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Comparative study of moisture adaptable breast support using engineered fabric design in seamless knitted sports bras

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Abstract

Purpose – This study aims to investigate if engineered compression variations using moisture-responsive knitted fabric design can improve breast support in seamless knitted sports bras.

Design/methodology/approach – An experimental approach was used to integrate a novel moisture-responsive fabric panel into a seamless knitted bra, and the resulting compression variability in dry versus wet conditions were compared with those of a control bra. Air permeability and elongation testing of between breasts fabric panels was conducted in dry and wet conditions, followed by three-dimensional body scanning of eight human participants wearing the two bras in similar conditions. Questionnaires were used to evaluate perceived comfort and breast support of both bras in both conditions.

Findings – Air permeability test results showed that the novel panel had the highest variance between dry and wet conditions, confirming its moisture-responsive design, and increased its elongation coefficient in both wale and course directions in wet condition. There were significant main effects of bra type and body location on breast compression measurements. Breast circumferences in the novel bra were significantly larger than in the control bra condition. The significant two-way interaction between bra type and moisture condition showed that the control bra lost compressive power in wet condition, whereas the novel bra became more compressive when wet. Changes in compression were confirmed by participants' perception of tighter straps and drier breast comfort.

Originality/value – These findings add to the limited scientific knowledge of moisture adaptive bra design using engineered knitted fabrics via advanced manufacturing technologies, with possible applications beyond sports bras, such as bras for breast surgery recovering patients.

Keywords Adaptable design, Compression, Moisture-responsive, Seamless knitting, Sports bra

Paper type Research paper

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1. Introduction

Sports bras are functional garments designed to reduce the repetitive motion of breasts during physical exercise, and they play an increasingly important role in optimizing performance of female athletes (Norris *et al.*, 2021). Without appropriate breast support, exercise can become a painful activity, and women have been reporting avoiding exercise all together, or issues with back and neck pain, as well as irreversible breast tissue sagging (White *et al.*, 2011; Zheng *et al.*, 2007). The only female anatomical features that provide breast support are the Cooper's ligaments behind the breast mass, and the breast skin. A high percentage of both active women (44%–72%) and female athletes (44%) reported experiencing exercise-induced breast pain, as well as frictional injuries caused by their sports bras (McGhee and Steele, 2020). Existing research suggests that bras in general act as external support mechanisms for women' breasts. However, the relationship between breast mass and breast motion during exercise, and the bra design is very complex (Arch *et al.*, 2018; Liang *et al.*, 2019; McGhee and Steele, 2020).

1.1 Sports bra design

Several studies have reported relationships between a decrease in breast mass displacement and wearing bras offering increased breast support (Starr *et al.*, 2005; Zhou *et al.*, 2009; Scurr *et al.*, 2011; Lu *et al.*, 2016). Breast displacement can be minimized via compressive bras that provide pressure to the wearer's chest. However, given the complexities of breast shape and anatomy, current commercial compression bras are reported to apply excessive, uncomfortable pressure to the wearer's breasts (Bowles *et al.*, 2012). Another way of controlling breast displacement is via encapsulation sports bras that separate each breast in designed cups, often with the use of under-wires that lead to a loss of comfort while exercising (Norris *et al.*, 2021). A hybrid-type sports bra design, which combines both compression and encapsulation feature, provides breast elevation and compression at the same time, and has been shown to reduce breast displacement and breast discomfort more efficiently (McGhee *et al.*, 2013; Ching-Sui *et al.*, 2017).

In addition to the above-mentioned types of designs, sports bras are also engineered to have various levels of breast support based on the intensity of the intended physical activities: high, medium or low support (Zhou *et al.*, 2013). However, the relationship between design elements, cup style, materials, number of fabric layers, bra strap width, neckline height, band closure and breast support level, has not been evaluated in a consistent manner. Several studies reported that wearing high-impact sports bras reduced vertical breast displacement in comparison to everyday bras, and the underbust band width was significantly correlated with variability of breast displacement (McGhee *et al.*, 2013; Starr *et al.*, 2005). Cai *et al.* (2016) stated that management of breast displacement must consider details of mainly four bra components: straps, underbust band, bra circumference and two intersecting seams across the cups. In an earlier study, Lorentzen and Lawson (1987) found that perceived breast support is correlated with high modulus knit fabrics, stabilized straps and compression of breasts. An added layer of fabric to the bra cup pad was found to slightly reduce the breasts' displacement during exercise (McGhee *et al.*, 2013), and the degree of fabric stretch influences the efficiency of a sports bra (Venkatraman and Tyler, 2015). Gorea and Baytar (2016) reported that wearing removable breast pads affects the compression level between sports bras of low and medium support levels. However, breast displacement is also highly dependent on wearing the appropriate bra size.

1.2 Sports bra size

The sizing systems in apparel industry in general, but more so in the bra industry, have been proved to lack consistency and reliability, as most of them are based on dated statistical models derived from anthropometric data collected back in 1940s (Zheng *et al.*, 2006). Women may have difficulties choosing a well-fitting bra, despite the abundance of bra styles and bra-sizing tutorials on the market (McGhee and Steele, 2020). Most bra sizing systems consider only two body measurements, bust girth and underbust girth, with the difference between these measurements being designated as cup size measurement (Bowles *et al.*, 2012). However, sports bras, due to their compressive designs, generally do not have a cup size specification, and women are advised to check a "sister sizing chart" to identify their sports bra size match (Lau and Yu, 2016). Some studies suggest that different breast cup sizes require different levels of breast support, therefore bra sizing is problematic when the same design is proportionally applied to all bra sizes (Starr *et al.*, 2005). Moreover, bra size and fit are related to overall bra comfort and performance in various sweating conditions, thus comfort evaluation is a complex subject. A knowledge gap was identified on how changes in bra fabric characteristics during dry versus sweaty conditions influence bra fit and perceived sizing.

