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Thermal and Mechanical Characteristics of Cotton Knitted Fabric Made of Non-twisted Hollow Yarn for Inner Wear

KyoungOk Kim [a], Toko Manabe [a], Masayuki Takatera [a,*], Nagisa Hirata [b], Kyosuke Kanda [b], Masatoshi Kawakami [b]

[a] *Shinshu University, Faculty of Textile Science and Technology, 3-15-1Tokida, Ueda, Nagano, 386-8567, Japan*

[b] *Kondo Cotton Spinning Co., Ltd, Marunouchi 2-18-25 Naka-ku Nagoya, Japan*

Abstract

The characteristics of a weft knitted fabric made of new cotton non-twisted hollow yarn targeting an inner wear product were investigated. The weight, thickness, thermal characteristics, tensile, shear properties, bending properties and surface properties of the knitted fabric and four commercially available inner wear fabrics were measured using a KES-FB system. The measured properties were examined to examine the usefulness of the new fabric for inner wear. Fabric characteristics were compared in a multiple comparison test. The knitted fabric made of non-twisted hollow yarn is lighter and fuller than commercially available inner wear fabrics. The shear stiffness and bending rigidities of the knitted fabric were similar or lower than ones of commercially available cotton inner wear fabrics. The surface properties of the new fabric were similar to ones of commercially available inner wear fabrics. The fabric also has a lower Q-max value (the peak value of heat transferred), lower thermal conductivity, and higher heat retention rate and is therefore warmer than the commercially available fabrics. It is thus considered that knitted fabric made of new cotton non-twisted hollow yarn is suitable for inner wear.

Keywords: Weft Knitted Fabric; Non-twisted Hollow Yarn; Inner Wear; Thermal Properties

1 Introduction

Cotton knitted fabrics have been widely used for many clothing items, especially for innerwear. To improve the handle of cotton fabric, yarn manufacturing processes such as carding and combing, and finishing treatments such as mercerization are carried out [1-3]. Thermal and mechanical properties are considered as important characteristics for the comfort of cotton knitted fabrics. Many researchers investigated the relationship between thermal comfort taking into account knitting structure and yarn properties [4-6]. On the other hand, synthetic fibers with excellent functionality have been developed in recent years [7] and many fabrics are used for inner wear [8].

*Corresponding author.
Email address: takatera@shinshu-u.ac.jp (Masayuki Takatera).

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Meanwhile, several studies on skin damage caused by clothing have been reported [9-11]. Ohkawa [9] reported skin problems caused by clothes. In the study, a questionnaire survey was conducted for a total of 2386 men and women, ranging from infants to elderly people, throughout Gunma Prefecture in Japan. Most skin problems were caused by inner wear. Iwaki et al. [10] investigated the consciousness of the elderly towards inner wear. They reported that the elderly believe that skin problems may be due to synthetic fibers although there is no evidence for this. Kawai [11] summarized the cases of skin disorders caused by textile products. That study found that skin damage occurred through physical irritation due to textiles having poor moisture permeability or through the pressing and rubbing of textiles on the skin. Rietschel [12] reported that sweat-resistant nylon products cause sweat rashes. The First Research Group of Japanese Society [13] conducted experiments on the irritation of skin due to clothing. They clarified that as the fiber becomes thicker, the bending stiffness and the compression recovery increase and skin irritation increases. They also found that the skin irritation becomes more evident as the number of twists of the yarn increases when the fiber thickness is constant.

On the above basis, it is considered that ideal inner wear will generate less pressure when a material that is soft and generates less friction is used. In addition, to reduce skin irritation, it is considered that a thin thread with a small number of twists is preferable.

As a fabric for inner wear, a knitted fabric made of a new cotton non-twist hollow yarn has been developed as shown in Fig. 1. The untwisted cotton fiber bundle is wrapped with covering cotton fiber. The knitted fabric is expected to be soft, have excellent heat retention, and be light and thin [18]. These properties could be suitable for inner wear. Andrysiak et al. [19] investigated the thermal resistance of woven fabrics made of a cotton hollow yarn. However, it used woven fabric made of twisted hollow yarn. The thermal and mechanical properties of the knitted fabric will be different from those of the woven fabric. The present study investigated the properties of the developed knitted fabric and compared them with the properties of commercially available inner wear to examine the usefulness of the developed knitted fabric for inner wear.

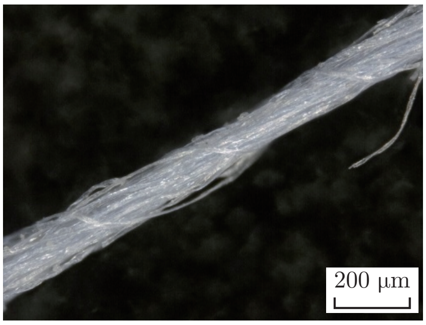


Fig. 1: Cotton non-twist hollow yarn

2 Experiment

To investigate the characteristics of knitted fabric made of cotton non-twist hollow yarn, we measured the weight and thickness at 50 gf/cm^2 using a KES-FB3 compression tester [14]. Tensile, shear, bending and surface properties were measured using KES-FB1-4. Thermal characteristics (i.e., the peak value of heat transferred (Q-max), thermal conductivity, and heat retention rate) were also measured using a KES-FB9 device [15,16]. Ventilation resistance was also measured using KES-F8 with wind speed about 15 m/s, slightly strong wind. The air content of the fabric was calculated as [17]

$$\text{Air content}\,(\%) = (1 - d_1/d_0) \times 100, \tag{1}$$

$$d_1(\text{g/cm}^3) = w/(1\ 000 \times t), \tag{2}$$

where d_1 is the apparent specific gravity (g/cm^3), d_0 is the density of the fiber (g/cm^3), w is the area density (g/m^2), and t is the thickness (mm).

