledge from consumer studies highlighting women preference for cotton in activewear, exhaustive research has been done on studying cotton single-jersey knitted fabrics and the relationship between the knitting machine and fabric parameters. Gokarneshan & Thangamani (2008) found that the change in the knitted loop shape in cotton/spandex-knitted fabric makes this fabric’s properties different from 100% cotton knitted fabrics. McGregor & Naebe (2013) studied the comfort properties of 81 single jersey knitted fabrics, with various fiber, yarn, and fabric characteristics, using the Wool Comfort Meter (WCM) which has been calibrated using wearer trials of wool knitwear (p. 606). Their findings were that tighter fabrics were less comfortable and that progressive blending of cashmere with wool increased comfort assessment. Yarn elongation and yarn quality also affected fabric comfort properties.

Fibers with a finer denier have a special place in activewear. With the development of micro-denier fibers, which are defined as fibers with fineness less than 1 decitex, knitted fabrics became softer and more pliable (Chattopadhyay, 1997). Decitex is the standard measurement for the count grading for filament and spinning yarns. This standard is recognized by all international institutions in the man-made fibers industry, and it represents mass in kilograms per 1,000 meters’ length of fiber. Additionally, knitted fabrics with micro-denier fibers have superior dimensional stability and wicking properties, resulting in better comfort and making them ideal for activewear (Srinivasan et al., 2005).
Although conventional polyester fiber cannot provide the high-level comfort of cotton, Coolmax, an evolved polyester-based fiber with a specific cross section, significantly improves the comfort performance in terms of moisture wicking (Hayes & Venkatraman, 2016). Wicking is the transmission of liquid through a textile by capillary action (Collier et al., 2009). Another new wicking fiber is Cocona, made from coconut shells, that is used in Champion’s Vapor sports bra. Merino wool has also been reported to have properties suitable for activewear; pure Merino wool has been blended with other fibers to regulate absorption, wicking, air circulation and to enhance the comfort of the wearer (Venkatraman, 2016). Blending wool with polyester or wool with bamboo improved the moisture management properties of the fabrics compared with 100% wool and 100% bamboo fabrics (Troynikov & Wardiningsih, 2011). Horrocks (2000) highlights new fibers developed as an overall consumer desire for comfort and well-being; one such development being the scented fiber CRIPY 65, developed by Mitsubishi Rayon, aimed for manufacturing scented garments.

Post-millennium fiber innovation has concerns for sustainability. While it is necessary to produce sports apparel that has high-performance characteristics such as strength, wicking ability, and comfort, it is also necessary to look at alternate textiles other than synthetics such as polyester. Looking into the future, it is beneficial to seek sustainable manufacturing practices, using natural fibers, if they can provide comparable end products to the ones made of synthetic fibers (Skomra, 2006).

Teijin in Japan created recycled polyester and Cargill Dow developed polylactide polymers from corn (Hayes & Venkatraman, 2016, McCann, 2015). Other new eco-friendly fibers are: Fox Fibre®, a naturally colored grown cotton; Tencel®, a synthetic
fiber produced in a closed loop system with no water or air pollution; Ingeo ®, the world’s first artificial fiber made entirely from renewable resources; SOYSILK ® resulted from waste from tofu manufacturing process (Collet, 2014).

During the selection of fiber types used for the design of sports bras, it is important to consider the physiological parameters of the wearer’s body; particularly, the sweat patterns, thermal regulation and stretch and recovery of the female upper body (Venkatraman, 2016). Havenith et al. (2008) compiled a sweat body map, showing median regional sweat rate values for male and female runners, rounded to nearest 10 g and averaged over left and right symmetrical zones that could be used for a regionalized engineering of fiber composition (p. 23). For female runners, the center front area between the breasts accumulates the most sweat, as shown in Figure 2.6. As a garment worn close to the body, the sports bras have been expected to have cooling properties during times of intense physical activity.

Figure 2.6. Body sweat maps for female and male runners (Havenith et al., 2008, p.23).
Responsive Fibers and Materials

Beringer (2013) reported on the innovative temperature-regulating fiber technology, which is engineered to use the body’s own sweat to achieve a cooling effect. The CoolCore technology, which claims to last for the entire lifetime of the garment, works three different ways: wicking (moves sweat from the body), moisture transportation, and regulated evaporation from the garment. Sarkar et al. (2010) reported on the dimensional changes of hygroscopic yarns when utilized to develop responsive fabric structures. They found that engineered openings in the fabric widen or narrow depending on moisture content, leading to improved air permeability in conditions of high moisture content, similar to body sweating. The improved air permeability of these specially designed fabrics can enhance body cooling for better comfort.

Textile science literature shows that conventional fibers swell as they absorb moisture (Hatch, 1993). This causes the yarn to swell, which in turn reduces the air permeability of the textile structure. INOTEK™ textiles, marketed by MMT Textiles Limited, a London based company, claim to function in the opposite manner. When they absorb moisture, INOTEK™ textiles become more permeable to air. INOTEK™ fibers close, causing the yarn to tighten. This creates microscopic pockets of air in the textile structure. In dry conditions, INOTEK™ fibers open up like a pine cone, reducing permeability to air and increasing their insulation properties (Inotektextiles, 2015).

Currently, digital sensing technologies and new manufacturing methods have allowed engineers to develop new classes of responsive, shape changing, smart materials, using nanofibers and conductive materials (Scott, 2015). Moreover, garment embedded electronics offer exciting new possibilities for enhancing the functionality of garments,
especially in performance activewear (for example heart rate monitoring sports bras). However, the mass manufacturing feasibility, as well as the environmental impact of these technologies, has been debated (Dunne et al., 2005).

Some recent literature has been exploring responsive properties of natural fibers aiming to improve the functionality of garments (Bowles, 2012). Both cellulose and protein natural fibers have dynamic moisture absorption properties; fibers increase in volume in the presence of moisture, almost entirely in the radial direction, and there is little-observed change in the overall length of the fiber (Stamboulis et al., 2000). Scott (2005) found that the dimensional change at a local scale within individual fibers is amplified throughout a knitted structure because fibers are not used individually; instead, they are spun into yarns in a systematic way. This creates a dimensional change on the fabric scale, providing an underlying actuation mechanism to the entire system. In this responsive knitted system, natural fibers act as sensors and actuators, therefore reacting to changing moisture levels in the environment.

The systematic design of all levels of the textile (fibers, yarns, fabric, and form) as illustrated in Figure 2.7, shows that, rather than applying additional technology to a knitted substrate, such as wearable technology does; the nature of knitted fabric itself can be designed as a natural, biological inspired responsive form.
**Figure 2.7.** Internal factors allowing for the design of fabric performance (adapted from Venkatraman, 2016, p.58).

**Biomimetic Design Approaches**

Hardaker and Fozzard (1997) found that the bra design process relies heavily on the expertise of the designers and involves a high level of heuristics knowledge, as well as a trial-and-error prototyping approach. Nature is a source of integrated design examples that evolved through countless iterations too. Biological mechanisms are able to inform efficient functional systems that, rather than being based on external mechanical elements, are triggered by the own properties of the material, therefore creating integral design solutions that have high degrees of responsiveness (Dompioti et al., 2010).

Moreover, in a biomimetic world, we would manufacture the way animals and plants do, using the sun and simple compounds to produce completely biodegradable fibers, ceramics, plastics, and chemicals (Benyus, 1997). Another nature’s strategy that
could apply to functional design is that nature always fits form to function (Benyus, 1987; Das et al., 2015; Schmitt, 1969).

Biomimetics, a term created by Otto Schmitt in the 1950s for the transfer of ideas and analogies from biology to technology, has produced some significant and successful devices and concepts in the past 50 years but is still empirical (Vincent et al., 2006). Scott (2005) observed that, while technology solves problems largely by manipulating usage of energy, biology uses information and structure, two factors largely ignored by technology.

Biomimicry or biomimetics, only recently begun to reach its full potential since the invention of Velcro, the biomimetic-equivalent of hooks in natural burrs created by George de Mestral in 1948. More recently, in 2013, Michael Phelps surpassed his own 200-meter butterfly swimming world record wearing Speedo’s Fastskin swimsuit, a shark-skin based design on knitted fabric, aimed to reduce the friction drag in the water (Speedo, 2013). X-BIONIC is another company using biomimetics to innovate in the area of functional clothing design (X-BIONIC, 2013). Their garments use complex warp knit structures to create muscle control, support tissue and create local compression. The intricate mapping of the tightly knitted fabric sends signals along the spine to the brain, allowing the body to cool down through perspiration. These claims; however, were not verified as no research has been published on such ground-breaking innovation (Hayes & Venkatraman, 2015).

Many facets of biomimicry have evolved since its inception, and projects can now be broadly categorized under two main topics: (a) mimicking mechanisms found in nature, such as water-proof glue developed by studying of adhesives produced by
mollusks), and (b) utilizing or incorporating nature itself into novel devices, such as new strong but light materials that were designed by studying the structure of bone (Scott, 2010). Nature utilizes hierarchical structures to form responsive systems (Abel, 2013). Knitted fabric can be analyzed in a similar hierarchical way as fabrics are composed of yarns, which were made from fibers (Eadie & Ghosh 2011). In addition to these three hierarchies identified by Eadie and Ghosh (2011), Scott (2013) added a fourth one, final form, in this research being the sports bra as a garment. This hierarchy provides the means to establish the most complex geometries through increasing and decreasing the number of stitches knitted, and through partial knitting where stitches are held to generate 3D form.

Nature relies on a few basic materials, which are combined in an extensive variety of shapes and forms to determine material properties (Benyus, 1997). Hierarchy is important because it allows materials to exhibit exceptional properties and diverse functionality through adapting structure across many different levels from nano- to macro- (Vincent, 2008). Specific material properties can be altered without changing every component at each level. By introducing more levels of hierarchy it is possible to make structures more efficient in relation to the material required to achieve certain functionality (Pawlyn, 2011). For example, extensibility of knitted fabric can be changed through: (a) fiber; wool is more extensible than flax (linen), (b) yarn; a high twist yarn has more extensibility than a low twist yarn, and (c) fabric; a tuck stitch has greater extensibility than a knit or miss stitch. These factors could be altered independently or all together to gain the optimum extensibility for the desired fabric application (Scott, 2015).

By making a functional analogy to natural systems via the biomimetic framework, the aim is to develop knitted fabrics that can change shape in response to changing environmental conditions, without any other control mechanisms or energy. Passive
actuation in plants is a useful model for analysis, as movement is actuated by environmental changes, controlled by cell structure, and does not require further energy supply for actuation (Fratzl et al., 2007). For example, when the environment is dry, plants wilt and their tissue becomes soft, but in presence of adequate moisture, they absorb the water and their tissue becomes more rigid, uprising. This responsive analogy is intended to guide the design process of seamless sports bras prototyped in the experimental part of this research.

**Design Process Models**

The design and development of apparel products is a creative problem-solving type of process (Orlando- DeJonge, 1984). “The creative problem solving(design) process is most easily understood as a sequence of stages or stopovers on a journey to a given destination…(it) involves the conscious application of incentives, intentions, decisions, actions, and evaluations” (Koberg & Bagnali, 2003, p.16). There are many ways of describing the design process, or, in the case of functional design or engineering design, the product development process. When trying to organize the abundant information gathered and needed in the design process, the use of a theoretical framework proved to be an efficient method for mapping out the design stages (Watkins & Dunne, 2015). A theory is “a set of ideas developed to explain facts” (Crouch, 2012, p.82). In this section of literature review, design process models are presented, including apparel design, engineering design as well as responsive apparel design process models, highlighting how each of them refers to the sports bra design process.
Apparel Design Process Models

According to Buciarelli (1994), design work is a social process, in which different persons have to work together within a design team. An essential part of the design work is thus communication, negotiation and making compromises within this team. This is particularly applicable to sports bras design, as the complex technology determines many functional outputs that the designer alone might not be able to foresee. There is a growing literature distinction between being a designer using already developed and well-defined technologies, and a designer involved in creating new foundations and the use of new technologies, or technologies that are not so developed (such as in most functional design) (Berglin, 2008).

Most design research is aimed at ‘directly’ improving the design process through methods often ignoring differences between designers, design contexts and design objects (Dorst, 2008). According to Gunther et al. (1999), designers may employ design process methods based on their formal training: the scholar/designer academically trained in the apparel design discipline, categorized as “M-designer” (methodology designer) uses more time to complete design tasks compared to a “P-designer” (practice-based designer) who usually gets their design knowledge from work experience (such as technicians). P-designers work on each “sub-problem” in the conceptual design stage, reiterate and partially skip stages in the process because their goal is the product, not the process. Also, P-designers do not document the design process (Zhang, 2014). M-designers often consider method development as an objective of their research, besides the product design, therefore their design process is more linear, with careful documentation and reporting at each stage of the process (Zhang, 2014).
In the case of seamless knitwear, the design has led technological advances for many years, but, since the technology became more complex, the design process requires extensive technical knowledge of the machinery (Black, 2002). Therefore, a hybrid design process must be created, bringing together the M-designer and the P-designer.

Activities describing typical design processes are often divided into a sequence of alternations between opposite forms of behavior, such as ‘divergent’ (exploratory search for ideas and information) and ‘convergent’ (narrowing down and selecting most feasible ideas) type of thinking (Watkins & Dunne, 2015). Lawson (1986) describes the ‘inventive flash’, or creative ideation for problem-solving, as a combination of three brains: the emotional brain, the physical brain, and the intellectual brain.

Therefore, knowledge of reality and seamless industry practices, as well as an accurate formulation of the biomimetic model and interactions between the variables involved in the sports bra design process must be pursued, in order to correctly frame the responsive sports bra design process. Regardless of the number of steps between divergent and convergent, or explicit and intuitive, or rational and imaginative, or left-brain and right brain, or between all three brains highlighted by Lawson (1986) and Thring & Laithwaite (1977), the design process is rarely a linear type of activity. Koberg & Bagnall (1981) provide a few views of framing the design process: (a) sequential in a linear fashion, (b) continually repeated in a circular manner, and (c) reiterative and returning to any stage to refine prior steps (Figure 2.8).

In one of the early design process models, Orlando-DeJonge (1984) proposed a seven-stage process framework as a linear structure specific for a functional design problem, targeted to specific user needs, combining the creative process with strategy
control (Orlando-DeJonge, 1984). This design model starts with a customer specific request for a design and ends with design evaluation after prototyping. There is no mention of reiterations or reconfigurations of the design problem and solution after the final design evaluation. For the case of a seamless sports bra, the design evaluation step often requires reiterations and prototype development adjustments; once the knitting machine is programmed, it will knit the entire bra tube, even if stitches are being dropped or other pattern inaccuracies occur (Spencer, 2010). While capturing the basic design steps, Orlando-DeJonge’s (1984) model is not specific enough for functional apparel design in general.

Lawson (1986) questioned Orlando DeJonge’s (1984) design process linearity, by proposing an iterative model that goes on until a desired quality or state has been reached. Lawson (1986) divides the overall design process into only three stages: analysis, synthesis, and evaluation, which can be described as: (a) breaking the problem into parts, (b) putting the parts together in a new way, and (c) testing and discovering the consequences of applying the new arrangement into practice. This is repeated until the reached solution is satisfactory. This design process approach does not apply to functional apparel design though, but it can be useful for the artistic design process.
Figure 2.8. The design process variations: (A) linear, (B) circular, (C) reiterative (Watkins & Dunne, 2015, p.3).

By contrast, focusing on large-scale apparel manufacturing for consumption, Regan et al. (1998) proposed a design engineering theory as a linear, seven-step process, detailing the mass production apparel development process, including: problem recognition, problem definition, exploration of the problem, search for alternatives, evaluation, and decision making, specification of a solution, and communication of a solution. In Regan et al. (1998) design engineering theory, the design evaluation occurs a few steps before the end of the process, aiming to avoid mistakes in mass manufacturing. The linearity of this design process is not appropriate for the specific case of seamless sports bras design.
Disregard of the large-scale apparel manufacturing or small-scale customer ordered apparel, identifying user’s needs is one of the starting points and a variable that often shapes the entire functional design process. Tullio-Pow & Strickfaden (2015), in their review of studies of specialized apparel for users such as, premature infants (Bergen et al., 1996), pilots (Tan et al., 1998), sailors (Bye & Hakala, 2005), adolescent girls with disabilities (Stokes & Black, 2012), and bicycle patrol officers (Black & Cloud, 2008), revealed that some referenced DeJonge’s (1984) design process framework, while others used Lamb & Kallal’s (1992) FEA model.

The Lamb & Kallal’s (1992) FEA model and the accompanying six-step apparel design framework were created for a general apparel design framework, not specific to functional apparel design. In the FEA model, the user’s needs and wants have three classifications: functional, expressive, and aesthetics. While the functional consideration is about the utility of an apparel product, the expressive aspect relates to the “communicative, symbolic aspects of dress” (Lamb & Kallal, 1992, p.43). The aesthetics component refers to “the human desire for beauty” (Lamb & Kallal, 1992, p.43). The target consumer and her/his culture are key elements in the FEA model, and the FEA classifications are not mutually exclusive, they can and often overlap. The apparel design process is critically linked to product development process aimed at specific target markets (Lamb & Kallal, 1992). Regardless of how a target market is defined, the analysis of consumer needs is accomplished by determining their functional, expressive, and aesthetic requirements. Based on the FEA model as well as a few other design process models (Hanks, Belliston, & Edwards, 1977; Koberg & Bagnall, 1981), Lamb & Kallal created the apparel design framework that became very popular. The FEA design
framework cannot be used for the design and development of seamless sports bras, being unidirectional, missing the reiteration loops that textile development before the entire sports bra is designed are required.

Factors of function, expression, and aesthetics have been shown to influence what a woman will find important and desirable in sport specific clothing (Cassleman-Dickson & Damhorst, 1993; Dickson & Pollack, 2000). Many studies adapted the FEA model by adding other variables to fit specific functional apparel design requirements. Lamb and Kallal (1992) reminded the reader that the consumer’s needs must be analyzed and identified before a design process can even begin. Bye and Hakala (2005) also supported the idea that a designer should first clearly understand a user’s needs, and then translate those desires into a final design.

**Engineering Design Process Models**

The term design also refers to engineering design and the innovation and product development processes in engineering, not only to apparel design: “Engineering design is the use of scientific principal, technical information, and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency” (Fielden, 1963, p.27). While Lamb & Kallal’s (1992) design process model is widely used and applicable to functional apparel design, since this research project involves exploring new technologies at the textile design level (seamless knitting machines), it is necessary to review some engineering design process frameworks.

A design solution is strongly influenced by the lifestyle, training, and experience of the designer, and the creativity and effort a designer puts into a design and product
development process varies, depending on the type of design problem (Juster, 1985). According to Evbuowwan et al. (1996), design problems that confront engineers and designers can be classified into the following types: (a) routine designs; these are considered to be derived from common prototypes with the same set of features and the structure does not change, (b) redesigns; these involve modifying an existing design to satisfy new requirements or improve its performance under new requirements, and (c) non-routine designs, original or new designs.

Moreover, routine designs can be categorized in two ways, one as either adaptive or transitional, which are designs that adapt a known system to a new task. The non-routine, original designs can be categorized as innovative designs or creative designs. Innovative designs are scenarios where new variables or features are introduced which bear some resemblance to existing variables or features, and the decomposition of the problem is known, but the sub-problems and various alternatives to their solution must be synthesized. In other situations, alternative recombination of the sub-problems may yield new designs. It is also considered that solving the same problem in different ways, or different problems in the same way (by analogy), would fall under this class. In the case of creative designs, new features are introduced which bear no similarity to features in the previous prototype and the resulting design has very little resemblance to existing designs. For creative designs no design plan is known, a priori, for the problem under consideration (Evbuowwan et al., 1996).

A responsive seamless sports bra design based on biomimetic framework could be a redesign since improvements to an existing product are targeted, but also, a creative design, based on the biomimetic system analogy. Based on Evbuowwan et al. (1996)
design classification, it can be observed that each type of design may need to use a different type of design and development process (Daalhuizen, 2014). Lawson (1997) stated that “recognizing the nature of the problem and responding with an appropriate design process seems to be one of the most important skills in design” (p.109). Therefore, many engineering design process frameworks were proposed and some systematic reviews were published by Evbuowwan et al. (1996) and Heimdal (2009) to name just a few. The engineering and product design research communities have produced an abundance of process models, as it builds on a tradition of methodology development (Blessing & Chakrabarti, 2009). Within that tradition, engineering design researchers, similar to the apparel design researchers, typically develop a design process model or framework as a product of their research (Daalhuizen, 2014).

For example, Ulrich and Eppinger (2008) view the design and product development process as a generic process, consisting of six phases (Figure 2.23). Their perspective is based on an engineering design context, framing the design process in three ways: (a) as an initial creation of a large number of alternative concepts, and then the subsequent narrowing of alternatives and increasing specifications, (b) as an information processing system, with the process beginning with many information inputs, and concluding when all information has been created and communicated, and (c) as a risk management system, where various risks are identified in the early phases. Eliminating the uncertainties and validating the functions of the product conclude the process (Ulrich and Eppinger, 2008). Much like the apparel design processes described, these three ways also describe an evolution from divergence (many concepts, much information, many risks), to convergence (concept specification, information selection, risk management). The specific case of seamless knitted sports bra design has even more complexities, since
it involves the textile design process as a process within the entire framework, and, based on the biomimetic system framework, all components in the design model are interrelated.

Jones (1992) views the engineering design process as three stages: divergence, transformation, and convergence. Divergence is the stage where the boundaries of the design situation are extended in order to have a large enough space in which to seek for a solution. Transformation is the stage where creative idea search takes place. Finally, convergence is the stage after the problem has been identified and the objectives have been fixed. At this stage, a range of options is reduced to a single chosen design. This reiterative model is similar to Lamb & Kallal’s FEA model (1992), but it highlights the importance of transformation as a creativity undertaking within the design process.

Although all designs involve creative problem-solving, the ideation process is not often included in engineering process models (Heimdal, 2009). Many studies have shown that the oldest and still most prevalent method for problem solving, regardless of the class of problem, is trial-and-error (Stein, 1975; VanGundy, 1992, Heinsohn, 2005). However, psychological inertia often leads a designer away from a creative solution of the problem. The term psychological inertia was introduced in creativity and innovation research to refer to the effort made by a person to preserve the current stable state or to resist change in that state (Savransky, 2000). Psychological inertia (or psychological barrier) greatly affects the time needed to solve a problem, and in case of commercial products, a long time to get the design to market is a key barrier to innovation (Heinsohn, 2005).

However, the trial-and-error method is appropriate for simple, well-defined, routine closed problems, and it should be used for open problems only when the overall
direction of solution search is known (Osborn, 2013). In the case of a seamless sports bra, although trying to look for solutions regarding the responsiveness of the functional design system, the problem has many variables, and the best solution is most likely outside the ‘solution space for current solvers’ as named in Savransky’s (2000) trial-and-error model.

TRIZ, an acronym that comes from the Russian phrase “teorija rezhenija izobretatelskih zadach,” which translates into English as the theory of innovative problem solving, is “a human-oriented knowledge-based systematic methodology of inventive problem solving” (Savransky, 2000, p.22). TRIZ is often used in engineering fields to solve non-routine designs (Altshuller, 1984). TRIZ is also known for its successful transfer of inventions and solutions from one field of engineering to another (Vincent et al., 2006). Since the aim of biomimetics is also to transfer functions from biological systems to man-made systems, TRIZ has been used as a problem-solving platform (Bogatyrev, 2000; Vincent & Mann, 2000). TRIZ is basically a collection of tools and techniques developed by Genrich Altshuller and Rafik Shapiro in 1940, that ensures the accurate definition of a problem at a functional level and then provides strong indicators towards highly innovative solutions (Altshuller, 1999). TRIZ as a theory, describes how inventions are generated, based on the extensive analysis of thousands of patents (Lovel et al., 2006). However, the nature of biology and engineering are very different, since organisms develop through a process of evolution and natural selection, creating classifications (hierarchical, parametric, or combinatorial), while engineering is a decision-making process, with rules and regularities (Vincent et al., 2006). What brings these two fields together is the resolution of a technical conflict. Vincent et al. (2005) analyzed over 2,500 biological conflicts and their resolution in biology, sorted by levels
of complexity (p.476). They found that, in the biological systems, the main variety of function is achieved by manipulations of shape and combinations of materials at larger sizes achieved by high levels of hierarchy, suggesting that engineering fields should be adapting and combining the already existing materials instead of developing new materials each time a new functionality is needed (Vincent et al., 2005). However, since there is no ongoing classification of man-made materials as they interact with each other, but rather a technical specification for each of them and empirical tests of various combinations and functions, the biomimetic inspired solutions created using TRIZ are done on a case by case study (Savransky, 2000; Heinsohn, 2005). In each of these cases, the design process is different, following the specifics of the functional design, with the aim of solving a functional problem and not of that of creating an innovative design process. Therefore, a detailed classification of existing materials, as well as their interrelations and functions was created, as part of the responsive sports bra design process, combining TRIZ theory and biomimetic framework.

**Responsive Apparel Design Process Models**

The terms “smart” or “intelligent” are commonly used to describe responsive materials and textiles of different kinds (Abel, 2014). Some use these two words almost interchangeably, whereas others draw clear distinctions between the two (Addington & Schodek, 2005). In this research, while the aimed result is to create a responsive sports bra design via responsive textiles, the term ‘smart’ is not used to describe the end product. This is due to the fact that most of the literature regarding smart apparel and smart textiles, uses the term “smart” alongside products that are responsive due to embedded electronics, either at garment level or textile level (Dunne, 2009). This
proposed study is about achieving responsiveness via natural fibers and textile structure system and not embedded electronic systems, so the term *responsive sports bra* is used instead of the smart sports bra. However, the design process should be similar at least at the concept and research stages. Based on Evbuowwan et al. (1996) classification of design, a responsive sports bra could fit in the creative design category, meaning that new variables or features are introduced bearing some resemblance to existing variables or features, and the decomposition of the problem is known, but the sub-problems and various alternatives to their solution must be synthesized.

A clear design brief is essential to drive the product-design development process of smart apparel (McCann, 2009). The garment-design development process is created with disparate yet interdependent stages in a critical path that should start with mapping of the end-user needs. This informs progression through a sequence of stages from fiber and textile selection and finishing to garment prototype development. The aesthetics, comfort, and functionality of a smart garment are highly dependent on each stage of the sequence. An efficient technology integration cannot be added as a layer, but rather should be considered simultaneously throughout the design development process (Roepert, 2006). The functionality of the design of the smart clothing must be verified in both laboratory and field tests.

For successful design development of smart apparel, the design critical path of technical textiles and functional clothing and that of electronics cannot be considered separately (Dunne, 2009). This cross-disciplinary design set-up is no longer regarded as the job of only one designer (Bradock & O’Mahony, 2007). As in the case of a seamless sports bra, technical knowledge from textile or electronics developers needs to be
combined with design knowledge and design process management. McCann’s (2009) critical path can serve as a start-up platform for the design process of a seamless sports bra since it has seamless knitting mentioned in the process, but the big difference between biomimetic inspired responsive solution and electronics embedding solution will require further evaluation and considerations.

Other suggested design process models go through the five steps of idea generation, design, prototype development, evaluation and design refinements and lastly production planning (Suh, 2010). Most systematic product development approaches are based on the engineering design process theory (Lewis & Samuel, 1989). A comparative chart illustrating various design process models was made by Suh (2010), showing that each of these activities is not sequential, but overlapping. Each stage begins before the previous one is finished.

McCann et al. (2005) view smart clothing as apparel whose user has four categories of needs: demands of the body, demands of the end-user activity, demands of the culture, and aesthetic considerations. The demands of the body represent a holistic approach to body-clothing interaction (McCann, 1999). In order to accommodate user requirements during the functional clothing development process, Caroll & Kincade (2007) introduced a co-design phase where designers and consumers share their ideas to design the product. The consumers are directly involved throughout the product development process. Developing a detailed framework illustrating the most important variables of the design problem and the relationships between these variables is a critical step in the design process of functional apparel design (Watkins & Dunne, 2015). It is also one of the most difficult parts of the design process because there is no one typical
example of a framework. Final evaluation of the design involves taking a critical look at the decisions made in the decision process. In functional design, it may involve numerical ratings or tests with human subjects. Watkins & Dunne (2015) suggest setting up evaluation procedures prior to ideation to make certain that the choice of evaluation technique is not influenced by the final design selected. However, all evaluations should end with a look toward the future. Aspects of designs that did not meet the goals should be explored again aiming for improvements.

