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Effect of stitch patterns on moisture responsiveness of seamless knitted wool fabrics for activewear

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Abstract

Purpose – The purpose of this research was to investigate the effect of knit fabric stitch patterns, as indicated by fabric thickness variations, on moisture responsiveness for different seamless knitted wool-based fabrics.
Design/methodology/approach – Forty fabrics were created on a Santoni Top-2 circular knitting machine by using combinations of jersey, tuck and float stitches in combinations of wool/Nylon, wool, and spandex yarns. Physical properties of the knit fabrics as well as changes in fabric thickness during dry, wet, after 30 min air-drying and after 60 min air-drying conditions were compared. Repeated measures ANOVA tests and bivariate correlation analysis were conducted.
Findings – The results indicated that changes in moisture conditions had a significant effect on fabric thickness, and these changes differed by stitch pattern groups. Float patterns and tuck/rib patterns showed a continued relaxation of fabric thickness through all conditions, but tuck stitches and rib stitches showed a thickness recovery. Wool swatches, unlike the wool/Nylon swatches, increased their average thickness in after 60 min air-drying condition compared to 30 min air-drying condition.
Originality/value – This research documents the moisture responsive properties for wool based yarns, as emerging natural functional materials for seamless knitting industry, with applications in garments for activewear as well as healthcare.

Keywords Circular knitting, Moisture responsive, Wool, Fabric thickness

Paper type Research paper

1. Introduction

The amount of moisture, which textile fibers are capable of absorbing, affects their use in activewear. The reversible dimensional changes of the textiles when actuated by human body moisture, such as sweat, are referred to as "moisture responsiveness" (Sarkar *et al.*, 2010). Moisture-responsive fabrics have potential applications not only for improving the functionality of activewear but also in the development of smart clothing that responds to changes in the physiological conditions of the wearer to improve athletic performance and achieve maximum comfort (Fratzl and Weinkamer, 2007).

Fabric structures play an important role in the moisture transport. Knitted fabrics were once thought of as inferior to woven fabrics due to their relative instability; however, innovations in both yarn and manufacturing technologies have elevated knitted fabrics to have qualities that far outweigh those offered by woven fabrics (McCann, 2009). Particularly, the use of weft knitted fabrics in activewear has increased due to user-needs of stretchable,

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wrinkle-resistant and tight- fitting garments (Venkatraman, 2015). Fine-knitted fabrics used for next to skin compressive garments, such as sports bras, are produced on computerized seamless knitting machines that use micro-denier size yarns. These machines can create various knitted fabric structures side by side, such as combining jersey, tuck, or float stitches in each row, while also combining multiple yarn types, such as Nylon, polyester, cotton, wool and spandex. Additionally, the plain plating feature allows the use of two yarns that show separately on the two sides of the fabric, most commonly spandex yarn on one side and another yarn on the other side. This construction creates fabrics with special moisture management properties, with established applications in close-to-skin activewear (Lau and Yu, 2016).

Many studies reported on the properties of knitted fabrics made of various fibers and yarns as applied to activewear (Stegmaier *et al.*, 2005; Vincent, 2006; Tiwari *et al.*, 2013). Scott (2018) found that, when actuated by moisture, the dimensional change at a local scale within individual fibers is amplified throughout a knitted structure. Variations in loop length, stitch structures, yarn twist and knitting technology have been found to significantly influence the moisture transport properties of the fabrics (Őner and Okur, 2013). Liu and Hu (2011) found that knitting patterns influence a fabric's mechanical properties and compression characteristics. However, Tiwari *et al.* (2013) found that, among several knitted compression fabrics, there were no specific effects on moisture management properties when different knitting densities of the fabrics were compared. Choi and Ashdown (2000) reported that the mechanical properties of weft knitted fabrics used for outerwear vary according to knit structures, fibers, yarns and densities, which in turn affect the knit's hand significantly. Cooke (2011) found that fabric thickness affects moisture absorbency, and knitted fabrics are generally much thicker and more compressive than woven fabrics when made of similar yarns. A higher content of spandex results in higher thickness of circular plated knitted fabrics (Lau and Yu, 2016).

