The Journal of The Textile Institute

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjti20

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To cite this article: Adriana Gorea, Huantian Cao & Sarah Megivern (25 Jun 2024): Towards optimization of sports bra strap design: the role of stitch pattern and stitch length (SL) on the properties of seamless knitted fabrics, The Journal of The Textile Institute, DOI: 10.1080/00405000.2024.2365495

To link to this article: https://doi.org/10.1080/00405000.2024.2365495

Published online: 25 Jun 2024.

THE JOURNAL OF THE TEXTILE INSTITUTE
https://doi.org/10.1080/00405000.2024.2365495

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RESEARCH ARTICLE

Towards optimization of sports bra strap design: the role of stitch pattern and stitch length (SL) on the properties of seamless knitted fabrics

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ABSTRACT
The purpose of this study was to investigate the effect of SL and stitch patterns on seamless knitted fabric properties as applied to sports bra strap functionality. Different tuck stitch patterns commonly used for seamless knitted activewear, were knitted with a Santoni machine setting for stitch SL = 70. Textile testing was conducted to narrow down the patterns suitable for bra strap. Significant interactions between pattern and SL on thickness, weight, air permeability, elongation, and breaking force were found. The results confirmed some of the existing knowledge about the influence of tuck stitches on the dimensional properties of weft knitted fabrics, such as increasing their density and stability, but also revealed new insights for patterns with more complex tuck stitch repeats when varying SL. Moisture management measurements for various SL values proved to be critical in selecting the best stitch pattern (tuck pattern#10) and SL = 115 that could lead towards optimization of sports bra strap design and highlighted the inconsistent tuck pattern fabric behavior in the presence of moisture.

ARTICLE HISTORY
Received 5 December 2023
Accepted 28 May 2024

KEYWORDS
Design; seamless knitting; sports bra; strap; stitch length

Seamless knitted garments have been called the future of next-to-skin apparel, offering excellent comfort, elasticity, and breathability, along with many advantages over the traditional cut-and-sewn manufacturing method, by eliminating raw material waste and time required for assembly operations (Troynikov & Watson, 2015; Datta & Seal, 2022). Sports bras category has seen an influx of seamless knitted designs offering a wide range of functional improvements made possible using superfine yarns and body mapping with the stitch-by-stitch design capabilities of the seamless technologies (Lau &Yu, 2016; Gorea et al., 2021). The current market reports forecast that sports bras will eventually replace the traditional bras, but more functional improvements are needed to support women's participation in all daily activities (PRNewswire, 2020, Feb 10). Advancing the science behind improving comfort and breast support will allow the sports bras to 'offer a freedom that lasts a lifetime' (PRNewswire, 2020, Feb 10, p.1).

The topic of design space exploration has been recently proposed as an innovative approach for the design process of sports bras, by enhancing the earliest stages of the engineering with design parameterization of sports bra features, particularly the materials used (Bosquet et al., 2020). A review of the literature findings is presented below.

Sports bra design

Starr (2002) found that elasticity, absorbency, and durability are important considerations for sports bra materials, however, restricting breast movement during exercise is a key challenge for the design of sports bras. Among key design elements influencing breast movement and comfort, such as under-band tightness, neckline shape, and cup design, bra straps can have far reaching impacts, as overly tight straps have been found to cause discomfort and potentially shoulder and neck pain and headaches (Bowles et al., 2012; kCha, 2012; Zhou et al., 2013). Previous research on bra straps indicates that their elastic property, their friction property, the length, and the width of the elastic fabric strips have impacts on the breast support and functional performance of bras (Zhang et al., 2021; Norris et al., 2021). The bra strap tensile stress is normally affected by elongation and elastic modulus along the direction of its length (Zheng et al., 2008). Zhang et al. (2020) evaluated the influence of the different bra strap factors on the displacement of the bra strap. Their Finite Element Method (FEM) simulation results showed that, among other factors, material elongation and friction coefficients have significant impacts on preventing displacement of the bra strap during movement (Zhang et al., 2020).

Knitted fabric properties

As a garment worn next-to-skin, a sports bra requires high fabric comfort, therefore knitted fabrics are preferred, with variations of stich structures such as jersey, rib, and interlock being widely used. Many fabric parameters have been found to influence fabric comfort, such as fiber type, yarn factors (twist, bulk, count and finishing treatments), knitting parameters (stitch length (SL), courses per inch, wales

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per inch), fabric weight, and post knitting finishes (Özdil et al., 2007). Kane et al. (2007) investigated textile comfort for knitted fabrics *via* measurements of four factors: (1) softness, (2) ability to absorb moisture, (3) air permeability, and (4) dissipation of heat and insulating properties. Their study reported that SL was the key factor on controlling all the weft knitted fabric physical properties, and SL along with stitch structure significantly affected comfort, handle, and moisture management properties (Kane et al., 2007).

Stitch structures (patterns) have been heavily investigated and found to have a significant influence on dimensional and physical properties of weft knit fabrics (Yesmin et al., 2014; Asif et al., 2015; Assefa & Govindan, 2020). Onofrei et al. (2011) reported that a knitted fabric's *moisture wicking ability*, an important property for next-to-skin fabrics, is influenced by the knit stitch structure. Chidambaram et al. (2011) reported that *air permeability* values showed concomitant increases as the yarn linear density and SL increased, therefore air permeability is also an important property that should be investigated. Selli and Turhan (2017) found that air permeability for knitted fabrics decreased unproportional to the mass of fabrics, and rib type fabrics had higher air permeability values compared to single jersey type fabrics.