Based on the overview of design process models, a customized design process framework will be developed by adapting the critical path proposed by McCain (2009) with the specifics that will rise from the biomimetic system exploration and TRIZ theory as applied to sports bra design. While the proposal of a new design process framework is not an objective of this thesis, documenting the design process is an important task of any design work as it can be used for future studies and applications (Zhang, 2014).

**Literature Review Summary**

Activewear marketplace has experienced a convergence of functionality, comfort, and fashion creating new complexities for the product developers and designers (Quinn, 2010). A desire for healthy lifestyles, prompted women to increase their participation in sports, while also wearing the sports bras for longer times and during various activities (Warner-Campbell, 2010). Knitting technology has made great advances in recent years, yet there is a gap between the capabilities of the knitting machines and much of the current commercial sports bras, which does not yet harness this potential in terms of innovative design (McCann & Bryson, 2009).
The literature review highlighted that extensive research has been done regarding sports bra design relative to bra comfort, design features, fit, sizing, and breast support. The use of new technologies to evaluate functional features of sports bras has also generated vast amounts of data, with 3D Body Scanning and motion capture cameras being the most used tools (Zhou, 2009). However, a literature gap was found regarding studies of sports bras that have adaptive, responsive properties. The few examples of responsive sports bras commercially available have embedded electronics or involve e-textiles in order to monitor biometrics, and their design and product development processes have not been published, being under patent protections (Cho et al., 2009).

Few researchers have studied the responsive behavior for fibers and textiles Berglin (2008), Brandt et al. (2008), Pakhchyan (2008), and Scott (2013, 2015) being the most cited studies. There are two known conventional methods to integrate responsive function into textiles: “either using the textile as a supporting under layer for the application of response creating materials, such as conductive fibers, or, by introducing conductive yarns or smart materials into the textile development during knitting or weaving” (Scott, 2015, p.25). However, both of these approaches focus on the integration of smart yarns or materials into the existing material of the garment, rather than considering the entire garment function. Moreover, the interdisciplinary design approach of wearable electronics has helped define a critical path for the design and product development process of smart functional apparel, but in the case of seamless sports bras, that design process needs to be re-evaluated and expanded.

According to Feng and Liu (2012) and Onofrei et al. (2011), the most important characteristic of functional clothing in general is to create a stable microclimate close to
the skin to support the body’s thermoregulatory system in any physical environment. Tactility and aesthetics are also considered important qualities of garments (Emirhanova & Kavusturan, 2008). Based on all these characteristics, knitted fabrics are commonly preferred not only for activewear but also particularly for sports bras (Mikucioniene & Milasiene, 2013). While there are many studies researching fiber, yarn, and knitted fabrics properties, a gap was found in literature exploring how all the materials function in relation to each other, as a hierarchical system design. Particularly, the seamless knitted sports bra has specific functional design requirements to achieve compression or encapsulation, moisture management, breathability, comfort, but those were researched from the consumer end, in terms of consumer preferences of design, and not from the design end of the product development process (Bowles, 2012). Lau (2014) found that there is a lack of knowledge about the relationship between the key knitting parameters, the mechanical properties of knitwear, the spots bras dimensions, wearer body dimensions and fit perception. There is a need for scientific research to study the relationship between the knit variables as used by the knitting technician and the sports bra function as perceived by the wearer.

Many of the innovations in textile and materials as related to enhancing activewear performance have been informed by biomimicry (McCann, 2005; Chapman, 2002; Vincent and Bogatyrev, 2006; Bar-Cohen, 2006). However, biomimetic research and its applications to functional apparel design have been done on a case-by-case basis. No literature was found to cover a biomimetic design approach to a sports bra design in general. TRIZ as an engineering problem-solving tool was found to be combined with a biomimetic framework in order to suggest innovative solutions to functional design
(Sevransky, 2010). Lovel et al. (2006) developed a theoretical design proposal for a bra strap design, using a biomimetic and TRIZ combined framework, by classifying properties of 250 patents of existing bras. However, designing the bra strap without considering the strap as a part of the entire functional system of the sports bra, proves that study to be just a theoretical exercise of TRIZ framework, without practical applicability. Therefore, the aim of this research is to cover the mentioned literature gaps, by proposing a biomimetic inspired sports bra solution that will offer women a responsive, adaptable sports bra, to encourage healthier lifestyles as well as to accommodate for the athleisure trend.
CHAPTER 3: METHODS AND PROCEDURES

Introduction

Using both exploratory and experimental approaches, the following research questions were investigated:

1. What are the current materials and processes used in the product development process of seamless sports bras?

2. What component materials and structures of a seamless sports bra system offer responsive behavior when actuated by body moisture? How are these materials and structures informed by the tenants of biomimicry?

3. How can a sports bra be designed to function as a responsive system using wearer’s body moisture as system actuator?

A diagram compiling the research methods and their relationship to the research questions is shown in Figure 3.1. The timeline of developing the methods for this research was separated into three different stages, each stage corresponding to the methods for each research question. The timeline for collecting and analyzing data for each stage overlapped, as some information needed for methods on Stage 2 required preliminary data analysis of results from Stage 1 and preliminary data collecting from Stage 3, and methods for Stage 3 needed results from Stage 1 and Stage 2. A visual representation of the timeline is shown in Figure 3.2.

Stage 1: Case Study Methods for Question 1

Based on the theoretical frameworks of TRIZ and biomimicry, a qualitative exploration of the current materials and practices in the design and product development
process of a seamless sports bras is required. The methods employed for the first stage of the research were derived from the question stated to be investigated:

Research Question 1: What are the current materials and processes used in the product development process of seamless sports bras?

<table>
<thead>
<tr>
<th>Research Questions</th>
<th>Research Objectives</th>
<th>Methods</th>
<th>Data analysis</th>
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<tbody>
<tr>
<td>1. What are the current materials and processes used in the product development process of seamless sports bras?</td>
<td>1. Analyze the current design process practices for seamless knitted sports bras and identify design process components and interactions.</td>
<td>Exploratory data collection</td>
<td>Thematic analysis (MaxQDA)</td>
</tr>
<tr>
<td>2. What component materials and structures of a seamless sports bra system offer responsive behavior when actuated by body moisture? How are these materials and structures informed by the tenants of biomimicry?</td>
<td>2. Identify feasible materials for biomimetic inspired responsive sport bra design</td>
<td>Experimental data collection</td>
<td>Data mapping (Excel)</td>
</tr>
<tr>
<td>3. How can a sports bra be designed to function as a responsive system using wearers body moisture as system actuator?</td>
<td>3. Create prototypes for responsive seamless sports bra design</td>
<td>Prototype design</td>
<td>Visual analysis</td>
</tr>
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<td></td>
<td>4. Measure responsiveness of prototypes using human subjects</td>
<td>Prototype evaluation</td>
<td>Comparative analysis</td>
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**Figure 3.1.** Proposed research framework.

**Figure 3.2.** Order of data collection.
After informal private discussions with industry activewear designers and machine knitting technicians during the researchers own industry practice, it was apparent that the seamless sports bra design process relies heavily on the expertise of the manufacturing technicians, and involves a high level of heuristics knowledge. This exploratory part of the research aimed at collecting information pertinent to details of materials and processes used for the design and product development of a high support seamless sports bras. According to Creswell (2012), the qualitative research process is inductive, meaning that the researcher begins with a large amount of interview data, and then proceeds to label participants’ quotes and group them in order to arrive at specific, thematic findings. Creswell (2012) stated that there are five steps in qualitative research designs; these include: (a) identification of participants and locations, sampling approach identification, (b) gaining permission to use the locations for research purposes, (c) specifying information that is applicable for research questions, (d) instrument development, and (e) data collection implementation.

Since this part of the research required an in-depth understanding of a specific technology and product design process, the case study research method was employed. Yin (2009) stated that case study research involves the study of a case within a real-life situation or setting. Some researchers, such as Stake (2005), argued that case study research is not a methodology, but a choice of what is to be studied. Other researchers present it as a strategy of inquiry, a methodology, or a comprehensive research strategy (Denzin & Lincoln, 2005; Merriam, 1998; Yin, 2009). Creswell (2012) stated that case study research is a methodology that involves multiple sources of information (observations, interviews, audiovisual material, and document and reports), and reports a
case description and case themes. Therefore, detailed descriptions answering questions such as “How?” or “Why?” (Yin, 2009) about the process of design of seamless sports bras were collected from the case study subject, along with direct observation notes, videography and photography.

**Case Study Sample for Stage 1**

The only subject in this within-site study was a Santoni seamless knitting technician with over 20 years of experience in developing seamless sports bras for both, major activewear companies (Adidas, Hanes, Champion, Nike, Calvin Klein, etc.) as well as for specific high performance customers engaged with events like U.S. Olympics 2016 and Nascar. His expertise was considered relevant and abundant, since he owns a Santoni seamless knitting lab equipped with a complete range of three different diameters Santoni machines, and is actively developing sports bras design prototypes using various fibers, yarns, and knitting structures. The location of the case study was in North America.

Approval of IRB application was obtained from Iowa State University to ensure rigorous human subjects’ methodological compliance (Appendix A). Over a period of two days, the researcher shadowed the case-study subject by observing the entire process of developing a sports bra in his lab, collecting data via interviews, observations, notes, photography, video and audio recording. The design of the sports bra that he demonstrated was a generic design of a high support sports bra, that he previously produced, and is not protected by a non-disclosure design agreement. The reason why a high support bra was chosen is that its design process is more complex, involving more decisions about fibers, yarns, knitting patterns and garment silhouette that are relevant to the purpose of this research. Interview questions were designed to reference not only
materials and processes used but the communication and design decision-making process too.

Before the interview began, the subject was asked to sign an informed consent (Appendix B). Because the subject’s own business facility was used for demonstrations, his identity and his business’ identity are kept confidential. Photography and videography focused on the activity being demonstrated and was edited out for identification marks. The case study used a semi-structured interview approach, starting with a general list of questions, but allowing the subject to openly intervene with demonstrations, examples, and interruptions as required by the manufacturing process (Esterberg, 2002). This initial list of questions is referred to as protocol by Creswell (2007 and is considered indispensable by McCracken (1988b) (Appendix C).

The first few questions asked the subject to speak about his overall experience in the knitting industry, as well as how he defines his role within the design and product development process of a seamless sports bra via question “Please state your role in the design and manufacturing process of a seamless knitted sports bra.” Next, the topic of the specifics in the design process was addressed, with the question “How does the process of design start for a seamless sports bra?” Details were asked through “Please detail the initial communication process.” Technology comparisons were opened for discussion with the questions “How is this different from the design process of a cut-and-sew sports bra?” and “How is this different from using other seamless technology, not Santoni?” The subject was asked to retrospect on his experience, talking about challenges with communication via “What challenges you see in communicating design specifications for a seamless sports bra?” Moreover, details about technology limitations
were prompted with the questions “Are there restrictions regarding the type of sport bra silhouettes given by the seamless technology? Why?” After the overall design questions, information about materials was addressed through the questions “How does the process of material selection take place? Please elaborate.” and “What challenges you see in material selection?” Specifics on design details were asked via “What type of stitches and knitting patterns you mostly use for seamless sports bras? Why?” Unexplored areas of the seamless knitting machine were questioned through “Are there any features of the Santoni technology that are not being used in making a seamless sports bra? Please elaborate.” Demonstrations on the knitting equipment were prompted with questions such as “How long does it take to program the machine?” “What type of information you consider critical for the programming of the knitting pattern?,” and “Are there any knitting machine preparations done?” Information and a discussion on bra sizing were started with the question “How do you decide what size of bra you make on what machine? Please elaborate the seamless sports bra sizing system.” Also, the subject was asked to reflect on his long tenure working as seamless knitting technician, and address the Santoni limitations with the question “What challenges exist in programming sports bras on circular Santoni machines?” Next, timing questions were asked: “How long does it take for the machine to knit a sports bra tube?” and “What knitting patterns take longer? Why?” Specifics about yarns and fibers were opened up through questions “How many different yarns can be fed into a knitting program?” and “How many yarns are commercially used for seamless sports bras? Why? Please elaborate.” The subject’s experience with quality testing was reviewed via questions “Are there any tests done after the tube is knitted?” and “How is the support level of the sports bra tested?” The product
finishing process was discussed too: “Please detail the finishing process for seamless sports bras.” A summative discussion was prompted by “Is there anything you would like to add?” During each interruption/pause during the interview, the researcher made reflective notes and comments aimed to help with organizing the data (Creswell, 2007).

**Case Study Data Analysis**

In qualitative research, data analysis is an integral process of data collection and analysis (Regan et al., 1976). Tesch (1990) suggested that data analysis includes segmenting text, decontextualizing text, coding, and recontextualizing text. Common to qualitative research is the establishment of categories to interpret the data (Ely et al., 1991).

The data collected through the three days resulted in 45 video and audio recordings that were immediately uploaded onto the password protected cloud file storage, in compliance with IRB requirements (Appendix D). All recordings were made with the researcher’s iPhone 6, with high-resolution settings. Next, the recordings were transcribed by the researcher as close to verbatim as possible and saved as a Word document. Open coding is a qualitative analysis method offering an in-depth analysis of the data. The target of the first data analyses is “the production of codes that relate directly to the data” (Böhm, 2004, p.271). According to the Grounded Theory, open coding allows for breaking down the data, row by row, extracting concepts that eventually can be organized in building blocks leading to a model. In order to enhance the trustworthiness and dependability of the qualitative data, multiple measurements were conducted to achieve confidence of the reliability in what the researcher coded. The researcher and the audit coder (one of the co-major professors), independently coded 5
minutes from the transcript of Video 1, then compared the results. All coding was done using MaxQDA (Version 12) software, a leading software tool for researchers analyzing qualitative data. This initial coding resulted in close to 0% agreements. Another 5 minutes from Video 1 transcript were chosen and again an independent coding was done by both researchers, resulting in 38% intercoder agreement. Creswell (2013) suggests 80% as the minimum intercoder agreement threshold, to reach reliability of the data analysis. Therefore, Video 16 was chosen for another round of independent coding, and this time the researchers reached an 80% agreement. The intercoder agreement was calculated by multiplying the number of coders by the number of agreements and dividing by the sum of the total number of codes assigned by the two coders. Reaching a minimum of 80% intercoder agreement assures the trustworthiness of the data analysis. The researcher then singularly coded the rest of the data, with several reviews from the audit coder, obtaining a total of 650 different codes. A process of comparison and constant refining was used to organize the codes in themes and subthemes (Glaser & Strauss, 1967).

After grouping the themes in general categories, axial coding was employed in order to highlight relationships between categories. Axial coding allows researchers to systematize the data (Strauss & Corbin, 1998). The resulting coding guide with its categories, subcategories, themes and subthemes as resulted from the axial coding is shown in Appendix E.

The visual extrapolation and representation of the axial coding is achieved via selective coding, a third stage in the process of Grounded Theory analysis, where a core category is being identified as important to the subject or to particular interest to the
researcher, and constantly related to the other categories, validated with specific examples from the interview data (Creswell, 2007). Integrating the categories and themes results in a new model, a model created by the subject’s own perceptions and experiences (Strauss & Corbin, 1998). Charmaz (2006) considered these resulting visual representations as an integral part of the grounded theory methodology.

**Initiating the Design Process for the Responsive Sports Bra Prototype**

Once all the interview data was analyzed, the researcher was able to start the design process for the responsive sports bra prototypes. The main result of Stage 1 analysis, the mapping of the design and product development process of a seamless sports bra, also led to identifying all the materials, processes and fabric designs possible using the Santoni seamless technology, as well as the subsystems that hold back innovative designs. The researcher was able at this point to start a technical package template, a design communication tool, in which prototyping design details could be filled in as design information became available from the further data analysis of Stage 2.

**Stage 2: Knit Fabrics Testing Methods for Question 2**

An experimental research design was used to test and identify responsive behavior from various fibers and yarns feasible for seamless sports bras design, as analyzed in Stage 1, aiming to answer the following question:

**Research Question 2:** What component materials and structures of a seamless sports bra system offer responsive behavior when actuated by body moisture? How are these materials and structures informed by the tenants of biomimicry?

Textured Nylon yarns and stretch elastane yarns are commonly used for seamless sports bras, some examples being 78/68/1 nylon 66 (where 78 represents the Dtex of the
Nylon66 textured yarn, 68 represents the number of filaments, and 1 represents the number of plies of yarn), 20-20/10/1 cover core spun yarn and 210 D bare elastic yarn (Lau, 2014; Zheng et al., 2008). Bare elastomeric yarns can provide excellent elongation and recovery properties to fabrics, and are essential for second skin garments such as sports bras (Voyce & Towlson, 2005). These nylon and polyester yarns are used due to their moisture wicking properties.

However, using the biomimetic framework, a responsive behavior of fibers was looked upon. Wello et al. (1952) observed large changes in the swelling properties of different fabrics made of natural fibers (wool, cotton etc.) due to the presence of moisture. Based on the mapping of materials and processes created in Stage 1, combined with literature research and supplier sourcing, the list of responsive materials for investigation was narrowed down from wool, cotton, linen, and silk to just wool and wool blends. Literature suggests that wool blends are feasible responsive fibers that are already used in activewear and seamless knitting industry, but not yet in sports bras.

**Knit Fabrics Samples**

As a result of the interview data from Stage 1, yarn specifications required for Santoni seamless machines are 50/1 or 60/1 yarn size, and yarn should be available in both S twist and Z twist. Research regarding suppliers of fine wool yarn feasible for circular seamless knitting equipment led to the identification of two companies: Südwolle in Germany and Xinao Textiles in China. Südwolle Group, located in the Nürnberg metropolitan region, is the world’s market leader for worsted spun yarn for weaving, circular and flat knitting in pure wool and wool blends (Suedwollegroup.com). The Group offers a comprehensive stock range/stock service on all standard worsted yarns,
wool, and blended yarns, from Nm 9 to Nm 120 (1 Nm= 1,000 meters/kg). An inquiry to their United States sales representative led to finding out that they sell in the United States only a blended yarn, 90% wool 10% Nylon in the 60/1 size. A shipment of 8 cones (8 lbs.) of each S twist and Z twist, undyed yarn, was purchased.

The second company, Xinao Textiles, is a worsted Merino yarn spinner for flat and circular knitting, a global supplier for Merino wool top and wool yarns (www.chinaxinaogroup.com). The company offered to sponsor this research and shipped samples of their Element, 19.5 Nm, 100% merino wool, 16 cones of 50/1 size in color Navy and 20 cones of 60/1 size in color Light grey. The Navy color yarn, which was finer than the Light grey one, was eliminated from sampling, due to breakage problems during pilot testing in Santoni knitting machine.

A third yarn was needed for the body of the bra, to replace the nylon yarn used by current sports bras. After several inquiries for recycled Nylon yarns at different domestic suppliers, a 78/68/1 100% eco-nylon yarn was found and purchased.

Zheng et al. (2008) suggested that knitting patterns have an effect on a fabric’s mechanical properties and compression characteristics, particularly, circular knitting pattern could have better mechanical (and resulting compression) properties than basic flat knitting jersey knitting patterns.

Therefore, the fabric tests were decided to be done using swatches cut out from seamless knitted tube panels. The knitting patterns were programmed on the Santoni CAD system. Santoni technology allows for a wide range of textural patterns to be designed, combining tuck, miss, plain and float stitches, as well as alternating the wool and spandex yarns.
In order to decide what patterns should be selected out of the countless possibilities, research of biomimetic moisture absorbing patterns was done. In the context of a sports bra design, the areas where wool fibers should be used was decided by analyzing the human sweat maps (Figure 2.6). The area between the breasts as well as under the breasts accumulate the most sweat (Havenith et al., 2008). Under the breasts is also an area where breast support is needed, while between the breasts, ventilation is needed. Therefore, both lightweight (permitting ventilation) and heavyweight (strong dimensional stability) patterns were decided to be tested; the placement of the wool yarn patterns was decided to be just in the front of the bra, below the breasts and between the breasts, while the rest of the bra will be made out of the recycled nylon yarn.

Responsiveness tests were aimed for the wool yarn only, so no swatches were knitted in the recycled nylon yarn. The wool yarn was combined with the standard Nylon covered spandex that gives sports bras material compression (20-20/10/1 Nylon cover yarn and 210D bare elastic).

Twenty different patterns were knitted, each pattern using two different yarns at a time as to replicate the fabric structure of seamless knitted sports bras, in two yarn combinations:

1) 90% wool 10% Nylon yarn, undyed, with 20-20/10/1 Nylon cover yarn and 210D bare elastic, and

2) 100% wool yarn, dyed light grey from the supplier, with 20-20/10/1 Nylon cover yarn and 210D bare elastic.

The patterns for each yarn combination were knitted in two different circular tubes, for easier handling, as shown in Figure 3.3. Detailed views of all patterns, along
with their pattern description and Santoni CAD stitch diagram are presented in Appendix F.

Figure 3.3. The two knitted tubes of the Wool/Nylon/Spandex combination, including all 20 patterns. Photo taken by the researcher.

An example of a Santoni CAD seamless knit stitch pattern is shown in Figure 3.4, the yellow squares represent knit stitches and the black squares represent float stitches.

Figure 3.4. Santoni CAD stitch pattern screenshot.

The seamless knitted tubes were air-dried for 48 hours in standard conditions (20 °C, 60% RH), then laundered in cold water (60 °C) for 60 minutes in a revolving drum washing machine (GE) and tumble dried at low temperature (70 °C) for 90 minutes, in order to relax the knitting but not alter the wool yarn texture. A similar procedure was
used by Choi & Ashdown (2000), except that in this experiment, the knitted tubes were washed only once and not multiple times, as to follow the industry practice highlighted in Stage 1 of this research.

Regarding moisture management of various fabrics, the literature shows that, as water vapors move through the fabrics, the fabric fibers absorb and desorb moisture, which may impact the fabric characteristics (Horrocks & Anand, 2000). Also, moisture management properties of fabrics were found to change statistically significantly, by the change in knitting type and tightness (Öner & Okur, 2013). Moisture management testing as per AATCC 195-2009 performed on SDL Atlas moisture management tester (MMT) was initially considered but, after studying the textural properties of the swatches, it was deemed inappropriate. All fabric swatches were designed for high moisture absorption, therefore exhibiting textural properties as well as linear symmetry patterning.

Moreover, the testing was limited to just gathering the physical measurements for all swatches. All patterns were knitted on 28 gauge and same yarn tension settings used for the production of sports bras. Due to extreme density of most of the swatches, courses and wales stitch densities were not able to be counted via direct visual inspection, even with the use of a magnifying glass. Therefore, the number of courses were calculated by dividing the number of courses knitted for each pattern (460) by the physical width in the relaxed state of each pattern stripe after being cut out from the knitted tubes. Similarly, the number of wales was calculated by dividing 1,344 (the total number of needles on the circular Santoni machine) by the physical flat measured width of the tube pattern, multiplied by 2 for circumference (Figure 3.5).
Mass per unit area measurements were determined according to ASTM D3776/D3776M-09ae2 (2009). Three different fabric swatches of 10cm x 10cm were accurately cut out from each pattern and each tube and were weighted on an electronic scale set for grams’ unit. Each reading was transformed in g/m² (Table 3.1).

Furthermore, fabric swatches of 5”x5” were accurately measured and cut out from each pattern and each tube. The swatches were immediately placed in individually labeled plastic bags to prevent moisture absorption during the testing process, as shown in Figure 3.6.

**Figure 3.5.** Flat measuring the cut-out knitted tubes for each pattern.

**Figure 3.6.** Fabric swatches cut out from the knitted tubes, labeled and stored during the testing process.
Prior to the fabric thickness measurements, all fabric swatches were conditioned in a conditioning equipment, set at standard atmospheric conditions: $20\pm2^\circ C$, $65\pm2\%$ relative humidity (RH) for 24 hours, according to ASTM D1776-08e1 (2009).

Determination of thickness of fabric samples in the laboratory is usually carried out with the help of a precision thickness gauge. Using a Schröder fabric thickness gauge, the fabric was kept on a flat anvil and a circular pressure foot was pressed onto it from the top under a standard fixed load of $4.14 \pm 0.21$ kPa ($0.60 \pm 0.03$ psi). The thickness was read directly from the dial indicator, in mm up to 10mm, in 10 different places of each fabric swatch (ASTM D1777-96e1, 2011) (shown in Figure 3.7). The mean value of all 10 readings is recorded to the nearest 0.01m and reported as the thickness of the sample.

![Determination of fabric thickness via dial gauge.](image)

**Figure 3.7.** Determination of fabric thickness via dial gauge.

The same thickness test was performed three more times: (a) after wetting, (b) after air drying for 30 minutes, and (c) after air drying for 60 minutes. Five swatches at a time were placed on a clear plastic sheet and secured with vertical inserted pushpins, without stretching the fabrics. In order to simulate the human sweating conditions, a salty
solution that is currently used for moisture management testing was used. Average human sweat contains around 1000 milligrams of sodium per liter (Das et al., 2007, p. 203) and literature shows various synthetic sweat recipes being used for textile testing. For this test, Yao, Li, & Kwok (2008) recipe of 1 liter distilled water and 9 grams of sodium chloride was used. Research also suggested that, for studies involving clothing, moisture tests should be conducted using a liquid with surface energy properties similar to those of human perspiration, and therefore heated to the human skin temperature of 35°C (Hernett & Mehta, 1984). Each swatch was then sprayed with 2.25 gr of salty solution via 5 spray shots applied at 4” distance right above the swatches, at an approximately 45-degree angle (shown in Figure 3.8).

![Figure 3.8. Applying moisture to knitted swatches.](image)

Time of applying moisture was accurately recorded for each swatch, on a separate label. Fabrics were allowed to absorb the moisture for 1 minute, then the thickness measurements were performed, in 10 different places of each fabric swatch, and the mean value was recorded. The time of the measurements was recorded on each swatch’s label. The wet swatches were then placed on metal wire racks and allowed to air dry at room temperature of 70°F, simulating the conditions in which a person would keep the wet
sports bra on after a workout. After 30 minutes, and then after 60 minutes, the thickness measurements were performed and recorded again, for each swatch. Swatches made out of 100% wool yarn were labeled “W” and swatches made of the 90% wool 10% nylon blend were labeled “WN” (Appendix F).

**Data Analysis of Knit Fabrics**

As per the biomimetic framework, the moisture effect on the fabric was thought to activate the wool fibers and make the fabric swell. Moreover, when the moisture dries out, the fabric should go back to its pre-moisture physical properties. Therefore, percentage changes in thickness between dry and wet conditions, and between dry and air dry conditions were calculated and compared using Microsoft Excel. Averages and standard deviations were computed to highlight differences between various patterns. Fabric (knit) densities were calculated by multiplying wales/cm with courses/cm. Weight/thickness ratios were computed for each swatch for the dry condition and results were compared (Choi & Ashdown, 2000).

**Stage 3: Seamless Bra Prototype Development Methods for Question 3**

This part of the research used an experimental design method, using results from the previous two stages as well as literature review.

Research Question 3: How can a sports bra be designed to function as a responsive system, using wearers’ body moisture as system actuator?

The prototype design and development part of this research incorporated specific process findings from the Stage 1 and 2 of the research. A sports bra user-needs map was created based on the literature review (Figure 3.9).
After the results from Stage 2 were analyzed, decisions about the original design, on which patterns should be placed on the high sweating areas, were made. The design focus of the new bra was on the functional part of the responsive wool patches, while the back of the bra was made in the recycled Nylon yarn. Various patterns were considered, as a result of combining sweat maps, high-stress areas around the breasts, body kinetics as well as ventilation required areas (Figure 3.10).