1.3 Sports bra comfort

For a garment worn close to skin, such as a sports bra, sensorial comfort pertains to the wearer's perception of fabric satisfaction (Bowles *et al.*, 2012). Fiber, yarn, fabric, finish, garment design and fit are reported as factors of sensorial comfort (Sweeney and Branson, 1990). The general approach to assessing how a bra or bra fabric is perceived by the wearer involves psychological scaling (Li, 2001). Liu *et al.* (2019) listed breast stability, wearing comfort and breast shape as key factors for sports bra comfort evaluation.

Some studies describe innovative attempts of creating fabrics with dynamic moisture properties, designed specifically for sportswear applications, aimed at narrowing the gap between perceived bra fit and comfort in dry versus sweaty conditions (Lin *et al.*, 2015). Dynamic water pumping fabrics (DWPF) are such an example. These are a type of knitted fabrics designed engineered with novel alternations of hydrophilic and hydrophobic yarns/fibers, to facilitate variable moisture transfer. Gorea *et al.* (2020) referred to such fabric design as "moisture-responsive" fabric. Lin *et al.* (2015) demonstrated that DWPF fabrics, when used in the cup area of sports bras, could decrease breast skin temperature by absorbing the sweat during running, however their study did not include breast support evaluations. McGhee and Steele (2020) suggested that adaptable sports bras that can respond to the individual activities of women by adjusting the level of support to match the breast displacement have the potential to optimize both breast support and sports bra comfort. Bra construction adaptability features, such as adjustable straps and underbust band with fasteners, are common features in cut-and-sew sports bras but are not feasible for seamless knitted sports bras (Lau and Yu, 2016).

1.4 Sports bras manufacturing

The recent advances in material technologies have created new design opportunities for fabrics and their assembly into performance garments (Zhou *et al.*, 2009). Sports bras are generally made of stretch, knitted fabrics, containing spandex that provides large extensibility and high recovery rate (Lau and Yu, 2016). However, previous research on optimizing functionality of sports bras seldom explored the effects of fabric structure on breast support and comfort. Breast displacement, depending on the size of breasts and intensity of exercise, unevenly stretches the knitted bra material, and it can change the compression levels in different areas of the sports bras (Maleki *et al.*, 2011; MacRae *et al.*, 2011).

Seamless knitting has been the main technology used for manufacturing compression sport bras for the past decade (Lau and Yu, 2016; Gorea *et al.*, 2021). Making a bra out of a circular knitted highly elastic tube, and eliminating the cup and side seams, provides increased fabric and fit comfort (Radvan, 2013). This technology can create three-dimensional (3D) shaping in the breasts area and can vary the tension of the knitted material stitch by stitch, to provide engineered compression levels (Tiwari *et al.*, 2013; Lau and Yu, 2016). However, few studies investigated the design of seamless knitted sports bras for adaptable compression and breast support (Yan *et al.*, 2014; Pei *et al.*, 2019; Gorea *et al.*, 2020).

1.5 Sports bra evaluation

Evaluation of a garment's pressure or local compression on the human body is done using piezoelectric or air-pack pressure sensors, particularly for medical grade compression garments (Luo *et al.*, 2016). In such cases, compression values and readings correspond to various comfort levels as perceived by the wearer (Oner *et al.*, 2018). However, compression sports bras are not being designed or evaluated with the same precision, and no studies were found to propose a compression classification system for sports bras that would quantify the general labels of "low," "medium" and "high" impact breast support levels (Zheng *et al.*, 2007; Bowles *et al.*, 2012). Studies of pressure predictive models combining knitted fabric structure and its elastic properties, along with body curvature captured via 3D body scanning techniques have been limited, experimental and focused on the lower limbs, where body shape variability is less complex than breast area (Luo *et al.*, 2016). However, it has been recognized that the cross-sectional curvatures (slice circumferences) directly influence pressure magnitude exerted by compression garments (Liu *et al.*, 2019).

The use of 3D body scanning technology has been increasingly successful for determining breast shapes and evaluating garment fit (Istook and Hwang, 2001; Pei *et al.*, 2019; Oh and Chun, 2014). Gorea *et al.* (2020) used 3D body scanning to evaluate sports bra compression changes before and after a moderate intensity physical activity. Specifically, capturing the body circumferences and comparing their changes in various sweating conditions validated the compression variability of a novel sports bra. Among the limitations of previous studies are the lack of a control bra for comparative evaluation, a scientific understanding of moisture-responsive material properties and large variability of participants sweating rates (Gorea *et al.*, 2020).

Therefore, the purpose of this study is to investigate whether moisture adaptive knitted fabric structure can improve breast support in seamless knitted sports bras. For this study, breast support as indicated by breast compression variations will be evaluated using breast slice circumferences extracted from 3D body scanning of human participants. This study adds to the previous body of knowledge aimed at gaining a deeper understanding of how advanced knitting technology and textile engineering can improve breast support function in moisture adaptive sports bra design, with possible applications beyond sportswear, such as bras for recovering breast surgery patients.

2. Experimental

2.1 Garment development

A Santoni SM8-TOP2V circular knitting machine was used to prototype the seamless sports bra, a common technology used by the industry and available at a product development facility in North Carolina, USA. Two prototypes were designed specifically for this study, differentiated by the novel inclusion of a moisture-responsive knitted panel on the inside layer of the experiment sample, to manage moisture (sweat) during physical activity. This panel was adapted from a previous study (XXXX, 2020) and was constructed by the alternation of hydrophobic (wool fibers) and hydrophilic (nylon fibers) yarns. These alternating yarns were arranged in patches that absorbed sweat and curled to increase garment compression on the body. The second bra, used as a control sample, did not have a moisture-responsive panel, and was made of 95% nylon and 5% spandex. The bra designs are depicted in Figure 1, on a professional swimwear size 36B Alvaform dress form.