As water vapors move through the fabrics, the fibers absorb and desorb moisture, which furthermore creates a responsive behavior of the fabric (Horrocks and Anand, 2000). At the fiber level, it was established early on that the presence of moisture causes large changes in the swelling properties of natural fibers (Welo *et al.*, 1952; Hatch, 1993). 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. Wool fibers have the highest moisture regain compared with all fibers (Baird, 1961). Blending wool with polyester or wool with bamboo can improve the moisture management properties of plated circular knitted fabrics, compared with 100% wool and 100% bamboo fabrics (Troynikov and Wardiningsih, 2011). Additionally, Venkatraman (2015) stated that pure merino wool blended with other fibers regulate moisture absorption, wicking, and air circulation of knitted fabrics. Increasing the cashmere content in cashmere/wool circular knitted fabrics reduced the fabric thickness (McGreggor and Postle, 2008). Emirhanova and Kavusturan (2008) reported on the significant effect of knit structure and moisture relaxation processes on the thickness of the wool/ polyester blend knitted fabrics.

Currently, digital sensing technologies and new manufacturing methods have allowed engineers to develop whole new classes of responsive textiles, using nanofibers and conductive materials (Scott, 2018). Although some researchers have studied the responsive behavior for natural fibers and knitted fabrics when actuated by regular moisture in the environment (Berglin, 2008; Scott, 2018), only a few studies have been found to focus on knitted fabric changes due to human body moisture, such as sweat. Moreover, despite the increased use of fine denier wool yarns and seamless knitting technology for compressive activewear, a knowledge gap was found regarding moisture responsive properties of fabrics created by such a combination. Therefore, the purpose of this research was to investigate the effect of knitted stitch patterns on moisture responsiveness, as indicated by fabric thickness variations, for different seamless knitted wool-based compression fabrics.

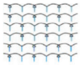
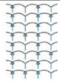
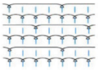
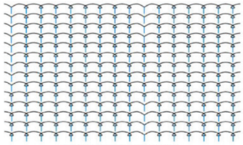
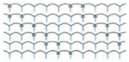
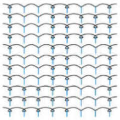
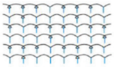
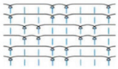
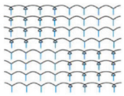
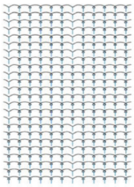
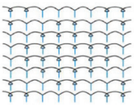
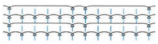
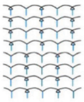
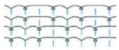
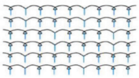
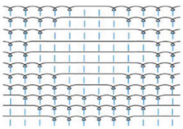
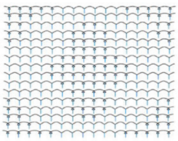
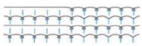
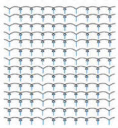
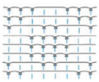
2. Methods

Our experimental samples consisted of 40 different fabrics knitted on a Santoni Top-2 circular knitting machine. Two different wool yarns were used to knit 20 different patterns in each yarn. The first yarn was undyed, 19.5 Nm, 90% wool 10% Nylon, 60/1 size. The second yarn was in light gray color, 19.5 Nm, 100% merino wool, 60/1 size. The yarn specifications were selected to fit the Santoni Top-2 machine. To simulate the commercial applications of seamless knitted fabrics for compression activewear, such as sports bras, each yarn was plated during knitting with 20–20/10/1 cover core spun 210 D bare elastic yarn. Each of the two yarn combinations were knitted in bands of 460 courses, using 20 patterns (combinations of tuck, jersey and float stitches), in a 28-gauge seamless tube. The distribution of stitch patterns used was as follows: 3 float stitch variations, 2 rib patterns, 13 tuck stitch variations, and 2 rib/tuck combo patterns. The stitch patterns are shown in Table 1.