The overall silhouette of the bra considered details related to high support in sports bras, resulted from the literature review, such as high front neckline, crisscross back straps, encapsulation and compression features. Shoulder strap slippage, strap-cutting into the shoulder and band tightness around the chest area are the most important factors of bra discomfort (Bowles, 2012). Therefore, the underbust band was shaped at center front, to better fit the angle of the female body rib cage, rather than being horizontal and cutting across underbust as all current sports bra have typically done.
Figure 3.10. The design process for responsive sports bra proposal: inspiration (A), sweat maps and breast anatomy research (B), sketching (C), translation of sweat maps into bra blocks (D), and preliminary flat sketches (E).

A combination of rib, tuck and mesh patterns, chosen based on results from Stage 2, was placed in areas requiring support and ventilation (Figure 3.11). An insert of stronger spandex yarn (40 denier versus 20 denier) was added along the straps and ending at underbust, a new addition to the design of current bras that use the same 20 denier spandex all over the bra area. Overall, comfort considerations were important, as literature found that often, bras that offer the most support were the most uncomfortable ones at the same time (McGhee, 2010).
Figure 3.11 The design of outside layer of the newly proposed bra, front and back views.

For the inside layer of the bra, where the functional responsive system was intended, two different patterns were chosen for the wool areas: the part under the bust needed to be thick and highly, absorbent, and the part between the breasts right below the neckline needed to be quick drying but textural. During the wetting process of the wool swatches, a curling of the edges was observed that was much more substantive on the lighter weight patterns than on the heavier weight patterns. That type of responsiveness to moisture, that actually induces mechanical motion on the edges of the patterns was found to be useful to be placed between the breast and right below the neckline at center front. The aim was to have that part of the fabric curl and become highly textural when activated by moisture. In order to maximize the area containing fabric edges, circular islands of wool yarn were designed and a plain jersey pattern was placed in them (Figure 3.12).
Figure 3.12. The design of the inside layer of the newly proposed bra, front and back views.

The tech pack of the new responsive sports bra design was completed and sent out to the knitting lab for prototyping, including garment specs that were created using a generic size Medium sports bra from the market (Appendix G). The results from Stage 1 interview revealed that the initial specs are just guidelines, and final specs are developed after several wear trials. The purpose of this initial prototyping was to test the concept of a responsive system via wool yarn, so the emphasis was on knitting patterns and materials and not so much on the overall silhouette of the sports bra. However, if the concept proves viable, improvements on the fit and a follow up with patent registration as well as a commercial application is intended.

During execution of the prototyping, the knitting technician incurred several problems while trying to draft the stitch pattern from the tech pack. The 100% wool yarn exhibited high breakage when was threaded into the floating pattern. Repeated attempts
were made by the knitting technician by adjusting the yarn tension, but efforts were unsuccessful. Therefore, that yarn was deemed unfeasible for production. Moreover, while trying to knit the new bra using the 90% wool 10% nylon yarn, the selected patterns for the wool area were not being compatible with the stitch selection for the shaping of the bra, such as the center front cinching between the breasts for offering encapsulation. So, some of the patterns that were chosen for the design were changed in the prototyping stage to accommodate the Santoni knitting machine limitations, as well as to allow for production feasible solutions.

Design decisions regarding edge finishes also intended to follow the biomimetic framework. Currently, sports bras have elastic tape sewn to the armholes, to finish the cutout fabric edges resulted from the carving of the bra silhouette out of the seamless knitted tube. While the elastic trim was found to help with the problem of bra strap slipping off the shoulders, new solutions were contemplated (Bowles, 2012). After consulting with the knitting technician, it was concluded that there is no option available within the knitting machine, such as special stitches, to allow for outlining the bras and not unraveling when cut out. Therefore, out of the options of sewn-in binding, a wider (5/8”) nylon/spandex trim was selected, allowing for a softer edge of the bra around the armholes and neckline. Twenty bras were manufactured, allowing having one bra for each human subject that will wear test the sports bras.

After the bras were received from the knitting lab, each bra prototype was measured against the specs to make sure they are all of the same measurements. At this time, it was observed that they were missing the binding around the edges. After checking with the knitting technician, it was communicated that sewing room logistics
prevented the technician from having the bras finished as per the tech pack sewing specifications, and due to the required advance scheduling of the body scanning subjects, the decision was made to ship the bra samples without having the trim on. Since the trim gathers the edges during sewing and shortens the overall strap lengths, it was furthermore decided to hand sew the straps shorter for each bra, at the same level as the existing shoulder seam, about 4” shorter on each shoulder, an amount estimated by the sewer in the manufacturing facility. This type of situation is common in the industry, and it speaks to the results of the interview in Stage 1, highlighting the special situations that occur during prototyping and require spontaneous solutions. The decision was made to pursue the wear testing trials, as the strap lengths were adjusted and they were not directly impacting the moisture responsive system designed inside the bras.

Testing of the prototypes is an intrinsic part of the functional design process, as highlighted by Watkins & Dunne (2015). Factors used in making a decision on whether to incorporate users in testing a prototype usually include the product newness, complexity, innovativeness, timing, and price-point (Watkins & Dunne, 2015). If a product is new, expensive, and/or complex, the product will be tested with users, which reduces the uncertainty and risk. In the case of the responsive sports bra, the testing was needed to confirm system responsiveness as actuated by human sweat instead of the saline solution used in Stage 2, as well as the rate and area of perspiration.

**Seamless Bra Prototype Wear Testing Sample**

Semi-professional athletes, such as female college students participating in team sports, were recruited for the 3D body scanning testing of the prototypes, in order to minimize the variability of body shapes around the bust area. After obtaining an
Institutional Review Board (IRB) approval from Iowa State University, for use of human subjects for testing (Appendix H), recruiting was done, aiming to select a minimum of 20 subjects.

The requirements for the volunteering participants were as follows: (a) over 18 years old, (b) have a bust circumference, measured at the fullest part, of 37” (+/- 1”), and (c) able to run on the treadmill for 30 minutes. The recruiting email is attached in Appendix I. Moreover, an informed consent was asked to be signed by all participants, at the beginning of the testing session (Appendix J).

Fifteen female subjects were selected to participate in the bra testing. The subjects were invited to the campus 3D body scan lab and asked to bring their own running shoes, a t-shirt and running shorts. A Textile/Clothing Technology Corporation [TC]² NX-16 3D body scanner was used to collect scanning data. The scanner was calibrated before the testing sessions started. After signing the informed consent document, the bra prototypes were randomly assigned to the subjects.

The 3D body scanning of each subject was conducted in several different conditions. The respiratory state has been found to affect bra size determinations, as the difference between underbust band circumference during inhale versus exhale ranges from 0 up to 6 inches, with a mean standard deviation of 1.9 inches (McGhee and Steele, 2006). Therefore, fully inhaled (subjects held respiration for 10 seconds during the scan) and exhaled (regular breathing with minimal accessory muscle effort) conditions were recorded for each scan. To track the responsiveness of the bra prototypes to body moisture, as well as the material comfort and recovery after 30 minutes of rest, subjects were scanned eight times as shown in Table 3.1:
Table 3.1. Scans collected via 3D body scanning from each participant.

<table>
<thead>
<tr>
<th>Description of subject condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan #1  Wearing no Bra, inhale</td>
</tr>
<tr>
<td>Scan #2  Wearing no Bra, relaxed</td>
</tr>
<tr>
<td>Scan #3  Wearing Sports Bra, inhale, before run</td>
</tr>
<tr>
<td>Scan #4  Wearing Sports Bra, relaxed, before run</td>
</tr>
<tr>
<td>Scan #5  Wearing Sports Bra, inhale, after 30-minutes run on treadmill</td>
</tr>
<tr>
<td>Scan #6  Wearing Sports Bra, relaxed, after 30-minutes run on treadmill</td>
</tr>
<tr>
<td>Scan #7  Wearing Sports Bra, inhale, after 30 minutes rest</td>
</tr>
<tr>
<td>Scan #8  Wearing Sports Bra, relaxed, after 30 minutes rest</td>
</tr>
</tbody>
</table>

The participants stood in the body scanning booth in an upright position, with both arms placed on the handles of the scanner (Figure 3.13). For the bottom part of the body, scanning knee-length pants were handed to the subjects to wear for all scanning conditions.

Figure 3.13. An example of a subject’s upright posture during the 3D body scanning sessions.

After the No Bra scan that was intended to collect the subject’s basic body measurements in the breast area, the subjects put on the assigned bra prototype and conducted Scan #3 and Scan #4 (“Before Run” condition). Before going to the treadmill room that was across the hallway from the 3D body scanning laboratory, subjects were
asked to fill out the first part of a questionnaire, aimed to collect data about their perceptions of fit and comfort of the bra. For the running session on the treadmill, participants wore their own running shoes, their own running pants, and the provided bra prototype. The treadmill was placed in a conditioned room, i.e. an environmental chamber, with a constant temperature set up for 70°F and humidity level of 35 (+/- 5%). Several fans were turned on in the room to ensure proper ventilation. Each subject designed their 30 minutes run according to their own level of comfort, simulating real-life situations. At the end of the timed running session, a bottle of water was offered and each subject filled out the “After Run” part of the survey. Next, they walked across the hallway to the scanning booth and conducted the “After Run” Scans # 5 and #6. A chair was offered to sit down and rest in an adjacent room, for 30 minutes. After the timed resting session, each subject conducted Scans #7 and #8, then they filled out the “After 30 min Rest” part of the questionnaire. After collecting the survey and the worn bra prototype, a $15 gift card from Amazon was handed to each subject before they left.

**Questionnaire Design**

Moisture management properties of textile materials are often linked to perceived comfort, and researchers have used both objective and subjective measurements to investigate the moisture management performance of fabrics (Jeon, Yoo, & Kim, 2011). Literature suggests that evaluation of fabric comfort includes many components and often the wearer cannot consistently describe the sensation of comfort (Doyle, Tester, & Thompson, 2015). Specifically, when investigating comfort of fabrics with wool content, the fabric hand, or the sensorial comfort when the fabric touches the wearer’s skin, has been identified as one of the most important measures of the overall comfort (Li, 2001).
Therefore, all participants were asked to fill out a questionnaire at various times during the 3D body scanning process, aimed at evaluating their perceptions of comfort (see Appendix K). The questionnaire had four parts, including: (a) demographics, (b) evaluations of bra features before run, (c) evaluations of bra features after run, and (d) evaluations of bra features after 30 minutes’ rest. Additionally, one open-ended question asking for additional overall comments followed the survey’s main four parts. The demographic information collected was participants’ age, weight and height, ethnicity and fitness level. Age, weight and height were open-ended questions; ethnicity, and fitness level were closed-ended questions. A descriptive diagram of the bra prototype was included in the survey, to familiarize the participants with the terminology of bra features they were asked to evaluate. Terms such as “bust area,” “bra straps,” and “underbust band” were visually placed on the sketch of the bra. Each section of the survey was clearly marked with red colored bold titles, such as “Before Run,” “After Run,” and “After 30 minutes Rest.” Since the same questions about the comfort of bra features were asked repeatedly, the survey parts were printed on separate pages and handed to the participants only at the needed time, as to minimize the bias from seeing their previous answers.

The opening question on “Before Run” section of the questionnaire asked the subjects to rate the ease to slide bra over their head and shoulders, aiming to gauge how easy is to put on the bra. Subjects had to circle the most appropriate number on a Likert scale from 1 (meaning hard) to 7 (meaning easy). Following the scale, a section for “Any comments?” prompted the subjects to comment openly in their own words.
The bra features questions that were repeated on all remaining parts of the survey asked subjects to rate underbust band tightness from 1 (too tight or too loose) to 7 (feels just right); bra straps tightness (same scale as previous); support in the bust area (from 1 (unsupported or too tight) to 7 (feels just right); fabric feel from 1 (itchy) to 7 (soft), and a second scale from 1 (dry) to 7 (wet); and lastly, overall comfort (from 1 (uncomfortable) to 7 (comfortable). After each of the above-mentioned scales, “Any comments?” prompted the subjects to be explicit about their ratings. Moreover, on questions where they circled low ratings for too tight or too loose, they were asked to specify which option applies by circling “too tight” or “too loose.”

Interval scales are the most common type of scales used in garment wear-testing because they are fairly easy to administer (Hollies and Goldman, 1977). When investigating the bra underband tightness, Lau (2009) used a visual analog scale (VAS), consisting of a 10 cm line with polar ends in “0” representing “too tight” and “100” representing “too loose”. Choi (2007) evaluated the bra wearer’s comfort sensation using a 5-point Likert scale. However, some researchers suggested that the use of Likert-type scale leads the subjects into suppressing their own feelings by trying to fit in a certain number (Russell & Bobko, 1992). Therefore, each question in the survey had a separate “Any comments?” additional prompt to record the subject’s personal reflections.

In the last survey part that was filled after the subjects rested for 30 minutes, a question about ease to slide bra over their head and shoulders aimed to gauge how easy is to take the bra off [scale from 1 (hard) to 7 (easy)]. Lastly, an open-ended question about overall comments asked participants to give a descriptive overview of their experience wearing this new concept bra.
Data Analysis of 3D Body Scanning

In addition to the basic bust area, girth measurements such as underbust and bust, scan slices provided by the scanner’s software enable the visualization of the body in a much deeper manner than surface analysis. Scan slices are often used to visually represent changing size and circumferences (Lee & Hong, 2013). The starting slice was determined by the lowest level (relative to the floor) of the “Under Bust Full” slice measurement provided by the scanner software. Using the data collection method proposed in a previous study by Gorea and Baytar (2016), scan slice measurements at various heights along the sports bra surface were compared to identify compression rate changes during the various scans. Sixteen slice measurements taken at 0.25” intervals between under bust and armpit levels were collected for each scan condition. A rate of change, similar to a growth rate, is a rate that describes how one quantity changes in relation to another quantity. In this study, the rate of change in slice circumferences for each height level was calculated by subtracting the slice circumference from the no bra circumference, and dividing the result by the no bra circumference measurement, for each subject, bra, sweat condition and respiratory state (Gorea & Baytar, 2016). Visual analysis of scan contours of various slices was also conducted, looking for confirmation of textural changes of the bra material due to moisture absorption.

For the questionnaire part of the wear trial, despite the small sample size, some repeated measures statistics were also analyzed besides the descriptive and frequencies statistics, for each of the variables evaluated: ease to slide bra over head and shoulders, underbust tightness, bra strap tightness, support in the bust area, fabric feel and overall
comfort. The answers to the open-ended questions were analyzed in relationship to the quantitative data, as to confirm or not the main conclusions.

**Validity and Reliability**

To provide trustworthiness to the collected data and validity to the results, multiple methods were used throughout the three stages of this research. During the case study (Stage 1) part of this research, triangulation between the researcher, audit coder and literature review was used to validate the methods and analysis of the qualitative data. The inter-rater reliability coefficient for open coding of the transcribed data was calculated as the number of agreement scores divided by the total number of decision scores. After multiple measurements, the inter-rater agreement was slightly above 80%, which is considered acceptable for the validity of qualitative research (Touliatos & Compton, 1988, p. 122). Moreover, the researcher and the audit coder, as well as another co-major professor, discussed and negotiated the relationships and major findings from the open coding process.

For the reliability and validity of the quantitative data and its analysis results from Stage 2, the researcher consulted with the co-major professor, as well as used textile standard procedures (ASTM) to guide the knit fabric textile testing process. Also, by disclosing the collected data, the results are verifiable. Photo-documentation of all stages of the responsive sports bra prototype development and prototype evaluation phases add to the reliability and replicability of the research project.

During the prototype development and wear testing conducted in Stage 3, using both qualitative and quantitative data, statistical analysis and supporting comments from the surveys and interviews, allowed the researcher to confirm the statistical results. Also,
by disclosing the collected data, the results are verifiable. Using both qualitative and quantitative data enhanced the study’s reliability. Moreover, as per Glesne (2006), validity was achieved through extensive engagement with the research and the research process, as well as by comparing core categories and axial themes that emerged from the Stage 1 of the study through Stage 2, and with the data from the prototype evaluation Stage 3 of the research.
CHAPTER 4: RESULTS

This chapter presents the results for each of the three stages of this research, in separate subchapters. Just like the previous chapter, that detailed the research methods used for collecting data for each stage, the presenting of the results was guided by the research questions that were investigated at each stage.

Stage 1: Case Study Results

The research question corresponding to the first stage of the research was:

Research Question 1: What are the current materials and processes used in the product development process of seamless sports bras?

To answer this question, excerpts from the case study interview, using participant’s own words, were presented and used to support the conclusions. In order to identify the materials and processes used in the design and product development of a seamless sports bra, it is necessary to establish the expertise of the person interviewed and his role in the process, along with his skills, while keeping his identity confidential as agreed.

Upon analysis of the interview responses, one particular answer stood up as an overall representation of the subject’s role in the process, as well as highlighting the equally important roles of design and product development: “I’m the designer, the product development, the developer.” Besides having more than twenty years of technical expertise on Santoni knitting programming and prototyping, the subject sees his role in the process as an overall non-specialist decision maker, and often throughout the interview, he constantly referred to the many skills a person having his role must have. While the interviewer’s skill set was not marked as a major theme in the interview
because it does not relate directly to the materials and processes of the product development being investigated; however, it is important to present them as part of the subject’s profile, to aid with validity and reliability of the data. These skills were categorized into three main themes: Work Style, Professional, and Personal; as shown in Figure 4.1.

<table>
<thead>
<tr>
<th>Work Style</th>
<th>Professional</th>
<th>Personal</th>
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<tbody>
<tr>
<td>collaboration</td>
<td>knowledge of industry practice</td>
<td>self-starter</td>
</tr>
<tr>
<td>singularity</td>
<td>specialized knowledge</td>
<td>ability to visualize 3D to 2D transitions</td>
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<tr>
<td>one-on-one communication</td>
<td>programming and coding skills</td>
<td>quantitative skills</td>
</tr>
<tr>
<td>interdisciplinary</td>
<td>long tenure</td>
<td>honesty</td>
</tr>
<tr>
<td></td>
<td>knowledge gained through training and crash courses</td>
<td>empathy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>curiosity</td>
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Figure 4.1. Subject’s skill set as emerged from the interview.

It is also notable that, while spending most of his time and tenure in a specialized role, that of a Santoni knitting technician, the subject used a creative field to describe the unique and singular role of the technician in the product development process:

“Technicians for example, are much like painters, or like artists.”

Work Style

During the interview, the Subject used many examples from his interactions with customers, that revealed various ways of working. The Work Style main theme includes sub-themes of collaboration, singularity, one-on-one communication, and interdisciplinary.


**Collaboration.** One of the specifics of the seamless knitting technician work is that he/she needs to work together with the sewing team to be able to engineer the stitches that will serve as guides for the sewers to trim put the outline of the sports bra. This collaboration has a unique characteristic, because clear communication as well as demonstration from the sewer’s part is essential to the efficient execution of the knitting solution: “And a lot of times what I knit, is not quite right in the sewing machine, so she has to come back and say Hey, can you change this? do that.”

**Singularity.** In contrast with the previous sub-theme, there are also many instances where the knitting technician works by himself, relying on his own understanding of the information. Practically, collaboration at the project translation into the knitting program stage is avoided: “You know, you get one technician, one project, one technician, another project.”

**One-on-one communication.** Most of the project briefing sessions rely on initial face-to-face meetings, where one-on-one communication skills are relevant to the future working relationship. The examples given during the interview highlighted the multitude of this type of scenarios:” And, because I had a lady come in here and she sat down, and she had a fairly good idea… and I spent an hour talking to her, and then I got to ask her about the price point.”

**Interdisciplinary.** Besides the Subject’s own skills, the case study discussion revealed details about the skills that the customers, sitting on the other side of the knitting technician, often have. Entrepreneurs bring up experiences from various fields, and the product developer needs to be able to relate and communicate with such people: “She went there for a cut and sew seminar that they have, where you go there for 3 days and
learn about how textiles work, because she’s a chef, she didn’t know anything about textiles.”

**Professional**

The Subject’s experience in the seamless apparel industry led to the development of an impressive set of professional skills. The *Professional* main theme includes sub-themes of *knowledge of industry practice, specialized knowledge, programming and coding skills, long tenure, and knowledge gained through training and crash courses.*

**Knowledge of industry practice.** Through his over twenty years of networking in the seamless knitting industry, the Subject is able to recommend manufacturing solutions or production feasibility advice: “But if I was to run cotton, like I said, if you went to any manufacturer and wanted to do a program in cotton, they’re not gonna want to do it.” By being able to speak from another supplier’s point of view and adding sourcing information, the product developer expands his role in the product development process.

**Specialized knowledge.** One of the greatest skills of the knitting technician is his ability to provide design input based on his specific knowledge of the seamless development process, a skill that takes year to master and it is a practice based skill:

But still… it’s an educated guess, but it’s still a guess, because when you sew this neckline, it’s gonna change. And I’ve done it enough that I can interpret approximately how much is gonna change, but I never know exactly.

**Programming and coding skills.** Besides the particularities of assembling the garment, the knitting technician has specific knowledge about programming the Santoni equipment, meaning knowing how to draft a stitch pattern, how to design a stitch combination, and how to write a chain program that executes the knitting: “I mean you
really have to know the machine to know how to program,” and “So you basically have design input in each of these lines of code? Subject: Yes!” Learning how to program a Santoni machine is achieved via specialized training at the Santoni headquarters, or, by being trained on the job. However, the person leaning how to program has to have skills appropriate for acquiring this type of knowledge:

The CAD part however, I can teach someone …ah… computer literate… this part I can teach someone computer literate to do very well in 3 months, and within 6 months, if they’re really smart on the computer they can even be better than me. Because this is a lot of artistic work, it’s just a lot of tedious dot dot work, you don’t really need to know what the dots do, you just need to know how to do it. This part can be taught easily, with not much time. This is the inside layer of the bra, this is the outside layer of the bra, and this pattern goes with this chain. This part [showing the chain program], it’s gonna take you 10 years to master. This is the hard part.

**Long tenure.** Having extended experience with a highly specialized knitting equipment is important for gaining insights into what are the limitations and opportunities for innovation within a new garment development project. The specialized knitting technicians usually take pride in their long tenure, and even if they prefer to see their role as a non-specialist, more of managerial contributors, they will mention their specialized long tenure: “In this particular role, I’ve been in this role for …10 years; prior to that, I was in a technical position, ahh… for the last 20 years.”

**Knowledge gained through training and crash courses.** The entrepreneurial spirit of the Subject prompted him to seek training opportunities outside the practice within the job, and this quality has been mentioned as related to the customers and other people in the seamless knitting industry. Continuing to look for learning opportunities is a way of keeping relevant within a changing industry, and therefore, employable:

I was working on sock machines… that made socks, Santoni machines that made socks, similar technology, and Santoni came out with this machine, and they
knew it’s gonna be a pretty good seller in the US, so I went to Italy, I spent 3 months in Italy, and I literally just sat down and in 3 months learned it.

**Personal**

Besides skills developed through working relationships and specific professional interactions, the Subject revealed personal characteristics that help him with product development projects. The *Personal* main theme includes sub-themes such as: self-starter, ability to visualize 3D to 2D transitions, quantitative skills, honesty, empathy, and curiosity.

**Self-Starter.** Seizing new product development opportunities requires a self-starter attitude, and the Subject spoke at length about the many ideas he has and plans on pursuing:” I’m gonna make a seamless burn shirt, because I think the quality … and I’ve got others, I even got the one from Big Brand Y… and they all no good.” The self-starter approach is common in the seamless industry, as many technicians own knitting machines or their own factory and constantly trade equipment:

I’ve got a guy in California that’s got a 14” machine and wants to sell it. He wants to sell it really cheap. And he keeps asking me, and I tell him “it does me no good to develop anything on 14 “machine, there’s nobody has 14” machines.

**Ability to visualize 3D to 2D transitions.** A required skill that is common in the apparel industry as a whole is the ability to visualize 3D garments in 2D patterns. In seamless knitting is even more necessary, as the knitting stitches are proportionally deformed in the finished garment versus the square pixel shape on the coding screen. Approximating lengths and distances and spontaneously translating these measurements in pattern drafting is a survival skill for a knitting technician: “So here is your back strap...you got one on this side, these are your 2 back straps. You can see the distance
from here to here is not the same [comparing knit 3D to 2D screen].”

**Quantitative skills.** Learning and memorizing coding shortcuts, stitch counts and creating sizing algorithms require quantitative skills. Many quick math computations are being done in mind while trying to figure out a knitting pattern: “There are 1,344 needles. A basic tank top would be 2,000 courses. So I do 1,344 by 2,000.”

**Honesty.** Being a businessperson and a knitting specialist in the same time, the Subject can see product development opportunities that take an honest approach to communication and interaction with other business people to result in a fruitful collaboration. Honesty has been mentioned many times during the interview, as a treat business people appreciate and look for in a collaborator: “So, I went to Mr. X and I said, Mr. X, your shirt is inaccurate. I said this is my shirt. So he said, Can you make me a shirt? And I said yes.”

**Empathy.** As a person presented with new requests of functional apparel developments from various businesses, the Subject needs to show empathy in order to understand the functional requirements and their reasons. The interview revealed that being open to uncommon apparel applications opens up opportunities for creativity and innovation: “And she goes to these shooting competitions for so and so, and she wanted a bra…and it sounded a little bit off the wall at the beginning, but the more I got into it, it is really interesting.”

**Curiosity.** Along with experience and expertise, the product developer is faced with decisions on time management and self-learning approaches. Setting time aside for exploration needs initial inquiry and curiosity, and deep knowledge of a subject brings up such inquiries:
I’ve been doing it 20 years, and there are cams on the machine that I would just like an open book, where I would just sit and play with the machine. But I never had the opportunity to do that because there are things to do.

**Interview Framework**

After analyzing the entire interview data, five over-arching themes were identified and visualized as two of them being the decision making platforms filtering through the other three as pillars: *Company Type* and *Planning* as the two over-arching themes, and *Marketing, Product Development and Production* as the three pillars. However, the main message from the interview was that everything in the process of developing a new product is related to each other, and all decisions should consider the multiple implications. Each of these over-arching themes had overlapping major themes that furthermore had sub-themes and micro-themes as detailed below in the chapter and shown in Figure 4.2.

*Figure 4.2. Interview Framework with over-arching themes, major themes, and sub-themes.*
Company Type

The *Company Type* over-arching theme grouped information pertinent to the variety of organizations that pursue seamless product development, each of them with specific organizational structures and communication chains. Since seamless technology prompted faster and more efficient production of sportswear, the large volume of the new product brought to market led to the increased role of branding as a tool for promoting sales and revenue growth. Therefore, *Branded Organizations*, as well as *Experience Level* emerged as major themes, with a few sub-themes.

**Branded organizations.** Although having customers ranging from big brands all the way to start-ups and new entrepreneurs, it became evident that the process of design and product development varies greatly:

It depends on the company; I mean, if you working with somebody like Big Brand X, you’re gonna deal with several different people…ah… a lot of the companies, a lot of the people I work with are…ah… online companies, it’s just they sell online, they’re single owners…and you know, you deal with only one person.

Overall, big brands are more organized and streamlined, but also offer more complexities such as big teams and more processes. Being more focused on revenue generation, their product development process is heavily monitored, documented and concerned with commercial applicability.

**Experience level.** This major theme encapsulated information about the various degrees of knowledge the businesses, through their product development teams, have with seamless industry. Sub-themes here were: *Established customer base, Small companies/Entrepreneurs* and *Newbies.*
Established customer base. With a few exceptions from some big brands, that have an established customer base and properly documented specifications of their products and processes, the overwhelming conclusion was that most companies do not have the basic knowledge about starting a seamless new development:

And your larger customers will know what a tech pack is, and that’s with specs, with the fabric, with how much stretch...with you know, all the pertinent information for it…and all the way down to people that know absolutely nothing about textiles.

Small Companies/Entrepreneurs. A pre-conceived idea about seamless product development process is prevalent among the small companies/entrepreneurs that approach the subject for his seamless expertise:

But many people come in here with absolutely no concept of even seamless, but somebody just told them that hey, that looks like a seamless, something that Subject can do for you, or you know, Subject Company Name can do, why don’t you go talk to them, and they come in…and they don’t have any prior seamless experience and nothing to base this project on.