Kane et al. (2007) showed that the combination order of jersey- tuck stitches played a significant role in all the fabric properties. The addition of tuck stitches improved fabric properties like abrasion resistance, air permeability, water absorbency, thermal insulation, compression, bending, shear, tensile properties, and handle values (Kane et al., 2007). The gathering of knit loops forming the tuck stitches reduces the fabric length and lengthwise stretch, because the tuck stitches and the stacking of the loops causes them to pull the yarn from adjacent knitted loops; generally, fabrics with tuck stitch formations provide greater stability and shape retention (Uyanik & Topalbekiroglu, 2017). However, fabrics having tuck stitches have been found to have higher weight and thickness properties compared to single jersey circular knitted fabrics (Spencer, 2001; Uyanik & Topalbekiroglu, 2017; Bouagga et al., 2021). The number of tuck stitches and their locations are also important factors for the SL calculation, impacting the course and wale densities as well as the elongation properties (Uyanik at al., 2016). For knitted fabrics, lower tensile resistance has been associated with smaller bra pressure on the body and increased comfort but decreased breast support (Zhuo et al., 2011). Sun et al. (2021) found that *elongation* of the bra shoulder straps has a negative relationship with relative nipple displacement, therefore tighter straps are better for breast support, but benchmarking cannot be done due to complexity of design details (number of fabric layers, edge finishing, width of straps and orientation, etc.).

Seamless knitting and SL

Seamless knitted bras are made on Santoni (Brescia, Italy) circular weft knitting machines which are typically 10—24 inches in diameter. The machines knit tubes of fabric that impart shape to the garment by using individual needle selections and varying the industrial settings for SL, elastic yarn tension, and the stitch type (plain jersey, miss or tuck) (Zheng et al., 2009). A higher level of SL means that the knitted stitch loop has a longer yarn length. Generally, for uniformly knitted fabrics, SL is the length of yarn in millimeters (mm) of one knitted loop, calculated by dividing the total length of unraveled yarn from a specified number of wales and courses into the number of stitches forming that amount of fabric (Assefa & Govindan, 2020). However, the elasticity of the seamless knitted fabrics is enhanced by the incorporation of elastane yarns, or core-spun yarns with elastane core, as plating yarns that are knitted along with the main yarn, making SL determinations complex (Lau & Yu, 2016). Abramavičiūtė et al. (1970) found that the length for loops knitted using more than one yarn tend to be shorter than loops knitted with only one yarn. The calculations for SL are challenging when multiple stitch structures are involved along with the fabric shrinking which results after wet processing. However, knitting machine gauge (number of stitches per inch) and SL have been found to be the two critical knitting parameters that directly affect all knit structure related fabric properties (Nazir et al., 2014; Chidambaram et al. 2011; Charalambus, 2007; Kane et al., 2007).

The tubular body-size garments made on circular knitting machines have different degrees of extensibility in different areas, due to designed variations in SL, stitch type and stitch patterns (Gorea et al., 2021). Using this technique, the sports bra cups are usually knitted with a higher SL value, while the remaining parts, such as the under-bust band, back regions and straps could be knitted with other values for SL (Mitchell, 2005). The SL for Santoni knitted garments is being managed *via* a software setting, with a default value of 70, and increases and decreases in increments of 10 can be placed anywhere on the bra tube fabric to allow shaping for breasts and tighter straps (Figure 1).

Barhoumi et al. (2018) demonstrated that the tightness of the fabric is significantly dependent on the variation of stitch and showed that an increase in SL involves a decrease of fabric tightness factor and aptitude to exert pressure on the body. This finding agrees with that reported by Marmaralı et al. (2017), who concluded that with lower SL, stitch spacing is reduced, and this allows the knitted garment to be denser and more compressive. However, Nazir et al. (2014) investigated interlock type of circular knitted fabrics and observed that an increase in SL led to a decrease in fabric weight and increase in fabric thickness, highlighting the unpredictability of three-dimensional mechanics of weft knitted fabrics when various stitch types and yarns are used.

In the practice of sports bra product development, multiple trial-and-error samples are created experimenting with various SL values for the under-bust band and cup shaping, to determine the appropriate pressure on the body and breast compression level (Gorea et al., 2020; Bosquet et al., 2020). Despite the importance of sports bra straps as detailed above, no studies have been found to investigate

