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# Experimental design and evaluation of a moisture responsive sports bra

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## Abstract

Women prefer to wear a sports bra not only for exercising, but also during resting and daily activities, highlighting deficiencies in current sports bra designs. The purpose of this study was to design, develop, and evaluate a sports bra that offers responsive behavior, in terms of breast support and comfort, both during rest and running conditions. A biomimetic design framework guided the conceptual phase, and moisture responsive plant biomechanics offered a feasible functional model. Fourteen sports bras were developed and wear- tested using college athletes. The moisture responsive panels inside the bra absorbed the sweat generated during running, making the fabric thicker when wet (statistically significant via 3D body scanning results), while maintaining comfort and perceived breast support through sweaty conditions (confirmed via questionnaire results). Adjustments to the underbust band tightness should be pursued, aiming to further improve sports bra functionality, promoting women health and their lifestyles.

**Keywords:** Sports bra, Moisture responsive, Seamless knitting, Functional design, Biomimetics, 3D body scanning

## Introduction

The consumer practice shift of wearing activewear apparel during everyday activities, called *athleisure*, led to a change in expected comfort and functionality of a key clothing item, such as the sports bra (Dhanapala 2015). For women participating in exercise, breast support is crucial, and consumers regard this feature as the main function of a sports bra (McGhee et al. 2013). Generally, sports bras are designed to provide increased levels of support to a woman's breasts, often by compression, in order to restrict movement of the breasts during exercise, at the expense of comfort during resting activities (Dhanapala 2015). Although major developments in fiber and textile technologies have been employed to improve sports bra design and its functional properties, the sports bra industry is struggling to offer an adaptable and responsive design, which can support the breasts during high impact sports, such as running, and also feeling comfortable during rest (Burnett et al. 2015).

In the design of functional apparel, the evidence-based methods combined with the creative processes of fashion design frame the traditional user-centered design approach (Watkins and Dunne 2015). However, many of the innovations in textiles and materials

with adaptive and responsive properties have been informed by biomimicry, or biomimetics, which is an emerging theoretical design framework “that seeks sustainable solutions by emulating nature’s time-tested patterns and strategies” (Frumkin et al. 2011). Biomimetics represents the convergence between biology and engineering, and its applicability to various product design challenges offers opportunities for knowledge transfer between domains, as well as the potential emergence of a new body of knowledge (Cohen and Reich 2016).

Biological systems have been found to offer feasible design analogies to functional apparel design, because they manifest responsive behavior when actuated by environmental factors such as light, moisture, pressure, and motion (Frumkin et al. 2011). Like the functional hierarchy found in the natural systems, a typical sports bra design has several layers of materials (fiber, yarn, and fabric), constituting inter-related subsystems that react when the wearer moves, sweats, and eventually dries out. Instead of drying out the perspiration of the wearer by using moisture wicking fibers and fabrics, as it is the current design practice, a responsive solution is required to absorb the perspiration back into the system. The moisture-induced changes at the material level should preserve the functional properties of the sports bra, such as breast support and perceived bra comfort, through both dry and wet conditions. This mechanism is defined in this study as “responsive behavior.”

Therefore, the purpose of this experimental study was to design a sports bra that offers responsive behavior when actuated by the perspiration of the wearer, meaning the sports bra maintains its comfort and breast support both during rest (dry conditions), as well as during running exercise (sweaty conditions). The biomimetic design framework was used to guide the sports bra conceptual design phase, while Smart Apparel Design Process (SADP) critical path proposed by McCann (2009) was employed for the prototype development and evaluation. No previous studies were found to apply the emerging biomimetic framework to sports bra design, all the way to prototyping and evaluation. The results of this investigation, conceived via an inter-disciplinary framework, provide an innovative approach to improving the design of a key apparel item for women, the sports bra, aiming at encouraging healthier lifestyles, as well as filling significant knowledge gaps.

### **Sports bras as functional apparel**

Sports bras are an essential piece of sporting equipment, and their main purpose is to support a woman’s breasts as she practices sports or physical activities (McGhee et al. 2013). Burnett et al. (2015) found that continuous and repetitive movement without external breast support can result in breast soreness, pain, and sagging. However, the geometrical complexity of women breasts makes designing sports bras with effective breast support difficult (Bowles et al. 2012). The most common complaint is insufficient breast support, especially among the larger breast sizes, with some designs performing better than others, and efficient breast support in design features is often traded off for comfort (Dhanapala 2015). Moreover, McGhee et al. (2013) found that breast movement and bra discomfort are key barriers to exercise, highlighting the two main user-needs: breast support and bra comfort.

### **Breast support**

Currently, sports bras are generally classified into two main categories: (a) compression and (b) encapsulation bras. Compression designs offer breast support by uniformly pressing both breasts against the chest wall, while encapsulation designs separate the breasts and support them individually (Luk and Yu 2016). Compression sports bras with higher necklines were found to better restrict the upward movement of the breasts (Bowles et al. 2012). Starr et al. (2005) claimed that encapsulation bras are more effective in controlling breast movement than compression bras. Other studies reported no significant differences between the two types of bras regarding their reduction of vertical breast displacement (White et al. 2009; McGhee et al. 2013). However, the reduced number of sport bra designs tested represents a significant limitation of the findings. Sports bras that have a combination of compression and encapsulating features were found efficient in managing breast support for women with large breasts (Morris et al. 2017).

Many other factors, such as bra materials, assembly details, and shoulder strap design were found to influence breast movement and support (Zhou et al. 2013). The shoulder straps are essential to support the mass of the breasts, but they often are perceived to be uncomfortable by causing too much pressure on the shoulders (Mills et al. 2015). Crossing the straps at back was found to prevent them from slipping off the shoulders, and use of inelastic materials for wider straps was more efficient at managing breast displacement (Bowles et al. 2012). A comprehensive review of mostly empirical studies of breast motion, biomechanics, and sports bra designs reported inconsistent findings in terms of most efficient design solutions for managing breast support (Zhou et al. 2013). Moreover, the traditional bra sizing system has shortcomings and is unable to cover a broad range of unique anatomical breast shapes (McGhee et al. 2013). Most studies have assumed that breasts are symmetrical, resulting in potentially misleading design recommendations (Mills et al. 2015).