Newbies. Moreover, even some big brands that expand their product line from general textiles to apparel goods, included in the newbies micro-theme, they decide to develop a pre-conceived product in seamless without having basic knowledge about the technology applications: “For example, when you work with somebody like Big Non Apparel Brand X, they don’t know anything about apparel.”

Planning

The second over-arching theme that filters many of the decisions in the seamless product development process is Planning, or in Subject’s words: “So there is a lot of thought that goes into development process.” Major themes identified were Time, Logistics, Materials and Exceptions, each having several sub-themes (Figure 4.3.).
The second over-arching theme, Planning, and its major themes and sub-themes.

**Time.** The time component of planning in any business is crucial. Specifically, for seamless developments, sub-themes such as prototyping, operations, long technology learning curve, and progress monitoring; emerged as influencing the design decisions of seamless products.

**Prototyping.** Most companies under-evaluate the time necessary for prototyping, as they are not aware of the entire seamless process that involves multiple people and places: “Sewing, when it leaves here is one day out and one day back. That’s two days. And it’s normally at least three-four days, so we’re looking at six-seven days to get it sewn only.”

**Operations.** Besides the time planning for the prototyping, there is also a time component for planning the operations as part of the costing process, where time becomes “total allowable minutes,” a term used in apparel product development to refer to the time it takes to sew a product:

The sewing is hard to break down by minutes because it has to go to several different stations, it has to be… you know, there are several operations and… you have to put the binding on, then you have to close the shoulders, then you have to bar tack you know, where you close the shoulders so it won’t unravel, so it’s 3 different operations.
Long technology learning curve. In regards to the programming part of the Santoni knitting machine, the learning curve for the pattern configuration, pattern drafting and chain program coding is long and, for a new product, things might have to start from scratch, adding unplanned time to the process: “So even though we have the pattern, the pattern is the most time consuming part.” and “All of the development is CAD generated, so I have to sit around at the computer and actually create the style, on the computer.”

Progress monitoring. Because business planning in general requires monitoring and communicating updates, the process of progress monitoring itself is a big part of the Time theme. Progress monitoring happens via one-on-one phone calls, e-mails, site visits, messages and software notifications and needs to be implemented to ensure timely delivery of processes.

Logistics. This is the second major theme of Planning, which overlaps with all other themes, and refers to the activity of organizing and executing the planning of the product development processes. Sub-themes such as storage, transportation, product complexity, and manufacturing capacity were identified.

Storage. This category includes multiple references to equipment that needs to be purchased and placed within the chain of operations to secure protection of goods from one place to another: “Once you orient the goods, you put them in some type of container, and they’ll go into sewing.”

Transportation. The means for relocating materials and goods are mentioned often during the interview, and this is one business aspect often disregarded by the product management team, but emerges as a time consuming activity. However,
prototypes and materials keep moving between different manufacturing facilities, another type of activity that requires planning: “once they’re dyed, again, they’ll be moved to sewing, and… they’ll be sewn.”

**Product complexity.** The amount of design details and functional engineering of a seamless product often involves additional planning, sometimes financial planning, as out of normal processes and materials are needed: “It didn’t come in the counts and twists that I needed, so I had to spend $30,000 to get the yarn.”

**Manufacturing capacity.** The capability of a manufacturing supplier to execute production of a new garment design is another sub-theme that emerged quite often during the interview, as the Subject expressed his frustration with customers developing products that are not coordinated with the manufacturing equipment of the intended seamless factories. Most seamless facilities have high production capabilities that require different planning right from the early product development stages: “And Big Manufacturer X for example, got 110 machines.”

**Materials.** This is the third major theme of the Planning over-arching theme. Sub-themes such as yarn supply chain, minimum yarn requirements and material usage were identified.

**Yarn supply chain.** Deciding on the type of fiber used for a seamless design is one of the important early decisions in the product development process, and require planning due to the segregation of the yarn supply chain by fiber type: “You’ll notice that in fabric, like if I want cotton fabric I call A company, but if I want nylon fabric, I call B company.”
Minimum yarn requirements. Each of the yarn suppliers, as well as the fiber suppliers, they have minimum purchase requirements, especially if the yarn is customized as often happens in the seamless developments. Moreover, in order to thread the Santoni knitting machines, there are minimum yarn calculations that need to be considered. In the case of a regular sports bra, the least amount of yarn required to make one prototype “it will be 16 cones, cause you got 8 nylons, 8 spandexes and ….2 elastics for the band. Minimum.”

Material usage. Besides estimates for the yarn needed, there is also planning involving the trims and edge finishes. All seamless sports bras have a sewn in trim binding than needs to be attached to the bras before the garments are dyed. Therefore, material usage was identified as another sub-theme that occurs not only in prototype development but also in production, overlapping with other themes: “They’ll be dyed, and once they’re dyed, if it’s a bra for example, if I’m dying 100 bras blue, I’m gonna put enough binding in the dye to sew the 100 bras, so you’ve got matching blue binding.”

Exceptions. The last major theme of Planning emerged as Exceptions. Special situations often occur in the process of developing new products, but the Subject expressed frustration as they are never really planned. Sub-themes are special cases, complications and emerging trends.

Special cases. The Subject spoke about many situations when the customers asked for special treatments of the products, or unusual engineering for uncommon functions:” I’ve actually had a lady, this is actually to the extreme, but I had a lady for whom I made a bra that wanted me to treat it with insecticide. For the Zika virus.”
**Complications.** This sub-theme captures the situations when the knitting equipment needs special handling due to changes in design and/or materials: “Cause as it is with any equipment, there’s gonna be many variables.” This sub-theme also overlaps with *Time* major theme, as the long learning curve of the knitting technology impacts the severity of the complications.

**Emerging trends.** This category groups innovation led developments, where companies would introduce a new fiber or yarn or garment construction and the product development process would be altered to accommodate the new materials. Also, from the technology side, some manufacturers started to acquire new Santoni equipment that would need to be integrated into the regular seamless product development, and this process needs reverse planning back through the product development channel. Some of the emerging trends mentioned during the interview are: “Micromodal is a fabric that’s really making a good move into seamless” and “The industry from the get-go has used 13” and 15” machines. And even up until five years ago, you never heard of a 17” machine. Now there are 17” machines here, in the States.”

**Marketing**

The over-arching theme of *Marketing* was identified as a major pillar between *Business Model* and *Planning*, being equally important as *Product Development* and *Production* over-arching themes. The major themes, sub-themes and some micro-themes within the Marketing are shown in Figure 4.4.

**Distribution.** As a major theme, this category incorporates information pertinent to sales venues, and the subject mentioned throughout the interview many different channels his customers used, the most prominent being marked as sub-themes: *Online*
Retailing, Special Events, Big Brands Omni-Channels, and the Emerging Low-End Distribution channel. The sales venues often came in the interview conversation as related to price point or quality of seamless products, so this major theme in Distribution is overlapping with Product Development and Production at a minimum.

**MARKETING**

<table>
<thead>
<tr>
<th>DISTRIBUTION</th>
<th>PRICING</th>
</tr>
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<tbody>
<tr>
<td>Online Retailing</td>
<td>Pre-Determined Price Point</td>
</tr>
<tr>
<td>Special Events</td>
<td>Seamless as Cost Down Strategy</td>
</tr>
<tr>
<td>Big Brands Omni-Channel</td>
<td>High Performance High Value</td>
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<tr>
<td>Emerging Low-End Distribution</td>
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**DEMAND**
- Drivers
  - Brands
  - Comfort
  - Differentiation/Authenticity
  - Performance
  - Price
- Creating Demand
  - Advertising
  - Innovation

**Figure 4.4.** Marketing over-arching theme and its components.

*Online retailing.* This sub-theme was prevalent among all distribution venues, very popular with small companies/entrepreneurs, and the Subject mentioned that the customers were very knowledgeable of their own online customer profile and price range: “And she says, well, I wanna sell this on Facebook, to at-home mothers, and I need to sell it for $4 or less.” The price point is a driver of product development for the online retailing distributors.

*Special events.* As a separate sub-theme, special events were mentioned as related to special products requiring performance features and detailed engineering, such as for United States Olympics, Nascar, shooting events, cheerleading activities, etc.: “a company that is … supplies 90 % of the racing shirts, burn shirts that go into Nascar.”
and “I made her some bras for a big shooting show, a trading expo I guess, and she’s going to go out there sell her bras now.”

**Big brands omni-channel.** This sub-theme grouped information related to the large companies, with well established brands in activewear, that are more knowledgeable of the seamless product development process and they also have higher standards of quality, fit and process management. These companies also rely on less input from the knitting technician during the product development process, and their products are more standardized as to fit large quantities of mass production: “To whereas Big Brand X, I may have 10% input in their project.”

**Emerging trend of low-end distribution.** The Subject often expressed frustration with this new venue of selling seamless sports bras, and he referred to this sub-theme as related to quality tradeoff for costing purposes, as well as related to the customer’s lack of knowledge about the fit particularities and the function of seamless sport bras: “But you know… you used to see Santoni only in Victoria Secret, Bebe, you know…higher end, but now you see seamless in stores such as Five Below.”

**Pricing.** This was the second major theme identified within the Marketing overarching theme, and price point was marked as a very important topic related to product development process, was brought up constantly during the interview, right from the beginning:

They’ll ask me what a tech pack is and I tell them: look, I need to know what you want, what it’s supposed to do, and when people come in, I like to get all the information that is pertinent to the project, even price point. I always ask price point.
The issues that emerged related to pricing were categorized as *pre-determined price points*, *seamless as cost-down strategy* and *high performance high value* that were marked as sub-themes.

**Pre-determined price point.** Many of the customers approaching the Subject with seamless project developments expressed a price point they already had in mind, and this practice was encouraged by the Subject: “So by asking about the price point, I didn’t waste any of my time or her time on development, because I couldn’t meet her price point.”

**Seamless as cost-down strategy.** Another category of projects related to pricing are the ones where companies are looking into switching to seamless technology as a way of lowering the price point of an existing product, *seamless as cost-down strategy*, most often switching from the more expensive cut-and-sew construction: “They’re saving so much more money by going seamless with this… this is a perfect example of a seamless knock off of a cut and sew.”

**High performance high value.** Within this sub-theme, pricing examples were grouped of companies marking up the price of their highly engineered seamless functional garments, as a way of communicating added value. By using the seamless technology, much more engineering can be infused in the garments, and for the performance activewear customer, pricing is not as important as the value they get from well-designed garments: “The dance tights that I made for Company Y, are much superior to the cut and sew ones, much superior!” and “But it’s $110 shirt, so you know… it goes hand in hand.”
**Demand.** The last major theme identified under Pricing is *Demand*, with two sub-themes, *Drivers* and *Creating demand*, and a few micro-themes. The Subject spoke at length about various ways seamless technology helps companies differentiate their brand on the market in order to create customer interest and ultimately sales of their product.

**Drivers.** The micro-themes categorized as *Demand Drivers* were: *brands, comfort, differentiation/authenticity, performance and price*. The Demand is being managed differently depending on each organization type.

*Brands.* Some big *brands* that are already established in other categories of apparel use seamless knitting technology as a platform to enter the undergarments category, therefore initiating innovative product development projects:

You got Big Brand X in boots, you got Big Brand X in jackets, you got Big Brand X in gloves, but nobody makes a base layer Big Brand X, cause up until now nobody was able to make the yarn, the PTFE, small enough to run on a machine that could produce a base layer. So they produced the PTFE yarn, and came to me and wanted to make a shirt with PTFE.

**Comfort.** Among all demand drivers, *comfort* was mentioned as one of the most important features that relate directly to the design of the product and that companies are continuously trying to improve: “It was the most uncomfortable thing, terrible looking, I mean we immediately figured it out that it was not sellable.”

**Performance.** Comfort is often grouped with *performance*, another demand driver that refers to the functional properties of a garment. Although many new seamless developments focus on performance at the material and fabric level, the Subject has more of an overall approach to performance, from the silhouette and knitting techniques level:

Here is a seamless. OK? If you look on the double layer, I put venting on the inside... the mesh... the inseam; feel this one and feel that one! This is so much more comfortable. It’s not even a comparison how much more comfortable...
And look how much smaller it looks, but it actually fits, because it got so much more stretch!

Differentiation/authenticity. Seamless knitting machines offer the possibility of engineering every stitch of a knit fabric, so this feature is regarded by many companies as an opportunity to differentiate/authenticate their products, even though they might not design much functionality behind the selection of every stitch: “If you use the same mesh all the time… to look even more engineered.”

Price. And the overlapping micro-theme of price is also mentioned as a demand driver, as companies are constantly looking into adding value to their products but controlling their costs: “To do this is seamless, to add that ventilation engineering, it won’t cost anything.”

Creating demand. This category is another marketing sub-theme that groups micro-themes such as advertising and innovation. Similar to any other product promotion, the seamless garments also need to be brought up to the attention of potential customers via printed marketing materials, social media as well as word of mouth.

Advertising. Seamless products often do not look appealing on hangers in a store, due to their extreme shaping and soft material, so creating shelf appeal through design is important: “Now this don’t look good for shelf appearance at all.” Advertising also transforms the shapeless undergarments into consumer desirable garments: “But once we got it right, I mean it is beautiful, it’s functional, and it looks like... they sent me the photos from the photoshoot and it looks absolutely magnificent when you put it on a girl.”

Innovation. This category is a micro-theme in Creating Demand, but it overlaps with Product Development and Production major themes, it flows through the entire
product creation process. As long as companies use different product development facilities and different knitting technicians, they will end up bringing to market different product variations:

Again, development is... I am an artist. And if you give, if you tell two artists to go in a room and paint a picture of a bird, you gonna get two different birds, two different colors, two different everything.

Overall, one message expressed by the Subject in the interview, is that Marketing often feeds demand into the seamless Product Development process, but product innovation is what gives Marketing the tools to create more product demand, creating a self-sustaining business cycle. This statement represents the idea behind the relationships showed in the Product Development map, where Innovation is a hidden over-arching theme, often hidden within the Product development process.

**Product Development Framework**

A separate framework was developed to graphically illustrate the complexity of the Product Development process for the seamless knitted sports bras. Similar in the layout with the previous over-arching themes, the Product Development encapsulates overlapping major themes such as *Design, Prototype and Function*. However, *Innovation* is the supporting over-arching theme that, while related to all other over-arching themes such as *Company Type, Planning, Marketing* and *Production*, it is directly impacting *Product Development*. Within Innovation, three major themes were categorized such as: *Opportunities, Resources* and *Creativity* (Figure 4.5).

**Design.** As a major theme, *Design* groups many sub-themes, such as *design elements, techniques, and design process*, all of them having micro-themes. Within the
micro-themes, there is a wide variety of elements that need to be taken in consideration when designing seamless products in general and particularly, a seamless sports bra.

Figure 4.5. Product Development Framework, showing major themes, sub-themes and relationships to Innovation for Santoni seamless knitted Sports Bras.

**Design elements.** As applied to seamless products, this category groups information about: aesthetics, surface design, garment type, shape manipulation, texture design, material selection, colors and design details.

**Aesthetics.** Two more sub-categories were identified at this level, such as symbolism and branding/logo design. During the knitting process, the Subject designs patterns, and often he is asked to coordinate these patterns with the overall garment concept and aesthetics considerations. In the case of a seamless uni-suit he developed for United States Olympic Rowing teams (men and women), he chose symbolism to aid with
pattern decision: “this pattern for ventilation… that’s boat oars.” As part of the product
differentiation as a marketing strategy, logo placement and branding are crucial, not only
for seamless garments in general, but particularly for performance activewear. Seamless
knitting machines allow for logo placement anywhere on the garment, but the logo design
itself needs to be translated into knitted stitches; the Subject has to make that
transformation as accurately as possible: “I tell them look, let’s do this stitch, I think this
stitch will look good, and we may do several iterations and make changes.”

Surface design. Moreover, the logo design can also be a surface design element,
in which case sublimation and heat seals are used. Thermal considerations of the fibers
used in the knitting are key factors for the decision of which type of thermal transfer to
use:

You have screen print and sublimation. Screen print is when you put the ink out
there… and you know, it’s gonna peel and start coming off? Sublimation will last
as long as the fabric, because it’s so hot…., when you put in on… the ink actually
melts into the fabric, becomes part of the fabric, that’s why it stretches as much as
the fabric.

Pattern design is another way of creating surface interest. The Santoni seamless
machine, via only three stitch selections (plain knit, float stitch (creating visual rib stitch)
and tuck stitch) offers a wide range of possibilities for pattern design, reflected into pixel
by pixel design on the CAD system: “And I have needle by needle selection… so I have
2,688,000 options in a bra.” The Subject displayed a collection of patterns he created as
reference, some of them shown in Figure 4.6.

Garment type. Selections of surface designs depend on garment type, and
seamless garment construction allows for some variations. Layering is the most common
method of providing functionality and thermal comfort to seamless bras in particular.
Performance garments can have additional features, such as crisscross straps, thumb holes, even seamless sleeves. Cut and sew construction that currently is used for many active wear garments is being used as a garment modeling, as a development platform for some seamless garments. However, cut and sew construction can provide features that are not possible via seamless knitting, such as looser fitted garments.

Figure 4.6. Pattern designs on Santoni seamless knitting machine: (A) combinations of two-colors jacquard, (B) different ways of separating patterns, and (C) garment shape engineering on the seamless knitted tube.

An emerging garment type is that of hybrid garments, that have the inner layer made in seamless knitting and the outer layers in cut and sew construction: “The inside
had to be seamless. You had no choice. You cannot do engineering like this in cut and sew. It’s just not feasible.”

*Shape manipulation.* Seamless knitting also allows for the garment *shape manipulation*, creating various silhouettes via rouching, cinching, selective stretch (Figure 4.7):

> I can do some things under the cups, I can put in very heavy rouching under the cups for lift, I can put this cinch in for separation, I can make the straps, I can take half way up the strap put an engineered stitch in the strap to make it less stretch....or more stretch...whichever one you want.

![Figure 4.7. Shaped elbow area (A), and breast encapsulation (B).](image)

*Texture design.* This design element is not driven only by the yarn selection. There are knitting techniques in Santoni seamless, such as reverse platting, which can give the seamless garments a fashion look (Figure 4.8).

*Material selection.* This is an important decision in seamless product design, and should be made very early in the design process. There are mainly two material sub-categories that are closely related to each other: *fibers* and *yarns*. 
Figure 4.8. Seamless textural designs via reverse platting (A), and “bucci “technique (B).

For fibers, spandex used in the form of nylon covered spandex yarns is a required material to be used, due to compression properties expected from seamless garments. Currently, the spandex fiber market has a limited commercial offering, and that determines the compression range existing in seamless developments: “Basically you have a 10 denier, a 20 denier and a 40 denier.” The denier is actually determined by the covered Nylon yarn:

That’s commonly what is commercially available to seamless industry, and, with that, you can have a cover, it’s always a covered spandex, and you can cover it with a small Nylon, a 20 denier Nylon, normally, sometimes a 10 denier Nylon, and occasionally a 40 denier.

Besides the spandex, Nylons are predominant in seamless product design:” probably 80% is nylon/spandex.” The reason for the Nylon popularity is its durability and feasibility of garment dyeing in bright colors, making it fashionable, therefore stimulating customer demand:

That’s just what the market is demanding right now. There is no reason, I mean Nylon spandex is dyeable, atmospherically dyeable. In cut and sew you have a lot of polyesters, you don’t see Nylon much in cut and sew, it’s more polyester fabrics. And polyester blended fabrics. The reason for that is, in polyester is raw goods, they’re dyeing rolls of fabric. In seamless, we dye the garment. So that’s
why we use Nylon. We can’t use polyester, is really uncommon to see polyester in seamless, because of the dyeability.

Some of the new emerging performance fibers are still derived from Nylon.” A lot of those are derivatives of Nylon and polyesters, blended and treated with antimicrobial or something, but still a Nylon or a polyester. “Natural fibers are an emerging trend in apparel industry, however, their use in seamless has limitations due to fiber properties during manufacturing process. Specifically:

Cotton is not a fan of seamless at all. You very rarely see cotton used in seamless […] when you run cotton, cotton creates a byproduct called fly. If you’ve ever been in a cotton mill, when they running cotton, you see little pieces of … cotton fly.

By contrast, wool is more seamless friendly, by having the same dyeability properties as Nylon:

It has a tiny bit of fly, but the difference is wool dyes the same as the nylon, it’s a direct dye, so if the contamination gets onto your nylon, you don’t see it. Cotton dyes totally different, cotton is acid dyed, so when you got … in other words, if I make this garment half nylon and half wool, I put it in the same dye bath, it’s gonna dye exactly the same color. Cotton no, cotton is a different dye. So the little bit of contamination you get from wool, it doesn’t show up on the garment.

Therefore, fiber properties are a driver in fiber selections, and natural fibers are often used in blends with Nyloons or other new fibers in order to enhance fabric comfort:

So they did a bunch of testing, we started with nylon and PTFE. Nylon and PTFE didn’t really work well either, it had that sticky wet clingy feeling to the skin, it wasn’t a nice feeling… so then we went to … they wanted to go to cotton and I told them no, so that’s when we decided to go to wool. And the wool … we were amazed, I mean this is a pretty nice shirt. It feels pretty good, it’s pretty comfortable…

The second material selection decision refers to the yarns, and topics such as yarn size, yarn twist, yarn mixing options, and specialty yarns must be considered (Figure 4.9).
Figure 4.9. Cone of generic 20D bare spandex yarn used for seamless knitting. Photo taken by the researcher.

The yarn selection is based on the overall yarn properties, as size and twist are limited by the small 28 gauge of the Santoni knitting equipment. Besides having a size range limit of 40-80 denier for any yarn used in the machine, the yarn also has to be available in both S and Z twist, in order to balance out the knitted tube and not have twerking of the patterns. Double covered yarns offer enhanced hand feel to the fabrics:

A double covered spandex would be a 20 denier spandex covered with 2 ends of 10 Nylon. And double covered yarns are very expensive, obviously, but the end and the feel of the double covered yarn is very, very nice.

However, the overall yarn selection for seamless product design is still too limited:

So you’ve got three different sizes of spandex that can be covered with four different sizes of nylon. Now having said that, you can cover them in two different ways: you can cover them conventionally, which is actually you take the nylon and twist it around the spandex, or you can air entangle it, which is called air covered, which is just tack it together, and so… you’ve got seven different variations that you can now do two different ways.

When considering new fibers and new yarns, the prototype development considers similar knitting machine setting and garment specifications as for the generic
Nylon yarn, which is a 78/68/1 Nylon 6.6 multifilament textured yarn. Repeated iterations and trial and error process eventually leads to decisions of new yarn feasibility for seamless design and production: “I’m gonna use similar yarn, even though their name is Eco-yarn or Repreve, but they’re all Nylons and they’re all 70 deniers.”

**Color.** This is another design element that needs consideration, as color is often the buying decision factor at the consumer level. In seamless, the garments are being entirely dyed instead of being assembled using colored materials. By mixing yarn fiber content, such as nylon and polyester, patterns can be achieved in the dyeing process because each fiber will dye a different color. Trial and error iterations create the color combinations that guide the decision making process. Moreover, the trim around the garment edges need to also be chosen in the same fiber as the body of the garments in order to match the dyed color, unless having a contrast trim is a pre-determined design. Other color combinations can be created by having one yarn that does not dye, such as PTFE, and the other one dyeable, so an heathered effect is obtained during the garment dyeing process.

**Design details.** Other elements considered during the design process are finishing of garment edges and closures. A few instances are mentioned in the interview where customers wanted zippers or buttons added to garments such as yoga pants or sports bras. While these items can enhance the textural and functional aspect of the clothing, the fact that they need to be inserted into a seamless knitted tube brings out several complications that eventually are reflected in poor quality, longer lead-time and eventually increased price without justifying the added value: “Buttonholes. Anything…. like a thumbhole, you know, the thumbholes that are in the running shirts now, where you put your thumb
in there, when you run? To add that hole, costs more than the yarn in the shirt.” The finishing of the garment edges is a considerable decision in seamless products, as the silhouette of the garment needs to be cut out of the seamless tube, and that cutting edge is usually sealed with a temporary 4-threads overedge stitching, which is not consistently straight or aesthetically pleasing. The alternative is laser cutting that has been featured by new products on the market, but the laser cutting edge melts the yarns and does not further stretch with the garment during the wear. Moreover, having laser cutting on a seamless tube presents its own challenges. Therefore, the industry practice is to have a binding sewn around the edges at neckline and armholes. The quality of the binding is a decision choice, as options are available at the trim suppliers. In the case of a single layer garment, self-binding is another option.

**Techniques.** All the design elements presented above are assembled in seamless knitted products via several techniques: knitting, sewing, and wet processing. All these techniques are used in a seamless product, but in different degrees. Knitting is the technique that basically construct the material and the seamless tube, after which the garment is being carved out and sewn, later on dyed and softened.

**Knitting.** Circular machine knitting via Santoni Top-2 machine is the particular technique that was investigated in this research. Santoni seamless machines offer capabilities of creating plain jersey stitches, float stitches and tuck stitches. Besides knitting using only one yarn, Santoni circular machines have the capability of plating, a technique of knitting using two yarns at a time (ground and plated yarn). Combinations of yarns and needle selections lead to various knitting patterns as well as design limitations (Figure 4.10).
Figure 4.10. Diagram of plated knitting, showing both the ground yarn (1) and plated yarn (2). (Lau, 2014, p. 109)

Usually the Nylon yarn is the ground yarn and the spandex yarn is the plated yarn. By combining this technique with missed stitches, textural patterns are achieved aided by the higher stretch recovery of the spandex versus the Nylon yarn. “Reverse platting is when you reverse the yarns, and you are floating the spandex.” The same plating technique is used to simulate rib structures, since Santoni circular machines cannot make a purl stitch required for a typical rib alternation.

Normally the floats that you see on the back on the float is the nylon, and in this case, is the spandex. When you float that spandex across there, the spandex pulls it in, and that’s what creates the illusion of having the large rib on the outside.

The seamless knitted garments are knitted in a single tube, where the shape of the garment is marked by special stitches in such a way that, after the tube is completely out of the machine, a person can see the marks of the garment outline on the knitted tube and can cut it out to be assembled. For a seamless knitted bra, shoulder seams are still needed to attach the front and back panels of the bra. The knitted marks used for outlining the garment are not visible on the finished garment, and designers do not design the seamless tube and all the stitches needed, just the finished garment: “Big Brand X doesn’t have those on the spec sheet. Big Brand X doesn’t know you have to put those on to get it
Sewn.” Santoni circular machines use CAD software to program all the knitting, so much of the design is done via computer:

The majority of all adjustments and tensions and everything are done, the stitch and calibrations are done in the computer, only a few things can actually be done on the machine, and of these few things, is the positive yarn feeders, this is actually a storage feeder that I’m gonna run one of the yarns through... if I wanted to use it on the storage, air flow feeder at the top is another example of a storage feeder, and what these feeders do is, they let the yarn go in at a described tension, whatever tension I put on in here, manually, and... sometimes you want more tension, sometimes you want less tension.

Pattern drafting is the process of translating the product’s silhouette in 2D form. Adobe Creative Suite can be used, but the Subject uses the Santoni CAD software that seems slow and outdated. Templates are often used to speed out the process. While drafting shapes where various stitch selections will be used, color coding is helpful. A product can have as many different pattern as the designer choses. Furthermore, the next step in the knitting design is to assign each color on the pattern draft a pixel-by-pixel design of the pattern intended to fill that part of the garment, and this step is called pattern configuration (Figure 4.1).

![Figure 4.1. Santoni CAD pattern drafting software screen.](image)

The colors of the pixels are limited, to reflect the stitch selections mentioned (plain, miss and tuck). Yellow means the needle catches both yarns, as in plain jersey, black means the needle misses both yarns, therefore creating a tuck stitch, and red means
the needle catches the spandex and misses the nylon, creating a float stitch. After pattern configuration, a chain program is created and launched, which communicates to the Santoni knitting machine, the needles, cams, and feeders are to be activated to execute the configuration pattern. All the knitting programming needs special skills that have a long learning curve as previously mentioned in the Planning section. The Subject often mentions the software challenges regarding programming new styles, as starting a program from “scratch” is tedious and needs repeated iterations to completion. Therefore, a pattern database is maintained and used as reference for every new design. The chain programs are never created from scratch; they are just slightly modified as needed.