The seamless knitted tubes were air-dried for 48 h in standard conditions (20 °C, 60% RH), then laundered 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). The number of courses per inch for each stitch pattern was calculated by dividing the total number of courses knitted for each pattern (460) by the physical width in the relaxed state of each pattern stripe, after being cut out horizontally from the knitted tubes. Similarly, the number of Wales per inch was calculated by dividing 1,344 (all needles on the 14" diameter circular Santoni machine used) by the physical flat width of the tube pattern, multiplied by 2 for circumference. Fabric swatches of "5°×°5" were accurately measured and cut out from each circular pattern band. Swatches made from 100% wool yarn were labeled "W" and swatches made of the 90% wool 10% Nylon blend were labeled "WN". All fabric swatches were conditioned in a conditioning equipment, set at standard atmospheric conditions: 20 ± 2°C, 65 ± 2% relative humidity (RH) for 24 h, according to ASTM D1776-08e1 (2008). Mass per unit area measurements and fabric thickness were determined according to ASTM D3776/D3776M-09ae2 (2009) and ASTM D1777-96e1 (2011). Using a Schröder fabric thickness gauge, each fabric swatch was kept on a flat anvil and a circular pressure foot was pressed onto it from the top under a standard fixed load of 4.14 ± 0.21 kPa (0.60 ± 0.03 psi). The thickness was read directly from the dial indicator, in mm up to 10 mm, in 10 different places of each fabric swatch (ASTM D1777-96e1, 2011). The mean value of all 10 readings was recorded to the nearest 0.01 mm and reported as the thickness of the sample. The physical measurements of all fabric swatches are shown in Table 2.

To investigate the responsiveness to moisture activation for each fabric, the thickness test was performed three more times: (a) after wetting, (b) after air- drying for 30 min, and (c) after air-drying for 60 min. In order to simulate the human sweating conditions, a salty solution that is commonly used for moisture management testing and suggested by activewear textile research literature, consisting of 1 L distilled water and 9 g of sodium chloride was used (Yao *et al.*, 2008; Vasconcelos *et al.*, 2017). Each swatch was sprayed with 2.25gr of the salty solution via 5 spray shots applied at 4" distance right above the swatches, at an approximately 45-degree angle. Each swatch was placed on a clear plastic sheet and secured with vertical inserted pushpins, without stretching the fabric. Time of moisture actuation was accurately recorded for each swatch. Due to the initial hydrophobic properties of the wool fibers, fabrics could absorb moisture for one minute, then the thickness measurements for the "after wetting" condition were performed (Hatch, 1993). The wet swatches were then placed on metal wire racks and allowed to air dry at room temperature of 70°F. The thickness

Table 1.
Knitted stitch patterns

Stitch pattern code	Stitch pattern description	Stitch diagram*	Stitch pattern code	Stitch pattern description	Stitch diagram
#1	tuck 2x2 vertical		#11	tuck 3x 1 alternate	
#2	rib 3x 1 alternate		#12	tuck 9 needle	
#3	tuck diagonal		#13	tuck 2x 8 alternate	
#4	tuck triangle		#14	float 2x2	
#5	tuck squares		#15	tuck 16 needle	
#6	tuck diamond		#16	rib 4x2	
#7	tuck 4x 1 vertical		#17	tuck 2x1 rib x1	
#8	tuck 2x2 alternate		#18	float diamond	
#9	tuck quilt		#19	tuck rib	
#10	tuck cinching		#20	float diamond reverse	