The key performance variables that distinguish between levels of breast support needed during various sport activities are still unclear, and there is no industry standard to determine the performance of sport bras (Zhou et al. 2013). The types of exercises considered in the breast motion studies are mainly walking, running, jogging, and aerobics, and the breast displacement was found to be the highest in running (McGhee et al. 2013). Therefore, sports bras are designed with specific levels of support or compression, based on the nature of the intended activities or motion: (a) high, (b) medium, or (c) low support (Zhou et al. 2013). Burnett et al. (2015) found that each woman has her own comfort tolerance for how much breast support she needs. However, women often prefer to wear a sports bra during most of their daily activities, not just for exercising (Bowles et al. 2012). Therefore, the demand for multifunctional sports bra, which incorporate both, breast support and comfort during various activities, has increased (Dhanapala 2015).

### **Bra comfort**

Lawson and Lorentzen (1990) found that bras that effectively controlled breast displacement scored lower on comfort variable. McGhee et al. (2013) linked breast elevation and

compression to increased breast discomfort, and proposed the inclusion of thick foam pads inside encapsulating bra cups. The tightness of the underbust band was reported to be a comfort deterrent for women to wear a sports bra (Chen et al. 2016). While breast comfort is related to breast displacement, velocity and acceleration, Starr et al. (2005) stated that perception of bra support and perception of comfort are multi-dimensional variables that also involve the transport of moisture and air through the fabric.

### ***Fabric selection***

The use of fabrics with dynamic moisture properties improve the wearer's thermal comfort, and sports bras should have good moisture management properties (Tiwari et al. 2013). Therefore, moisture wicking fibers and fabrics are commonly used for sports bras, along with fabrics designed to allow ventilation (Watkins and Dunne 2015).

Innovations in both yarn and manufacturing technologies have elevated knitted fabrics to have comfort qualities that far outweigh those offered by woven fabrics (McCann 2005). Particularly, the use of weft knitted fabrics in activewear has increased due to the demand of stretchable and tight-fitting garments. (Watkins and Dunne 2015). As a garment worn close to the skin, the seams constructing the sports bras have been found to be uncomfortable, therefore seamless knitted designs made with circular knitting machines emerged (Yip and Yu 2006). Seamless circular knitting machines have been the primary technology used for manufacturing compression sport bras, due to achieving uniform compression levels around the body (Tiwari et al. 2013). The addition of spandex yarns in circular knitted fabrics create a compressive fit that is maintained without deformation during the product life (Lau and Yu 2016). Moreover, a major advantage of creating sports bras on circular knitting machines is the ability to create seamless three-dimensional shaping, such as encapsulating breast shaping, as well as engineered compression and ventilation within different areas of the garment (Lau and Yu 2016). Zhou et al. (2013) found that seamless sports bras are not preferred as daily bras, due to their unflattering compression of the breasts, even though they scored highest on comfort.

### ***Moisture management***

Many studies reported properties of knitted fabrics made of various fibers and yarns capable of absorbing moisture (Troynikov and Wardiningsih 2011; Tiwari et al. 2013; Venkatraman 2015). Commercial sports bras contain elastane, polyamide, or polyester fibers that are lightweight, easy to wash, dimensionally stable, and dry quickly (Zhou et al. 2013). However, (Cotton Incorporated's Lifestyle Monitor Lifestyle Monitor 2015) surveyed 1,500 men and women, and around 70% of women said they prefer cotton and cotton blends for activewear, and 81% associate better quality with all-natural fibers. Although polyester or polyamide fibers cannot provide the high-level comfort of cotton, Coolmax<sup>®</sup>, an enhanced polyester derived fiber, was found to significantly improve moisture wicking and comfort (Venkatraman 2015). Kaplan and Okur (2008) argued that it is necessary to study and use natural fibers in activewear, if they can provide comparable functionality to the ones made of synthetic fibers. Cocona<sup>®</sup>, a new wicking fiber made from coconut shells, is used in Champion's Vapor sports bra, and it is claimed to outperform Coolmax<sup>®</sup> (Lau and Yu 2016).

The structure of the fabric itself can enhance the moisture management properties designed at the fiber and yarn levels (Scott 2015). For example, knitted fabrics made with Teijin's Fibaliver<sup>®</sup>, in presence of moisture, change their stitch density to improve air permeability, and then revert to the dry properties in absence of moisture (Lau and Yu 2016). 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. However, few studies have been investigating the responsive properties of natural fibers as applied to improving the functionality of activewear (Watkins and Dunne 2015).

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 (Scott 2015). Merino wool is an emerging performance fiber, and it has been reported to have properties suitable for activewear, and several seamless knitted sports bra designs are currently on the market made from Smartwool<sup>®</sup> yarns (Millington and Rippon 2017). Pure Merino wool has been blended with other fibers to regulate moisture absorption, wicking, air circulation and to enhance the comfort of the wearer (Venkatraman 2015). 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 and Wardiningsih 2011). Wool has been found to have better responsive behavior when actuated by moisture than cotton, because wool has approximately a 30% increase in diameter when absorbing moisture, one of the highest out of all natural fibers (Scott 2015; Sarkar et al. 2010).

Moreover, during the selection of fiber and fabric types used for the design of sports bras, it is important to consider the sweat patterns of the wearer (Venkatraman 2015; Watkins and Dunne 2015). For female runners, it was found that the center front area between the breasts accumulates the most sweat (Havenith et al. 2008), and that is where moisture management has to be systematically designed into the details of the fiber, yarn, fabric, and shape of the sports bra. Moreover, researchers have used both objective and subjective measurements to evaluate the moisture management performance of sports bras (Bowles et al. 2012).

### **Design process for sports bras**

Watkins and Dunne (2015) stressed the importance of thorough understanding and framing of the user needs for all design activities. However, sports bras marketplace has experienced a convergence of functionality, comfort, and fashion, highlighting new user needs, and creating new complexities for product developers and designers (Dhanapala 2015). Therefore, various researchers focused on limited target cohorts of sports bra users, with specific anatomy and functional requirements (Barner and Morris 2016; Morris et al. 2017). Watkins and Dunne (2015) suggested the User Centered Design (UCD) framework as suitable for a wide range of functional clothing designs. The UCD approach leads the designers through five stages: (a) mapping of the exact user needs, via questionnaires, interviews, and focus groups, (b) determination of user goals for the product to be successful, (c) designing of solutions, (d) evaluation of solutions through wear-testing with actual users, and (e) assessment of the solutions (Morris et al. 2017).