Along with pattern drafting, sizing needs to be planned and designed too, as commercial application is always a targeted outcome of all seamless developments. Given the limits of the diameters of the circular knitting machines, knitting technicians use stitch size to accommodate more garment sizes on the same diameter machine:

And into sizes, is a mathematical calculation from my standpoint… in other words, if I do a medium… you see, if I do a medium bra, these are X and Y, this is X and this is Y.. you have the stitch value… And for the medium, for example, on stitch value I usually go up 8 points, and per sizes, I usually do 64 courses. Now that depends on the yarn, but this is just generally. Which means if I have a medium, I would make it 64 courses longer, and I would make the stitch 8% bigger and boom- you have a large. So this is just a series… that way, you know the sizes are in sequence. You know the Large is 22% bigger than the Medium. You know the Small is 22% exactly smaller than the Medium.

*Sewing.* This is a necessary operation in seamless product development, even though it appears to be minimal compared with cut and sew products. While sewing is part of engineering a garment in regular cut and sew construction, in seamless, all the garment engineering is done via knitting, and sewing is used just to assemble some parts of the garment. Since knitting a sports bra takes a long time during planning and
programming, and only 4-6 minutes for knitting the tube, the sewing labor is the biggest
time and price component, so efforts are made to minimize it. Sewing specifications are
needed for production, but not so much for product development, as the shoulder seam of
the sport bras need to be adjusted for length after wear trials and several fit sessions.
Temporary sewing is sometimes used at the product development stage. There is not
much creative input in the sewing stage for this specific product. Many seamless products
are targeting the reduction of seams in cut and sew garment.

**Wet processing.** Often referred as dyeing of seamless knitted products, this
technique actually involves more processes than just garment dyeing. After the knitted
tubes come out of the knitting machine, the “goods are oriented,” meaning the tubes are
folded in specific ways depending on the type of garment. This prevents them from
creating unwanted marks on the knitted fabric. After the goods are oriented, they are
placed in bins and allowed to relax for 24 hours, basically allowing the yarns to recover
and reach equilibrium after the very fast knitting process. During the design and product
development process, wet processing can happen at different times, depending on the
novelty of the design. If the yarns used and the garment specs are entirely new, a
preliminary shrinkage test will be done right after the tubes are allowed to relax, to check
the shrinkage and sizing. The Subject referred to this process as “boiling the tubes,”
meaning they are subjected to a hot water washing cycle and tumble drying. If the sizing
resulted from this process is as desired, specs are created and recorded for the next
product development stages. However, if the style and yarns are commonly used, the
preliminary wet process is skipped, garment is sewn and sent to dyeing in the colors
specified by the tech pack. Different colors require different time planning for the dyeing process:

If you gonna dye it, the dye process… if it’s white, it’s gonna take about one hour and a half, if it’s a light color it’s gonna take about two hours, and if it’s a dark color, a black, it’s gonna take about three hours for the dyeing process.

Textile dyeing is regarded by the research literature as one of the most environmentally damaging processes, and questions were asked about the necessity of garment dyeing: “But the reason they dyed this, is because number one: to give it the color, number two: to add a softener, and number three: to shrink it. “Also, “it might be white but still, even to make white you have to go through wet processing, because the way you get white is … Nylon is already white but what makes it white is they put a blue optical in it to reflect the light, and that’s what the wet processing does.” Therefore, adding a softener is a regular industry practice for seamless knitted products. During the wet processing stage, other fabric treatments can be added too, such as antimicrobial finishes. The design of the garment can also prove to create complications during the wet processing: if the garment is made of different fibers, such as nylon and cotton, these fibers have different dyeing properties, and therefore will not lead to the perceived uniform coloring look. Many factors affect the resulted color of the products after going through wet processing, such as fibers, sewing thread, trim fiber content, size batch of the dyeing lot, water temperature, color recipe itself, etc.

**Design Process.** This category is the third sub-theme of Design, and groups information about the way concept and idea is brought to the prototyping stage. Topics discussed related to design process were: inspiration, design references, experimentation, and decision making.
Inspiration. As a common theme related to regular apparel design process, inspiration as a prompter for a new design proved to be not as prevalent in seamless product design, as most new ideas come from already existing products. The functional part of seamless garments is usually the design focus, and aesthetics are more concerned with color and brand aesthetics. At the product development level, inspiration becomes untraceable: “Big Brand X... they don’t look for inspiration,” and “Yes, this is one aspect of it, of knocking off of something that’s already out there.”

Design references. Ideas for new developments are mostly taken from already existing garments or previous developments, and companies do keep good records and collections:

As you know, the designers, they buy a lot of swatches, they buy a lot of garments, when you go to their offices, I mean, they got garments hanging in there, because they will find a garment that they like one particular thing in that garment and they will buy it to show and make reference to when they make their development.

Moreover, the Subject assembled a database of knitted patterns that he cataloged and offers to knit in the yarns specified by his customers, to aid with the design decision-making process.

Experimentation. Trying new techniques and materials in the design process is highly desirable but often unachievable at the level of Subject’s satisfaction, and frustration has been expressed during the interview. The technology itself has opportunities for creating unique garments, but time resources are scarce:

I put the first machines in the United States, I’ve been doing it 20 years, and there are cams on the machine that I would just like an open book, where I would just sit and play with the machine. But I never had the opportunity to do that because there are things to do. Because there are cams on the machine that I’ve never moved, I don’t even know what… that cam always has been in. What if I take it out? What happens?... I don’t know. You know? What if I take the needle
lowering cam out and put the tuck cam in and … do the pattern in green. What’s gonna happen? I don’t know. What if I do that and do the pattern in red, what’s gonna happen? I don’t know. There are things on the machine that you can do that I’ve never messed with, that I know it’s gonna produce something different, unique.

Part of experimentation, trial and error is common at the prototyping stage; garment mock-ups are also common as ideation at customer level. Some experimentation occurs for the surface design:” I was experimenting, I put a heat press down here.”

Decision-making. This is the activity that allows the design process to progress to the prototyping stage. Depending on the structural organization of the customer companies, the Subject has different levels of freedom in decision-making and design input, ranging from 10% to 90%. Communication is important and decisions often involve changes in materials, design elements or timing. Having a flexible and adaptive personality is key in maintaining an efficient working relationship: “Here’s what I’m trying to say: sometimes I hit the spec perfect, and they made me change it.”

Function. Most garments developed using seamless knitting technology are functional garments that require User Profiling. Topics identified as related to the user profile are user perceptions, and user specific needs.

User perceptions. In the functional design literature, the topic of user perceptions is discussed extensively. During the interview, the perceptions of the end user of the seamless knitted garments were mentioned mostly when dealing with entrepreneurial start-ups. In such cases, the user was the same as the business customer, therefore instant feedback on product fit and design was provided. Issues such as fit, fabric feel, comfort, and wearability were discussed. Trial and error iterations allowed for the Subject to understand the perceptions of the user and adjust accordingly:
They would fit it, and then it would come back to me, and they can say, you know, they knew a bit about textiles obviously, but they didn’t know, they’ll come back to me and say “Can you make this stitch a little tighter, a little looser? Can we move this out another inch?"

**User specific needs.** This category incorporates communication regarding designing seamless apparel for customers performing specific activities, or having particular physical profiles. Among the specific functions discussed were: ventilation, kinetics, impact absorption, wicking, posture control, cooling, conductivity, support, water repellent, lifting and antimicrobial. Some of these functions required engineering at the stitch level, others involved applying special treatments in the wet processing stage. Most of these functions; however, required additional tests and iterations, both at the material level as well as at the user level. Designing garments for specific functions often means problem solving:

There is a lot of engineered products that I have to find a solution for, and there are lots of engineered products that people come in here that they already have a solution for but they don’t know how to, you know…

**Problem solving.** This sub-theme is a topic that was heavily mentioned and transcends *Functionality* theme into the *Prototyping* theme. Most of the issues in problem solving category highlighted the diversity of pre-conceived solutions customers have about specific functional problems. While translating these solutions in a real garment, additional problems need solutions at the material selections level, wet processing as well as fit and sizing levels. Communication during the problem solving process brings up issues such as information description (graphics, interpretation, color-coding, comparisons and analogies), as well as information management (information transfer, documentation, decision making).
Prototype. This is another major theme addressed in Product Development, and prototyping process starts with the Tech Pack, including information about: yarn development, garment development, sizing, fit, and costing of a new design. Many of the topics discussed under problem solving and communication categories in Functionality, are also reflected in The Tech Pack, a category that sits at the intersection of all Product Development sub-themes, being not only the initiator of the Product Development process, but also the concluder before the design moves into the Production stages: “The process of design starts from… I like to call it a tech pack, I always ask the customers for a tech pack.” While an initial tech pack is required to start prototyping, as a communication tool, the tech pack is actually an evolving instrument that serves as an information recorder during the entire product development process, not only the prototyping stages.

Yarn development. This activity is one of the first issues addressed in prototyping, unless a generic yarn is being used. The decision to go one way or another is made based on the design details communicated in the tech pack: “99% of the time I chose the yarns for the product based on the tech pack that I receive, based on the information that I’ve got from the customer.”

Garment development. Regarding this topic, the choice of the seamless technology often came into question: why do customers want to develop the garments via seamless knitting? Given the wide range of customer knowledge regarding the Santoni technology potential, it is useful to identify from the early stages if this knitting technique is the most appropriate for solving the functional problems at hand: “There’re some
things that should…there are some things that are perfectly match for seamless. And there are some things that are absolutely not a match for seamless.”

**Sizing.** This aspect is a major issue in apparel industry in general, so the limited range of circular knitting machines exacerbates the problem and needs special consideration. Algorithms were developed at the programming level to deal with a proportionate distribution of the tubular knitted fabric across five different sizes: extra small, small, medium, large and extra-large. However, not all designs preserve functionality when proportionally enlarged for sizing. For example, compression sports bras are designed to be tight fitting. However, some customers will wear larger sizes because they have a lower comfort tolerance to tight garments, trading off breast support for comfort. Vanity sizing is also present in seamless designs, and brands at both ends of the pricing range will alter their sizing specs to capture more customers:” And the reason for that is the customer. For example, Victoria Secret’s Large and Walmart’s Large is two different larges.” Sizing ambiguity is common for projects involving special events: “I made a 400 unisuit for Olympics, do you think anybody gave me any specs? I mean who’s gonna give me the specs?” The only constant when it comes to sizing is the size of the first prototype, and that is a Medium size. The reason for that is there are less body shape variations within the cluster of size Medium than in any other size cluster: “99% of the time, when you take Medium size people, Medium size people bodies tend to be relatively more the same size than X-large bodies, or Small bodies. “Therefore, all new designs are prototyped on size Medium, and after all details are established, then a size run is completed and sent out to the customer to be fit. After fitting all sizes, adjustments
to specs can be made as to not have a consistent proportion between the sizes, but a more realistic size distribution based on wear trials.

**Fit.** This topic is directly related to *sizing*, and besides addressing issues with the correct fit per size, it also incorporates ideas of how seamless garments are designed to fit from a silhouette aspect. Having a higher spandex content compared with other apparel items, seamless apparel is made to compress and shape the body, therefore garments are engineered to the exact shape of the user:

I had to do a lot of engineering for different places on the body, and the dance costume fits really tight in certain areas, and you have to have… dancers are really skinny and really small, and you have to really… around the waist…you have to take all of that excess fabric out so it goes, you know, flat to the body.

**Costing.** As a term related to pricing, costing is addressed right from the beginning of prototyping, since successful product development is eventually related to the market success of a commercial product. The price point of a new development is expected to be communicated in the initial tech pack, since the yarn selection can greatly impact the final pricing. Tradeoffs are expected during the prototyping and decision making process, garment construction and fit being manipulated via materials selection to reflect the desired price point:

most people have always have a seam down the sleeve, so the average person wouldn’t even notice it if you took it away… but it’s gonna cost a lot of money and cause a lot of heartache to take it away…and for the benefit of taking that away I don’t think it’s worth it.

Concluding the *Product Development* major theme, the tech pack is a reflection of brand organization, design communication, prototyping details and functional solutions for a new product. Every new product gets a unique degree of infusion of
Innovation at some point during the Product Development process, otherwise it is not new.

Innovation

This category was identified as the hidden over-arching theme. Major themes in Innovation are Creativity, Opportunities, and Resources. Each of these themes overlapped during the coding process, highlighting the necessity of resources and opportunities for creativity, as well as the necessity of creativity to generate resources and opportunities.

Creativity. Includes topics such as: risk taking, out of the box thinking, by chance, and wondering. During the interview, the Subject often referred to various instances where creativity was displayed as a result of the above mentioned key words. While the end result is similar, that of producing an innovative, new idea about a process or product, the ways creativity can be achieved is abundant, as indicated in the following statements by the Subject: “And it may not do nothing, but you don’t know until you do it,” and “It’s up to the developer to look to the program to see what it needs, sometimes I need good luck.” Standardization of processes often leads to products that look similar and create a conventional look, so trying to break the circle on conventionality requires creativity: “This is a pretty simple thing. But I can show you products that really took some thinking outside the box, that is conventionally not thought about in seamless.”

Moreover, it took time for the creative process to evolve:

“A great machine to make panties. Then, it just seemed that everybody was making panties, that’s all they made: ladies underwear. Nobody, at that point, nobody ever thought of making a zipper hoodie for a man, on seamless. It wouldn’t even come to their mind.”
Opportunities. This is a group of topics that is similar to that of Demand in Marketing, and it refers to events that stimulate product development: line diversification, continuity of innovation, evolving markets, and lack of specific products. Specifically, big apparel brands are chasing revenue increases via expanding their product line, and that creates demand for new product development. If the manufacturing supply chain is kept the same to control costs, then innovation happens at the technology level, with products being made in a different way:

But if you watched the evolution [of Santoni], we started out with just panties, and then we figured out we can make a camisole to go with these panties. And then well, we can make a camisole, we can put a sleeve on it to make a shirt. Well, if we can make a shirt, if we can put a hood on it we can make a hoodie. And then it just kept on going, going, going till where we are now.

In the same time, fashion is evolving in its cyclical manner, and, while technology pushes the boundaries of garment construction, the fashion trends bring back styles that are new again via new yarns and new finishes. Seamless products, once being a high-end luxury, are now marketed in low-end distribution stores such as Five Below, as well as reaching children wear market. Moreover, the users are evolving, markets are expanding to reach global customers, and users’ needs change, creating gaps in the market for products covering these needs. All these factors are opportunities for innovation and are driven from both technology as well as consumer levels.

I think there are a lot of things that can be done on a Santoni and I think there are a lot of things you gonna see five years from now being done on a Santoni, that you wouldn’t even think of doing today.

Resources. As an Innovation sub-theme, this category includes components such as global markets, existing products and unfulfilled technology potential. Overlapping with Creativity and Opportunities, Resources, or the lack of resources, are often seen as
an inhibitor of innovation. However, the global markets are opening access for the manufacturers to new seamless knitting equipment, as well as bringing in new existing products that can serve as design references and inspiration. Creativity has been more often stimulated by the lack of resources than their abundance; therefore, pure experimentation with the knitting equipment can result in innovative products before the market creates a demand for them: “The beautiful thing about the Santoni machine is the technology exceeds the creativity of the people using the technology.”

The last over-arching theme and the last stage after Product Development is Production, with components shown in Figure 4.12. These components have several sub-components that were identified during the interview process.

![Production Over-Arching Theme and Its Major Themes and Sub-Themes](image)

**Figure 4.12.** Production over-arching theme and its major themes and sub-themes.

**Production**

Production is a big consideration of the seamless product development. Sub-themes such as operations, quality and sustainability were discussed. The prototype development is made with production considerations at all times, in order to set up quality standards for operations. Sustainability is a relatively recent theme, as more and more big brands are questioning the entire production process.
Operations. Grouped under this sub-theme are topics such as: feasibility for mass production, efficiencies, and sourcing and logistics. Many of the decisions in product development are related to feasibility for production or for mass manufacturing.

Feasibility for mass production. From the early stages of tech pack development, the designer has to map out the size range and specifications. In seamless knitted products, the specs will determine the type of production manufacturing equipment needed, and a knitting technician should be able to identify the manufacturing supply chain needed: “I have people come here all the time that say: Oh, I wanna do this and I wanna do that: can you do that? I say yes, I can do that, but it won’t make sense for production.” Sometimes the feasibility is related to knitting equipment, sometimes is just cost related: “But in the real world, once it leaves here and goes out for production, nobody’s gonna want to do this for you, and if they do, it’s not gonna meet your price point because it’s gonna be so expensive.”

Efficiencies. Production efficiencies capture design decisions impacting the time and logistics of production. Some patterns require more time to be knitted, such as a lace-like “bucci” pattern, which is the most time consuming to execute. Some yarns break often due to low tensile strength, such as wool and some cottons. Also, wet processing has its own efficiency requirements due to washing machine capacity and dye lot minimums. All these considerations should be included in the design decision-making process.

Sourcing and logistics. Lastly, sourcing and logistics groups information about fiber and yarn supply chain, equipment available at manufacturing facilities, audit and supplier credit check. Manufacturing facilities have their own business operations and
they may accept production orders or not based on the particularities of the design: “I’m not gonna make this in cotton for you because if I developed this in cotton, and you go out to get it manufactured, nobody’s gonna want to manufacture that for you.”

**Quality.** An abundant group of topics focused on specific quality issues were discussed, including: *inspection methods, improving quality, and testing.*

*Inspection methods.* Various methods of checking for quality are spread out throughout the product development process and are indicative of the quality issues production might have. Each step in prototyping needs rigorous documentation in the tech pack to serve as reference for quality control methods in manufacturing. Orienting the goods, stretch tests, wash color fastness and measurement checks against the specs are the most common and minimal quality control methods. The final goods inspection is not always sufficient, and often companies will have their own trained quality inspectors on site at the factories to monitor seamless goods production.

*Improving quality.* Insuring in process quality control leads to improving quality. Also, overall better specification of the product development and prototyping processes translates into better quality from production: “You wouldn’t check everyone but you will periodically check for defects…” Sometimes the stich-by-stich selection feature of Santoni equipment is used to mark places on garment for heat seal placements, to ensure consistency.

*Testing.* Testing is depended on the functional features of the seamless garment. If the garments are not advertised as “certified,” then no standardized testing has to be done. Often, wash tests for abrasion, pilling and color fastness are applied at the product development stage to record the results, set up as production standards, and then followed
up in production with selective testing. For garments using special fibers, such as conductive yarns, wash test are done to determine the life expectancy of a functional panel: “We need to know how many times you can wash it before it just falls apart…and that was 50.”

**Sustainability.** An overall awareness with issues of honesty, ethics and good business practices were reflected in micro-themes such as: *protecting the environment, reducing waste,* and *recycling.* Improving the efficiencies at the wet processing stage has a direct impact on the environment. Most consumers prefer to wash their activewear in warm water, so dyeing recipes are created to withstand color wash fastness tests in warm washes. This is not a sustainable trend, and efforts should be made to design and promote environmentally friendly garments that can be washed in cold water. Seamless knitting technology offers the advantage of dyeing garments versus using pre-dyed fabrics, so switching from cut and sew to seamless is reducing fabric waste: “If they come to me and want 1,000 shirts, it’s no problem for me to make them, because I’m piece goods dye, I can dye any amount of any color that you want… and I have no leftovers.” Another advantage of seamless products is that soiled garments from the knitting process can be used for the dark color dyeing, therefore recycling damaged products. Recycled yarns are also emerging, such as recycled nylon. Also, since yarn usage per seamless knitted garment is very low, left over yarn is never trashed: “You don’t throw away any yarn.”

The mapping of the interview highlighted not only major themes and sub-themes, but also the relationships between all these categories. As discussed previously, the main message from the Santoni seamless knitting case study is that, the design and product development process of a seamless sports bra needs to take in consideration all of the
categories discussed, as each of them contains information affecting the quality of the final product. Moreover, the knitting technology itself, the Santoni seamless knitting equipment, imposes limitations and shapes the product development process of a sports bra. A Santoni Top-2 circular knitting machine used for manufacturing current commercial seamless sport bras, and also used for the development of the responsive seamless sports bra prototype, is shown in Figure 4.13.

In order to develop the responsive seamless sports bra prototype, investigations of the capabilities of the knitting technology were made in the Stage 2 of this research, through creating various knitted fabrics and testing them for responsiveness when actuated by moisture.


**Knit Fabrics Testing Results for Stage 2**

The second stage of this research aimed at following up the investigation, in a systematic manner, at the material structure level of a sports bra. The quantitative data collected in the second stage of this research aimed at answering the following question:
Research Question 2: What component materials and structures of a seamless sports bra system offer responsive behavior when actuated by body moisture? How are these materials and structures informed by the tenants of biomimicry?

Considering the biomimetic framework, the design and development of a seamless sports bra is similar to a system design, as the wearer’s body moisture affects the properties of the materials in the garment. The results from the Stage 1 revealed that the seamless knitting technology brings limitations to the way a seamless sports bra is constructed. The double layer construction however, allows for a separation of functions between the material knitted inside and that of the outer layer. Biomimetic systems use the wearer’s generated sweat/moisture to actuate the system. The current sports bras on the market do not have a different material fiber content or construction for the two separate layers, treating both of them as venues for moisture wicking. The concept of the responsive sports bra was to have the inner layer as a moisture absorbing mechanism and the outer layer as a moisture wicking.

The focus of the textile testing data collected on Stage 2 was on identifying seamless knitted patterns and stitch combinations that will speed up the moisture absorption process while also enhancing the responsive properties of the materials. The wool fibers were used for their high moisture absorption properties and changes were expected to be seen at the knitted material level. As explained in Chapter 3 (Methods), the knit fabrics that were tested used a Nylon-covered spandex yarn in combination with the main yarns of 100% wool or 90% wool 10% Nylon. In this discussion of results, the spandex was omitted from the yarn content description, to shorten the communication
flow. The first yarn will be referred to as “wool yarn,” and the second will be referred as “wool/ Nylon yarn.”

In the dry condition, the thickest fabric was pattern #15 in wool/Nylon yarn, with 5.27 mm in measured thickness, and the thinnest fabric swatch was pattern #14 in wool/nylon yarn, with 1.38mm in thickness. Overall, the thickness of the swatches had a mean of 2.23mm with a standard deviation of 0.78mm.

The next data analysis focused on identifying differences between fabric thickness in the dry condition of the same pattern but knitted in the two different yarns: wool yarn versus wool/nylon yarn. Sixty percent of the fabric swatches were thicker in wool yarn than the wool/nylon yarn combination, but the mean differences in change rates were extremely small, just 0.007%, with a standard deviation of 0.066. Pattern #15 (tuck 16 needle) was the thickest in wool/nylon yarn versus wool yarn (0.09% difference rate) while patterns #16 and #17 were the thickest in wool yarn versus the wool/Nylon yarn (0.12% difference rate) (Figure 4.14).

![Figure 4.14](image)

**Figure 4.14.** Pattern #15 (tuck 16 needle) made in wool yarn: technical front (A), and technical back (B).

The next data analysis aimed to identify how the knitted patterns reacted to moisture, one minutes after sprayed with saline solution, a condition that is referred in
this chapter as “wet” condition. Fabric thickness change rates were calculated between dry and wet conditions for all 40 swatches. The mean of the changes was -6.3%, with a standard deviation of 2.7%. The fabrics that showed the most change were made in the wool yarn: pattern #14 (float 4x4) had a thickness reduction of 12.4% when wet relative to dry condition. Pattern #15 (tuck 16 needle), also showed a significant thickness reduction of 11%. The fabric that showed the least change, practically unchanged, was also made in the wool fibers, pattern #12 (tuck 9 needle), with a thickness reduction when wet of 0.4% (Figure 4.15).

![Figure 4.15](image)

Figure 4.15. Pattern #12 (tuck 9 needle) showed practically no change in thickness between dry and wet conditions: technical front (A), and technical back (B).

These results were surprising, as the fabric thickness was expected to increase not reduce when wet. Overall, the thickest fabric when wet was still pattern #15 in wool/nylon yarn (5.02 mm thickness) and the thinnest was still pattern #14 in wool/nylon yarn (1.31 mm thickness). The average thickness in wet condition was 2.09 mm with a standard deviation of 0.73 mm. Literature revealed that the diameter of the wool fibers expands up to 30% when wet, and this fiber thickening was expected to translate into fabric thickness. Scott (2009) argued that knitted structures further enhance the responsiveness of fibers as seen through their physical dimensions when actuated by
moisture, but the method used in this research of measuring the fabric thickness, via a pressured dial gauge was not able to capture that positive change.

Moreover, results of fabric thickness changes after 30 minutes of air-drying were analyzed and a mean change of 2.07% was found, with a standard deviation of 0.72. Pattern #1 in wool yarn was the thinnest this time (1.31mm), while pattern #15 in wool/nylon remained the thickest (4.9mm). Analyzing the fabric thickness changes after 60 minutes of air-drying revealed a minimal mean change of 0.003% relative to the 30 minutes thicknesses, with a standard deviation of 0.03%. The thickest fabric after 60 minutes of air-drying was still pattern #15 in wool yarn though (5.03mm) and the thinnest was pattern #1 in wool yarn also (1.33mm).

Since the goal of this analysis was to identify responsiveness to moisture via comparative analysis, fabrics with uncommon behaviors were singled out. In the analysis of thickness change in wet condition relative to dry condition, all fabrics became thinner when wet. However, in the 30 minutes-air drying condition, pattern #10 in wool/Nylon yarn and pattern #14 in wool yarn displayed a significant positive change as relative to the wet condition, meaning that they became thicker after 30 minutes-air drying compared with their thickness when wet (Table 4.1). Their change rates were almost 8%. Also, pattern #10 displayed a significant difference between wool yarn fabric and wool/Nylon fabric at the 30 minutes-air drying stage versus the wet stage, an almost entirely opposite and extreme reaction compared to all the other swatches. The wool yarn swatch became thinner by 7.4% while the wool/Nylon yarn swatch became thicker by 7.7% relative to the wet thickness.
Table 4.1. Knit Fabric thickness data in Dry, Wet, after 30 minutes- air drying, and after 60 minutes- air drying conditions.

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In order to understand if there is a statistical significance between the changes of the fabric thickness in the three conditions, several repeated measures statistical tests were run using JMP software, the first one comparing the differences between after 30
minutes- air drying and Wet conditions. The results show that, on average, thickness after 30 minutes of air-drying measures 0.02mm lower than the thickness in the Wet condition. The small $p$-value of 0.0069 ($p < 0.05$ indicates strong evidence against null hypothesis) shows that this difference is statistically significant, and also not due to chance. The null hypothesis is that there is no difference between the average thickness between the two conditions tested.

Similarly, differences between after 60 minutes- air-drying and Wet conditions were checked for statistical significance, too (Figure 4.16).

![Figure 4.16. Matched pairs graph of the thickness differences for after 60 minutes- air drying and Wet conditions. Knit Fabric Swatch Number 30 in this graph is knit pattern #15, the thickest pattern, and it is an outlier for this test.](image)

This time, no significant changes were found, as on average, thickness after 60 minutes of air-drying measured 0.006 mm lower than the thickness in the Wet condition. The large $p$-value of 0.76 indicates that this difference is statistically not significant.

Since a quick drying fabric was aimed to be identified to be used for the sports bra areas that required ventilation, the thickness after 60 minutes of air-drying were compared to the dry condition thickness. The mean thickness after 60 minutes- air drying condition was 2.09mm with a standard deviation of 0.79mm. The mean thickness change
between 60 minutes- air drying measurement and that of dry thickness, of all fabrics, was 6.0%, with a standard deviation of 3.2%. The fabrics that had the largest change rate between 60 minutes- air drying and dry conditions were #3 in wool (11.6% thinner than dry) and only one fabric had a positive change, pattern #15 in wool, showing 3.7% increase in thickness compared with the dry condition.