In addition to the moisture adaptive panel, the design followed literature guides for efficient breast support for sports bras, such as hybrid-type compression design (encapsulation of breasts and compression features), high neckline, crossed back straps and both wider strap and underbust band. The overall fabric structure included a combination of ventilation (via mesh patterns) and limited elongation properties (via tuck stitch patterns) to aid moisture wicking at underarms, between breasts and back areas, as well as breast support in the straps and encapsulating cups areas (Figure 2). Both bra samples had the

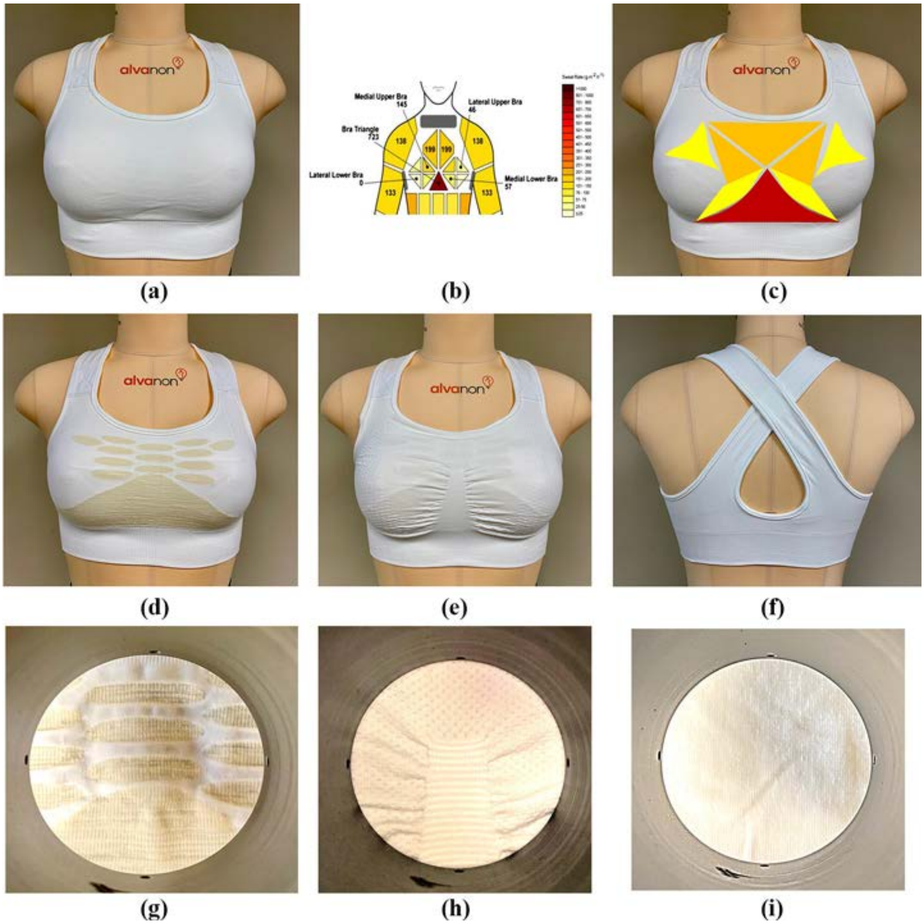

Figure 1.
(A) Inside layer control bra, (B) Breast area sweat map for women athletes, adapted from Smith and Havenith (2012), (C) Overlay of sweat map on the inside layer of control bra, to guide moisture responsive panel design, (D) Inside layer novel bra, (E) Outer layer, same for both bras, (F) Back bra design, same for both bras and both layers, (G) fabric testing area for novel bra inside layer, (H) fabric testing area for outside layer (same for novel and control bra), and (I) fabric testing area for control brainside layer

same garment specs, following a market bought sample as a size guide, as follows: bust width = 14⅛ in., underbust band width = 12¾ in., center front height = 6½ in., side height = 4½ in., total bra length from shoulder to band = 11 in. and strap width at shoulder fold = 1¾ in.

2.1.1 Moisture-responsive panel design. Santoni SM8-TOP2V seamless knitting technology (28-gauge, 14 in. diameter) allows the integration of various moisture management characteristics on the front and the back sides of a fabric, along with a two-fabric layer design for a sports bra (Lau and Yu, 2016; Gorea *et al.*, 2021). A seamless knitted sports bra is generally being knitted as a circular tube that gets folded at the underbust level, creating an inside bra layer and an outside bra layer that can be engineered separately for different functions. Using a combination of nylon yarn and nylon covered spandex yarns ensures overall moisture wicking abilities for both bra layers, as well as compression (Lau and Yu, 2016; Gorea *et al.*, 2021).

For this study, to obtain different physical properties on each side of a fabric, a one-way moisture transfer function was created by using two yarn types: each with different inherent moisture management properties. One yarn was 90% wool/10% nylon (size 60/1), and the other one was 100% nylon covered 210 D bare elastic (size 20–20/10/1). Each type of yarn was isolated to one side of the fabric structure by using a yarn plating technique. This knitted structure created a fabric with a hydrophilic side and a hydrophobic side. Moreover, the jacquard knitting technique allows for the insertion of different yarns in specific areas of a fabric, therefore sweat absorbing wool yarn areas were placed where women athletes sweat the most, as guided by Smith and Havenith (2012) sweat maps (Figure 1B and C). For this study, the specific sweat rates for each smaller division in Figure 1B were not taken into consideration, as being outside the scope of this research. The floats of 100% nylon yarn (size 78/68/1), used for the rest of the bra body and visible on the back of the fabric, were manually cut to maximize the curling and increase the elongation properties of the wool islands when activated by moisture. Figures 1G and 3 detail the moisture-responsive panel design inside the novel bra. The control bra did not have this yarn combination panel inside; instead, all-over jersey stitches with the body nylon yarn and nylon covered spandex yarn were used. Figure 1G–I shows the differences at center front between novel bra and control bra. The inside bra layer was the same for both bras.