However, (Frumkin et al. 2011) argued that there is a growing distinction between designing products using already developed and well-defined technologies, and designing products using new technologies and embedded functions. The efficient integration of a responsive function into textiles cannot be achieved as an added layer, but it has to be considered simultaneously throughout the design development process of the entire product (Watkins and Dunne 2015). McCann (2009) proposed the Smart Apparel Design Process (SADP) framework, as an inclusive guide for the responsive (smart) garment design process, which considers all the challenges that embedded technologies bring to the prototype development. The suggested design critical path through disparate yet interdependent stages, includes the following: (a) identification of end-user needs, (b) textile development, (c) garment development, (d) integration of smart technologies, (e) garment manufacturing, (f) distribution, and (g) end-of-life recycling. Each stage begins before the previous one is finished, and many can overlap (McCann 2009). This systematic design process is currently used in the industry for developing sports bras with embedded biometric monitoring functions.

Although all designs involve creative problem solving, the ideation process is not often included in design process models (Cohen and Rich 2016). *Biomimetics*, a term defining the process of transferring knowledge from the responsive natural systems into technology, has been a theoretical model that produced significant innovations in the past half of the century (Vincent et al. 2006). Breakthrough innovations often result from functional analogies between different domains, such as biology and functional apparel design (Vincent et al. 2006). However, biomimetic research and its applications to functional apparel design has been done on a case-by-case basis. Cohen and Rich (2011) proposed a multi-disciplinary six steps iterative biomimetic design process: (a) problem definition, (b) biomimetic problem definition, (c) identify analogical source, (d) abstract design solution, (e) transfer solution to biomimetic application, and (f) evaluation and iteration. This sequence of steps, overlapped to SADP framework, created a hybrid design process that better fit the purpose of this study.

### Research gaps and questions

Sports bras studies that were reviewed in the previous sections concluded that, despite the existing wide range of styles, manufacturing approaches and design processes employed, there is a significant need for improved sports bra design (Bowles et al. 2012; McGhee et al. 2013; Zhou et al. 2013; Lau and Yu 2016). The increased focus on designing for efficient breast support, resulted in many designs that are uncomfortable and actually deter women from practicing sports (McGhee et al. 2013; Bowles et al. 2012). Moisture management at fiber and fabric levels was found to be related to perceived bra comfort, but no studies investigated the variations in perceived comfort and breast support between dry and sweaty conditions (McCann 2005; Venkatraman 2015). Moreover, no literature was found regarding studies of sports bras that have adaptive, responsive properties. The few examples of responsive sports bras commercially available involve e-textiles in order to monitor biometrics, with bras producing an electronic output to a watch or a phone, and not changing or adapting the fit and comfort functionality of the sports bra itself (McCann 2005). Although biomimetics have been used in enhancing performance of various functional apparel designs, no studies reported on attempts to

create a moisture responsive sports bra design using a biomimetic analogy. (Lovel et al. 2006) developed a theoretical proposal for a bra strap design, using biomimetic framework, but without developing a prototype and evaluating the solution.

By addressing the literature gaps mentioned above, the aim of this study was to develop a sports bra that is comfortable and supportive when dry, but, in a biomimetic manner, it can change its material properties to absorb the moisture generated by the wearer during running, to maintain perceived comfort and breast support when wet. In order to achieve this aim of the study, the following three research questions (RQs) were created, reflecting the main stages of the design process: (a) design (RQ1), (b) develop (RQ2), and (c) evaluate (RQ3):

RQ1: What biomimetic-inspired design features can be included in a moisture responsive sports bra?

RQ2: What challenges exist in integrating the moisture responsive design features into a sports bra prototype?

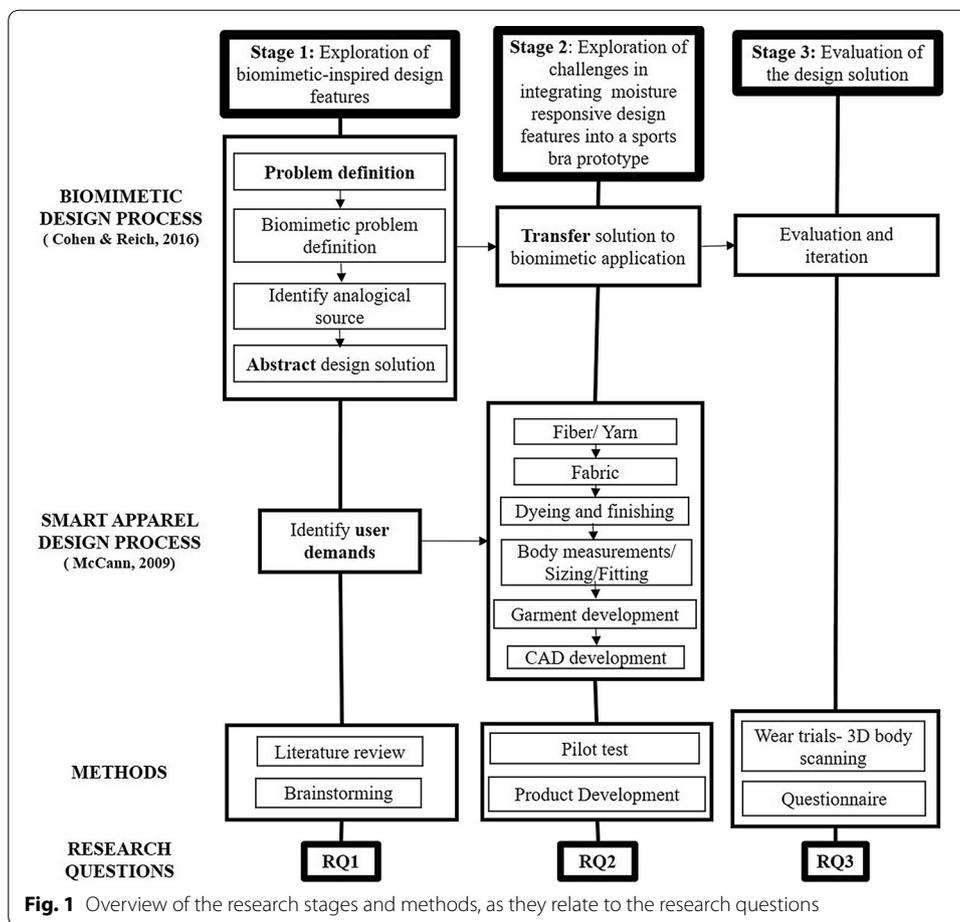
RQ3: To what extent would the moisture responsive sports bra prototype be successful, meaning that will maintain breast support and bra comfort in both dry and wet conditions?