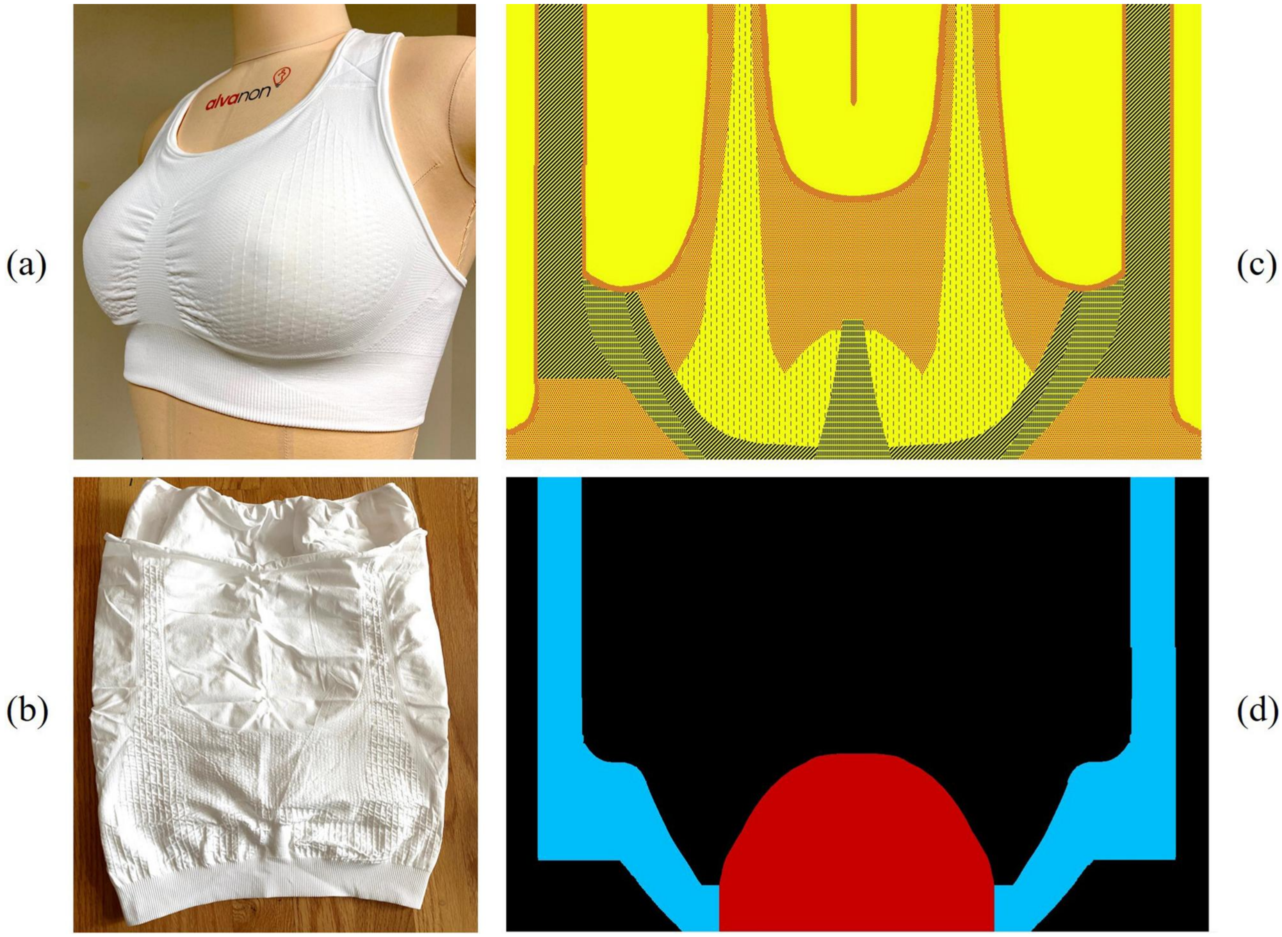


Figure 1. (a) A Typical seamless knitted sports bra design; (b) seamless knitted tube after the knitting process, before the bra straps and neckline outline are cut out to be assembled; (c) santoni knitting stitch pattern layout for shown bra, with various areas on the bra body being knit with various stitch patterns, and (d) SL diagram for shown bra design, where black areas use SL = 70, red area uses SL = 130, and blue area uses SL= 100.

the role of SL on seamless fabric properties that could improve functionality of bra straps, such as fabric elongation, breathability, and moisture management.

Therefore, the purpose of this study was to investigate the effect of SL, as a Santoni knitting machine parameter, and different stitch structures (patterns) on seamless knitted fabric properties to optimize sports bra strap functionality. The results of this research offer a scientific background that could help sports bra designers in selecting appropriate knitting parameters, advancing the functionality of sports bras, and improving women's wellbeing and lifestyle.

Method

Fabric samples

The seamless knitting technology used was an industrial 14-inches diameter, 8 feeders, 28-gauge, weft knitting Santoni SM8-TOP2 circular machine, one of the most advanced circular knitting machines in the industry, with the option to knit, miss or tuck on each of the 1344 needles at each feeder (Sterman & Almog, 2022). The yarns were selected from those currently used by the sports bra industry and fitting the Santoni SM8-TOP2 machine: Repreve® post-consumer recycled Nylon 1/70/68 semi dull natural yarn, plated during knitting with 20–1/40/13 Nylon cover core spun 210 D bare elastic yarn. Different tuck stitch patterns commonly used for seamless knitted activewear, were knitted using Santoni machine setting for stitch length (SL) =70, Repreve® yarn tension = 4 gr, and plating yarn tension = 2.5 gr. The knitted tubes were allowed to relax for 24 h at room temperature in the knitting development laboratory, then scoured and low temperature tumble dried according to standard seamless knitting industry practice (Lau & Yu, 2016).

The investigation of the effect of SL and different stitch structures on fabric properties was conducted in two steps: (1) selection of best tuck stitch patterns with low elongation and high air permeability measurements, and (2) investigation of selected tuck patterns made with three different SL values on moisture management.

Step 1. In this step, SL was set at 70, a default value for knitting sports bras, and twenty different stitch patterns commonly used for seamless knitted activewear were knitted. After manual stretch and elongation evaluation, six tuck stitch combination patterns, i.e. pattern numbers 1, 7, 8, 10, 11, 12, were selected. The selection was based on their relatively small lengthwise elongation compared to all the other samples. Table 1 shows the six fabric samples, their CAD stitch designs and their number of tuck stitches relative to the largest repeat, which is pattern #12 (18 wales x 32 courses = 576 stitches).

Step 2. Based on the analysis of Step 1 air permeability and elongation data, patterns #8, #10, #11 and #12 were selected, and tubes with SL = 110 and SL = 125 were knitted in these four patterns, relaxed, scoured, and dried. A 4x3 experimental design was used in this step, with two independent variables: knit stitch pattern and SL. The independent variable knit stitch pattern had four levels: numbers 8, 10, 11, and 12. The independent variable SL had three levels: 70, 115, and 125. Table 2 shows the physical properties of these fabrics.

Testing protocols

Prior to all measurements, all fabric swatches were conditioned in a conditioning equipment set at standard atmospheric conditions: 21 ± 2 °C, 65 ± 2% relative humidity (RH) for 24 h, according to ASTM D1776-20 (Standard Practice for Conditioning and Testing Textiles) (American Society for Testing & Materials, 2020). Fabric thickness was measured using a Schroeder fabric thickness gauge according to ASTM D1777-96 (Standard Test Method for Thickness of Textile Materials) (American Society for Testing & Materials, 2019). There were 10 replications of the thickness test. Fabric weights (GSM) were measured according to ASTM D3776/D3776M-09a (Standard Test Methods for Mass Per Unit Area (Weight) of Fabric) (American Society for Testing & Materials, 2017).