Key: Jersey stitch , tuck stitch , float stitch 

Swatch code	Thickness (mm)	Courses	Wales	Knit density (whales/cm × courses/cm)	Weight (g/m^2)	Weight/ Thickness
1W	1.49	46	20	920	336	22.49
1WN	1.46	46	19	874	352	24.19
2W	2.08	42	24	1004	412	19.8
2WN	2.17	42	23	962	404	18.62
3W	2.29	66	23	1511	472	20.58
3WN	2.3	66	23	1511	472	20.5
4W	1.73	51	23	1176	364	21.08
4WN	1.73	51	21	1073	376	21.72
5W	2.38	46	31	1426	520	21.89
5WN	2.49	46	30	1380	564	22.68
6W	1.93	46	22	1012	384	19.93
6WN	1.94	46	21	966	400	20.59
7W	1.66	58	18	1035	384	23.2
7WN	1.65	58	18	1035	396	23.94
8W	1.77	33	23	756	360	20.29
8WN	1.73	35	22	778	392	22.62
9W	3.29	77	24	1840	676	20.52
9WN	3.2	77	23	1763	674	21.06
10W	2.21	35	24	849	432	19.57
10WN	1.9	38	19	728	388	20.4
11W	2	48	22	1065	456	22.78
11WN	1.89	46	22	1012	460	24.29
12W	2.5	38	21	805	456	18.28
12WN	2.62	42	19	795	448	17.11
13W	2.64	58	23	1323	528	19.98
13WN	2.68	51	23	1176	576	21.48
14W	1.58	38	19	728	268	17.01
14WN	1.38	35	19	672	264	19.08
15W	4.84	92	22	2024	732	15.12
15WN	5.27	92	18	1656	920	17.46
16W	2.36	38	24	920	388	16.45
16WN	2.59	38	25	958	456	17.61
17W	1.88	42	21	878	324	17.23
17WN	1.66	38	20	767	312	18.84
18W	2.19	33	22	723	324	14.79
18WN	2.11	31	21	644	364	17.25
19W	2.08	35	23	814	416	20.02
19WN	2.21	35	23	814	416	18.83
20W	1.83	42	19	795	284	15.49
20WN	1.82	38	20	767	280	15.4

Table 2.
The results of physical fabric tests for all swatches

measurements were performed and recorded again, for each swatch, after air-drying for 30 min, and then after air-drying for 60 min.

Given the high density and visible porosity of some of the fabrics in this study, as shown in Plate 1 magnified fabric images, particularly the tuck stitch patterns, we encountered difficulties in consistently measuring the changes in fabric density between the various moisture conditions for all swatches. Therefore, we aimed at evaluating if fabric thickness changes could be an indicator for moisture responsiveness. Thickness measurement variances between the four moisture conditions (*Dry*, *Wet*, *After 30* min *air- drying, and After 60* min *air- drying*) were analyzed for all 40 swatches, using repeated measures analysis of variance (ANOVA) tests and SPSS 26.0 software. For all results, $p < 0.05$ was considered significant. Pearson correlation analysis was also conducted for physical measurements of all swatches to evaluate if any characteristics pairs are related. When discussing the results in the following sections, the spandex yarn was omitted from the yarn content description, to shorten the communication wording. The knitted swatches were referred by their main fiber composition, as “wool fabrics,” and “wool/ Nylon fabrics.”

3. Results

In the *Dry* condition, the thickest fabric among all was pattern #15 (tuck group) in wool/Nylon yarn (5.27 mm in thickness), and the thinnest fabric was pattern #14 (float group) in wool/ Nylon yarn (1.38 mm in thickness). In the Wet condition, the thickest fabric was still pattern #15 in wool/Nylon yarn (5.02 mm thickness) and the thinnest was still pattern #14 in wool/ Nylon yarn (1.31 mm thickness). Sixty percent of the knitted patterns were thicker in wool yarn than the wool/Nylon yarn combination when dry (shown in Table 3).

The descriptive statistics of the fabric thickness results showed a decrease in mean thickness of all swatches from 2.24 mm ($SD = 0.79$) in *Dry condition*, to 2.10 mm ($SD = 0.74$) in *Wet condition*, to 2.08 mm ($SD = 0.73$) in *After 30* min *air-drying condition*, but a slight increase afterwards, to 2.09 mm ($SD = 0.79$) in *After 60* min *air-drying condition*. These results confirmed the literature findings on the effect of relaxation of wool fibers when emerged in water, and that the fiber relaxation is transferred into reduced knitted fabric thickness (Scott, 2018).

The one-way repeated measures ANOVA tested the null hypothesis that there is no change in fabric thickness when measured in the various moisture conditions for all swatches ($N = 40$). The results indicated a significant effect of moisture condition on thickness, Wilks’ Lambda = 0.13, $F\,(2, 38) = 84.45$, $p < 0.01$, $\eta^2 = 0.87$. Thus, the null hypothesis was rejected. Analyzing the effects of fiber type and stitch type factors on thickness measurements, the multivariate test results showed no significant interactions between the four moisture conditions and fiber type or stitch type variables, but an exceptionally large effect of the moisture conditions on thickness measurements (Partial Eta Squared = 0.804) (shown in Table 4).