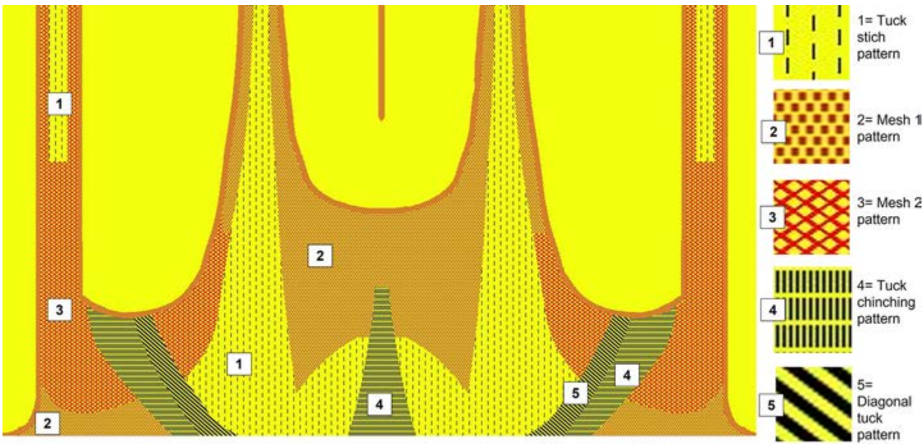

Figure 2.
Santoni CAD design of outer layer for both bra samples, showing the placement of tuck stitch patterns (1, 4 and 5) and mesh patterns (2 and 3). Plain yellow area represents jersey stitches, and it was cut out to assemble the bra

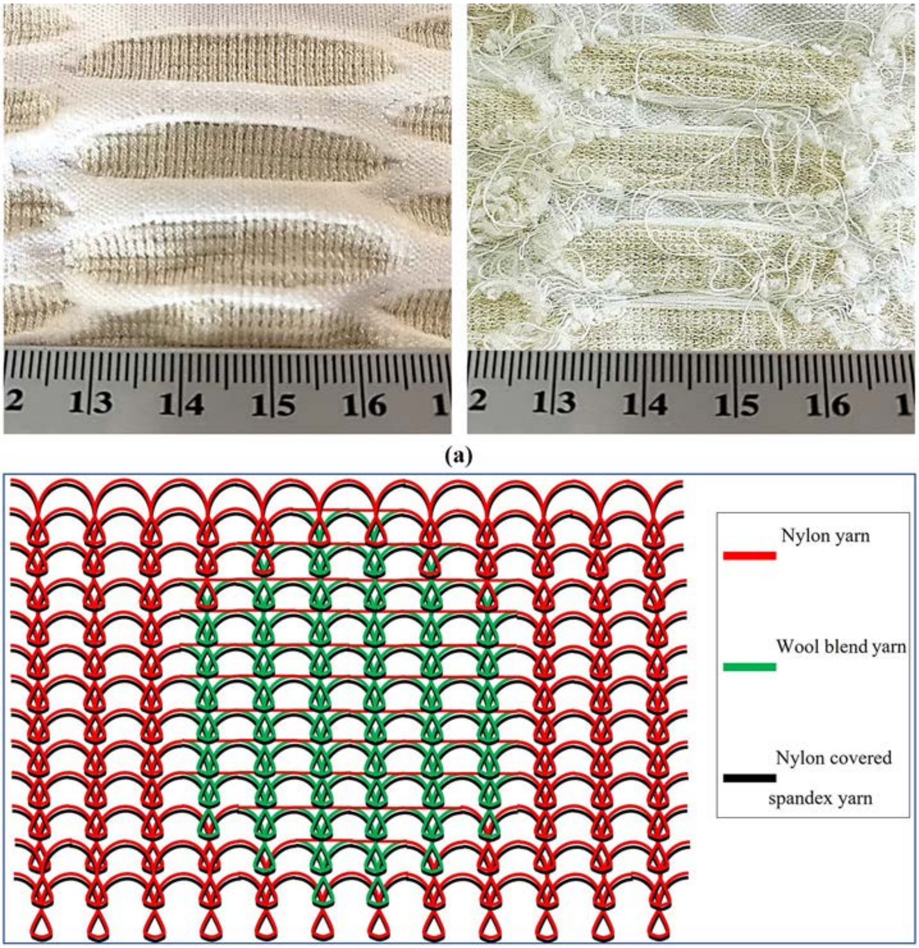

Figure 3. Novel panel knit stitch design: (a) technical front and back of 5 cm area at center front of bra, and (b) jacquard stitch design showing the yarn combinations and Nylon yarn floating

2.2 Material testing

The focus of the moisture adaptive sports bra design was on the most sweat-producing area of the female body during physical exercise, between the breasts, thus, material testing was similarly focused (Table 1). Physical fabric measurements were taken for a marked circular area at center front of the bra design, size of 20 cm^2, with fabric swatches cut out from each of the three fabric layers (shown in Figure 1G–I) such as novel bra inside layer, outside layer (same for novel and control bra) and control bra inside layer. The fabric swatches were conditioned at a standard atmosphere of 20°C and 65% relative humidity, for 24 h. Fabric weights in dry condition were measured, according to ASTM D3776-96 protocol. Given the textural and tri-dimensional formation of the novel and outer layer fabric swatches, fabric thickness, fabric density measurements and typical moisture management testing were not feasible, but air permeability testing has been previously found to be a good indicator for moisture responsiveness of such fabrics (Sarkar *et al.*, 2010; McCullough *et al.*, 2003). Air

Table 1.
Air permeability, fabric weight and elongation test results

				Elongation							
				Lengthwise				Crosswise			
	Air permeability (cc/cm^2/s)			Dry		Wet		Dry		Wet	
Fabric swatch name	Dry	Wet	Weight (g)	N (kgf)	E (%)	N (kgf)	E (%)	N (kgf)	E (%)	N (kgf)	E (%)
Novel panel	284.85	151.42	3.44	33.85	252.8	17.78	264	31.2	206	31.9	247.6
Outer layer	403.07	287.28	3.18	12.88	250	10.26	196	30.35	336.8	21.44	336.8
Plain panel	202.55	121.41	4.22	46.14	292	36.02	258	26.06	318.8	41.45	351.2

permeability testing was conducted in accordance with standard test method protocol ASTM-D737-04, using an AVENO AG18B-Automatic Air Permeability Tester set up for 200 Pa pressure difference between the two sides of the fabric swatch tested, through an area of 20 cm^2. Each fabric swatch was tested in dry condition first, followed by wet condition, to compare their moisture responsiveness. For wet condition testing, the swatches were sprayed with distilled water from a hand-held spray bottle held approximately 20 cm above each fabric swatch. Five full sprays were applied to each swatch, amounting to a total of 5 g of water, and each fabric swatch was tested for weight first, then, after 1 min to allow for water absorption, they were tested for air permeability (Table 1).