## Methods

This experimental research was completed in multiple stages, each reflecting one of the above-mentioned research questions, and combining Cohen and Reich (2016) biomimetic design framework with parts of SADP framework, as illustrated in Fig. 1.

### Stage 1: Exploration of biomimetic-inspired design features (RQ1)

In order to redefine the problem in biological terms, brainstorming for terminology related to “moisture absorption” led to biological terms such as “passive actuation,” “plant bio-mechanics,” “hydrophilic fibers and surfaces,” and “cell structure” (Helms et al. 2009). The abstraction process was guided by visual references of the above-mentioned terms, resulted from searches through published biology literature (Milwich et al. 2006). Cohen and Reich (2016) concluded that, the abstraction step often involves a so-called “Bio-WOW” moment, a metaphor for the moment of wonder achieved by observing biological mechanisms and realizing their possible functional applications in a different domain. When the environment is dry, plants’ cells and their tissue become soft, but in presence of adequate moisture, they absorb the water and their tissue becomes thicker and uprising. Similarly, a sports bra should be soft when dry and the wearer is at rest, but when perspiration occurs, the sports bra material should become thicker in the breasts area and maintain breast support during running. Upon drying off, the sports bra should return to the soft condition. This abstract responsive analogy found via creative functional comparisons between plants tissue and knitted material guided the design process of the responsive sports bra prototype. Google searches for images of microscopic views of plant cell structures in both dry and wet conditions were performed, and similar geometries to various



**Fig. 1** Overview of the research stages and methods, as they relate to the research questions

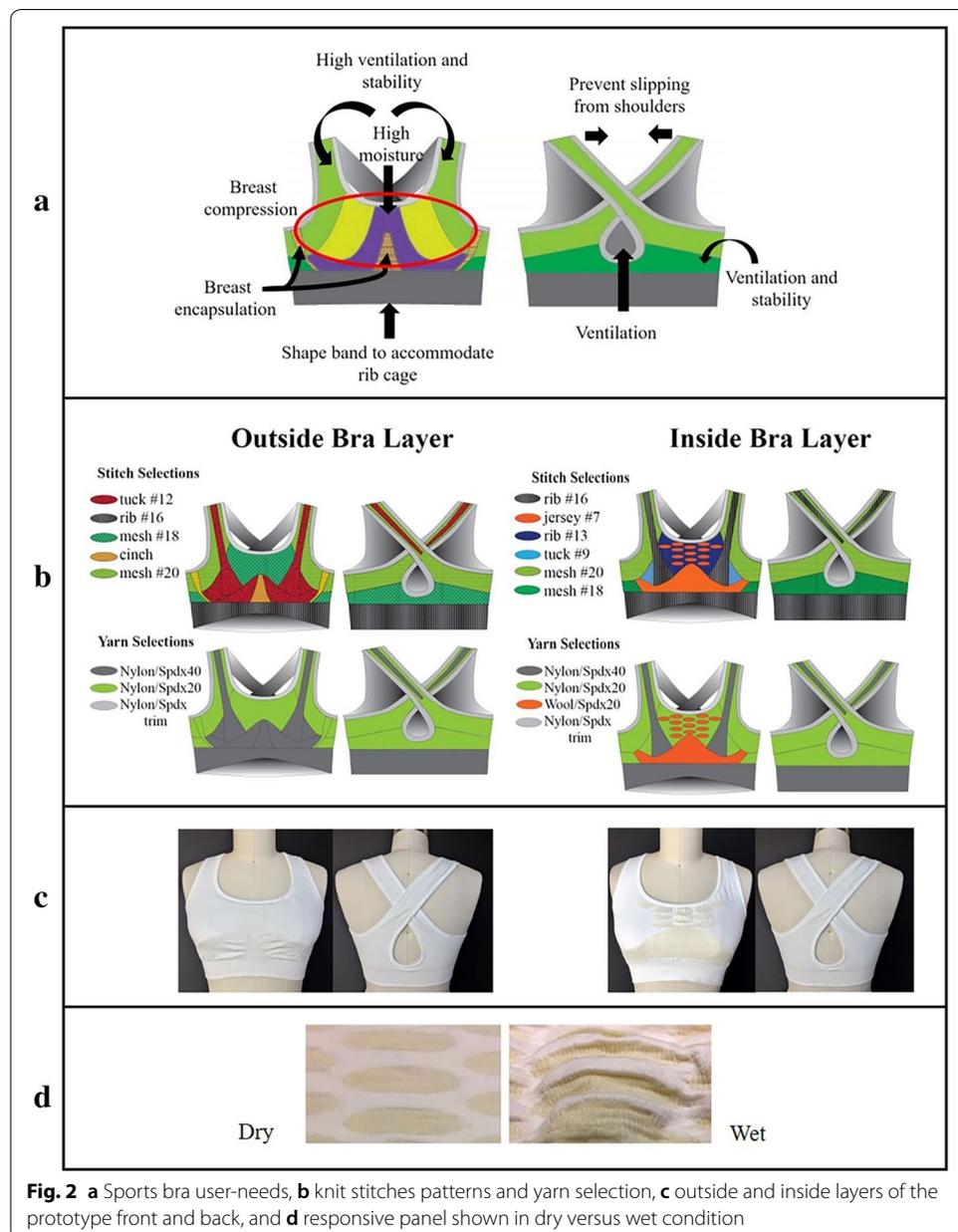
knitted stitches and patterns were noted. Therefore, a collection of fabric swatches was created, featuring knitted stitches and patterns with various yarns and knitting technologies, and used for experimentation.

For the purpose of this study, the user needs were mapped via results of previous research studies, along with the lead author’s learnings while working for several years in sports bra product development for a major athletic brand. Various areas of a sports bra design were outlined as a result of combining sweat maps, high-stress wearing areas around the breasts, body kinetics, and ventilation-required areas. Specifically, the tightness of the underbust band was found to be a comfort deterrent for women to wear a sports bra, so changing its design to better fit the shape of a woman’s rib cage should be considered (Chen et al. 2016). Compression sports bras were found to be more efficient when having higher necklines that restrict the upward movement of the breasts, and wider shoulder straps which help distributing the pressure on the shoulders (Bowles et al. 2012). Crossing the straps at back was found to prevent straps slipping off the shoulders (Zhou et al. 2013). Encapsulation sports bras separate the breasts using a center front insert (a gore or triangular shape), and breast cup side slings are usually placed inside to limit the lateral breast movement (Bowles et al. 2012). Moisture wicking fibers and fabrics are commonly used for sport bras, along

with fabrics that allow ventilation (Watkins and Dunne 2015). The intersection of the areas marked for presence of high moisture, as well as required breast compression, highlighted the necessary placement of moisture responsive parts of the new sports bra design (Domina et al. 2016). A graphic representation is shown in Fig. 2a.