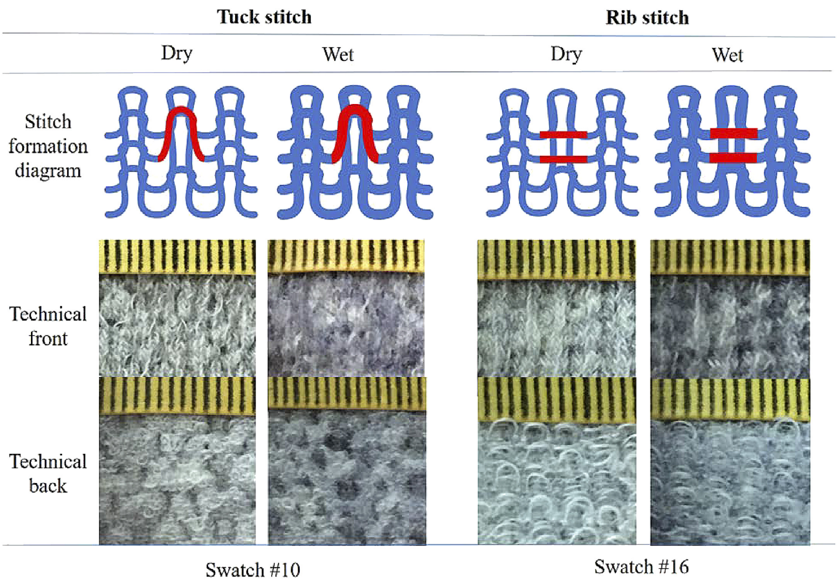


Plate 1.
Tuck and rib stitch examples of technical loop formations in Dry and Wet conditions, along with magnified images of example swatches, their technical front and back in both Dry and Wet conditions. Note that “rib” stitch in circular knitting is formed by a vertical row of float stitches, and not by alternating jersey with purl stitches as in general knitting terminology. The distance between 2 black ruler markings is 1 mm

Table 3. Thickness measurements for all swatches in all conditions, shown by Stitch Pattern Groups (Float, Rib, Tuck and Rib/Tuck combo stitches) and fiber group (Wool/Nylon and Wool)

Stitch patterns groups	Wool/Nylon group swatch code	Condition: Dry (mm)	Condition: Wet (mm)	Condition: After air-drying (mm) 30 min	Condition: After air-drying (mm) 60 min	Wool group swatch code	Condition: Dry (mm)	Condition: Wet (mm)	Condition: After air-drying (mm) 30 min	Condition: After air-drying (mm) 60 min
Float stitches	14WN	1.38	1.31	1.27	1.23	#14W	1.58	1.38	1.49	1.49
	18WN	2.11	1.92	1.91	1.9	#18W	2.19	2.14	2.09	2.14
	20WN	1.82	1.66	1.68	1.65	#20W	1.83	1.69	1.68	1.71
Rib stitches	#2WN	2.17	2.09	2.07	2.04	#2W	2.08	2.02	1.96	2.01
	#16WN	2.59	2.46	2.39	2.41	#16W	2.36	2.18	2.14	2.16
Tuck stitches	#1WN	1.46	1.37	1.36	1.34	#1W	1.49	1.35	1.33	1.33
	#3WN	2.3	2.14	2.14	2.08	#3W	2.29	2.09	2.02	2.03
	#4WN	1.73	1.6	1.58	1.58	#4W	1.73	1.56	1.55	1.57
	#5WN	2.49	2.44	2.4	2.37	#5W	2.38	2.21	2.18	2.2
	#6WN	1.94	1.83	1.83	1.82	#6W	1.93	1.72	1.7	1.71
	#7WN	1.65	1.55	1.51	1.52	#7W	1.66	1.58	1.52	1.53
	#8WN	1.73	1.7	1.67	1.67	#8W	1.77	1.66	1.66	1.68
	#9WN	3.2	3.07	3.05	3.03	#9W	3.29	3.04	3.05	3.12
	#10WN	1.9	1.75	1.88	1.85	#10W	2.21	2.08	1.93	1.98
	#11WN	1.89	1.79	1.79	1.79	#11W	2	1.89	1.88	1.9
	#12WN	2.62	2.5	2.38	2.33	#12W	2.5	2.49	2.45	2.46
	#13WN	2.68	2.54	2.52	2.44	#13W	2.64	2.55	2.54	2.52
	#15WN	5.27	5.02	4.9	4.94	#15W	4.84	4.31	4.33	5.02
Rib/tuck stitches	#17WN	1.66	1.5	1.49	1.47	#17W	1.88	1.78	1.77	1.77
	#19WN	2.21	2.05	2.02	1.99	#19W	2.08	1.93	1.94	1.93