Running the matched-pairs test to check for statistical significance of the differences in fabric thickness between after 60 minutes- air drying and Dry conditions, found that, on average, the after 60 minutes- air drying thickness measures 0.15mm lower than the thickness in the Dry condition. The small *p*-value of 0.0001 indicates that this difference is statistically significant, and also not due to chance.

Moreover, during the wetting process of the fabric swatches, mechanical change was observed, as Scott (2009) also documented via videography: the edges of the fabric swatches were curling at different speed rates. Attempts were made to find a method to quantify the changes for all swatches, but they were unsuccessful. The textural structure of the swatches made some patterns to curl upward while others to curl downward, and the pattern itself was observed to affect the degree of curling much more than the amount of moisture or the time allowed for responsiveness action. A clear difference between the wool yarn swatches versus the wool/Nylon swatches was not able to be quantified and evaluated. A few images were captured form a video recording the curling changes for pattern #10 in wool yarn, right after moisture actuation with saline solution, taken at 5 seconds time laps (Figure 4.17).
Figure 4.17. Screen shots from a video recording showing moisture responsiveness of pattern #10 in wool yarn: (A) 1 second after applied moisture, (B) 5 seconds after applied moisture, (C) 10 seconds after applied moisture, and (D) 15 seconds after applied moisture.

Pattern #1, however, the heaviest texture out of all patterns, had a curling towards the technical front too, but its technical front was not the side of the pattern that was feasible to have inside the layer of a sports bra. Technical front is the side of a knitted fabric that shows the jersey knit stitches. The other side, showing the purl stitches, is called the technical back. Pattern #15’s technical back was more appropriate for skin contact, but practically impossible to achieve due to the seamless knitting orientation of the tube when folded for the double layer construction (Figure 4.18).

Figure 4.18. Pattern #15 actuated by moisture, showing responsiveness to moisture actuation via curling towards the technical front (A), and view from the technical back of the swatch (B).

Based on visual observations of fabric behavior right after wetting, the conclusion drawn was that the lighter the fabric the more curling action happens. Heavier weight fabrics did not curl as much and as fast as the lighter weight fabrics. Therefore, analysis
of the fabric/knit densities were considered as a possible indicator of responsiveness (Table 4.1 shows all physical measurements recorded for all tested knit fabrics).

After estimates of wales/cm x courses/cm were computed, the mean value for the fabric/knit density of all 40 fabrics was rounded up to 1048 with a standard deviation of 345. There was almost no difference between wales/cm or courses/cm between the fabrics knitted with the two yarns, wool or wool/nylon. Pattern #15 had the highest courses/cm, approximately 92 courses/cm, while pattern #18 had the lowest courses/cm, approximately 32. For wales/cm, pattern #5 had the highest, 31 wales/cm, while pattern #7 had the lowest, approximately 18. The knit densities analysis revealed pattern #18 in wool/Nylon as the lowest density pattern, while pattern #15 in wool yarn had the highest density out of all (Figure 4.19).

**Figure 4.19.** Comparative analysis of knit densities for each pattern.

Furthermore, measuring the weights of each fabric, an average weight of 437.7 g/m² was found with a standard deviation of 133.2 g/m², with pattern #15 in wool/Nylon yarn being the heaviest (920 g/m²), and pattern #14 in wool yarn being the lightest (268 g/m²). Weight per thickness averaged 19.75 g/cm³, with a standard deviation of 2.57
g/cm$^3$. Pattern #11 in wool/Nylon had the highest weight/thickness (24.29 g/cm$^3$), while pattern # 18 in wool yarn had the lowest weight/thickness (14.29 g/cm$^3$) (Figure 4.20).

**Figure 4.20.** Pattern #18 (float diamond) shown in wool yarn: (A) technical front, and (B) technical back.

A linear correlation between fabric thickness in the Dry condition and fabric density was found, showing that with each unit increase in fabric density, the fabric thickness in the Dry condition increases by 0.0017mm ($r=0.53$, $n=39$, $p<0.001$) (Figure 4.21).

**Figure 4.21.** Bivariate plot of fabric thickness in Dry condition by fabric Density.

Also, significant correlations were found between fabric thickness in Wet conditions with Density as an independent variable ($r=0.51$, $n=39$, $p<0.001$), and thickness after 30 minutes- air drying and Density. ($r=0.52$, $n=39$, $p<0.001$) (Figure 4.22)
**Figure 4.2** Graphs showing the correlations between thickness in Wet condition (A), and after 30 minutes-air drying condition (B), with Density as an independent variable.

There was also a positive correlation between thickness in Wet condition and Weight of fabric \((r=0.86, n=39, p<0.0001)\). However, Weight/Thickness variable was not found significant to the Wet condition. Similarly, a positive correlation was found between fabric thickness for the after 30 minutes-air drying and Density variable \((r=0.52, n=39, p<0.0001)\), as well as with the fabric Weight variable \((r=0.85, n=39, p<0.0001)\). The Weight/Thickness variable was not found significant as related to thickness after 30 minutes-air-drying.

All the moisture tests conducted in Stage 2 of this research highlighted various similarities and differences between the ways the knitted fabrics change their physical properties in the presence of moisture. A complete data table with all the physical measurements made is presented in Appendix M. Additional testing was considered through MMT (Moisture Management Testing) methodology and Atlas MMT equipment, but textural qualities and linear symmetry of the ribbed swatches was deemed inappropriate for such testing. Although an increase in fabric thickness was believed to be observed, based on literature review, a relaxation of the wool fibers was observed, with fabrics becoming thinner when wet.
However, according to the biomimetic framework, the individual properties of the parts of a system (the sub-systems) can change in the presence of each other, as there are relationships and interactions beyond the mere construction of each inch of the fabrics. The orientation of the patterns within the sports bra system, the quantity and the degree of stretch they are subjected to during the wear change the physical properties that were just studied. Therefore, although individual pattern tests are useful to gain insight of the textile science behind the seamless knitted loops, for the purpose of designing an integrated responsive mechanism, the textile tests and evaluations of responsiveness was followed up via prototyping, wear testing and 3D body scanning in Stage 3.

**3D Body Scanning Results for Stage 3**

This part of the research presents decisions that were made, based on the results from Stage 1 and Stage 2, to answer the following question:

**Research Question 3:** How can a sports bra be designed to function as a responsive system using wearer’s body moisture as system actuator?

After compiling all the data and analysis from Stage 2, a few stitch patterns were highlighted that have above average properties in presence of moisture: pattern #15, a highly textured and heavy tuck combination, had high thickness properties, but low responsiveness to moisture in regards to creating a curling motion of the edges. It was therefore decided to use this pattern for the under breast area of a sports bra, where heavy moisture needs to be absorbed and fabric needs to be kept thick, to provide breast support.

Pattern #18 was highlighted as a lightweight mesh like structure that would dry fast, but the areas intended to have wool content were not designed to dry fast but have
high responsive action. The conclusion was that using the curling of the edges of a lightweight but relatively dense fabric would serve best the purpose of changing overall fabric structure above the breast area at center front. The selection of the stitch patterns to fill out the areas of intended responsiveness (shown in orange and purple colors in Figure 4.23) was as follows: pattern #15 was selected for the underbust area (shown in purple) and pattern #7 was selected for the islands above the breasts (shown in orange). All the other patterns, designed to be knitted using the recycled-nylon yarn, were chosen based on their construction, as to offer ventilation at the back (pattern #18), ventilation around the armholes (pattern #20), stability and support on the straps and on the front breast areas (patterns #16, #9, and #13).

*Figure 4.23.* Stitch pattern selection for the inside layer of the responsive system sports bra.

Based on the system design framework, the fabric of the sports bra knitted tube was planned to be further tested for moisture responsiveness after it is knitted according to the pattern specifications from above.

As mentioned in Chapter 3 (Methods), the chosen patterns for the responsive area of the sports bra were changed due to difficulties in knitting the 100% wool yarn. The decision was to use the 90% wool 10% Nylon yarn only. Furthermore, the heavily
textured tuck pattern that was chosen based on its physical properties to fill out the underbust area (shown in purple in Figure 4.23), pattern #15, could not be knitted in conjunction with the cinching pattern designed for the center front of the bra, intended to provide breasts encapsulation. Even after eliminating the cinching for the inside layer while keeping that design detail for the outer layer of the bra, the inside design could not be executed. Pattern #15 requires the knitting machine to execute 16 courses for each tuck stitch (meaning holding one stitch unworked for 16 courses while the rest of the stitches in the rows are knitted), therefore folding the extra courses and achieving the thick texture. This pattern was not suitable for a float outline inside the knitted tube, as it would have ended up with all the extra courses knitted at the back of the bra too. The decision was made to not have a tuck pattern for the underbust area, since the pattern was not carried around the body. A plain jersey stitch was used instead, as the only stitch pattern that the Santoni knitting equipment was able to consistently repeat for all the prototypes, without breaking the yarn too often. This event confirmed the results from the Stage 1 interview: design of a sports bra does not start and end in the original tech pack, but it evolves and changes in the knitting machine, until production feasibility is achieved. Pictures of the finished pattern selection for various areas of the new sports bra are shown in Figure 4.24. The details of pattern stitches selected and their placement on the bra for prototyping are shown in Figure 4.25.
Figure 4.24. Finished bra prototypes before the wear testing (outside layer front (A), and back (B), inside layer front (C), and back (D).
Figure 4.25. Details of the final patterns and placements on the prototype: back of outside layer (A), side of outside layer (B), center front of outside layer (C), and wool patches inside layer (D).

The 15 bra prototypes were measured before wear testing. Final specs were recorded in the tech pack as shown in Appendix M. Fifteen female subjects were selected to participate in the bra testing. Their ages varied between 18-32 years old. Nine of the subjects self-identified as European American, one as Hispanic American, one as Asian, one as African American and three as Other ethnicities. All subjects confirmed that they commonly wear size M sports bras. No other size conditions (such as cup size) were considered in the selection of the subjects, as is unclear if they affect compression levels.
at the bust area (Zheng et al., 2008). Averages and standard deviations of the demographic data collected via the questionnaire are shown in Table 4.2. The bust height, underbust height, bust girth and under bust girth were calculated from the body scanning data in no bra, relaxed condition.

**Table 4.2.** Subjects body measurements and fitness level [scale 1 (no exercising) to 7 (exercise every day)].

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23.3</td>
<td>5.06</td>
</tr>
<tr>
<td>Weight (lbs.)</td>
<td>136.7</td>
<td>10.7</td>
</tr>
<tr>
<td>Bust height (inches)</td>
<td>47.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Underbust height (inches)</td>
<td>44.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Bust girth (inches)</td>
<td>35.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Underbust girth (inches)</td>
<td>30.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Height (inches)</td>
<td>5' 4&quot;</td>
<td>1.9</td>
</tr>
<tr>
<td>Fitness Level</td>
<td>5.8</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The 3D Boy scanning data along with the survey questionnaire were analyzed for insights into the responsive system designed. Body scanning data revealed that many of the subjects had a bust girth measurement smaller than the specified 37” ( +/- 1”). This specification is a common sizing industry measurement for size M sports bras. All subjects expressed confirmation of proper fit of the bra when they tried it on, but as the running sessions started; comments such as “bra felt too loose” highlighted the fact that the bra size was actually not appropriate for their bust size.

The purpose of 3D body scanning sessions was to check the changes that the bra made to the body measurements while actuated by moisture, therefore tracking changes in bust compression between dry condition, after run condition and after 30 minutes’ rest condition. Proper sizing of the bra ensures the compression in the bust area is fairly uniform between subjects. Since 7 out of 15 subjects had the bust girth smaller than the
the decision was made to separate the data in 2 different groups, size Medium group, who had the required bust girth size, and size Small group, who had the smaller measurements (35” +/- 1”). The data of one subject was taken out of the two sets completely, since her bust girth measurement (calculated as the average between Inhaled and Relaxed in no bra wearing scanning conditions) was falling outside the Small group size too. Her average bust girth between Inhale and Relaxed conditions was 32.39”.

Therefore, only the data from 14 subjects was analyzed and their separation in the two size groups, group size Small and group size Medium is shown in Table 4.3.

**Table 4.3.** Subjects bust girth as measured via 3D body scanning, calculated as average between Inhale and Relaxed condition, at the Bust girth level indicated by the scanner.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Bust girth (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group size Small (35” +/- 1”)</td>
</tr>
<tr>
<td></td>
<td>S1</td>
</tr>
<tr>
<td></td>
<td>S2</td>
</tr>
<tr>
<td></td>
<td>S11</td>
</tr>
<tr>
<td></td>
<td>S12</td>
</tr>
<tr>
<td></td>
<td>S13</td>
</tr>
<tr>
<td></td>
<td>S15</td>
</tr>
<tr>
<td></td>
<td>Group size Medium (37” +/- 1”)</td>
</tr>
<tr>
<td></td>
<td>S3</td>
</tr>
<tr>
<td></td>
<td>S4</td>
</tr>
<tr>
<td></td>
<td>S5</td>
</tr>
<tr>
<td></td>
<td>S6</td>
</tr>
<tr>
<td></td>
<td>S8</td>
</tr>
<tr>
<td></td>
<td>S9</td>
</tr>
<tr>
<td></td>
<td>S10</td>
</tr>
<tr>
<td></td>
<td>S14</td>
</tr>
</tbody>
</table>

Circumferences at all slice levels between underbust and up 4”, a total of 17 slices, measured every ¼” were recorded and a change rates were calculated and compared between the various conditions: dry, after run and after rest. The mean measurements of all slices per each Subject and condition are shown in Table 4.4.
Table 4.4. Average slice circumference measurements (each slice measurement calculated as average between Inhale and Relaxed measurements) for each subject in each condition.

<table>
<thead>
<tr>
<th></th>
<th>Mean No Bra condition (inches)</th>
<th>Mean Dry condition (inches)</th>
<th>Mean After Run condition (inches)</th>
<th>Mean After Rest condition (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group size</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>33.53</td>
<td>34.02</td>
<td>34.62</td>
<td>32.68</td>
</tr>
<tr>
<td></td>
<td>33.56</td>
<td>32.55</td>
<td>33.56</td>
<td>34.07</td>
</tr>
<tr>
<td></td>
<td>32.13</td>
<td>32.07</td>
<td>32.23</td>
<td>32.29</td>
</tr>
<tr>
<td></td>
<td>33.71</td>
<td>33.85</td>
<td>33.90</td>
<td>33.95</td>
</tr>
<tr>
<td></td>
<td>33.02</td>
<td>32.66</td>
<td>32.05</td>
<td>32.62</td>
</tr>
<tr>
<td></td>
<td>33.50</td>
<td>33.57</td>
<td>33.97</td>
<td>33.66</td>
</tr>
<tr>
<td>Group Size</td>
<td>34.93</td>
<td>35.21</td>
<td>35.33</td>
<td>35.21</td>
</tr>
<tr>
<td>Medium</td>
<td>34.54</td>
<td>34.12</td>
<td>35.28</td>
<td>34.71</td>
</tr>
<tr>
<td></td>
<td>34.64</td>
<td>33.92</td>
<td>34.71</td>
<td>33.99</td>
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<td></td>
<td>34.74</td>
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<td>34.45</td>
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<td></td>
<td>34.22</td>
<td>34.24</td>
<td>34.72</td>
<td>34.42</td>
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<td></td>
<td>35.46</td>
<td>34.38</td>
<td>34.69</td>
<td>34.36</td>
</tr>
<tr>
<td></td>
<td>35.13</td>
<td>34.34</td>
<td>34.11</td>
<td>34.36</td>
</tr>
<tr>
<td></td>
<td>34.66</td>
<td>33.26</td>
<td>33.54</td>
<td>32.77</td>
</tr>
</tbody>
</table>

Statistical analyses for all 14 subjects were run in the JMP software, looking at significant differences between average slice circumferences between the conditions.

Between Dry and No bra conditions, results showed that, in average, the circumference in Dry condition is 0.36 inches smaller than that of the No bra condition. The small \( p \)-value of 0.03 shows that this difference is significant. In other words, the responsive sports bra prototype offers compression of the breasts in the Dry condition. A plot of the differences is shown in Figure 4.26.
Plots of the data per subject showed how the bra prototypes varied in compressing the breasts between the three different conditions (Dry, After Run, and After Rest), calculated relative to the No Bra condition. An example of the amount of data collected for each scan and subject, as well as a graphic representation of curve changes for each slice is shown in Table 4.5.

By analyzing the plots for all the subjects, variations were observed on the curve shape as well as the space difference between the three curves. In order to confirm responsiveness of the new bra system, the ideal situation would be to have no change between the Dry and After Rest curves, meaning that the bra fits exactly the same way, has the same compression rates at each slice level, after running and resting than it did when it was dry before the run. The difference between After Rest change rates and Dry change rates should be close to zero. In the same time, the curve for the After Run changes should be below the curve for Dry condition, meaning that the bra offered more compression after run because it got wet from sweating.
Table 4.5. Change rates of slice circumferences for Subject 3 (as an example), part of size Medium group.

<table>
<thead>
<tr>
<th>Subject 3</th>
<th>No Bra</th>
<th>Dry</th>
<th>Run</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ubust</td>
<td>30.79</td>
<td>31.415</td>
<td>31.665</td>
<td>31.315</td>
</tr>
<tr>
<td>Ubust +1/4&quot;</td>
<td>30.965</td>
<td>31.63</td>
<td>32.01</td>
<td>31.65</td>
</tr>
<tr>
<td>Ubust +1/2&quot;</td>
<td>31.205</td>
<td>31.97</td>
<td>32.39</td>
<td>32.115</td>
</tr>
<tr>
<td>Ubust +3/4&quot;</td>
<td>31.6</td>
<td>32.34</td>
<td>32.81</td>
<td>32.63</td>
</tr>
<tr>
<td>Ubust + 1&quot;</td>
<td>32.415</td>
<td>32.835</td>
<td>33.325</td>
<td>33.175</td>
</tr>
<tr>
<td>Ubust +1 1/4&quot;</td>
<td>33.435</td>
<td>33.495</td>
<td>33.895</td>
<td>33.79</td>
</tr>
<tr>
<td>Ubust + 1 1/2&quot;</td>
<td>34.35</td>
<td>34.15</td>
<td>34.51</td>
<td>34.445</td>
</tr>
<tr>
<td>Ubust +1 3/4&quot;</td>
<td>35.13</td>
<td>34.915</td>
<td>35.1</td>
<td>35.06</td>
</tr>
<tr>
<td>Ubust + 2&quot;</td>
<td>35.805</td>
<td>35.5</td>
<td>35.655</td>
<td>35.615</td>
</tr>
<tr>
<td>Ubust +2 1/4&quot;</td>
<td>36.4</td>
<td>36.1</td>
<td>36.12</td>
<td>36.1</td>
</tr>
<tr>
<td>Ubust + 2 1/2&quot;</td>
<td>36.99</td>
<td>36.565</td>
<td>36.585</td>
<td>36.5</td>
</tr>
<tr>
<td>Ubust +2 3/4&quot;</td>
<td>37.34</td>
<td>37.035</td>
<td>36.97</td>
<td>36.98</td>
</tr>
<tr>
<td>Ubust + 3&quot;</td>
<td>37.475</td>
<td>37.42</td>
<td>37.405</td>
<td>37.365</td>
</tr>
<tr>
<td>Ubust +3 1/4&quot;</td>
<td>37.565</td>
<td>37.8</td>
<td>37.755</td>
<td>37.65</td>
</tr>
<tr>
<td>Ubust + 3 1/2&quot;</td>
<td>37.55</td>
<td>38.185</td>
<td>37.99</td>
<td>37.875</td>
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<tr>
<td>Ubust +3 3/4&quot;</td>
<td>37.42</td>
<td>38.5</td>
<td>38.195</td>
<td>38.075</td>
</tr>
<tr>
<td>Ubust + 4&quot;</td>
<td>37.365</td>
<td>38.68</td>
<td>38.255</td>
<td>38.195</td>
</tr>
</tbody>
</table>

Figure 4.27. Graph showing the change rates of slice circumferences for Subject 3 (as an example), part of the size Medium group.

Therefore, calculations of the differences were made, and since the distribution of the change rates varied slightly from subject to subject depending on how the bra
compressed their breast tissue, the differences were averaged and the averages were compared (Figure 4.28). The plots show that, for the group size Medium, the red curve representing the average difference between After Run and Dry conditions, the values are mostly positive instead of negative, with the exception of Subject 10 which is -0.6%, and Subject 6 which is -0.1%. Subject 4 had the highest positive value, meaning that the bra had an average of 3.3% higher slice circumference change rates (as related to the No Bra condition) in the After run versus the Dry condition. In other words, the bra got looser during the run.

**Figure 4.28.** Comparative plots of average values for the differences in change rates of After Run – Dry and After Rest- Dry, for the 2 separate groups of subjects. As explained above, red curve should be negative and green curve should be almost flat, close to zero.

Statistical analysis via JMP software confirms that, showing in average, when including data for both size groups together, After Run circumferences were 0.32 inches larger than the circumferences in Dry condition. A small p-value of 0.026 shows that this difference is significant.
For the Small size group, it was expected that the bra was loose during the run and the positive values of the red curve confirm this fact. Surprisingly, in the Small size group, there is one subject that did experience smaller circumferences for the After Run versus the Dry conditions, Subject 13, with a -1.8% difference in the average values. However, the improper fit of the bra does not allow any solid conclusions on this finding for this group.

Regarding the green curve that should be close to zero, meaning that the bra recovered the compression power after drying out, the results shown in Figure 4.28 are encouraging. Subject 14 seemed to have experienced an enlarging of the bra, with the average value of (After Rest - Dry) being -1.4%. In the Small group size, Subject 1 and 2 have wild variations of these averages, so the expectation is that the questionnaire will confirm improper fit of the bra.

Statistical calculations for significance of the average differences between After Rest and Dry conditions, across all subjects, showed that, in average, the circumference of the 17 slices After Rest is 0.08 inches larger than the circumference of the slices in the Dry condition. However, the large \( p\)-value of 0.63 indicates that this difference is not significant.

A visual analysis of the slice circumference outlines showed a variable curvature of the responsive wool patches at the top center front of the bra, in the After Run condition when the bras were wet, with some scans showing a more pronounced change in the bra material outline, while other scans did not show any differences (Figure 4.29).
Figure 4.29. Examples of slice circumference outlines from scans of two different subjects, both in the After Run condition: outline showing severe deformation of the wool patch fabric area (A), and outline showing smaller deformation of the wool patch fabric area (B).

A visual inspection of the bras after the subjects took them off shows a pronounced change in the texture of the wool yarn area, with the edges of the round patches curling towards the technical front part of the fabric confirming the responsive properties of the chosen design (Figure 4.30).

Figure 4.30. Textural change of the inside bra layer, showing moisture activation of the wool areas (yellow white round patches have the edges curved up against the white areas of the recycled Nylon knit fabric).

Questionnaire Results for Stage 3

Questionnaire statistics were run and means and standard deviations for each question were calculated for the two groups. Group size Small and group size Medium are shown in Table 4.6.
Table 4.6. Descriptive statistics from the participant’s questionnaire.

<table>
<thead>
<tr>
<th>Questions</th>
<th>Group size Small</th>
<th>Group size Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BEFORE RUN (DRY)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ease to slide bra over my head and shoulders</td>
<td>6.8 0.4</td>
<td>6.3 0.5</td>
</tr>
<tr>
<td>Underbust band tightness:</td>
<td>6 1.5</td>
<td>4.7 1.7</td>
</tr>
<tr>
<td>Bra strap tightness:</td>
<td>5.2 2.4</td>
<td>4.7 2.2</td>
</tr>
<tr>
<td>Support in the bust area:</td>
<td>4.8 1.9</td>
<td>4.6 1.4</td>
</tr>
<tr>
<td>Fabric feel: Itchy/Soft</td>
<td>6.7 0.5</td>
<td>6.9 0.3</td>
</tr>
<tr>
<td>Fabric feel: Dry/Wet</td>
<td>1.3 0.6</td>
<td>1.6 1.1</td>
</tr>
<tr>
<td>Overall comfort</td>
<td>6.6 0.8</td>
<td>6.5 0.7</td>
</tr>
<tr>
<td><strong>AFTER RUN</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underbust band tightness:</td>
<td>5.8 1.4</td>
<td>4.6 2.4</td>
</tr>
<tr>
<td>Bra strap tightness:</td>
<td>3.8 2.6</td>
<td>5 2.2</td>
</tr>
<tr>
<td>Support in the bust area:</td>
<td>4.3 2.4</td>
<td>4.25 2.8</td>
</tr>
<tr>
<td>Fabric feel: Itchy/Soft</td>
<td>6.5 0.8</td>
<td>6.6 1.1</td>
</tr>
<tr>
<td>Fabric feel: Dry/Wet</td>
<td>4 0.9</td>
<td>3.4 1.5</td>
</tr>
<tr>
<td>Overall comfort</td>
<td>6.5 0.8</td>
<td>5.25 2.4</td>
</tr>
<tr>
<td><strong>AFTER REST</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underbust band tightness:</td>
<td>6.8 0.4</td>
<td>5.9 1.9</td>
</tr>
<tr>
<td>Bra strap tightness:</td>
<td>4.8 2.5</td>
<td>5.1 2.1</td>
</tr>
<tr>
<td>Support in the bust area:</td>
<td>5 2.4</td>
<td>4.1 2.3</td>
</tr>
<tr>
<td>Fabric feel: Itchy/Soft</td>
<td>6.3 1.2</td>
<td>6.6 1.1</td>
</tr>
<tr>
<td>Fabric feel: Dry/Wet</td>
<td>3.5 1.8</td>
<td>3.6 1.6</td>
</tr>
<tr>
<td>Overall comfort</td>
<td>6.5 0.5</td>
<td>6.4 0.9</td>
</tr>
<tr>
<td>Ease to slide bra over my head and shoulders</td>
<td>6.7 0.5</td>
<td>6.6 0.7</td>
</tr>
</tbody>
</table>

Moreover, the data was organized to facilitate comparative analysis of change significance between the three conditions, similar to the knit fabric testing data analysis from Stage 2 (Table 4.7). Matched pairs analysis was run for each of the bra features shown in Table 4.7 and the results are discussed below.

**Underbust band tightness.** Results revealed that, in average, there is no significant difference between the responses for underband bra tightness, between After Run and Dry conditions ($p$-value of 0.75, and mean difference of -0.14), but there is a significant difference between underband tightness responses between After Run and After Rest.
conditions \((p\text{-value} \text{ of } 0.01, \text{ and mean difference of } 1.15)\) as well as between After Rest and Dry conditions \((p\text{-value} \text{ of } 0.2 \text{ and mean difference of } 1)\) (Figure 4.31).

**Table 4.7.** Average questionnaire responses across both size groups for the three different conditions: Before Run (Dry), After Run, and After Rest.

<table>
<thead>
<tr>
<th></th>
<th>Dry</th>
<th>After Run</th>
<th>After Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underbust band tightness</td>
<td>4.09</td>
<td>4.07</td>
<td>3.91</td>
</tr>
<tr>
<td>Bra strap tightness</td>
<td>3.88</td>
<td>3.86</td>
<td>3.76</td>
</tr>
<tr>
<td>Support in the bust area</td>
<td>3.66</td>
<td>3.63</td>
<td>3.53</td>
</tr>
<tr>
<td>Fabric feel: Itchy/Soft</td>
<td>3.57</td>
<td>3.39</td>
<td>3.35</td>
</tr>
<tr>
<td>Fabric feel: Dry/Wet</td>
<td>3.46</td>
<td>3.42</td>
<td>3.45</td>
</tr>
<tr>
<td>Overall Comfort</td>
<td>3.21</td>
<td>3.45</td>
<td>3.26</td>
</tr>
</tbody>
</table>

**Bra strap tightness.** Results revealed that, in average, there is no significant difference between the responses for bra strap tightness, between any of the conditions. Average differences in mean responses between After Run and Dry conditions resulted in a mean difference of -0.43, with a high \(p\text{-value} \text{ of } 0.27\), showing not significant. Similarly, differences in After Run and After Rest conditions resulted in a mean difference of 0.5, and not significant \((p\text{-value} = 0.15)\). Lastly, differences between Dry and After Rest conditions resulted in a mean difference of 0.07, also not significant \((p\text{-value} = 0.72)\).