For each of the three different fabric designs, elongation strength (until breakup) was measured using a Tinius Olsen H5KT Benchtop Tester. Six fabric swatches, 150 mm $\times$ 50 mm, were cut in the wale direction, and six fabric swatches were cut in the course direction for each of the three fabric designs (ISO 13934-1:2014). All swatches were conditioned in standard atmospheric conditions of 20°C and 65% relative humidity for 24 h. The fabric swatches were clamped with a tension of 1 N, testing area of 100 mm $\times$ 50 mm, moving speed of 100 mm/min and accuracy of $\pm$2%. The reported result for force (N) and elongation percentage until breakup (E) for each fabric is the average measurement of the six fabric swatches (coefficient of variation did not exceed 5%). The same elongation testing protocol was used for wet condition, using a separate set of six fabric swatches for each fabric design. Fabric swatches were sprayed with 5 g of distilled water, and each fabric swatch was tested for elongation after 1 min, to allow for water absorption (Table 1).

2.3 Wear-trial participants

To minimize the variability of sweating during running and between participant body shapes, amateur female marathon runners were recruited from a north-eastern US university community. Institutional Review Board approval was obtained, and emails to runners' community were used for enrollment. The inclusion criteria were women who were at least 18 years old, actively engaged in regular moderate to intense physical exercise through participating in marathons and had maximum bust circumference of 37 in. $\pm$ 1 in. (94 cm $\pm$ 2.5 cm) and waist circumference of 29½ in. $\pm$ 1 in. (75 cm $\pm$ 2.5 cm) [representing generic seamless sports bra size Medium as per Kohl's (2019)]. The same size reference was used to develop the measurements of the sports bras size Medium that were wear tested. Multiple bras of each novel and control type were made to provide each participant with their own pairs for wear trial.

Eight women who actively participate in university marathon events were recruited for the study. Five of the eight recruited participants had ages between 35 and 44 years old, and the other three were between 45 and 54 years old. The average height of all participants was 163 cm (SD = 6.7), and their average body weight was 61.5 kg (SD = 7.8 kg). Their average bust girth was 90.15 cm (SD = 3.45 cm) and average underbust girth was 76.52 cm (SD = 3.67 cm), sizing them as US commercial band size of 34 and 36, and cup size A, B or C (QVC, 2020). A US standard bra sizing system was used to match the location of participants' population.

The participants were invited to a 3D body scanning lab located at a north-eastern university campus, where they signed an informed consent form and filled out a demographic survey (age, height and weight). Before scanning, manual measurements of the bust and underbust girth were made, with participants wearing a lightweight camisole and no bra, to determine appropriate sports bra size (McGhee and Steele, 2006). Each participant was given a novel and a control bra to try on to confirm fit and comfort for running. Participant fit was evaluated by the user through anecdotal verbal comments and written comments collected in the wear trial survey.

The running on the treadmill was at a speed and incline that was comfortable to each volunteer, in a conditioned room with no fans, a constant temperature set up for 70°F and humidity level of 46 (±5%) (Lin *et al.*, 2015). A Polar V800 watch was given to each participant to wear during each separate run, set to record their individual heart rates (HR) (Ruiz-Malagón *et al.*, 2020). They were encouraged to start running to warm up, then speed up to start sweating, and when they started to sweat, they verbally communicated that to the researcher. At that time, a timer was started for 15 min. Participants were instructed to maintain or increase the running activity intensity to continue to generate sweat, within the safety limits of their running comfort. At the end of the 15 min, each runner slowed down and cooled until they safely could step off the treadmill. HR data was collected for each participant and each run, resulting in an average of 125–160 bpm for intensity. A bottle of water was offered to restore hydration after the first run, and the participants drank the water and cooled down for 10 min before testing their second bra.

2.4 Test apparatus and protocol

A noncontact VITUS 3D whole body laser scanner by Human Solutions™ was used (Yu, 2004). The scanned body is captured as an avatar and can be "sliced" cross-sectionally for shape and measurements. In addition to the basic bust area girth measurements, such as underbust and bust circumferences, the distance between the slices as well as their circumferences can be automatically extracted via connected Anthroscan™ (Version 3.6) software program. Scan slices have been used in the study of compression apparel to visually represent variations in shapes and circumferences (Coltman *et al.*, 2017; Zheng *et al.*, 2007; Gorea and Baytar, 2016; Pei *et al.*, 2021). For this study, breast slice circumference measurements were considered an indication of breasts/bra compression.

The participants were first scanned when wearing no bra, to capture the basic breast area measurements. This scan was also used during data analysis to confirm the participant bra size that was determined via manual measurements. Respiratory state was found to affect the measurements for the breast area; therefore, each scan was done twice, and the data recorded were the resulting average between the two scans:

- fully inhaled (participants held respiration for 10 s during the scan); and
- relaxed (regular breathing).

After the no bra scans (inhaled and relaxed), each participant wore two bras (consecutively), a novel bra and a control bra. The following scans were captured for each bra, in the two breathing conditions (inhaled and relaxed):

- before run (dry bra condition); and
- after 15 min of sweating while running on treadmill (wet bra condition).

After finishing the scans for the first bra, participants rested for 10 min, removed the bra and towel dried their skin, before changing into the second bra. After each scanning condition the participants filled out a questionnaire about breast support and comfort features for each of the two bras. The variables in the questionnaire used a Likert-type scale of 1 (low) to 10 (high) and asked the participants to rate the following components of a bra comfort, as suggested by McGhee and Steele (2010):

- overall fit;
- ease to put on/off the bra;

- band comfort;
- shoulder strap comfort;
- fabric comfort;
- breast area comfort; and
- breast support level.