Effect	Value	*F*	Hypothesis df	Error df	Sig	Partial eta squared	Noncent. Parameter	Observed power[b]
Moisture Condition (M.Cond.)	0.196	41.110	3.000	30.000	0.000	0.804	123.331	1.000
M.Cond.* Fiber type	0.933	0.717	3.000	30.000	0.550	0.067	2.150	0.184
M.Cond.* Stitch type	0.876	0.456	9.000	73.163	0.899	0.043	3.312	0.171
M.Cond.* Fiber type* Stitch type	0.923	0.271	9.000	73.163	0.980	0.026	1.976	0.115

Note(s): a. Design: Intercept + Fiber + Stitch Type + Fiber * Stitch Type; b. Computed using alpha = 0.05

Table 4.
Multivariate Testsa for Fiber and Stitch type factors

Follow-up comparisons between moisture condition pairs indicated that eight out of twelve pairwise thickness mean differences were significant, $p < 0.05$ (Table 5). The statistically significant results showed that: (a) on average, thickness in the *Wet* condition measured 0.134 mm less than in the *Dry* condition, (b) on average, thickness *After 30* min *air-drying* measured 0.154 mm less than the thickness in the *Dry* condition, (c) on average, the *After 60* min *air- drying* thickness measured 0.147 mm less than the thickness in the *Dry* condition, (d) on average, the thickness in the *Wet* condition measured 0.020 mm higher than thickness *After 30* min *air-drying*.

Plots of interaction between fiber type factor and average fabric thickness for each moisture condition showed a crossover point at the *After 30* min *air-drying* condition level,

(I) M.Cond.	(J) M.Cond.	Mean difference (I-J)	Std. Error	Sig.**	95% confidence interval for difference** Lower bound	Upper bound
Dry	*Wet*	0.134*	0.019	0	0.081	0.186
	After 30 min	0.154*	0.019	0	0.099	0.208
	After 60 min	0.147*	0.019	0	0.095	0.2
Wet	*Dry*	−0.134*	0.019	0	−0.186	−0.181
	After 30 min	0.020*	0.011	0.441	0.01	0.051
	After 60 min	0.014	0.028	1	−0.065	0.092
After 30 min air-dry	*Dry*	−0.154*	0.019	0	−0.208	−0.099
	Wet	−0.020*	0.011	0.441	−0.051	−0.01
	After 60 min	−0.006	0.025	1	−0.075	0.063
After 60 min air-dry	*Dry*	−0.147*	0.019	0	−0.2	−0.095
	Wet	−0.014	0.028	1	−0.092	0.065
	After 30 min	0.006	0.025	1	−0.063	0.075

Note(s): * The mean difference is significant at the 0.05 level. ** Adjustment for multiple comparisons: Bonferroni

Table 5.
Pairwise comparisons for fabric thickness in various moisture conditions

but according to previous results, this interaction was not significant. The wool/Nylon group showed a relatively higher average thickness in the *Wet* condition compared to the Wool group, but also without being significant. However, it is notable that only the wool fiber swatches had an increase in average thickness *After 60* min *air-drying*, compared to the *After 30* min *air-drying*, suggesting a thickness recovery after the wet relaxation process (shown in Figure 1). Tuck stitch patterns #15 and #9, having the highest thicknesses in all conditions, were the ones that showed a significant thickness recovery in the *After 60 min air drying* condition when made in the wool yarn.