Air permeability measurements were made according to standard test method protocol ASTM D737-18 (Standard Test Method for Air Permeability of Textile Fabrics), using an AVENO (Fujian, China) AG18B- Automatic Air Permeability Tester set up for 200 Pa pressure difference between the two sides of the fabric tested, through an area of 20 cm^2 (American Society for Testing & Materials, 2018). Ten measurements were made, and their average was recorded. Tensile strength (until breakup) was measured using a Tinius Olsen (Horsham, PA) H5KT Benchtop Tester. Five fabric swatches, 150 mm x50 mm, were cut in the wale direction for each of the knit patterns, according to ISO 13934 protocol (International Organization for Standardization, 2014). The fabric swatches were clamped with a load range of 20 Newton (N), testing area of 100 mm x 50 mm, test speed of 100 mm/min, and extension range of 500%. The reported result for breaking force (N) and elongation percentage until breakup (E) for each fabric is the average of all measurements of the five fabric swatches.

Moisture management evaluations for Step 2 were made using a Moisture Management Tester (MMT, SDL Atlas, Rock Hill, SC) instrument, with upper and lower circular moisture sensors, and following AATCC 195 protocol (American Association of Textile Chemists & Colorists, 2011). All knit patterns were cut into 5 different swatches (8 × 8 cm) across the width of a knitted tube. The swatches were conditioned at 65 ± 2% relative humidity and 21 ± 2 °C for 24 h as per ASTM D1776-20 (Standard Practice for Conditioning and Testing Textiles) (American Society for Testing & Materials, 2020). Standard solution that mimics human sweat (0.9% sodium chloride) was applied onto the technical front of the fabric surface. Results recorded the following measurements for the top and bottom surfaces: Wetting time (sec), Absorption rate (%/sec), Maximum wetted radius (mm), Spreading speed (mm/sec), and overall moisture management capability (OMMC). OMMC is an index automatically calculated by MMT software, by combining the liquid moisture absorption rate on the bottom surface, the one-way liquid transport capability, and the maximum spreading speed on the bottom surface. The OMMC values were also scaled based on AATCC 195 standard (0-0.2 = very poor, 0.2- 0.4 = poor, 0.4-0.6 = good, 0.6-0.8 = very good, >0.8 = excellent) (American Association of Textile Chemists & Colorists, 2011).

Data analysis

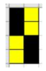
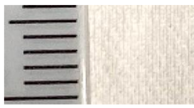
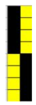
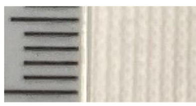
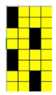
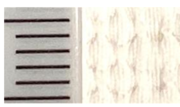
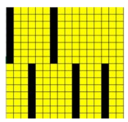
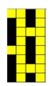
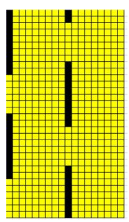
SPSS version 28 for Windows 19.0 statistical package program was used in the data analysis. In Step 1, the independent variable was pattern, and the dependent variables were air permeability, breaking force (tensile strength) and elongation. One-way ANOVA was used to assess the effect of pattern on air permeability, breaking force (tensile strength) and elongation. In Step 2, there were two independent variables: SL and pattern. The dependent variables were: (1) air permeability, (2) breaking force, (3) elongation, and (4) OMMT. Two-way ANOVA was used for data collected in Step 2. Linear regression using SL as independent variable and thickness, air permeability, breaking force, elongation as dependent variables for different pattern numbers was also conducted. For all statistical analyses, standard deviations (SD) were calculated and reported in the tables, and $p < 0.05$ was considered significant.

Results and discussion

The analysis of air permeability results from Step 1 are shown in Table 3 and indicate that, for SL = 70, all patterns had significant effect on air permeability. Patterns #8, #10, #11 and #12 have the highest values for breathability (above 250 l/m^2/s), and patterns #10 and #12 have the lowest values for elongation, as shown in Figure 2 (a and c). Among those, patterns #8, #10, #11, and #12 have either longer tucks, or more space between the tucks than patterns #1 and #7 (patterns #1 and #7 also have a smaller number of tuck stitches). These stitch structures make the four patterns to be lower density fabrics since several courses do not knit new stitches but gather the courses into tuck stitches, explaining the better air permeability results.

Patterns #10 and #12, having the highest numbers of tuck stitches, are more textural and are the thickest fabrics, explaining their lowest elongation among the six patterns (199% and 171% respectively). Pattern #12 has the lowest elongation, which is preferable in the context of this study,

Table 1. Knit structure and physical properties of the six fabric samples with SL = 70.

Pattern #	Fabric Image (Technical front)*	CAD stitch design repeat**	Number of tuck stitches in 576 stitches***	Density (courses/inch x wales/inch)	Thickness (mm)	Weight (gms)	Air permeability (l/m^2/s)	Tensile strength: Breaking force N	Tensile strength: Breaking force SD	Tensile strength: Elongation E (%)	Tensile strength: Elongation SD
1			288	4656	0.78	3.22	133	53.76	2.62	302.16	3.29
7			288	4691	0.79	3.23	125	45.86	3.99	207.00	93.94
8			144	3647	0.81	3.1	278	47.71	3.45	241.00	6.65
10			90	3593	1.12	3.28	275	30.76	1.60	199.00	7.89
11			216	4537	1	3.54	267	45.144	2.49	226	8.99
12			40	3144	1.11	3.06	275	18.07	0.43	171	4.56

*Distance between 2 black lines on the ruler is 1 mm.
**Legend: yellow pixel = jersey stitch, black pixel = tuck stitch.
***576 is the smallest repeat that includes all samples (Uyanik et al., 2016).