**Stage 2: Exploration of challenges in integrating the moisture responsive design features into a sports bra prototype (RQ2)**

Guided by SADP, an experimental textile development pilot test was conducted to identify moisture responsive behavior from various natural fibers and yarns feasible for seamless knitted sports bras designs (Gorea 2017). Bismarck et al. (2002) found that



both cellulose and protein natural fibers have dynamic moisture absorption properties; fibers increase in volume in the presence of moisture and there is little change in the overall length of the fiber. Particularly, wool fibers have the highest diameter increase (30%), as well as moisture regain compared with all fibers, and blending wool with polyester or wool with bamboo can improve the moisture management properties of circular knitted fabrics (Troynikov and Wardiningsih 2011). Millington and Rippon (2017) suggested that the emerging superfine wool blends could be used for moisture responsive fabrics in activewear.

Santoni circular knitting technology allows for the design of a wide range of textural patterns, combining tuck, miss, plain and float stitches; as well as alternating the wool and spandex yarns, but its high speed and 28-gauge sizing of the needles require particular yarn specifications. Only two different yarns were found to be available for sampling: (a) 90% wool 10% Nylon yarn, undyed, from a domestic supplier, and (b) 100% wool yarn, dyed light grey from an overseas supplier. By trial and error, the only yarn that was found to be feasible for preparing samples on a conveniently available Santoni Top 2 circular knitting machine was the 90% wool 10% Nylon yarn, size 60/1, undyed, supplied by Sudwolle, Germany. The other yarn was not strong enough and continued to break. To add compression qualities to the knitted fabric, this yarn was knitted together with 20–20/10/1 Nylon covered 210D bare elastic yarn (Yip and Yu 2006). Stage 1 results highlighted the need to combine moisture responsive with non-responsive yarns, therefore a commonly used 78/68/1 100% recycled Nylon undyed yarn was domestically sourced and used.

In order to simulate the human sweating conditions, a saline solution that is currently used for moisture management testing was used to test moisture responsiveness of the fabric swatches developed in the pilot study. For this test, Yao et al. (2008) recipe of 1-L distilled water and 9 g of sodium chloride was used, and moisture actuation was made by spraying at 4" distance right above the swatches, at an approximately 45-degree angle.

The seamless knitted sports bras are constructed by folding a knitted tube and creating two layers for the bra, the fold having ribbed stitches and becoming the underbust band (Lau and Yu 2016). For the inside layer of the bra, two different areas were selected for the moisture responsive placement as suggested by the sweat maps of Havenith et al. (2008): (a) the part under the bust needed to be thick and highly absorbent, and (b) the area part between the breasts right below the neckline needed to be quick drying, but textural, to aid breast support. For the later, hydrophilic-inspired circular islands of wool yarn were designed, simulating the high absorption arrangement of mushroom fields (Charpentier et al. 2017). The wool yarn floats between the islands were trimmed off, to allow for edges to curl when actuated by sweat. The plain jersey stitch pattern used for the wool patches was found in the pilot test to be the fastest edge curling, therefore the wool patches were filled with jersey stitches. All the other stitch patterns were placed on the new design based on their pilot testing fabric thickness results and hand feel, combined with the user-needs mapped in Fig. 1a. Design details are shown in Fig. 2b.

The textile development and bra prototyping took place at a domestic seamless knitting product development facility, used by several major sports bra brands. Based on findings from a previous study, seamless sports bras' first prototypes are generally developed in the middle size of their range from XS to XL, therefore medium-sized prototypes

were prepared for the wear tests (Gorea 2017). Garment specifications were prepared starting with a generic seamless bra sample purchased from the market, a Women's Tek Gear® Seamless Sports Bra, size Medium. However, the circumferences of the prototype's underbust band and bust were increased to 34" and respectively 36", allowing for a more comfortable fit. To avoid the industry customary seamless knitted garment dyeing process that results into extensive water waste, the new sports bra design specifications required no dyeing, just tumbled drying at low temperature for 90 min to relax the knitted fabric (Lau and Yu 2016).

### **Stage 3: Evaluation of the design solution (RQ3)**

Institutional Review Board approval was obtained prior to human participant testing. In order to minimize the variability of body shapes around the bust area, semi-professional athletes, such as female college students at a mid-western university participating in team sports, were recruited for the wear trials. Recruiting was made via university mass email, and inclusion criteria were women who were at least 18 years old, were actively engaged in regular physical exercise through participating in college team sports, and had maximum bust circumference of  $37'' \pm 1''$ . The bust measurement represented the bust size specification for the initial bra that was used for the prototype development, Women's Tek Gear® Seamless Sports Bra, size Medium, as stated in the Tek Size Chart on the product's website (Kohl's 2017 March 10). Following the steps of previously published wear studies of new functional apparel products, which typically used 8 to 15 participants (Morris et al. 2017), 14 female participants were selected for this study. Their average age was 23.3 years old ( $SD = 5.06$ ), their weight average was 136.7 lbs. ( $SD = 10.7$ ), and their average height was 5'4" ( $SD = 1.9''$ ). All participants signed an informed consent and filled out a demographic survey with questions about their age, height and weight.

A Textile/Clothing Technology Corporation [TC]<sup>2</sup> NX-16 3D body scanner was used to collect body measurements data between various sweat conditions. In addition to the basic bust area girth measurements such as under bust and bust, scan slices provided by the scanner's software were collected. Scan slices are often used to visually represent changing size and circumferences (Zheng et al. 2007). McGhee et al. (2013) found that respiratory state affects the measurements for underbust band circumference, therefore, fully inhaled (participantss held respiration for 10 s during the scan) and exhaled (regular breathing with minimal accessory muscle effort) conditions were recorded for each scan, and the data was averaged. To track the responsiveness of the bra prototypes, participants were scanned eight times as follows: (a) wearing No Bra, inhaled, (b) wearing No Bra, relaxed, (c) wearing bra, inhaled, before run, (d) wearing bra, relaxed, before run, (e) wearing bra, inhaled, after 30-min run on treadmill, (f) wearing bra, relaxed, after 30-min run on treadmill, (g) wearing bra, inhaled, after 30-min rest, and (h) wearing bra, relaxed, after 30-min rest. Questionnaire data was also collected, to evaluate the perceived comfort and breast support of the new prototype (Bowles et al. 2012).