Moreover, the plot for estimated marginal means of fabric thickness by moisture condition, for each stitch type group (shown in Figure 2) highlighted the similar behavior of the thickness variance of different stitch groups between the conditions, but also indicated that, besides the tuck stitch group, the rib stitch group also had a slight increase in thickness

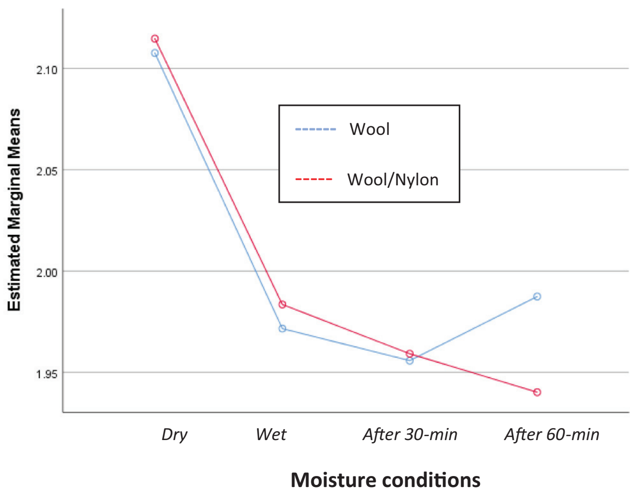


Figure 1.
Estimated marginal means of fabric thickness by moisture condition, for each fiber group

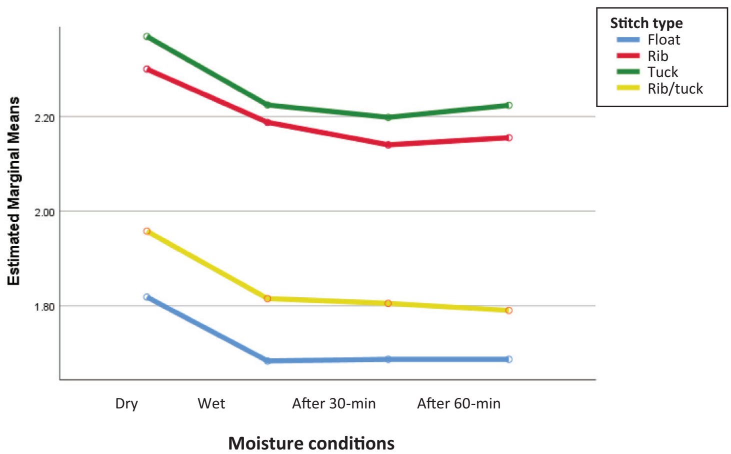


Figure 2.
Estimated marginal means of fabric thickness by moisture condition, for each stitch type group

After 60 min *air-drying*, relative to the *After 30* min *air-drying* condition. However, the rib/tuck stitch group displayed a continued relaxation of thickness even in the *After 60* min *air-drying* condition.

The above results suggested that other physical variables might have influenced the effect of thickness variance during the moisture changing conditions. The Pearson correlation analysis found a significant and strong positive correlation between the fabric thickness in *Dry* condition (M = 2.24, SD = 0.79), and fabric density in *Dry* condition (M = 1048.37, SD = 344.85), r (39) = 0.733, $p < 0.001$. Fabrics with higher thicknesses had higher density in *Dry* condition. A stronger positive correlation was found between the fabric thickness in *Dry* condition (M = 2.24, SD = 0.79), and fabric weight in *Dry* condition (M = 435.75, SD = 133.19), r (39) = 0.917, $p < 0.001$. Fabrics with higher thicknesses had higher weights in *Dry* condition.

4. Discussion and conclusion

The use of wool yarn as a natural functional material in seamless knitted activewear is in its infancy, and this current study fills the knowledge gap on evaluating moisture responsiveness as an emerging user-need for close-to-body garments. Our study particularly aimed at evaluating if fabric thickness could be an indicator of moisture responsiveness for various seamless knitted wool and wool/Nylon swatches. For this purpose, 40 fabrics were knitted using plated combinations of Nylon covered spandex with 100% wool, and Nylon covered spandex with 90% wool 10% Nylon yarns via 14”diameter Santoni seamless knitting machine. The fabric samples were knitted in 28-gauge seamless tubes with 3 patterns in float stitch variations, 2 patterns in rib combinations, 13 patterns in tuck stitch variations, and 2 patterns in rib/tuck combo patterns. The sampling selection was focused on creating a variety of stitch combinations that cover the fabric thickness range that Santoni seamless technology can create.