For all the body scanning sessions that took place in a room adjacent to the treadmill, the participants were in an upright position, with arms slightly raised to avoid underarm contact with the bra area. They wore an assigned novel bra, white compression shorts in their size, a swim cap to hold back the hair and no shoes. The same method was used for the scanning sessions with the control bras that followed right after the novel bra testing session.

2.5 Scan data extraction and analysis

The starting cross-sectional slice for each scan was determined by the automatic "Underbust Full" slice measurement provided by the Anthroscan^{TM} software. For consistency of slice positions, a customized Anthroscan^{TM} program was written by an Anthoscan IT support specialist to generate slice circumference measurements for all parallel slices above that Underbust Full starting level, at 0.6 cm (¼ in.) intervals, up to 8.75 cm (3½" in.). This area on the body included the maximum breast circumference level and captured the part of the body that was compressed by the moisture-responsive design panel at center front of the novel bras. Fourteen slice circumferences were therefore compared between all scanning conditions, for each bra, with slice 11 representing the maximum bust circumference for each participant in each scanning condition (Figure 4) (all slices were parallel to underbust level). Due to variations of breast anatomy and the compressive nature of the bra design, several scans showed two consecutive slices with the same maximum breast circumference, but Slice 11 was found to satisfy the maximum breast circumference across all scans and participants.

A three-way factorial repeated measures analysis of variance (ANOVA) was conducted to investigate differences in breast measurements due to compression effects between the control and experimental bras. The dependent variable consisted of compression breast circumference measurements in centimeters taken by the body scanner around the breast area locations while wearing the novel and control bras in varying moisture conditions. The repeated factors were: bra type with two levels: control bra and experimental bra; moisture condition with two levels: dry and wet; and body location with three levels: apex of the breast, upper breast (1.27 cm above the apex) and lower breast (1.27 cm below the apex). Each participant was measured at all levels of each factor. These levels were chosen due to their best overlap to the placement of moisture-responsive panels in the experiment bra, as well as to reported areas of greatest breast displacement during running (Arch *et al.*, 2018).

A second three-way factorial repeated measures ANOVA was used to look at differences in subjective fit measures (band comfort, shoulder strap comfort, fabric comfort, breast area comfort and breast support level) between the bra types and moisture conditions. A final two-way repeated measures ANOVA was conducted to look at differences in two overall subjective fit measures (fit and ease of putting on/off) between the two bra types. Data were analyzed using standard statistical software, SPSS, version 27. Significance was established at $p < 0.05$ for main effects. Bonferroni corrections were applied to p-values in follow-up contrasts to control for the Type II error rate involving multiple comparisons. Assumptions

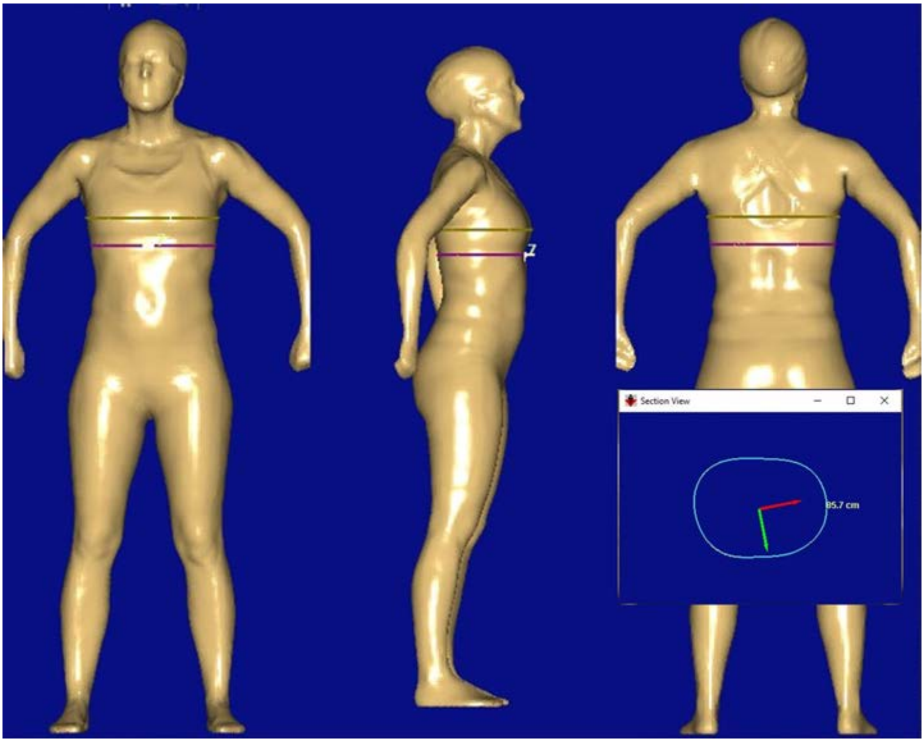

Figure 4.
Views of the 3D body scanning position of participants, showing Under Bust and Bust slice levels, and a slice circumference extraction screenshot

for repeated measures ANOVA, including normality and sphericity, were checked with the Kolmogorov–Smirnov test and Mauchly's test of sphericity, respectively.

3. Results and discussion

3.1 Material testing results

Air permeability test results confirmed that the three combinations of knit stitch design and yarn selections affect the breathability of the fabric swatches. Specifically, the plain panel swatch was the heaviest (4.22 g), and its air permeability in both dry and wet conditions were the lowest (202.55 and 121.41 cc/cm^2/s, respectively) (Table 1). The fabric panel of the outer bra layer, capturing the fabric gathering to encapsulate the breasts, was lighter than both the plain and the novel panel, but had the highest air permeability, therefore breathability, in both dry and wet conditions. The novel panel had values for weight and air permeability right in between those of the plain and outer layers.