Table 2. Physical properties of the 4 stitch patterns by 3 different SL, representing the samples of Step 2.

						Tensile strength			
						Breaking force		Elongation	
Pattern #	SL	Density (courses/inch x wales/inch)	Thickness (mm)	Weight (gms)	Air permeability (l/m2/s)	N/m^2	SD	E (%)	SD
8	70	3647	1.14	3.1	156.59	47.7	3.45	241	0.07
	115	4340	1.57	3.29	222.07	37.5	4.21	300	0.12
	125	5588	1.62	3.58	215.78	27.46	0.48	361.5	0.03
10	70	3593	1.12	3.28	181.78	30.76	1.60	199	0.08
	115	4480	0.95	3.42	183.09	23.35	1.08	269	0.06
	125	5136	0.98	3.34	179	24.07	1.61	307	0.25
11	70	4537	1	3.54	267	45.14	2.49	226	0.09
	115	4550	1.17	3.6	231	41.55	2.09	278	0.04
	125	6951	1.18	3.68	250	39.61	8.34	313	0.32
12	70	3144	1.11	3.06	275	18.07	0.43	171	0.05
	115	4096	1.14	3.1	226	16.67	0.87	330	0.30
	125	4891	1.26	3.23	267	16.36	0.44	352	0.18

Table 3. One-way ANOVA results of the effect of pattern on air permeability, breaking force and elongation.

Dependent variable	*p*-value	Tukey HSD result
Air permeability	<.001	7 < 1 < 11 < (10 = 12 = 8)
Breaking force	<.001	12 < 10 < (11 = 7 = 8) < 1
Elongation	<.001	(12 = 10 = 7 = 11 = 8) < (11 = 8 = 1)

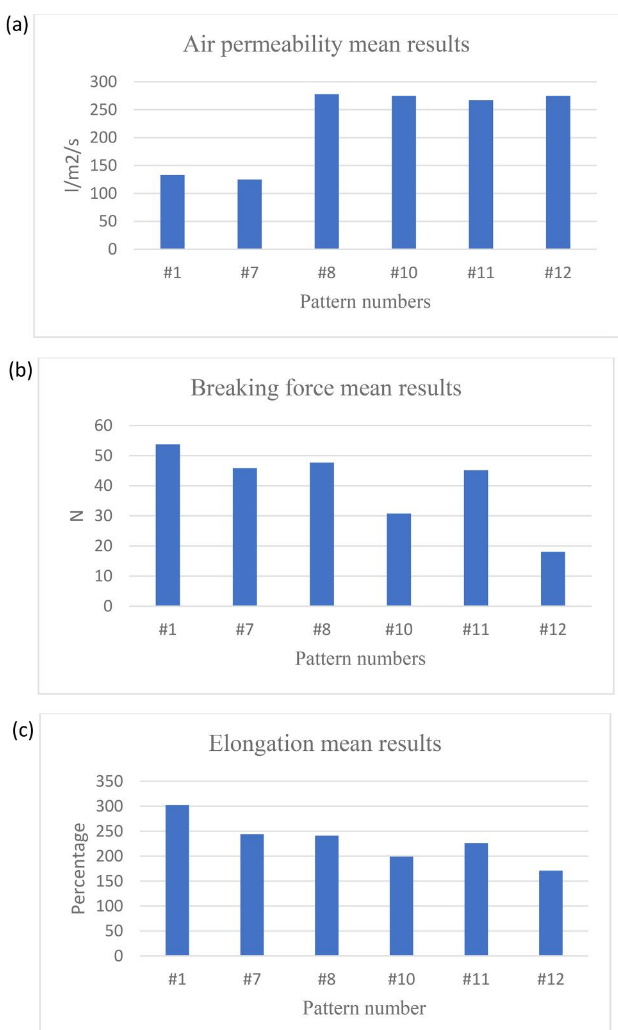


Figure 2. Step 1 results for: (a) air permeability, (b) breaking force, and (c) elongation percentage for patterns #1, #7, #8, #10, #11 and #12, at SL = 70.

but it also has the lowest breaking force value, indicating that the fabric can break relatively easily, and be problematic if used for the strap of a sports bra. These results validate the need to further investigate patterns #8, #10, #11, and #12, and the changes in their moisture management properties when SL is varied.

Step 2 plots of estimated marginal means for fabric density, thickness, and weight, shown in Figure 3, suggest gradual increases in fabric density with the increase in SL value for all patterns, and a gradual increase in fabric thickness and weight with the increase in SL value for all patterns except pattern #10. The two-way ANOVA results that tested the effects of pattern number and SL on thickness are shown in Table 4. There exists a significant interaction between pattern number and SL on thickness, confirming the findings of Bouagga et al. (2021). All differences between means for fabric thickness by the different SL values have been found to be statistically significant. Pattern #10 shows a higher fabric thickness for SL = 70 than SL = 115 or 125, which can be explained by the shorter distance between the tucked rows due to the shorter stitch length. Pattern #10 also has lower fabric weight for SL = 125 than SL = 115, which contrasts with its higher fabric thickness for SL = 125 than SL = 115. This finding suggests that the arrangement of knitted courses when longer tuck stitches are formed, such as in pattern #10, significantly influences fabric thickness and weight properties in an inconsistent manner across the three SL values, when compared with the other patterns tested.