Results showed a significant relaxation of thickness between *Dry*, *Wet*, *After 30* min *air-drying* and *After 60* min *air- drying* conditions, but some stitch groups showed a thickness recovery in the last condition. Particularly, tuck and rib stitch patterns, when made in the 100% wool yarn, had a slight increase in average thickness *After 60* min *air-drying* versus *After 30* min *air-drying* condition. However, the tuck/rib combo group did not show a thickness recovery in air-drying conditions. Given that both tuck and rib stitches involve a folding of the fabric in vertical and respectively, horizontal direction, as opposed to float stitch combinations that involve skipping stitches, the results showed that fabrics with higher stitch density were more responsive to moisture. According to Bueno *et al.* (2004), during the knitting process, the fabrics are subjected to wale-wise tensile stress, and this stress elongates and flattens out the stitches. Thus, after the relaxation during the wetting process, the tuck and rib stitch loop formations retracted faster than float stitches, resulting in fabric thickness recovery. The stitch formation diagrams shown in Plate 1 highlight the deviations in loop shape and length from regular jersey loop formations for tuck and rib stitch patterns, in both Dry and Wet conditions. The shorter loop length and their overlapping positions could explain the faster air drying and return of yarn crispiness, prompting to fabric thickness recovery after relaxation.

The tuck and rib stitch patterns in 100% wool yarn were also the thickest among all swatches, suggesting that the blending of wool with nylon reduces the seamless knitted fabric moisture responsiveness. However, further studies are needed to observe the thickness changes for a longer time period, as well as using more stitch structures in each group and more wool/Nylon blending combinations. The Nylon covered spandex yarn was added to each fabric swatch in order to simulate the current manufacturing methods used in seamless knitting activewear. Besides aiding in the recovery from stretching the knitted fabrics, particularly for fabrics made of wool fibers that tend to relax when subjecting to moisture, the hydrophobic properties of Nylon covered spandex yarn also help with moisture wicking properties desired for next-to-skin garments (Hussain *et al.*, 2015). However, the role of spandex in moisture responsiveness in this study must be further studied.

The relaxation of wool fibers when absorbing moisture is therefore confirmed, as stated by Őner and Okur (2013). Although strong positive relationships between knit fabric thickness, density and weight were found in the *Dry* condition, no method was found to accurately estimate fabric density variations during the other moisture conditions. The high density and porosity of wool seamless knitted fabrics have been a limitation for this study, preventing the consistent evaluation of fabric courses, Wales and general moisture management testing results through all moisture conditions. Several fabric swatches displayed a strong radial stitch patterning, such as the ribs and tuck stitches, resulting in visible differences in how moisture actuation leads to unique fabric deformation patterns. All swatches displayed mechanical changes when sprayed with the saline solution, but the speed and the way they curled and shrank, although visibly different, was hard to measure. Lighter weight fabrics tended to curl faster and roll more than thicker and heavier fabrics, suggesting that interdisciplinary studies of moisture actuation simulations on stitch geometry for seamless knitted wool fabrics could lead to the development of shape-changing knitted structures. Scott (2018) also recorded mechanical fabric actuation when differential tension in knitting hydrophobic and hydrophilic yarns were used, but her study was a visual design evaluation; quantifying the topologic changes in the knitting structures is a highly complex process that must be further determined.

The increased use of advanced knitting technologies for the development of functional apparel that demands dynamic moisture management properties requires more understanding of how the hierarchical structures created by fibers, yarns, stitches and patterns behave when actuated by human perspiration. Whilst this study brings new knowledge about the effect of stitch patterns on moisture responsiveness of seamless knitted wool fabrics made with a Santoni machine, further explorations of emerging performance wool fibers and yarns knitted on other type of machines, such as Shima Whole Garment and Stoll brands should be pursued (Venkatraman, 2015). The integration of moisture responsive knitted patterns or fabrics into close-to-body garments could potentially lead to methods of engineering variable compression, with applications beyond activewear, but also surgery recovery bandages and stockings.

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