The air permeability changes between moisture conditions were relevant to the moisture adaptive fabric design. McCullough *et al.* (2003) stated that fabrics with hydrophilic components, such as wool yarns, change their air permeability properties when subjected to different moisture conditions, and these results confirmed their findings. The control plain jersey panel had the smallest variance between dry and wet conditions (81.14 cc/cm^2/s), whereas the novel panel had the highest variance between the two conditions (133.42 cc/cm^2/s). The high values of air permeability for the outer layer panels are consistent with the moisture wicking design of the bras, as this fabric swatch was made of all nylon/spandex yarns and a combination of tucks and mesh stitch patterns. Even though all swatches decreased their air permeability when wet, the novel panel had the greatest variability, suggesting a higher responsiveness to moisture.

The fabric elongation results (Table 1) also show a significant difference between the three fabric designs. The elongation coefficient in wale direction decreased in the wet condition for all fabric swatches except for the novel panel, which had a 11.2% increase. The plain panel had the highest elongation coefficient when dry. In the course direction, the plain panel increased its elongation percentage when wet by 32.4% and the outer layer panel had no change. The novel panel had the highest increase in elongation in course direction too, a 41.6% difference between wet and dry conditions. These results are consistent with the moisture adaptive fabric structure that was aimed at creating through the knit stitches and yarn combinations.

3.2 Wear-trial results

The 3D body scanning data indicated no violations of the assumptions of sphericity or normality. Mauchly's test indicated no violations of the assumption of sphericity for the main effects of bra type and moisture condition nor for the interactions between body location and moisture condition, and bra type and moisture condition. The test did indicate a violation of this assumption for the main effect of body location, $X^2(2) = 16.09$, $p < 0.0005$; the interaction between body location and moisture condition, $X^2(2) = 7.73$, $p < 0.05$; and the three-way interaction between body location, bra type and moisture condition, $X^2(2) = 7.46$, $p < 0.05$. Therefore, corrections to degrees of freedom were made using Greenhouse–Geisser estimates of sphericity for the main effect of slice ($\varepsilon = 0.52$), the two-way interaction ($\varepsilon = 0.58$) and the three-way interaction ($\varepsilon = 0.58$). The Kolmogorov–Smirnov tests indicated no deviations from normality with insignificant test estimates for all combinations of bra type, moisture condition and body location.

There were significant main effects of bra type [$F(1,7) = 8.00$, $p < 0.05$] and body location [$F(1.04,7.25) = 35.90$, $p < 0.0005$] on breast circumference measurements (Table 2). Contrasts indicated that breast slice measurements in the experiment bra condition were significantly larger than in the control bra condition. For the contrasts involving body location, the mean measurements were 89.88 cm (SE = 1.88) for the breast apex, 91.60 cm

Factor	Sum of squares	df	Mean square	F	p
Bra type	5.950	1.000	5.950	8.000	0.025
Error	5.204	7.000	0.743		
Moisture condition	0.184	1.000	0.184	0.095	0.767
Error	13.556	7.000	1.937		
Body location*	203.878	1.035	196.901	35.897	0.000
Error	39.757	7.248	5.485		
Bra type × condition	2.548	1.000	2.548	11.082	0.013
Error	1.609	7.000	0.230		
Bra type × location	0.191	2.000	0.095	0.592	0.566
Error	2.253	14.000	0.161		
Condition × location*	2.241	1.160	1.932	13.204	0.005
Error	1.188	9.119	0.146		
Bra type × condition × location*	0.025	1.168	0.021	0.309	0.628
Error	0.563	8.179	0.069		

Note: *Adjustment to degrees of freedom using Greenhouse Geisser estimates of sphericity

Table 2. Results of repeated-measures ANOVA

(SE = 1.73) for the upper breast area and 88.03 cm (SE = 1.73) for the lower breast area. Significant differences in breast slice measurements were found between the lower breast and upper and the apex and upper breast. The mean difference between the lower breast and upper breast was 3.57 cm (SE = 0.59) and apex and upper breast was 1.73 cm (SE = 0.28). No significant differences in breast slice measurements were found for the main effect of moisture condition.

The two-way interactions between bra type and moisture condition [F (1,7) = 11.08, p < 0.05] and body location and moisture condition [F (1.16,8.12) = 13.20, p < 0.01] were also significant (Table 3). There was a greater difference in breast measurements in the dry condition than in the wet condition (Figure 5a). For the body location and moisture condition interaction, breast circumference measurements were higher in the wet condition for the lower breast and apex measurements than in the dry condition, whereas the upper breast measurements were lower in the wet condition) than in the dry condition (Figure 5b). The three-way interaction between body location, moisture condition and bra type was insignificant; thus, the two-way interaction effects were similar for both the control and novel bra types.

The breast support and comfort of the two bras were evaluated across a variety of measures via questionnaires. Participants rated the overall fit (including overall fit and ease of putting on and off) of the experiment bra as 9.25 (out of 10) (SE = 0.42) and the control bra

Table 3.
Means and standard errors of significant two-way interactions

Bra type	Condition	Mean	SE
Control	Dry	89.382	1.937
	Wet	89.795	1.953
Experiment	Dry	90.205	1.879
	Wet	89.967	1.915
Body location	Condition		
Lower breast	Dry	87.830	1.702
	Wet	88.238	1.767
Breast apex	Dry	89.786	1.852
	Wet	89.964	1.910
Upper breast	Dry	91.765	2.185
	Wet	91.441	2.139

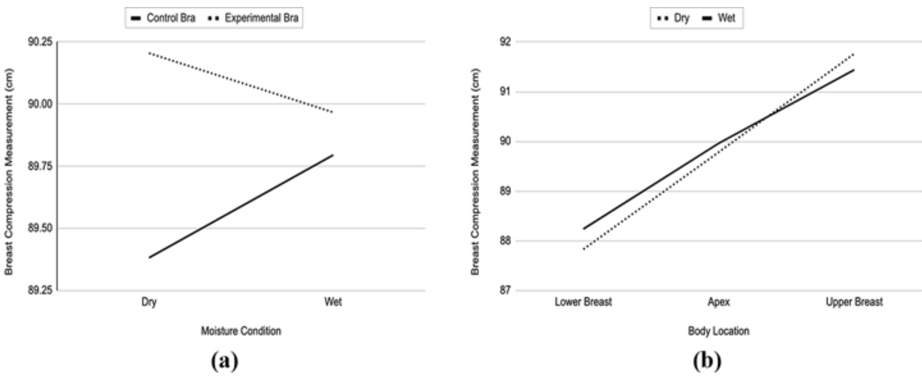

Figure 5.
(a) Two-way interaction between Bra type and moisture conditions, and (b) two-way interaction between body location and moisture condition

as 9.31 (SE = 0.42). For the fit measures gauged across moisture conditions, participants rated the experiment bra as 9.38 (SE = 0.27) and the control bra 9.46 (SE = 0.23).