### **Questionnaire design**

Doyle et al. (2015) found that evaluation of comfort includes many inter-related components, and often the wearer cannot consistently describe the sensation of comfort. For

the purpose of this study, since seamless sports bras are not designed with cup specific sizing, the bra fit was broken down in comfort components, and subjective bra fit was assumed to be captured in the overall bra comfort variable. Moreover, all participants were asked for verbal confirmation of appropriate size and bra fit after putting on the bra, before starting the scanning session. Hence, the questionnaire was focused on comfort assessment of various bra features for each different sweating condition: (a) before run, (b) after run, and (c) after 30- minutes rest. Additionally, one open-ended question was included, asking for additional overall comments. A 7-point Likert-type scale, anchored from low score (1) to high score (7) was used for each question (Lawson and Lorentzen 1990). Descriptive statistics were computed, for each of the variables evaluated in the questionnaire: (a) ease to slide bra over head and shoulders, (b) underbust band tightness, (c) bra strap tightness, (d) support in the bust area, (e) fabric feel (Itchy/Soft), (f) fabric feel (Dry/Wet), and (g) overall comfort.

### ***Wear testing protocol***

After collecting the basic body measurements in the breast area via the No Bra scans, the participants put on a randomly assigned bra prototype and conducted the scans for the Before Run condition. Afterwards, participants filled out the first part of the questionnaire, aimed to inform on their perceptions of breast support and comfort in the Dry condition. For the running session on the treadmill, participants wore their own running shoes, their own running pants, and a provided randomly assigned 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 ( $\pm 5\%$ ). Several fans were turned on in the room to ensure proper ventilation. Each participant designed their 30-min run according to their own level of comfort, simulating real-life situations. At the end of the timed running session, each participant filled out the After Run part of the questionnaire, then conducted the After Run scans. After the timed resting session, they conducted the After Rest scans, then filled out the corresponding part of the questionnaire.

In addition to the basic bust area girth measurements, scan slices provided by the 3D body scanning software are often used to evaluate body-changing circumferences (Lee and Hong 2013; Gorea and Baytar 2016). Seventeen slice circumferences taken at 0.25" increments upward from the underbust level were collected for each scan condition. This area represents the body surface covered by the sports bra, and included the moisture responsive system. Analyzing the variability of slice circumference measurements between the scanning conditions was considered as an indicator for responsiveness to moisture actuation. Means, standard deviations (at a 95% confidence interval) and pairwise comparisons between the means of all conditions were calculated for questionnaire ratings as well as 3D body scanning data, using standard (JMP 14 2017) statistical software.

## **Results and discussion**

### **Stage 1 Results for RQ1 (exploration of biomimetic-inspired design features)**

The actuation mechanism of plants when absorbing water was chosen to be an appropriate abstract analogy model for analysis, as plant bio-mechanics are controlled by various

cell structures that, under microscope, are visually similar to interloped stitches of a knitted material (Fratzl and Weinkamer 2007). Analogous to the fibers in the yarns, and the type of knitted stitches in a sports bra, the hierarchical structure and orientation of the cellulose fibers determine the overall shape and behavior of the plant cells (Charpentier et al. 2017). Specifically, the alternation of hydrophilic and hydrophobic cells in a plant structure is what prompts the bio-mechanic change in plant tissue, and this alternation was found to be feasible to be used in the selection of fibers, and yarns, combined with the ability of Santoni Top 2 knitting machine of creating intarsia patterns by varying the yarns between circular patches of hydrophilic yarns. As a result, the distance between the circular patches was determined by the limitation of the knitting machine, which requires a minimum of 40 stitches in order to cut off the floating yarn behind the pattern. The observed curling action of the edges of the hydrophilic circular patches resulted in the decision to cut off the floating yarns, to allow for full shape deformation of the moisture responsive knitted fabric.

#### **Stage 2 Results for RQ2 (exploration of challenges in integrating the moisture responsive design features into a sports bra prototype)**

Based on yarn selection and design decisions made in Stage 1 as well as the textile development pilot study, an industry customary tech pack was created to serve as guideline for specifications during the product development process. The knitting technician used Adobe Illustrator to draw the various stitch areas on a seamless sports bra template similar in shape and fabric density (28-gauge) with the one designed for this study. Stitch patterns determined during the pilot study were filled in the color-coded marked areas, then Santoni Top 2 specific software was used to calculate and integrate all the designed shaping for breast encapsulation and underband bust. A chain program was also created to control the tension and yarn changes for each machine needle. Although lateral encapsulation was initially designed for the inside layer of the bra, to aid with breast support, the intarsia alternation of the yarns complicated this part of the design. The decision was made to not incorporate the encapsulation inside the bra due to the technical difficulties, and to focus on the novel moisture responsive function of the prototype.

Seamless knitted bras 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 seamstress 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 with flatlock stitches. 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 bra shape. After the seamless tubes were knitted, they were folded in the middle of the underband, to reflect their final shape and avoid further wrinkles on the fabric during air-drying for 48 h in standard conditions (20 °C, 60% RH). The process was followed by laundering in cold water (60 °C) for 60 min in a revolving drum washing machine (GE) and tumble dried at low temperature (70 °C) for 90 min, in order to relax the knitting but not alter the wool yarn texture (Choi and Ashdown 2000).

Currently, most commercial sports bras have elastic trim sewn to the armholes, to finish the cutout fabric edges resulted from the carving of the bra silhouette out of the

seamless knitted tube. The elastic trim was found to help with the problem of bra strap slipping off the shoulders, therefore a wider (5/8") nylon/spandex trim was selected, allowing for a softer edge of the bra around the armholes and neckline. The final responsive sports bra prototype is shown in Fig. 2c. Twenty bras of this design were manufactured, all size medium, then measured and inspected against the specs to confirm measurements. Before proceeding with the wear testing, a random bra was chosen and the responsive panel was sprayed with the same saline solution used for the fabric moisture responsiveness testing. Moisture actuation was confirmed with visual analysis (before and after spraying) as shown in Fig. 2d.

### Stage 3 Results for RQ3 (evaluation of the design solution)

Pairwise comparison results for average slice circumferences in all scanning conditions, shown in Table 1, revealed a significant difference between the slice circumferences in Dry condition ( $M=33.76$ ,  $SD=0.86$ ) and the No bra condition ( $M=34.13$ ,  $SD=0.92$ );  $t(13)=2.40$ ,  $p=0.03$ . In other words, the sports bra prototype offered significant compression of the breasts in the Dry condition.