**Support in the bust area.** Results revealed that, in average, there is no significant difference between the responses for support in the bust area either, between any of the conditions. Average differences in mean responses between After Run and Dry conditions resulted in a mean difference of -0.42, with a high \(p\text{-value} \text{ of } 0.41\), showing not significant. Similarly, differences in After Run and After Rest conditions resulted in a mean difference of 0.21, and not significant \((p\text{-value} = 0.62)\). Lastly, differences between
Dry and After Rest conditions resulted in a mean difference of 0.21, also not significant ($p$-value = 0.69).

**Figure 4.31.** Underband tightness average differences in responses between After Run and After Rest conditions (A), and between After Rest and Dry conditions (B).

**Fabric Feel (Itchy/Soft).** Results revealed that, in average, there is no significant difference between the responses for Fabric feel (scale of Itchy to Soft) either, between any of the conditions. Average differences in mean responses between After Run and Dry conditions resulted in a mean difference of -0.21, with a high $p$-value of 0.46, showing not significant. Similarly, differences in After Run and After Rest conditions resulted in a mean difference of -0.07, and not significant ($p$-value = 0.33). Lastly, differences between Dry and After Rest conditions resulted in a mean difference of -0.29, also not significant ($p$-value = 0.80).
Fabric Feel (Wet/Dry). Results revealed that, in average, there is no significant difference between the responses for Fabric feel (scale of Wet to Dry) only between After Run and After Rest conditions, but there are significant differences between the other two scenarios. Average differences in mean responses between After Run and Dry conditions resulted in a mean difference of 2.14, with a low *p*-value of 0.001, showing significance. Similarly, differences in After Rest and Dry conditions resulted in a mean difference of 2.07, and also significant (*p*-value =0.001). Lastly, differences between After Run and After Rest conditions resulted in a mean difference of -0.07, but not significant (*p*-value = 0.88) (Figure 4. 32).

*Figure 4.32.* Fabric feel (Wet/Dry) average differences in responses between After Run and Dry (A), and between After Rest and Dry conditions (B).
**Overall Comfort.** Results revealed that, in average, there is no significant difference between the responses for Overall Comfort, between any of the conditions. Average differences in mean responses between After Run and Dry conditions resulted in a mean difference of -0.78, with a high p-value of 0.14, showing not significant. Similarly, differences in After Run and After Rest conditions resulted in a mean difference of 0.64, and not significant (\(p\)-value =0.2). Lastly, differences between Dry and After Rest conditions resulted in a mean difference of -0.14, also not significant (\(p\)-value = 0.5).

The focus of the questionnaire qualitative part of data analysis was on the group size Medium that was intended to appropriately fit the prototyped bra design. The questions were analyzed separately, per each of the three sections, as well as comparatively, as an evolution of bra features through the three stages, similar to how the body scan measurements were plotted out.

**Before Run**

The subjects expressed their satisfaction with the ease of putting the bra on, even though the straps were overlapped at the back. The consensus, reflected in the average rating of 6.3 out of 7, was that the bra was easy to slide over the head and shoulders, with one subject commenting that “I think the independent racer back straps really helped.”

**Underbust band tightness.** The results for the group size Medium were surprisingly lower than the results for the groups size Small, showing a variable degree of preference for the tightness when the bra is dry. The average rating of 4.7, with a standard deviation of 1.7 in the Medium size group resulted from 4 out of 8 subjects rating the bra as “too loose,” with one subject (from the Medium size group) adding that
“too loose: I feel like the bra may not be my specific size, and would like/prefer one with more support or compression.” By contrast, in the Small group size, only 2 out of the 6 subjects marked the bra as having a ‘too loose’ underbust band tightness. This difference might be explained by the body shape of the subjects as well as by their underbust girth.

**Bra strap tightness.** The results were similar to that on underbust band tightness, having the same mean of 4.7 out of 7, with even a wider variation of preferences (standard deviation of 2.2). Only 2 out of 8 subjects in the Medium size group rated the bra strap tightness as too loose, with one of them commenting that “too loose: I have a short distance between my shoulders and chest, so this is a common problem for me.” In the Small size groups, the ratings were better, 5.2 mean, but also with a wide range of preferences, one subject adding “too loose: I have a pretty small bust, so this particular strap length is too long.”

**Support in the bust area.** These ratings were similar to the previous tightness ratings, with a mean of 4.6, but with a smaller variability in the preferences (standard deviation of 1.4). In the Medium size group, 4 out of 8 subjects marked the bra as ‘unsupported’, with one comment being “unsupported: This bra would probably fit someone with a larger chest better.” Yet again, surprisingly, in the Small size group, the ratings for the bust area support were slightly better compared with those of the Medium size group. Two comments from the Small size group were “unsupported: It's supportive but loose in the boob area” and, unsupported: if I had to say one-it would be unsupported-it feels good now, not running, but the bottom edge is not as tight as my other bras and I wonder if I'll notice that while running.
**Fabric feel.** The results for both dryness and softness ratings were positive, but also reflective of the variable human perception of wetness: even though the bra was dry, before the run, one subject rated it as 3 out of 7 and another one as 4 out of 7, on a scale where 7= wet and 1= dry. Errors in understanding the scale can also be the cause for these selections. Another subject commented “can hardly feel a thing!”

**Overall comfort.** This bra feature before the run received fairly consistent high ratings, averaging 6.5 out of 7, with a standard deviation of 0.7. The only comment added in this section was “Very comfy!” by one subject from the Medium size group.

**After Run**

All subjects were considerably sweaty and wet after the 30 minutes running session on the treadmill. Their perceptions of all bra features were ranked slightly lower than in the dry condition.

**Underbust band tightness.** The ratings this time showed much more variations than in the dry condition before the run, with an average of 4.6 and a standard deviation of 2.4, versus 4.7 in dry condition and a standard deviation of 1.7, one comment being “too loose: my chest can't quite fill out this bra, they were bouncing a bit more than was comfortable.” Half of the subjects marked the underbust band tightness as “too loose.” However, one subject gave it a maximum rating of 7 and commented that “felt so much better than most sports bras.” In the Small size group, again, the ratings for the underbust band tightness were much higher than those in the Medium size group, with a mean of 5.8 and variability of 1.4, and some of the comments were “I was worried it would be loose, but it felt good during the run,” “stayed in place, didn't roll up,”, and “PERFECT.”
**Bra strap tightness.** This bra feature received slightly better ratings than the dry condition, 5 out of 7, but still half of the subjects in the Medium size group marked it as “too loose,” and one comment being “too loose: not as bad as I thought.” The ratings in the Small size group were poor and varied greatly for this bra feature, averaging only 3.8 with a deviation of 2.6, with 4 out of 6 subjects marking it as “too loose,” and a comment being “too loose: felt too long, didn't help support the bust.”

**Support in the bust area.** This feature also received lower ratings than in the dry condition, averaging 4.25 but with a wide variability of 2.8, 4 out of 8 subjects marked it as “unsupported,” and comments like “unsupported: a bit too unsupported for running, would be a comfortable yoga bra,” and “unsupported: definitely flopping too much.” Need pushed up or flattened down.” In the Small group size, the ratings were again better, just slightly better (mean of 4.3), with one subject giving a maximum 7 out of 7 grade and commenting “Felt like it worked with my body. “However, these results were still lower than the ratings in the dry condition.

**Fabric feel.** As the subjects displayed a variable sweating rate, this was reflected in their answers to the *fabric feel* question: the fabric still scored high for softness (6.6 out of 7), but only 3.4 for dryness. The under layer of the bra was specifically designed to absorb the moisture, therefore the answers to the dryness question were expected to be reflective of this fabric property. However, variable tolerances to wear wet fabric were showed through comments like “pretty dry for how sweaty I got!” and “Clung to me past workout when I really started to sweat.” In the Small size group, similar comments were made such as “It's a little damp from my sweat but not overly so,” and “very comfortable, breathable fabric.”
Overall comfort of the bra. The results for this question show that the mean was 5.25 with a standard deviation of 2.4, reflecting a positive comfort perception of the bra but a wide range of preferences. One subjects that gave a minimal rating to overall comfort considered tightness as decisive, and added the: “fabric material is good. Overall tightness need to be adjusted to fit users' bodies,” while another one that rated 1 out of 7 considered the purpose of the bra as decisive for comfort rating, commenting that “for running specifically. I think it would be a good yoga bra. Seems to wick away sweat well.” One subject that rated 7 out 7 for overall comfort added: “Really comfy, I think the sizing just wasn't perfect for me.” In the Small size group, the overall comfort of the bra in the after run condition was highly rated, 6.5 out of 7, with only 0.8 variability. Comments like “The bra is very light feeling, and didn't seem to get sopping wet like others I've had.”, and “Most comfortable bra I've run in. The armpit area fit was amazing, I couldn't even tell it was there” shows comfort as being perceived as related to the lack of awareness of wearing a bra at all.

After 30 minutes Rest

The results of the ratings after the subjects rested for 30 minutes were not significantly different from the ratings they gave to the same bra features right after the run, remaining slightly lower than the ratings in the dry condition.

Underbust band tightness. The ratings averaged 5.9 out of 7 with a standard deviation of 1.9. This was the highest rating out of all 3 conditions, averaging only 4.7 in dry condition and 4.6 in the after run condition, an observation true for the Small size group too, where ratings for underbust band tightness were close to perfect (mean of 6.8, standard deviation of 0.4). Only 3 subjects from 8 in the Medium size group marked this
feature as too loose, one commenting that “too loose: I think my sweat weighted down the middle portion a lot,” and another one “too loose: the band curls under because it is a bit too loose for me. I prefer the bras to be tighter around the underbust area.” In the Small size groups, the comments were “After the 30 min, the bra feels good, I can compare it with the first time I put it on. However, during the 30 min, I've experienced some changes over the underbust band from too tight to too loose,” “feels more snug (tight) then before.” One subject that gave a maximum 7 out of 7 rating commented that “Hasn't loosened at all due to moisture,” reflecting variable degrees of moisture perception.

**Bra strap tightness.** The average rating was 5.1, just 0.1 higher than in the after run condition, but 0.4 higher than in the dry condition. 3 out of the 8 subjects marked this feature as too loose, but one subject rated 7 out of 7 commented that “not too tight or too loose.” The Small size group had poor ratings of the bra strap tightness, averaging only 3.8 and a wide variability of 2.6, a result explained by their improper fitting of the Medium size bra prototype. However, one subject still rated 7 out of 7 and clarified “I like those bra straps because they don't loosen over the time I was running neither the time I was resting. It feels very comfortable to wear.” The subject that selected the minimum 1 out of 7 scale, added that “too loose: still loose, but they don't feel as though they're gotten looser since I put the bra on.”

**Support in the bust area.** The average was 4.1 with a wide variability of 2.3, the lowest rating out of all condition for this bra feature. Surprisingly, the Small size group had a higher average rating for the breast support, a mean of 5 but a wider variability, of 2.4. Six out of the eight subjects marked the breast support feature as “unsupported,” with
comments such as “unsupported: worse after resting,” “unsupported: This is not a bad fit, but I do personally prefer bras to have a bit of lift. This is comfortable but not lifted,” “unsupported: feels very loose/stretched out, loose in between breast,” and “unsupported: just slightly.” One subject that marked 7 out of 7 added the comment” feels like the underband formed to my body,” even though the breast area was showed in the questionnaire illustration as separate from the underbust band feature. These comments show a mixed perception for breast support, being associated with lifting and tightness, disregard of the wearing condition. Subjects expected the same sensation of tightness and lifting in all condition. In the Small size group, the average rating was higher, of 5 but still with wide variability of 2.4, and subjects made comments such as “It tightened!” “Sometimes I felt it too tight and I need to adjust myself the bust area,” reflecting contradictory changes in the bra: it got tighter in the bust area for the smaller bust size group, while it was too loose in the same area for the larger size group.

**Fabric feel.** For this question, softness remained rated high, with 6.6 average and variability of 0.7, almost the same for both size groups. One subject added “Still love how the fabric feels.” Regarding the perception to wetness or dryness of the fabric, the results showed an increase in wetting perception, averaging 3.6 versus 3.4 in the after run condition, results similar in both size groups (where 1= dry and 7=wet). Comments such as “dry in the front on the cups, a bit wet on underbust band in front and back” and “It may have dried a little, but the middle of my chest is still wet.” reflect the working mechanism of the wool patterns placed to absorb moisture in the front part of the bra. Some subjects compared the sensation with other bras they previously used, clarifying that “There is a slight itch on the right back side of the bra. Also, after sitting a while, the
bra is wetter than it was before running. However, it is better than a typical sports bra.” One subject associated wetness with comfort, mentioning: “It doesn't necessarily feel wet, but it's cool to the touch which gives it the feeling of being a little damp. Not uncomfortably so.” Among the positive ratings, comments such as “Seems to have dried fairly quick. Other bras tend to be soaked especially in middle of cleavage, but this one seems to have dried.” were made by one subject. Fabric wetness was also mentioned in areas outside the scope of the bra design, such as shoulder straps “It feels a little wet mostly in the shoulders area.” An indication of bra material changes between the conditions was suggested by the comment “it rapidly changed from wet to dry. My bra feels dry. During the first 10 minutes after running it felt very itchy and tight.”

**Overall bra comfort.** After the resting time, the subjects had positive reviews, with an average rating of 6.4 and relatively small variability of 0.9, consistent with the Small size group ratings. Comments made in the Medium size group were “Overall very comfortable. A few parts I wish could be tighter,” “Still comfy, I just wish it was dry,” and “comfortable but not very supportive,” reflecting associations of breast support, fabric dryness and tightness to overall comfort. In the Small size group, comments were “I would say the design of the straps and the support is very comfortable. However, the band is slightly itchy sometimes when it dries. Overall I like it,” “Very comfortable, it doesn't feel like it's leaving skin indentations and the straps aren't putting too much pressure on my shoulders,” and “Very comfortable- I'm still a little sweaty from my run which is why I didn't give it a '7'.

**Ease of taking the bra off.** This feature was included in the questionnaire because, as literature and consumer studies showed, after the sports bras get wet, they are
hard to remove. The prototype received high ratings averaging 6.6, and standard
deviation of 0.7, consistent between both size groups.

At the end of the questionnaire, subjects were encouraged to provide any other
comments about their experience wearing the bra prototype. One subject detailed her
experience in every condition, highlighting the changes she felt in the bra material as well
as her expectations from such a garment item:

Before: the first time I put it on, it felt so cozy, the fiber felt soft. The idea to wear
a bra is don't think about it so much neither worry about it. However, the support
in the bust area was neither too tight nor unsupported. During running: it felt
different from the beginning. The bra adjusted to my running posture, the support
in the bust area was tight but I liked it. I don't have to worry about losing the bra
straps. After: It seems that the bra adjusted again itself to my body. It came dry
quickly.

Another subject from the Medium size group reflected on the overall function and
expectations of a sports bra, and commented that: “Generally, this is a great bra.
Retrospectively, the most important point of comfort is supposed to be during the
workout. At that point, I barely noticed the bra which is the best you can ask for.”
Insights on breast support and how other sports bras manage that function were given by
the comments: “The bra was supportive and easy to breath in them even while fast
breathing when I was running. My other sport bras with great support feel tight when
running and trying to breath fast.” While survey results highlighted the lack of
appropriate perceived support in the breast area in different conditions, retrospectively,
one of the subjects gave it a high rating:

The bra was very comfortable. It felt less restrictive than my usual sports bras, but
felt just as supportive. The fabric was nice- soft and stretchy. It did have a cool-
to-the-touch feel after I had sweat in it- even after sitting for a while- which made
it feel a little damp but not very wet.
Although the sample size was very small compared with the population size of women who use a sports bra when running, the insights from the wear testing are useful to gauge user needs and user perceptions, aiding with improvements and further iterations of the prototype. As resulted from the case study interview data from Stage 1, the industry practice is to rely on the comments and observations from wear testing in order to correct and proceed with product development.

Given the wide range of methods, samples and mixed methods analysis presented in this chapter, a discussion of the overall results is needed.
CHAPTER 5: DISCUSSION

Each stage of this research provided the necessary data to answer the original research questions. The following research questions were used to guide this study:

1. What are the current materials and processes used in the product development process of seamless sports bras?

2. What component materials and structures of a seamless sports bra system offer responsive behavior when actuated by body moisture? How are these materials and structures informed by the tenants of biomimicry?

3. How can a sports bra be designed to function as a responsive system using wearer’s body moisture as system actuator?

The mapping of the information shared during the case study interview (Stage 1) was analyzed and led to the mapping of the product development process in relationship to all the other over-arching themes (Figure 4.2). However, the relationships between the themes showed that, while main directional patterns exist, every decision made during the design and development of a seamless knitted product affects every other department, as a subsystem, of the entire Business Model. As the Subject of the case study articulated: “Everything you do, everything you do in seamless it’s gonna affect something else. You’ve gotta think about what is the effect.”

There is a circular, interdependent relationship between Business Model and Planning as the pillars of the entire seamless apparel business model. The structure of the business decides the degree of planning, and the planning strategy of an organization is reflected back in the Business Model, as it creates opportunities or limitations of growth. These two pillar over-arching themes filter information through all the other over-arching
themes: Marketing, Product Development, and Production. In other words, each of the over-arching themes have, at some smaller level, sub-themes related to either Business Model, either Planning.

There are also circular relationships between Marketing and Product Development, as Marketing informs most of the new seamless developments, but in the same time, the opportunities discovered via iterations and customer interactions during wear testing in Product Development, will later make their way into the Marketing. Marketing and Production have a similar circular relationship, given by the specific nature of seamless business. Pricing as a major theme, plays a major role in Marketing, and serves as the liaison into Production, affecting Quality, Sustainability, and Operations as Production major themes. Production is also circularly dependent on Product Development, as the case study interview data showed that most seamless apparel new product development is being set up for Production from early design and development stages. Prototyping, as a major theme of Product Development, serves as the liaison to Production. A further discussion of the relationships found inside the Product Development over-arching theme itself is needed.

The Tech Pack Model

The following framework was created as a result of compiling the information from the interview, while looking ahead for a tool to communicate the proposal design of a responsive sports bra (Figure 5.1 and enlarged in Appendix L). While organizing the data for this model, the specifics of the seamless apparel development lab used for the mapping conducted in Stage 1 were considered, but various companies can have a
slightly different tech pack model based on the particularities of the seamless supply chain used.

![Tech Pack Model](image)

**Figure 5.1** The Tech Pack Model for seamless knitted apparel product development.

Direct relationships between decision-making sub-steps within the product development process and information recorded in the tech pack were identified (see enlarged in Appendix L). All the components such as *Design, Function* and *Prototype*, along with their sub-categories, were detailed in Chapter 4 (Results). This discussion will focus on the relationships identified spanning outside these themes, as they transform into *design process* communications via the tech pack document.

This Tech Pack Model captures the evolving nature of the document as a reflection of the design process, with information from one page relating to information from other pages, so as something changes, everything needs to be reviewed and updated. The case study Subject specified: “Anytime I make a revision, I’m changing something. That change is gonna change something else.” The starting tech pack in the design process will have only partial information, but as the prototype becomes approved for
production, all the pages will need thorough checking and completeness. The Design Process becomes the sub-theme that is at the center of the Tech Pack Model, as this is the message the tech pack needs to communicate to Production. The information managed during the design process was separated, as per the product development process mapped in Stage 1, in the following sheets, a common industry standard for recording production information: Design Sheet, Fabric Sheet, Spec Sheet, Construction Sheet, Fit History Sheet, Bill of Materials Sheet, and Quality Standards Sheet.

Analyzing the multitude of relationships between the various sub-themes in the Product Development and the information recorded in the Tech Pack, it is clear that the Fit History Sheet is a tool of recording the garment development process as a decision process, systematically, and emerges as an essential part for the design process. Therefore, the wear testing sessions are the events that lead to many of the decisions regarding design elements, sizing specs, construction, even user profile.

The Design Sheet and the Fabric Sheet are the two documents that essentially communicate the design details, and they are required for the initiation of any prototype project. The prototype development process will lead to specifics and information generating the Spec Sheet, Construction Sheet, and Fit History Sheet. The implementation of the functional properties of seamless apparel require determinations that get recorded in Bill of Materials Sheet as well as in Quality Standards Sheet.

The standardization of the format of a tech pack is often achieved by using web based product development platforms, or specialized supply chain software. These venues allow for each of the information fields recorded to be instantly updated when change occurs either at the design level, either at the supplier or yarn manufacturing
level. The complexity of the relationships in a such tech pack model is also specific to the design of each seamless product.

While design starts with drafting information regarding design elements such as silhouette, color, trims, knitted stitches, etc., the functionality of the prototype, decided by wear testing is what successfully advances the seamless product through development process and furthermore through production. The detailed documentation of all the iterations made during design process, will serve as a foundation for the development of future products.

**Theoretical Implications**

TRIZ theory and a biomimetic system design approach served as the theoretical foundation of this research. The analysis of the case study data that was conducted in Stage 1 confirms the necessity of considering all sub-systems of user and product interactions, as well as material development and production processes when proposing a new sports bra design. The Business Model proposed (Figure 4. 2), along with the analysis of the Tech Pack components (Figure 5.1), confirm the alternation of circular and linear relationships suggested by the literature design models. Particularly, Watkins & Dunne (2015) design process variations, as shown in Figure 2.8, captures the variety of decision-making situations within the seamless product development too.

Haimdal’s (2009) argument that ideation process is not included in engineering design models was confirmed for the case of the seamless knitted apparel. Seamless garments are often developed starting from a previous garment, and the design process does not include concept development, ideation or creative strategies. As for the functionality part of seamless garments, the interview analysis highlighted that trial-and-
error is the prevalent problem solving method for seamless functional garments, confirming Heinsohn’s (2005) findings. Moreover, the fact that ideation in seamless industry product development uses existing products and processes, confirms Savransky’s (2000) theory of psychological inertia for bringing innovation into market. Developing an innovative product takes time and many trial and error sessions that eventually are expensive. Current industry practice in apparel industry is to shorten product development and have new product on the shelf faster.

The insights into the organization of seamless industry also revealed that sustainability is a major theme within production processes, and sustainability starts with the selection of the materials used in the early design stages. The results from the material/fabric development stage of this research, Stage 2, showed that, while many designs are possible at the stitch by stitch level of the knit fabric, when trying to incorporate the textile design into the system of a sports bra, the knitting technology has limitations. Responsiveness of the knit fabric swatches was mostly observed after the wool patches were integrated into the sports bra system design, as shown by the 3D body scanning data. This finding confirms Scott’s (2005) methodology for documenting the responsiveness of wool knitted fabrics via videography, as the motion of the fabric edges, determined by the stitch structures, is more visible than the changes in the physical properties of the knit swatches. Even though some thickness changes were observed for a few patterns, these patterns were not possible to be integrated into the seamless knitted tube at the stitch specifications given by the overall sports bra silhouette. Particularly, pattern #15, the thickest knit fabric made on Santoni machine, folding 16 courses into one course by using tuck stitches, is not suitable for being inserted into a floating pattern at
the center front of the sports bra, while also having cinch stitches in the same place to provide breasts encapsulation. The initial design proposal had pattern #15 made in wool/Nylon yarn at the underbust area, a design decision made based on the textile testing data from Stage 2. Details of the initial design diagram is shown in Figure 5.2.

**Figure 5.2** Detail of the initial sports bra design proposal, showing pattern #15 placement at center front under bust area.

Although the textile science literature shows that natural fibers swell as they absorb moisture (Hatch, 1993), and this increase in fiber physical properties is enhanced by the knitted structures (Scott, 2005), the test results conducted in Stage 2 of this research found that knit fabric thickness decreased when the knitted swatches were actuated by moisture. Relaxation of wool fibers when absorbing moisture is therefore confirmed, as suggested by Öner & Okur (2013). The relationships between knit fabric thickness and density, weight and weight/thickness during various stages of air-drying after being actuated by moisture contribute to the gap of knowledge in the field of wool yarn knitted on circular machine.

The results from Stage 3 of this research showed that, the design and development of a responsive sports bra design is achievable using current technology, but further yarn and stitch engineering needs to be explored. The analysis of the results from the 3D body scanning data revealed that responsiveness of the new sports bra design was achieved but varied by subject, so improvement in the sports bra overall design needs to be pursued.
The responsive sports bra prototype offers compression of the breasts in the Dry condition relative to the No Bra condition (0.36” smaller in average). After the 30 minutes run, when the sports bra prototype became wet, results show that the bra was significantly less compressive relative to the Dry condition (0.32” larger). However, the After Rest average measurements were not significantly different than in the Dry condition, meaning that the sports bra was as compressive as in the Dry condition after the resting 30 minutes’ period.

The results from the wear testing showed that there is a significant perceived difference between underband tightness After Run relative to After Rest conditions, as well as between After Rest and Dry conditions. The positive comments related to the comfort level of the bra prototype as well as to the fabric feel and overall wearing experience highlight the success of the overall new concept design process. Watkins & Dunne (2015) suggested setting up evaluation procedures prior to ideation to make certain that the choice of evaluation technique is not influenced by the final design selected. However, this research study showed that, just as the design evolves and changes during the product development stages, the evaluation methods should change too to better capture the systematic approach of designing seamless clothing.

Though limited in scope, this research offers a framework for understanding the systematic design requirements of a highly functional apparel product manufactured via advanced knitting technologies. The detailed insights of an unexplored apparel product development process provide the groundwork for further studies.
CHAPTER 6: SUMMARY AND CONCLUSIONS

An overall review of the research, results and conclusions will be summarized in this chapter. Significance of this research will be addressed as well as recommendations for further studies.

The two-fold purpose of this study was to: (a) analyze the use of current materials and processes in the product development process of seamless sports bras, via industry interviews and observations, and (b) propose a design solution for a seamless sports bra that offers variable breast support during running versus resting activities. A biomimetic system framework was used to identify solutions to responsive interactions within fibers, yarns and knitting structures, when actuated by body moisture generated during running. Prototypes were developed via circular seamless knitting machines and tested using 3D body scanning technology.

Summary

The researcher conducted an in depth case study interview, by shadowing a seamless knitting expert during three days in his seamless knitting lab, observing the process of developing a sports bra. After transcribing, open coding, and conducting a thematic analysis based on grounded theory, a mapping of the interview was created that highlighted the materials and processes currently used by the seamless industry to develop seamless sports bras. Fiber and yarn properties were researched, looking for materials with responsive moisture management properties, which can be integrated into a seamless knitted sports bra design. Performance wool yarn and recycled Nylon were sourced and used to create knit fabric swatches that were further tested for thickness changes when activated by moisture. Forty fabrics were created using combinations of
knit, tuck and float stitches as offered by the Santoni Top-2 circular knitting machine, and using combinations of wool/ Nylon, wool, and spandex yarns. Physical properties of the knit fabrics as well as changes in thickness during wet conditions and various air-drying intervals were compared, then decisions were made for a seamless sports bra design proposal. The design proposal was communicated via a tech pack, that was structured as per the information resulted from the case study interview. Fifteen prototypes were manufactured and wear testing was conducted with human subjects. 3D body scanning was used to scan the subjects wearing the responsive sports bra in various conditions, in order to check the sports bra fabric responsiveness to perspiration moisture. Scanning data was analyzed along with a questionnaire that subjects used to evaluate various bra features, such as underbust band tightness, bust area support, strap tightness, overall comfort and fabric feel.

**Significance and Implications**

The proposed systematic approach to the sports bra design, integrating together all processes and materials of a hierarchy serving the same function, that of offering responsive breast support, provides a new framing for the design process of a sports bra as a functional design garment. The mapping of the Business Model, as well as the details of the relationships within the product development process and tech pack components offer a platform for further innovations and process knowledge.