Qualitative comments evaluating the novel bra comfort and breast support after the run included: "Doesn't feel wet," "I don't feel sweaty on the boobs," "Left strap [feels tight] in the neck" and "Molded in better, shoulder straps felt a little tight, feels weird under breasts." Comparatively, in the Wet condition, the control bra received comments such as: "Feel the sweatiness" and "Feel some sweat down the middle." These remarks confirm that the design changes between the two bras did influence their performance when participants were running and wet.

Both bras received positive evaluations for breast support, with one participant making a comparative comment, such as: "Feels different than the other bra [control bra], very comfortable," and another participant stating: "Really supportive, no bouncing." There were several comments on the straps, as some participants felt them too wide and/or too tight for their comfort, however, without being consistent in the comments between the two bras. One participant remarked only for the control bra, "Lower strap comfort," suggesting she liked better the tighter feeling of the experimental bra straps when wet.

3.3 Discussion

The designed differences in knit stitches and yarns between the two bras, specifically at center front between the breasts, were validated via textile testing. The variances in 3D body scanning bust slice measurements between moisture conditions suggest that the designed differences may cause changes in bra compression between dry and wet conditions. Results indicated that breast area slice measurements in the experiment bra were significantly larger than in the control bra. Given the all-over plain jersey stitch design but lower fabric weight of the moisture-responsive panel, compared with the plain panel inside the control bra, a more relaxed fit of the experiment bra was expected, reflected in the significantly larger slice circumferences in wet condition. This result is an indication that breast compression could be managed with a more comfortable fit.

Variations of breast shape and geometry as well as repositioning of the breast tissue during running lead to variances in bra compression between body locations (Gorea and Baytar, 2020). The results of this study confirm this fact, as the lower area of the breasts had more compression in the Wet condition than the Dry condition, whereas the upper breast had more compression in the Dry condition than the Wet condition. However, this behavior was common for both bras, suggesting that the breasts shifted upwards during running, a move that was not restricted by the actuation of the moisture-responsive panel. One explanation for this finding could be the limited data collected, as there were only three slices above the apex level that captured breast measurements, compared with ten slices below the apex level, but only slices 8, 10, 11 and 12 were found to have significant differences between moisture conditions. Other methods of capturing novel panel actuation and efficiency on managing breast support above the apex level shall be pursued.

The significant two-way interactions between bra type and moisture condition, and body location and moisture condition showed that the variations of breast slice circumference differences were in opposite directions: the control bra lost compressive power in wet condition, while the experiment bra became more compressive when wet. This is one of the most important outcomes of this study, suggesting the potential of managing breast compression via engineered knitting and moisture-responsive yarns.

The participant's remarks on strap tightness suggest that the actuation of the moisture-responsive panel in the experimental bra affects the elongation properties of the inner bra layer, explaining the bra straps feeling tighter and wider. Tighter straps have been associated with better breast support, but strap design shall be further studied to determine the optimal comfort parameters. Evaluations of fabric elongation should be further pursued for the center front panels as well as for the straps, as previous research found that, for fabrics with high tensile modulus such as seamless knitted fabrics, tighter compression was promoted as elongation increased (Wu *et al.*, 2020). The moisture-responsive panel in this research increased its elongation coefficient when wet. These findings along with the decrease of breast slice circumference measurements of the novel bra when wet, suggest that the novel moisture-responsive design may have increased compression of the bra, but further studies shall be pursued on more bra sizes, for validation.

4. Conclusion

The purpose of this study was to investigate if engineered compression variations using moisture adaptive fabric design can improve breast support in seamless knitted sports bras. The methods used were guided by the experimental design of Gorea *et al.* (2020), addressing some of the limitations of that study: the need of a control bra sample, textile testing to confirm moisture-responsive panel design and reducing the sweating variability of the participants by increasing their exercise fitness level. An experimental approach was used to integrate a moisture-responsive fabric panel into the center front area of a seamless knitted bra. The effects of the engineered novel panels on breast support and comfort were evaluated by using 3D body scanning of eight amateur marathon runners wearing the two bras in dry versus wet sweating conditions, in a conditioned environment. Air permeability testing of fabric panels at center front, along with elongation testing showed that, in wet condition, the wool yarns absorbed the sweat, and the knitted fabric reduced its air permeability but increased its elongation percentage. These changes in fabric physical properties were accompanied by a significant reduction in breast circumference slices of the novel bra in wet condition, indicating increased bra compression due to the moisture-responsive design of the novel bra.

This study has several limitations, including the convenient selection of available yarns for Santoni knitting technology, the limited number of participants and bra sizes, as well as the limitations of current 3D body scanning technologies. There are some studies researching methods of evaluating apparel compression on the body by using 3D body technologies, but all methods still need validations via secondary methods, therefore this study's slice circumference method should be further validated (Lee and Hong, 2013). Adaptable sports bras, meaning bras that can respond to the individual activities of women by adjusting the level of breast support while managing sweat and breast displacement, have the potential to minimize the shortcoming of the existing bra sizing systems, increasing women participation in sports and improving their overall lifestyle. This study adds to the previous limited body of knowledge aimed at gaining a deeper understanding of how textile engineering can improve breast support function in adaptive sports bra design, with possible applications beyond sportswear, such as bras for recovering breast surgery patients.

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