The only other statistically significant difference but representing the most important result, was found between slice circumferences in After Run condition ( $M=34.08$ ,  $SD=0.99$ ) and Dry condition ( $M=33.75$ ,  $SD=0.86$ );  $t(13)=2.51$ ,  $p=0.026$ , meaning that the slice circumferences became larger when the responsive patches got wet, in After Run condition, versus when they were dry before the run. Moreover, the results show that after partial drying, in After Rest condition ( $M=33.86$ ,  $SD=0.91$ ), the slice circumferences became smaller than in After Run condition, when wet ( $M=34.08$ ,  $SD=0.99$ );  $t(13)=-1.39$ ,  $p=0.19$ , but not significantly smaller. Lastly, the slice circumferences in After Rest condition practically returned to their Dry condition measurements, with the 0.08" difference in mean not being significant.

Descriptive statistics for the questionnaire results, as well as the comments for each variable in various conditions are shown in Table 2. The responsive behavior of the new sports bra was hypothesized to result in no significant changes between the ratings of

**Table 1 Means and standard deviations of all slice circumferences (in Inches) for all participants and scan conditions, and pairwise comparison results for average slice circumferences in different conditions**

Conditions	Statistic results				
	<i>M</i>	<i>SD</i>	<i>t</i>	<i>df</i>	<i>p</i>
No bra	34.13	0.92			
Dry	33.76	0.86			
After run	34.08	0.99			
After rest	33.86	0.91			
Condition pairs					
Dry-no bra	0.36	0.57	2.40	13	0.03*
After run-dry	0.32	0.48	2.51	13	0.03*
After rest-after run	-0.24	0.65	-1.39	13	0.19
After rest-dry	0.08	0.61	0.50	13	0.63

*M* mean, *SD* standard deviation

\* $p < 0.05$

**Table 2 Questionnaire results for all variables, participants, and conditions: means (standard deviations), and participants comments**

Variable	Condition		After run M (SD)	Comments	After rest M (SD)	Comments
	Dry M (SD)	Comments				
Ease to put on/ take off the bra	6.57 (0.51)	"I think the independent racer back straps really helped", "Fabric has a nice 'give' to it"	n/a		6.21 (1.42)	"My shoulders are broad, so getting bras off can be annoying. This one was easy to remove, however"
Underbust band tightness	5.29 (1.73)	"Too loose, just a tiny bit", "Slightly loose"	5.14 (2.07)	"I was worried it would be loose, but it felt good during the run", "Felt so much better than most sports bras"	5 (2.22)	"Feels like the underband formed to my body", "The bra feels good, I can compare it with the first time I put it on"
Bra strap tightness	4.93 (2.2)	"Too loose: I have a short distance between my shoulders and chest."	4.5 (2.35)	"Not as bad as I thought", "Not tight or too loose"	4.5 (2.31)	"I like those bra straps because they don't loose over the time I was running, neither the time I was resting. It feels very comfortable to wear"
Support in the bust area	4.71 (1.59)	"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"	4.28 (2.55)	"A little jiggly", "Felt like it worked with my body"	6.5 (1.09)	"This is not a bad fit, but I do personally prefer bras to have a bit of lift. This is comfortable but not lifted", "Feels very loose/stretched out, loose in between breast"
Fabric feel: Itchy/Soft	6.79 (0.43)		6.57 (0.94)		3.57 (1.65)	"Still love how the fabric feels"
Fabric feel: Dry/Wet	1.5 (0.94)	"Can hardly feel a thing!"	3.64 (1.28)	"Pretty dry for how sweaty I got!", "Clung to me past workout when I really started to sweat", "Very comfortable, breathable fabric!"	6.43 (0.76)	"It rapidly changed from wet to dry. My bra feels dry. During the first 10 min after running it felt very itchy and tight.", "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"
Overall comfort	6.57 (0.76)	"Very comfy!"	5.79 (1.97)	"Seems to wick away sweat well.", "The bra is very light feeling, and didn't seem to get sopping wet like others I've had."	6.64 (0.63)	"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!"

M mean, SD standard deviation

**Table 3** Pairwise comparison results for questionnaire variables in different conditions

Variables	Condition pairs														
	After run-dry				After run-after rest				After rest-dry						
	$\Delta M$	SD	t	df	p	$\Delta M$	SD	t	df	p	$\Delta M$	SD	t	df	p
Underbust band tightness	-0.1	0.44	0.32	13	1.504	1.07	0.38	2.79	13	0.03*	-0.9	0.34	-2.74	13	1.97
Bra strap tightness	-0.4	1.40	-1.15	13	1.456	0.5	0.33	1.53	13	0.301	-0.1	0.2	-0.37	13	0.56
Support in the bust area	-0.4	0.51	-0.84	13	1.167	0.21	0.42	0.51	13	1.240	0.21	0.54	0.40	13	1.39
Fabric feel (Itchy/Soft)	-0.2	0.28	-0.76	13	1.082	-0.1	0.07	-1.00	13	1.329	0.29	0.32	0.89	13	0.78
Fabric feel (Dry/Wet)	2.14	0.31	6.87	13	0.00**	-0.1	0.47	-0.15	13	0.235	-2.1	0.52	-4.00	13	2.00
Overall comfort	-0.8	0.50	-1.56	13	1.713	-0.6	0.48	-1.35	13	1.600	-0.1	0.21	-0.69	13	1.00

\* $p < 0.05$ , \*\* $p < 0.001$

the variables between the scanned conditions. However, pairwise comparison results, shown in Table 3, revealed significant differences in ratings for the underbust band tightness between After Run condition ( $M=5.14$ ,  $SD=2.07$ ) and After Rest condition ( $M=5.00$ ,  $SD=2.22$ );  $t(13)=2.79$ ,  $p=0.03091$ . Even though the underbust band tightness was designed to be larger than that of standard market bras, to allow for more comfort, the tightness needs improvements. One specific comment highlighted that women might have preconceived expectations about this variable: "I was worried it would be loose, but it felt good during the run." The only other significant ratings difference was found for the fabric feel (Dry/Wet) between After Run condition ( $M=3.64$ ,  $SD=1.28$ ) and What biomimetic-inspired design Dry condition ( $M=1.50$ ,  $SD=0.94$ );  $t(13)=6.87$ ,  $p=0.0002$ . The flurry of comments for this variable in the After Rest condition show that, as the body cools down after sweating, the perception of fabric wetness changes: "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."