The two-way ANOVA results that tested the effects of pattern and SL on air permeability, elongation, and breaking force are shown in Table 5. There exist significant interactions ($p < 0.001$) between pattern number and SL on air permeability, elongation, and breaking force. Air permeability results for Step 2 show that, compared to all SL values, SL = 70 offers the highest air permeability to all patterns except pattern #8, as shown in Figure 3(a). This finding could explain why SL = 70 is used as a default value for general seamless sports bra prototyping, since breathability is a key functional design feature for sports bras fabric. Patterns #11 and #12 show a decrease of air permeability for SL = 115, but a better breathability for SL = 125 than SL = 115. All differences in means between the various SL

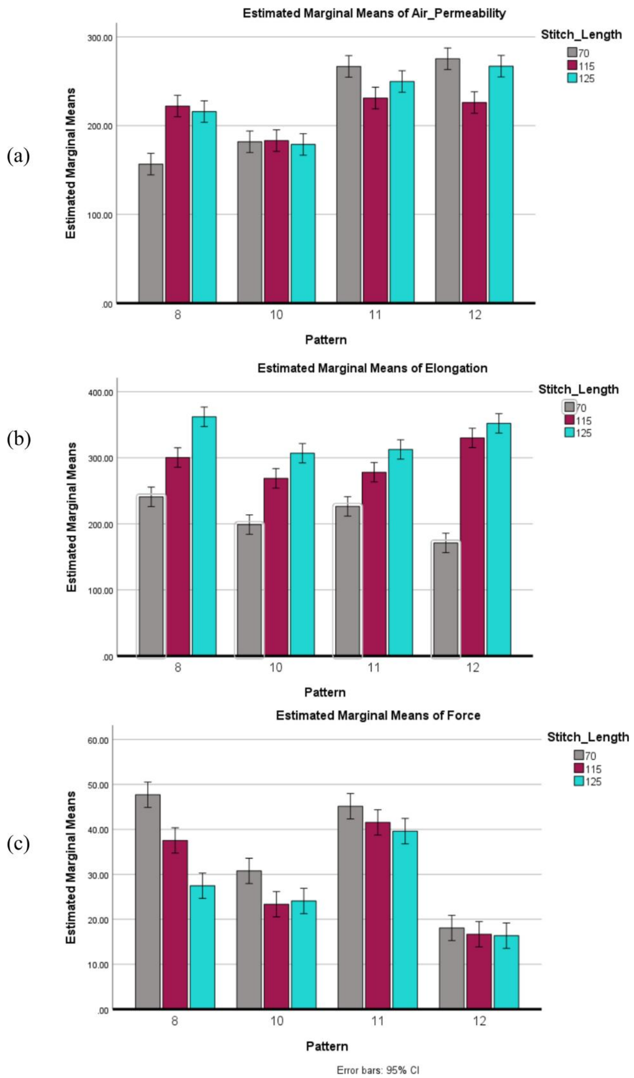


Figure 3. Estimated marginal means plots for the four patterns and three SL for: (a) air permeability, (b) elongation, and (c) breaking force.

Table 4. Two-way ANOVA results of the effects of pattern and SL on thickness.

Source	Degrees of Freedom	F	*p*-value
Model	11	317.4	<.001
Pattern	3	296.23	<.001
SL	2	390.37	<.001
Pattern * SL	6	303.66	<.001
R2	0.97		

are statistically significant. Pattern #10 shows the least difference in air permeability means between all three values of SL. The lack of a consistent pattern in air permeability results between these patterns and SL variations suggests that more fabric properties should be investigated to choose the most suitable for sports bra straps.

Breaking force and elongation plot results (Figure 3b and c) show a consistent behavior of a gradual increase in stretchability of all patterns with SL increases, but pattern #12 has the greatest increase in elongation between SL = 70 and the other two values for SL. However, the breaking force shows little variation for pattern #12 between all SL values, suggesting that this stitch structure needs the least force of all patterns to break it, disregarding the SL, a property not suitable for a bra strap due to increased pulling force exerted on bra straps during running or high intensity activities.

Table 5. Two-way ANOVA results of the effects of pattern and SL on air permeability, elongation, and breaking force (p-values).

Variable	Source	Degree of Freedom	F	*p*-value
Air Permeability	Model	11	41.4	<.001
	Pattern	3	110.39	<.001
	SL	2	4.11	<.019
	Pattern * SL	6	19.33	<.001
	R2	0.808		
Elongation	Model	11	67.43	<.001
	Pattern	3	18.6	<.001
	SL	2	301.73	<.001
	Pattern * SL	6	13.75	<.001
	R2	0.939		
Breaking Force	Model	11	65.48	<.001
	Pattern	3	196.58	<.001
	SL	2	38.51	<.001
	Pattern * SL	6	8.91	<.001
	R2	0.938		

Table 6. Linear regression of various variables vs SL for all patterns.

Variables	Pattern#	Coefficient constant	Coefficient SL	*P*-value	R2
Thickness	8	−0.257	0.015	<.001	0.987
	10	1.326	−0.003	<.001	0.842
	11	0.741	0.004	<.001	0.671
	12	0.959	0.002	<.001	0.357
Air permeability	8	74.985	1.192	<.001	0.915
	10	184.223	−0.029	.867	0.001
	11	296.321	−0.456	.023	0.127
	12	301.557	−0.44	.048	0.132
Breaking force	8	71.113	−0.325	<.001	0.79
	10	39.996	−0.135	<.001	0.811
	11	51.84	−0.094	.103	0.191
	12	20.246	−0.031	<.001	0.612
Elongation	8	101.265	1.933	<.001	0.855
	10	68.013	1.84	<.001	0.885
	11	123.683	1.439	<.001	0.767
	12	−63.232	3.364	<.001	0.949

Since there existed significant interaction between patterns and SL on thickness, air permeability, breaking force, and elongation, linear regression using SL as independent variable, and thickness, air permeability, breaking force, elongation as dependent variables for different pattern numbers was conducted (significant for $p < 0.05$). The results are shown in Table 6.