This research documented the exploration of responsive properties for wool and blended wool yarns, creating references for further studies into responsive properties of natural fibers and their applications into the advanced seamless knitting industry. The use of 3D body scanning to measure responsiveness of the sports bra prototypes provides an
alternative methodology for testing responsiveness of fabric, after it was integrated into a sports bra system design. The results of this research add to the scientific and applied body of knowledge in the field of textiles, sports bra, and breast support metrics. Advances in the science that connects body metrics to material manufacturing, in this case seamless knitting, will lead to improvements in the performance of the sports bras as functional apparel, supporting the increase in sports participation of women of all shapes and sizes. Moreover, this study brings to research information on seamless apparel manufacturing that was not previously investigated, setting up the grounds for an informed communication between design process and manufacturing practices of seamless sports bra.

**Future Research**

During the prototype development stages, several opportunities for further studies emerged. At the case study stage, an investigation into alternative knitting technologies and their product development processes, such as Shima Seiki and Stoll, could offer an alternative mapping of the product development process. Comparative analyses and best design practices should be revealed. At the knit fabric testing level, further wool yarn development steps should be pursued, to identify solutions for the yarn properties in order to better use the Santoni circular knitting technology. Fiber blends of wool with recycled Nylon or other eco-friendly fibers, yarn twists and yarn combinations could be explored. The knit fabrics resulted from these experimental approaches could be subjected to additional moisture management testing, to better fill the knowledge gap in the responsive materials field.
The responsive sports bra design proposed can be further improved based on the results of this research, and several iterations could lead to a commercial application and patentable innovation. The use of wool yarn as a functional material in activewear is in the infancy stages, as revealed by the difficult yarn sourcing process experienced during this study. The responsive system is applicable to other body areas and other functional problems, such as compression garments for medical applications. At the breast support level, other wool patch designs should be investigated, as suggested by the extensive breast support literature. White et al. (2015) suggested that the reduction of breast motion in the anteroposterior direction should be considered by the sports bra designers, in order to help reduce breast pain for female runners with larger breasts. Therefore, different placement and considerations for responsiveness of the materials could be explored.
REFERENCES


Safdle River, NJ: Pearson Education.


Compression Levels of Seamless Sports Bras Using 3D Body Scanning. 
Proceeding to 7th International Conference on 3D Body Scanning Technologies, Lugano, Switzerland.


Heimdal, E. J. (2009). Interactive Inspirational Tool for Responsive Textiles (Master's


Keen, J. (April 13, 2015). The First Jogbra Was Made by Sewing Together Two Men’s


APPENDIX A

IRB APPROVAL FOR CASE STUDY

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 50), please be sure to:

- Use only the approved study materials in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.
- Retain signed informed consent documents for 3 years after the close of the study, when documented consent is required.
- Obtain IRB approval prior to implementing any changes to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.
- Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences involving risks to subjects or others; and (2) any other unanticipated problems involving risks to subjects or others.
- Stop all research activity if IRB approval lapses, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.
- Complete a new continuing review form at least three to four weeks prior to the date for continuing review as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send you a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. Approval from other entities may also be needed. For example, access to data from private records (e.g., medical, employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. IRB approval in no way implies or guarantees that permission from these other entities will be granted.

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 202 Kingland, to officially close the project.

Please don’t hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.
APPENDIX B

INFORMED CONSENT DOCUMENT FOR THE CASE STUDY

This form describes a research project. It has information to help you decide whether or not you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary. Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

Who is conducting this study?
This study is being conducted by Adriana Gorea, PhD candidate; Department of Apparel, Events, and Hospitality Management at Iowa State University.

Why am I invited to participate in this study?
You are being asked to take part in this study because you are an expert on designing and constructing seamless sports bras on Santoni circular knitting machines. Additionally, you own your own knitting lab and have expertise related to current commercial applications of seamless sports bras. You should not participate if you are under age 18.

What is the purpose of this study?
The purpose of this study is to explore the process of design and manufacturing of seamless sports bras.

What will I be asked to do?
If you agree to participate, you will be asked to share your thoughts, experiences, and opinions of seamless sports bras design and prototyping in an interview. The interview is conducted in your workspace and photographs and videos of the bra making process will be taken. Written notes and observations will also be taken. Your participation will last approximately 24 hours, divided in 8 hours per day, during the course of 3 days, and will be audio-recorded. In addition, once data has been analyzed, you will be asked for feedback about the investigator’s findings and conclusions, a process called a member check. This will allow you to correct misinterpretations or fill omissions.

What are the possible risks or discomforts of my participation?
No names of people or organizations discussed in interviews will be reported in results. Generic names such as Mr. X will be used. Following the interview, you will be provided with results and allowed to make corrections or remove any information that may be harmful to you or others.

What are the possible benefits of my participation?
You may not receive any direct benefit from taking part in this study. I hope that this study will lead to a better understanding of the design process to offer guidance to designers and sports bra developers.
**How will the information I provide be used?**
Audio versions of your interview will not be shared with external parties. The information you provide via audio and video will be transcribed, reviewed, and coded by the investigator and used to complete research for a doctoral dissertation, potential conference presentations, and potential publication. The pictures and videos may be included in presentations and publications, but there will be no identifiable links to you. Your identity will be confidential. However, since this is a case study, I cannot guarantee your full confidentiality, even if your identity is not linked to your responses.

**What measures will be taken to ensure the confidentiality of the data or to protect my privacy?**
Records identifying you will be kept confidential to the extent allowed by applicable laws and regulations. Records will not be made publicly available. However, federal government regulatory agencies auditing departments of Iowa State University, and the ISU Institutional Review Board (a committee that reviews and approves research studies with human subjects) may inspect and/or copy study records for quality assurance and analysis. These records may contain private information.

The following measures will be taken for published reports of the study:
- Your name will be known only to the study authors.
- You will be assigned a pseudonym.
- Any names or organizations you mention during the course of our interview will be substituted with titles (i.e., “a designer” or “a product developer”).
- Videos and photographs will focus on your hands and bra making process, not on your face or any other identifiable parts. They will be edited to remove any identifiable parts.
- Interview transcripts, videos, photographs, and the key code for your pseudonym will be kept in a password protected file on an encrypted computer.
- Recordings of your interview will be destroyed within 3 years of the completion of the study.

The member check will allow you the opportunity to redact any information you consider too private or sensitive.

**Will I incur any costs from participating or will I be compensated?**
You will not have any costs from participating in this study. You will not be compensated for participating in this study.

**What are my rights as a human research participant?**
Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. You can skip any questions that you do not wish to answer.

If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or
Director, (515) 294-3115, Office for Responsible Research, 1138 Pearson Hall, Iowa State University, Ames, Iowa 50011.

Whom can I call if I have questions about the study?
You are encouraged to ask questions at any time during this study. For more information, please contact Adriana Gorea, agorea@iastate.edu, (302) 690-1842, or Dr. Fatma Baytar, baytar@iastate.edu, or Dr. Eulanda Sanders, sanderse@iastate.edu.

Consent and Authorization Provisions
Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document, that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant’s Name (printed) _______________________ Date __________________

____________________________________________
(Signature)

I allow use of photography of bra making process (Signature)

I allow use of videography of bra making process (Signature)
APPENDIX C

INTERVIEW PROTOCOL FOR THE CASE STUDY

Subject: Santoni Knitting Programmer and Technician

1. Please state your role in the design and manufacturing process of a seamless knitted sports bra.

2. How long have you been working in this role?

3. How many different people have this role in the design and manufacturing process of a seamless sports bra?

4. How does the process of design start for a seamless sports bra? Please detail the initial communication process.

5. How is this different from the design process of a cut-and-sew sports bra?

6. How is this different from using other seamless technology, not Santoni? Please elaborate.

7. What challenges you see in communicating design specifications for seamless sports bra?

8. Are there restrictions regarding the type of sport bra silhouettes given by the seamless technology? Why?

9. How is the sports bra support level (high, medium or low) translated into design of seamless sports bra?

10. How does the process of material selection take place? Please elaborate.

11. What challenges you see in material selection?

12. Is there any testing done at the fiber and yarn level that contribute to the material selection decision process? Why?

13. What step is next in the design process? Please elaborate.

14. What type of stitches and knitting patterns you mostly use for seamless sports bras? Why?

15. Are there any features of the Santoni technology that are not being used in making a seamless sports bra? Please elaborate.

16. How long does it take to program the machine?

17. What type of information you consider critical for the programming of the knitting pattern?

18. Are there any knitting machine preparations done?
19. How do you decide what size of bra you make on what machine? Please elaborate the seamless sports bra sizing system.

20. What challenges exist in programming sports bras on circular Santoni machines?

21. How long does it take for the machine to knit a sports bra tube?

22. What knitting patterns take longer? Why?

23. How many different yarns can be fed into a knitting program?

24. How many yarns are commercially used for seamless sports bras? Why? Please elaborate.

25. Are there any tests done after the tube is knitted?

26. What challenges exists during the machine knitting process? Why?

27. What step is next after the bra tube is knitted?

28. Please detail the finishing process for seamless sports bras.

29. How is the support level of the sports bra tested?

30. Is there anything you would like to add?

Thank you!
## APPENDIX D
VIDEO DATA METRICS

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APPENDIX E

CODING GUIDE

1. Company Type
   a. Branded organizations
   b. Experience Level
      • Newbies
      • Established customer base
      • Small companies/ entrepreneurs

2. Marketing
   a. Distribution
      • Online retailing
      • Special events
      • Big brands omni-channel
      • Emerging low end distribution
   b. Pricing
      • Pre-determined price point
      • Seamless as cost down strategy
      • High performance high value
   c. Demand
      • Drivers
         • Brands
         • Comfort
         • Differentiation/authenticity
         • Performance
         • Price
      • Creating demand
         • Advertising
         • Innovation

3. Product Development
   a. Design
      • Design Elements
         • Aesthetics
            Symbolism
            Branding and logo design
         • Surface Design
            Stitch placement
            Pattern design
            Thermal treatments
         • Garment type
            Layering
Performance garments
Cut and sew construction
Hybrid garments
- Shape manipulation
- Texture design
- Material selection
  Yarns
  Spandexes
  Yarn size
  Yarn twist
  Mixing options for yarns
  Specialty yarns
  Yarn properties
  Fibers
  Nylons
  Natural fibers
  Fiber blends
  Fiber properties
- Colors
- Design details
  Closures
  Garment edges
- Techniques
  Knitting
    Stitches
    Programming
    Pattern configuration
    Pattern drafting
    Software tools
    Chain program coding
    Use of templates
    3D to 2D translation
    Sizing algorithms
    Mechanics and limitations
- Sewing
  Sewing labor
  Sewing specs
- Wet Processing
  Garment dyeing
  Softening
  Special treatments
  Split manufacturing
- Design Process
• Inspiration
• Design references
• Experimentation
  Swatches
  Trial and error
• Design portfolio
• Decision making
  Communication
  Multiple approaches
  Pre-determined aesthetics
  Changes

b. Function
  • User Profile
    • User perceptions
      Wearability
      User feedback
      User knowledge
    • User limitations
      Specific activities
      User physical profile
      Trade offs
  • Specific functions
    Ventilation
    Kinetics
    Impact absorption
    Wicking
    Posture control
    Cooling
    Conductivity
    Support
    Water repellent
    Lifting
    Antimicrobial

  • Problem Solving
    • Pre-conceived solutions
    • Novel problems
    • Communication
      Information description
      Graphics
      Interpretation
      Color coding
      Comparisons and analogies
Information management
Information transfer
Information needed
Documentation
Decision making
Singularity
Co-design

c. Prototype
  * Communication
    - The tech pack
    - Brand organization
      Team dynamics
      Expertise level
  * The seamless choice
    - Santoni seamless equipment
    - Limitations
    - Specific features
  * Multiple stages
    - Yarn development
    - Garment development
      Multiple iterations
      Co-design
    - Garment sizing
      Size run
      Size consistency
  * Specifications
    - Evolving process
    - Variable specificity by brand
    - Specs decide knitting equipment
  * Fit
    - Fit to human body
    - Trade offs
    - Fit testing
  * Costing

4. Innovation
   a. Resources
      * Existing unique products
      * Versatility of technology
      * Global markets
   b. Creativity
• Risk taking
• Unthinkable
• Out of the box thinking
• By chance
• Unexplored
• Wondering
• Thorough knowledge
• Unconventional

c. Opportunities
• Line diversification
• Continuity of innovation
• Evolving markets
• Unfulfilled technology potential
• Targeted product development
• Lack of specific products

5. Planning
   a. Time
• Prototyping
• Operations
• Long technology learning curve
• Progress monitoring

   b. Logistics
• Storage
• Transportation
• Product complexity
• Manufacturing capacity

c. Materials
• Yarn supply chain
• Minimum yarn requirements
• Material usage

d. Exceptions
• Special cases
• Complications
• Emerging trends

6. Production
   a. Operations
• Feasibility for mass production
• Fast manufacturing
• Efficiencies
• Manufacturing limitations
• Sourcing and logistics
• Mixed manufacturing technologies

   b. Quality
• Inspection methods
• Improving quality
• Tracking
• Standardization
• Testing

c. Sustainability
• Protecting the environment
• Reducing waste
  • Seamless advantage
• Recycling
  • Yarns
  • Products
APPENDIX F

KNIT FABRICS TESTED

Legend of stitch diagram: yellow= needle catches both yarns (plain jersey), black= needle misses both yarns (tuck), red= needle catches only the spandex (float)

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<tr>
<th>Fabric</th>
<th>Yarns</th>
<th>Technical front (relaxed)</th>
<th>Technical Back (relaxed)</th>
<th>Technical front (zoom in 1cm)</th>
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<td>Technical front (zoom in 1cm)</td>
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<td>Stitch diagram</td>
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<td>Stitch diagram</td>
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<td>Customer:</td>
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<td>Date created:</td>
<td>18-Jun-17</td>
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<td>Season:</td>
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<td>Style Description:</td>
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<td>Fiber content:</td>
<td>wool/eco-nylon/spandex</td>
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<td>Project type:</td>
<td>Proof of concept- prototype development</td>
<td>Color:</td>
<td>undyed, natural yarn color</td>
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<td>Development Lab:</td>
<td>Seamless Knitting Solutions, NC</td>
<td>Knitting Technician:</td>
<td>Keith Sherril</td>
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</tr>
</tbody>
</table>

**Sketch**

**Front:**

- tuck #12
- rib #16
- mesh #18
- cinch
- mesh #20

**Back:**

**Trims:** 1/2" wide folded elastic binding, undyed

**Wet processing:** Wash tubes in cold water, tumble at low temperature, no dyeing

Updated: 6/18/2017
<table>
<thead>
<tr>
<th>Customer</th>
<th>Style #</th>
<th>Style Description</th>
<th>Project Type</th>
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<th>Fiber Content: wool/eco-nylon/spandex</th>
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<th>Tolerance (+/-)</th>
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**Measurement Description**

1. Band width at chest back
2. Band length
3. Bust across
4. Side Fold length
5. Center front height
6. Strap width at shoulder seam
7. HPS to bottom of band
8. Center back height

**PDM**

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<tr>
<td>11 1/4&quot;</td>
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<td>13 1/4&quot;</td>
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<td>14 1/4&quot;</td>
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<td>14 1/4&quot;</td>
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**Updated: 6/18/2017**

**Sketch:**
# Fabric Sheet

**Customer:** Adriana Gorea  
**Style #:** 1234  
**Date:** 18-Jun-17  
**Season:** N/A  
**Style Description:** Responsive Seamless Sports Bra  
**Fiber content:** wool/eco-nylon/spandex

**Project type:** Proof of concept- prototype development  
**Color:** undyed, natural yarn color  
**Development Lab:** Seamless Knitting Solutions, NC  
**Knitting Technician:** Keith Sherril

## Yarn Specs

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<th>Other specs/ Color</th>
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<td>2</td>
<td>Performance Wool</td>
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## Yarn Pattern Diagram

![Yarn Pattern Diagram](image1)

## Knitting Specs

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<table>
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<tr>
<th>Fabric Stretch:</th>
<th>Stretch test used:</th>
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</table>

## Knitting Pattern Diagram

![Knitting Pattern Diagram](image2)

**Updated:** 6/18/2017
Outside bra design details

Inside Bra Design details
APPENDIX H

IRB APPROVAL OF THE WEAR-TESTS

Date: 6/2/2017
To: Adriana Gorea
108 Parrish Lane
Washington, DE 19810

CC: Dr. Fatma Baytar
1074 LeBaron
Dr. Eulanda Sanders
31 MacKay

From: Office for Responsible Research

Title: Seamless Sports Bra Design: A Responsive System Solution II

IRB ID: 17-220

Approval Date: 6/1/2017
Date for Continuing Review: 5/31/2019

Submission Type: New
Review Type: Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- Use only the approved study materials in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.

- Retain signed informed consent documents for 3 years after the close of the study, when documented consent is required.

- Obtain IRB approval prior to implementing any changes to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.

- Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences involving risks to subjects or others, and (2) any other unanticipated problems involving risks to subjects or others.

- Stop all research activity if IRB approval is lost, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.

- Complete a new continuing review form at least three to four weeks prior to the date for continuing review as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. Approval from other entities may also be needed. For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. IRB approval in no way implies or guarantees that permission from these other entities will be granted.

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 202 Kingland, to officially close the project.

Please don’t hesitate to contact us if you have questions or concerns at 515-294-4566 or irb@iastate.edu.
APPENDIX I

PARTICIPANT RECRUITING EMAIL FOR THE WEAR-TESTS

3D Body Scanning Research
Volunteers are Needed

The purpose of this study is to collect data for our sports bra research to identify how sports bras made of moisture responsive yarns change body measurements.

We are looking for **female athlete volunteers** who:

- agree to participate in a 75-minutes body scanning session
- there is a $15 Amazon gift card compensation offered for your participation in the study, after the completion of your scanning session, along with a print out of your body measurements and your 3D body scan
- are over the age of 18
- have bust circumference of 37” (plus/minus1”)
- you should not participate if you are prone to seizures or have seizure disorders, or suffer from claustrophobia.
- participants must be able to run on treadmill for 30 minutes wearing their own running shoes.

If you are interested, please contact:
Adriana Gorea agorea@iastate.edu, Fatma Baytar baytar@iastate.edu or Eulanda Sanders sanderse@iastate.edu

Thank you!
APPENDIX J

INFORMED CONSENT DOCUMENT FOR THE WEAR-TESTS

Title of Study: Seamless Sports Bra Design- A Responsive System Solution

Investigators: Adriana Gorea, Ph.D. student
Fatma Baytar, Ph. D.
Eulanda Sanders, Ph.D.

This form describes a research project. Your participation in the study is completely voluntary. Please discuss any questions you have about the study or about this form with the researchers before deciding to participate.

Introduction

The purpose of this study is to explore how females’ breast area measurements change when wearing seamless sports bras made with different moisture responsive yarns, before and after running on treadmill for 30 minutes. A [TC]\(^2\) NX-16 3D body scanner will be used to gather body measurements. Your measurements will be used as research data and will not be publicized.

You are invited to participate in this study because you fit in the size M compression seamless bras (breast circumference of 37” plus/minus 1”). You are being invited to participate in this study because you represent one of the body sizes.

You should not participate in this study if any of the following are true:
- you are not a female athlete
- do not wear a size M sports bra
- under 18 years’ old
- are prone to seizures or have seizure disorders, as the 3D body scanner uses flashing light to digitally capture your measurements
- you suffer from claustrophobia
- not able to stand in the scanner booth without help
- not able to hold breath for 20 seconds.
- not able to run on treadmill for 30 minutes, while wearing your own running shoes.

Description of Procedures

If you agree to participate, you will be asked to:

1. Give your consent to participate in this study.

2. Wear tight fitting bike shorts and a sports bra for scanning (they will be provided by the researchers). Those garments are newly made and you will have your own to wear.

3. Have a full body scan taken with the [TC]\(^2\) NX-16 body scanner in 4 conditions, with 2 phases for each condition, for a total of 8 scans:
- In each stage (not wearing a bra, with bra before run, with bra after 30 min run, with bra after 30 min rest) you will be scanned while you fully inhale and hold for 20 seconds, followed by a relaxed respiration state scan.

- Summary of scans:

<table>
<thead>
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<th>Scan #</th>
<th>Description of subject condition</th>
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<tbody>
<tr>
<td>#1</td>
<td>wearing no bra (lightweight tank top), inhale</td>
</tr>
<tr>
<td>#2</td>
<td>wearing no bra (lightweight tank top), relaxed</td>
</tr>
<tr>
<td>#3</td>
<td>wearing Sports Bra, inhale, before run</td>
</tr>
<tr>
<td>#4</td>
<td>wearing Sports Bra, relaxed, before run</td>
</tr>
<tr>
<td>#5</td>
<td>wearing Sports Bra, inhale, after 30-minutes run on treadmill</td>
</tr>
<tr>
<td>#6</td>
<td>wearing Sports Bra, relaxed, after 30-minutes run on treadmill</td>
</tr>
<tr>
<td>#7</td>
<td>wearing Sports Bra, inhale, after 30 minutes rest</td>
</tr>
<tr>
<td>#8</td>
<td>wearing Sports Bra, relaxed, after 30 minutes rest</td>
</tr>
</tbody>
</table>

- Running on the treadmill will be at a speed and incline adjustable and comfortable to you, in a room with air conditioned set up at 70 degrees Fahrenheit and relative humidity set to 35 +/- 5%.
A dry and freshly laundered oversized towel will be provided to you to cover your body after the 30 minutes run on treadmill, while crossing the hallway to the scanning lab. You may also use the same towel on your body (on top of the sports bra and bike shorts) for the 30 minutes resting/drying stage. A bottle of water will also be provided to you during the resting stage, to restore hydration.

- You have complete privacy while changing clothes in the scanning room, and the researcher will see just your scanned body with no details, just data cloud points. You will have to wear only a sports bra along with a pair of knee length bike shorts. All garments will be new and provided.

4. Fill out a brief survey (age, weight, ethnicity, exercise level, perceived comfort level of provided sports bra before and after the run).

5. You may take a break at any time during the process if necessary. Otherwise, your participation will last for no more than 75 minutes.

**Risks or Discomforts**

This scanning technology has been used extensively in university, commercial and military settings. Even though no health-related harm associated with the white-light based body scanners has been reported in the literature / media so far, a person prone to seizures should not participate. Also, a person suffers from claustrophobia should not participate because scanning takes place in a booth with heavy and dark colored curtains. The scanner has no known harm to people who have implanted medical devices. The scanner is fully enclosed for privacy during the scan, and the researcher will be outside of the scanner enclosure to ensure comfort of the participants. Participants can activate the scanner without the assistance of the researcher, by using a button inside the scanner.
Each participant will be assigned a participant number and her name will not be associated with the data collected.

The general risk of running on the treadmill is that of falling down. This risk will be minimized by making sure you are wearing comfortable running shoes and the shoe laces are tight, as well as by being supervised by the researcher during the entire 30 minutes of run. Holding the handrails while you are running on the treadmill also minimizes the risk of falling. You will be shown the treadmill and instructed on how to adjust speed and incline prior to starting the run session to make sure it is comfortable to you at all times.

Benefits

If you decide to participate in this study, there may be no direct benefit to you. Understanding the factors influencing breast support is necessary for future development of better functioning sports bras to prevent wearers from soreness and pain. It is hoped that the information gained in this study will benefit the researcher who will collect data and will benefit future continuation of the study.

Costs and Compensation

You will not have any costs from participating in this study. However, if you request you will be provided with a copy of your body measurements and a file that contains your virtual avatar (you will see your measurements and your avatar right after the scanning sessions). A $15 Amazon gift card will also be offered to you at the end of the scanning session, for your participation in the study.

Participant Rights

Participating in this study is completely voluntary. You may choose not to take part or to stop participating at any time, for any reason, without penalty or negative consequences.

Confidentiality

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy your records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: Your name will not be associated with the demographic survey, body scanning data, apparel pattern, or test garments that will be created. All data will be assigned a participant number. Body scans taken will not include your face or other distinguishing characteristic such as tattoos. If the results are published, your identity will remain confidential.
You are encouraged to ask questions at any time during this study.

- For further information about the study contact Adriana Gorea at 302-690-1842, agorea@iastate.edu or Fatma Baytar at baytar@iastate.edu, or Eulanda Sanders at sanderse@iastate.edu.

- If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

**Consent and Authorization Provisions**

Your signature indicates that you voluntarily agree to participate in this interview, that the study has been explained to you, that you have been given the time to read the document, and that your questions have been satisfactorily answered.

Participant’s Name (printed) __________________________________________

__________________________________________  ______________________
Participant’s Signature                              Date
APPENDIX K

BEFORE, AFTER RUN, AND AFTER RESTING WEAR-TEST

QUESTIONNAIRES

Seamless Sports Bra Design- A Responsive System Exploration
Participant Code: _______ Participant Name: ___________________ Bra number: ______

Demographic Information
1. Age: ___________years.
2. Weight: _________ lbs.
3. Height: _______ ft. _______ inches.
4. Ethnicity:
   - European American
   - African American
   - Native Hawaiian and Other Pacific Islander
   - Asian
   - American Indian/Alaska Native
   - Hispanic American
   - Other (please specify): ___________________________

5. Fitness level (please circle most appropriate number):

   No intentional exercising 1 2 3 4 5 6 7
   Exercise every day

For the following questions, you will be asked to rate features of the bra as shown in the image below:
BEFORE RUN
(Please circle the most appropriate number. You can write comments if you’d like
to give us more feedback)

6. Ease to slide bra over my head and shoulders:

<table>
<thead>
<tr>
<th>Hard</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Easy</th>
<th>7</th>
</tr>
</thead>
</table>

Any comments?

7. Underbust band tightness:

<table>
<thead>
<tr>
<th>Too tight or too loose</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Feels just right</th>
<th>7</th>
</tr>
</thead>
</table>

If appropriate, please circle one: too tight too loose

Any comments?

8. Bra straps tightness:

<table>
<thead>
<tr>
<th>Too tight or too loose</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Feels just right</th>
<th>7</th>
</tr>
</thead>
</table>

If appropriate, please circle one: too tight too loose

Any comments?

9. Support in the bust area:

<table>
<thead>
<tr>
<th>Unsupported or too tight</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Feels just right</th>
<th>7</th>
</tr>
</thead>
</table>

If appropriate, please circle one: unsupported too tight

Any comments?
10. Fabric feel:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itchy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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</tbody>
</table>

Soft

Wet

Any comments?

11. Overall comfort:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncomfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Comfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Any comments?

12. Underbust band tightness:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tr>
<td>Too tight or too loose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feels just right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If appropriate, please circle one: too tight too loose

Any comments?

13. Bra straps tightness:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too tight or too loose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feels just right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If appropriate, please circle one: too tight too loose

Any comments?

14. Support in the bust area:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsupported or too tight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feels just right</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AFTER RUN
15. Fabric feel:

If appropriate, please circle one: unsupported too tight

Any comments?

16. Overall comfort:

Any comments?

AFTER 30. Min REST

17. Underbust band tightness:

If appropriate, please circle one: too tight too loose

Any comments?

18. Bra straps tightness:

If appropriate, please circle one: too tight too loose

Any comments?
19. Support in the bust area:

<table>
<thead>
<tr>
<th>Unsupported or too tight</th>
<th>Feels just right</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

If appropriate, please circle one: unsupported too tight

Any comments?

20. Fabric feel:

<table>
<thead>
<tr>
<th>Itchy</th>
<th>Soft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dry</th>
<th>Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>3</td>
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</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Any comments?

21. Overall comfort:

<table>
<thead>
<tr>
<th>Uncomfortable</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
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<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Any comments?

22. Ease to slide bra over my head and shoulders:

<table>
<thead>
<tr>
<th>Hard</th>
<th>Easy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
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<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td></td>
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</table>

Any comments?

Any overall comments?

THANK YOU!
APPENDIX M

PHYSICAL MEASUREMENTS OF THE TESTED KNIT FABRICS

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Thickness (mm)</th>
<th>Courses</th>
<th>Wales</th>
<th>Knit density (whales/cm X courses/cm)</th>
<th>Weight (g/m2)</th>
<th>Weight/Thickness</th>
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<tbody>
<tr>
<td>#1W</td>
<td>1.49</td>
<td>46</td>
<td>20</td>
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</tr>
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