For all other variables, there was no significant difference between the responses in any of the conditions, confirming the responsiveness of the bra design in maintaining bra comfort as well as perceived breast support. Some comments on the breast support variable showed personal preferences related to aesthetics versus comfort: "This is not a bad fit, but I do personally prefer bras to have a bit of lift. This is comfortable but not lifted." The participants expressed their satisfaction with the ease of putting the bra on as well as taking it off, reflected in the average ratings above 6 out of 7 across all conditions. Particularly, one participant commented: "I think the independent racer back straps really helped." Furthermore, in the open comments section, one of the participants captured the successful experience of wearing the responsive bra, concluding after the wear test:

*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 resting, it seems that the bra adjusted again itself to my body. It came dry quickly.*

## Conclusion and implications

This study focused on the conceptualization, product development, and evaluation of a sports bra design aimed at integrating moisture-responsive functionality that aids breast support. The use of biomimetic framework as functional inspiration offered a feasible analogy to plant biomechanics, which furthermore led to the engineered alternation of performance wool and Nylon yarns, as hydrophilic and hydrophobic materials respectively. Moreover, images of moisture absorptive patterns, such as mushroom fields, led to the design of circular shapes into the knitted material, that was further developed via the jacquard knitting capabilities of the advanced Santoni Top 2 seamless knitting technologies. The size and shape of the inserted wool patches were also determined by the number of stitches allowed by the machine in order for the floating yarn to be automatically trimmed off. Therefore, the process of systematic

integration of a moisture responsive function from fiber to yarn, to knitted structure, and to final garment shape, highlighted the need for more scientific research into how advances in knitting manufacturing technologies can transfer innovation into garments.

The use of wool yarn as a moisture responsive material in activewear is in the infancy stages, and yarn sourcing for the superfine size required by Santoni knitting machines was difficult. Therefore, collaborations with fiber and yarn manufacturers were proven essential in pursuing a biomimetic inspired design, confirming the interdisciplinary nature of this framework, and facilitating opportunities for inter-domain innovations (Cohen and Reich 2016). The exploration of a biomimetic analogy was initiated by aiming to help users' needs of adaptable breast support in different sweating conditions, while maintaining comfort. Integrating and developing the moisture responsive mechanism from the material all the way to a wearable sports bra prototype that could be evaluated and tested, required the use of SADP, a process framework for smart apparel design (McCann 2009). Particularly, considering the sizing and manufacturing limitations of developing seamless sports bras, but maintaining consistency in evaluating moisture responsiveness both at material and garment levels, were challenging. Further studies should be done for adding color to the new prototype and maintaining its moisture responsiveness.

The use of 3D body scanning technology was a convenient yet experimental method to measure the changes in breast compression variability in various moisture conditions, as captured by averaging slice circumference measurements (Gorea and Baytar 2016). The moisture responsive panels inside the bra were designed to absorb the sweat generated during running, making the inside fabric thicker when wet versus dry, and a statistically significant difference was found in average slice circumferences in After Run condition (wet) and Dry condition. Moreover, the results showed that after partial drying, the slice circumferences became smaller than when wet, but not significantly smaller, and practically returned to their Dry condition measurements but not exactly. These findings suggest that further studies are needed with longer resting time period, to find out if this moisture responsive system returns to its dry measurements, or what changes can be done at material design level to ensure the return to dry measurements.

The questionnaire aimed at evaluating if the overall sports bra design managed to maintain the comfort and appropriate perceived breast support through various sweat conditions despite the changes at the material level. The results revealed significant differences in ratings for the underbust band tightness between wet and partial dry conditions, therefore some improvements are needed. The underbust band did not have any moisture responsive panels, as its placement on the body is below the area of maximum sweat accumulation which is between the breasts (Havenith et al. 2008). However, these results suggest that integration of wool patches in the underband could lead to improved comfort in this area. Moreover, further studies on correlation between body temperature variability between conditions and perceived comfort should be pursued, confirming the broad, systematic and iterative nature of McCann (2009) SADP framework. Many participants compared this sports bra prototype with their current sports bras, and remarked on the comfort improvements. There were

many comments such as “Too loose” regarding various bra features; however, the participants’ personal tolerances and expectations of sports bra tightness should be further studied. The aim was to create a bra that would be comfortable to wear for daily activities as well as for exercise, therefore a longitudinal study should be pursued, and a control bra shall be included.

Multiple factors involved in bra sizing and fitting, as well as the variety of body shapes, exercise types, and sweating add complexity and limitations to this study. Fiber and yarn selection, based on testing made with technology and knowledge available at the time of the study, were other limitations. Also, among several 3D body scanner types that are currently available, significant differences exist in capturing specific body measurements (Watkins and Dunne 2015). Advances in scanning technologies will demand re-evaluation of results and might lead to different design improvement recommendations. Overall, the evaluation of responsive functional apparel was confirmed to be challenging (Venkatraman 2015), as scientifically measurable performance characteristics often are influenced by intangible personal preferences, such as aesthetics and social trends.

The biomimetic-inspired approach to the sports bra design, integrating together all processes and materials of a hierarchy serving the same function, provides a novel framing for the design process of a sports bra as a functional design garment. The use of advanced sports bras manufacturing technologies, such as Santoni seamless knitting for prototyping this new design, makes this current study relevant for the development of commercial sports bras. The current study also bridges the knowledge gap between academic research and commercial practice and creating opportunities for improving women health and their lifestyles (Watkins and Dunne 2015). Moreover, this research adds to the scientific and applied body of knowledge in the fields of textiles and moisture responsive compression, with possible applications to post-surgery recovery garments or medical bandages.

#### **Acknowledgements**

Not applicable.

#### **Authors’ contributions**

AG carried out the data collection, analyzed, drafted and edited the manuscript, FB and ES contributed significantly to the data analysis and manuscript editing. All authors read and approved the final manuscript.

#### **Funding**

Part of this research was funded thanks to the Donna R. Danielson Endowment fund.

#### **Availability of data and materials**

The datasets used and analyzed for the current study are available from the corresponding author on reasonable request.

#### **Ethics approval and consent to participate**

IRB Institution is Iowa State University, Ames, IA, USA (IRB number: 17-220).

#### **Competing Interests**

The authors declare that they have no competing interests.

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Received: 13 August 2019 Accepted: 9 February 2020

Published online: 05 July 2020

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