Specifically, for all pattern numbers, there existed significant linear regression between SL and thickness. The SL coefficients for patterns #8, #11 and #12 were greater than 0, suggesting that, increasing SL in patterns #8, #11, and #12 would increase fabric thickness. The SL coefficients for pattern #10 was less than 0. Increasing SL in pattern #10 would decrease fabric thickness. This fact could be explained by the lower number of tuck stitches and the closer stitch arrangement for pattern #10, compared with the other 3 patterns, as shown in the CAD diagram in Table 1. The increase in SL leads to an increase of yarn loops in the fabric with the lowest density among the 4 patterns, explaining why the fabric thickness would decrease with SL increase.

Table 6 shows significant linear regression between SL and air permeability for patterns #8, #11, and #12. Since SL coefficients for pattern #8 was greater than 0, increasing

SL in pattern #8 would increase air permeability. Pattern #8 has short tucks (2 rows only); therefore, SL increase will contribute to larger stitch loops all around the tucks, making the fabric more open and breathable. The SL coefficients for patterns #11 and #12 were less than 0, therefore, increasing SL in patterns #11 and #12 would decrease air permeability. These two patterns have longer tucks, so there will be more fabric gathered with SL increases, adding bulk and lowering their breathability.

There also existed significant linear regression between SL and breaking force for patterns #8, #10, and #12. The SL coefficients for all patterns were less than 0, meaning that increasing SL would decrease the breaking force. The significant linear regression existing between SL and elongation for all patterns (SL coefficients for all patterns were greater than 0) suggests that increasing SL would increase elongation, a fact consistent with the elasticity of a fabric structure made by knitted loops. Figure 3 confirms these results.

Moisture management data collected in Step 2 (Table 7) shows that pattern #10 with SL = 115 has the best OMMC category (very good) among all fabrics. The rest of the results show wide variances not only between the different patterns, that range from 'very poor' to 'very good', but also a wide variance between SL values for a single pattern, such as pattern #11 (from 'very poor' for SL = 125, to 'poor' for SL = 115, and to 'good' for SL = 70). Pattern #8 has consistent poor moisture management properties across all SL values, and pattern #10 has the best moisture management properties overall. Patterns #11 and #12 decrease their OMMC with increases in SL (shown in Figure 4).

The results shown in Figures 3(a) and 4 do not align with Nazir et al. (2014) findings, showing inconsistent trend behavior between patterns when comparing the air permeability with OMMC variances: trying to improve the air permeability of a stitch pattern by using a higher value SL did not consistently lead to a decrease in OMMC. This fact could be explained by the use of different fibers and/or stitch structures, as Nazir et al. (2014) used cotton yarns and interlock fabrics, suggesting the need for further studies on tuck stitch patterns.

Considering all the results discussed above, the data shows that pattern #10 in SL = 115 would be the best choice for seamless knitted sports bra straps, within the context of this study (yarns and knitting technology selection). Patter#10 is different from the other tuck patterns by the way of creating the thickest fabric *via* a more complex tuck stich repeat within a small number of tuck stitches in 576 knit stitches (576 is the smallest repeat that includes all samples), as shown by CAD diagram in Table 1: it has tucks of 8 courses with alternating spacing between tucks in two different ways. This finding is supported by the cross-examination of multiple fabric properties, such as fabric density, thickness, weight, air permeability, elongation coefficient, breaking force, and overall moisture management capabilities, for three different SL values. Elongation and breaking force testing alone were not sufficient for highlighting optimal fabric properties for a seamless sports bra strap.

Table 7. Summary results for MMT measurements by each pattern and SL.

Pattern #	SL		Wetting Time (TS)		Absorption rate (%/sec)		Max wetted radius (mm)		Spreading speed (mm/sec)		One way transport capability (%)	OMMC
			Top surface	Bottom surface	Top surface	Bottom surface	Top surface	Bottom surface	Top surface	Bottom surface		
8	70	Avg	4.65	3.05	42.33	45.09	15.00	17.00	2.43	2.25	90.66	0.38
		SD	0.09	2.24	1.78	4.54	0.00	2.74	0.05	0.35	10.13	0.02
	115	Avg	5.62	5.60	33.92	40.55	13.00	13.00	1.89	1.81	132.76	0.36
		SD	0.30	0.54	1.54	1.23	2.74	2.74	0.37	0.26	60.19	0.08
	125	Avg	5.52	5.82	28.93	44.18	17.00	14.00	2.04	1.81	144.06	0.38
		SD	0.09	0.21	10.46	2.29	7.58	2.24	0.26	0.23	53.11	0.07
10	70	Avg	4.78	3.82	39.83	56.12	18.00	19.00	2.61	2.71	170.62	0.52
		SD	0.65	1.96	13.01	22.33	4.47	4.18	0.16	0.16	108.29	0.07
	115	Avg	10.96	5.66	56.16	51.42	11.00	14.00	0.94	1.51	367.36	0.61
		SD	1.42	1.76	2.44	19.98	2.24	4.18	0.15	0.29	60.70	0.07
	125	Avg	11.11	4.36	67.35	46.95	16.00	16.00	1.36	1.71	324.62	0.57
		SD	1.18	1.20	8.62	6.65	8.22	8.22	0.80	0.80	29.77	0.09
11	70	Avg	6.11	5.86	53.84	69.20	18.00	20.00	2.44	2.68	154.61	0.53
		SD	0.63	0.61	2.45	2.56	2.74	0.00	0.25	0.14	11.57	0.02
	115	Avg	10.46	3.90	43.15	49.58	15.00	11.00	0.99	1.60	−41.36	0.21
		SD	1.78	4.22	8.07	17.37	8.66	2.24	0.14	0.51	110.73	0.06
	125	Avg	10.43	7.55	79.41	55.64	15.00	10.00	1.11	1.00	−195.60	0.13
		SD	1.23	5.23	13.80	12.49	8.66	0.00	0.21	0.04	28.80	0.04
12	70	Avg	9.05	6.51	57.53	58.52	16.00	19.00	1.71	1.96	252.90	0.54
		SD	1.34	2.34	27.08	11.71	2.24	2.24	0.15	0.47	105.23	0.12
	115	Avg	9.93	9.39	82.00	69.97	15.00	15.00	1.49	1.34	−220.28	0.19
		SD	0.50	2.07	7.69	11.19	0.00	0.00	0.06	0.15	49.99	0.02
	125	Avg	11.41	12.45	70.12	63.80	17.00	13.00	1.26	1.10	−180.99	0.16
		SD	1.01	1.27	11.56	2.85	7.58	2.74	0.30	0.15	85.63	0.01

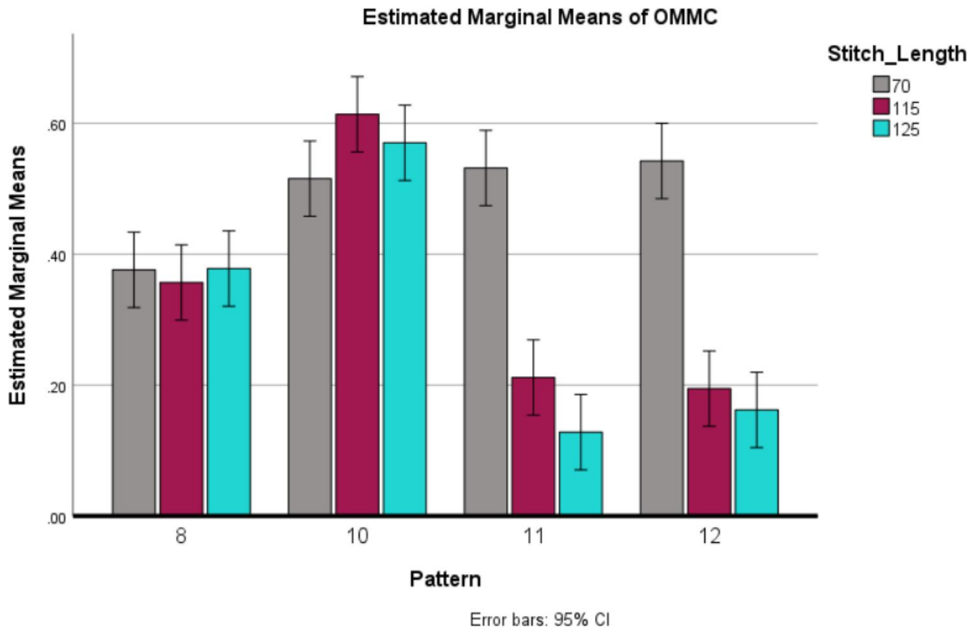


Figure 4. Plot for estimated marginal means for OMMC values for each pattern and SL.

Conclusion

The purpose of this study was to investigate the effect of SL and different stitch patterns on seamless knitted fabric properties as applied to sports bra strap functionality. Different tuck stitch patterns commonly used for seamless knitted activewear, were knitted with a Santoni machine setting for stitch SL = 70, using Repreve® recycled Nylon covered spandex yarns. Textile testing was conducted to narrow down the patterns suitable for bra strap in two steps: (1) selection of best tuck stitch patterns with low elongation and high air permeability measurements, and (2) investigation of the selected tuck stich patterns on moisture management variance when made with three different SL values. The results confirmed some of the existing knowledge about the influence of tuck stitches on the dimensional properties of weft knitted fabrics, such as increasing their density and stability, but also revealed new insights when varying SL of tuck stitches. Particularly, as shown by pattern #10, the complex arrangement of knitted courses when longer tuck stitches are formed (8 courses of tuck stitches, alternated within 6 wales, SL = 115), significantly influenced the fabric thickness and weight properties in an inconsistent manner across the three SL values, when compared with the other tuck stitch patterns examined. Therefore, the inherent three-dimensional geometry of the knitted fabric using complex tuck stich patterns leads to inconsistent interactions between fabric parameters when SL is varied, suggesting the need for deeper textile studies when choosing stitch patterns for seamless sports bras. Mathematical modeling of knitted fabrics could help, but more data from experimental studies, such as this one, is needed to build efficient algorithms. Moisture management measurements for various SL values proved to be critical in selecting the best stitch pattern and SL combination for optimizing sports bra strap design and highlighted the inconsistent tuck pattern fabric behavior in the presence of moisture.

Limitations and future research

This study had several limitations, such as the selected yarns, stitch patterns, SL values and knitting technologies. Seamless knitted garments are generally garment dyed, and further studies shall investigate the effect of wet processing parameters along with variations of SL and stitch patterns on fabric properties. Wakefield-Scurr et al. (2022) showed that repeated cycles of washing and drying of sports bras sightly diminish the support function of sports bras, therefore studies of how laundering affects the elongation and moisture management properties of pattern #10 with various SL values should be pursued. Considering that the design elements of a seamless sports bra are inter-dependent, as reported by Zhou et al. (2013), further investigations should be conducted on how the findings of this study can be implemented onto a complete sports bra design. Identifying the relationships between SL and stitch patterns when designing the straps of seamless sports bras in various sizes shall also be pursued *via* interdisciplinary collaborations and theoretical modeling, elevating the design and manufacturing potential *via* seamless knitting technologies.

The results of this research offer a scientific background that could help seamless sports bra designers in selecting appropriate knit stitch patterns and stitch size parameters, advancing the functionality of sports bras, and improving women's wellbeing and lifestyle. Moreover, these findings could be used for the design of other seamless activewear garments that require elongation stability and great moisture management, such as compressive medical garments and wearable technologies.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Funding for this research was provided by the University of Delaware, Unidel grants, HENSwear pilot projects.

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