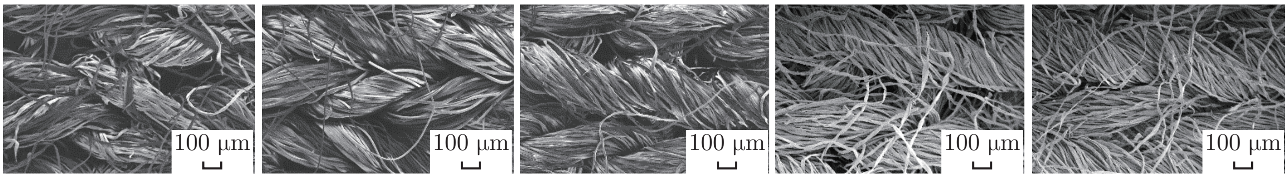
Table 1: Specifications of samples

Sample number	Yarn type	Composition	Structure	Stitch density (/inch) wale/course	Air content (%)
1	Non-twisted hollow yarn	Cotton 100%	Plain stitch	49.6/47.2	94.3
1×2			Two layers of sample 1		
1×3			Three layers of sample 1		
1×4			Four layers of sample 1		
2	Filament yarn	Polyester 38%, Acrylic 32%, Rayon 21%, Polyurethane 9%	Plain stitch with stretch yarn	63.4/44.2	84.3
3	Twisted yarn	Cotton 100%	Rib stich	49.0/34.0	89.6
4	Twisted yarn	Cotton 100%	Rib stich	48.0/30.6	90.4
5	Twisted yarn	Cotton 100%	Interlock	39.4/38.6	90.9

We prepared sample 1, which was a knitted fabric of the non-twisted hollow yarn having a (designed) linear mass density of 7.4 tex. We also obtained four samples of commercially available inner wear that is popular on the Japanese market. The specifications of the samples are given in Table 1. Surface pictures and SEM pictures are shown in Figs. 2 and 3. A single fabric of sample 1 was transparent and light enough to make layered fabrics. Thus, as variations of sample 1, we made layered fabrics comprising two to four layers without bonding points. We made measurements of each sample five times and used average results. The measurement results were tested adopting an analysis of variance and the Tukey method for multiple comparisons. The experimental environment had a temperature of 20 ± 1°C and relative humidity of 65% ± 4%.

(a) Sample 1 (b) Sample 2 (c) Sample 3 (d) Sample 4 (e) Sample 5

Fig. 2: Surface pictures of knitted fabric samples

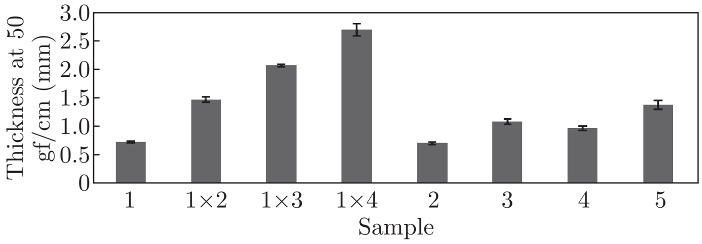


(a) Sample 1 (b) Sample 2 (c) Sample 3 (d) Sample 4 (e) Sample 5

Fig. 3: SEM pictures of knitted fabric samples

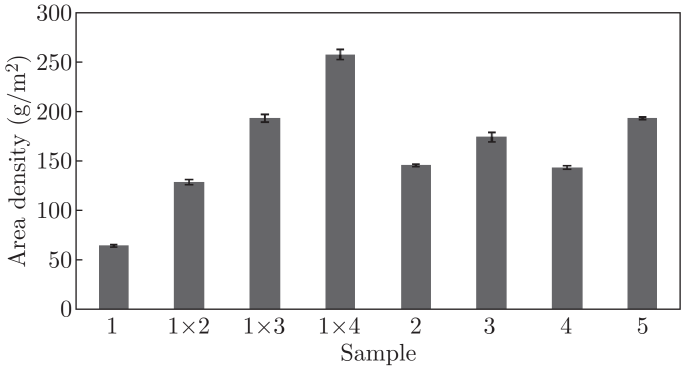
3 Results and Discussion

Fig. 4 compares the thicknesses of samples. The thicknesses of samples 1 and 2 were similar and greater than thicknesses of samples 3 and 5 with a significant difference at the 1% level and greater than the thickness of sample 4 with a significant difference at the 5% level. Fig. 5 compares the weights per unit area of samples. The area density of sample 1 was the lightest among samples. Even sample 1×2, which is the two-layered version of sample 1, was lighter than the commercially available samples with a significant difference at the 1% level. Although the thickness of sample 1 was similar to that of sample 2, the area density of sample 1 (64 g/m^2) was less than half that of sample 2 (145 g/m^2) with a significant difference at the 1% level. Samples 2, 3, 4, and 5 had similar weights per unit area. The knitted fabric made of non-twisted hollow yarn is therefore lighter and fuller than commercially available inner wear fabric.



(no significant differences between samples 1 and 2, 1×2 and 5, and 3 and 4; significant difference at the 5% level between samples 1 and 4; significant differences at the 1% level for other sample pairs)

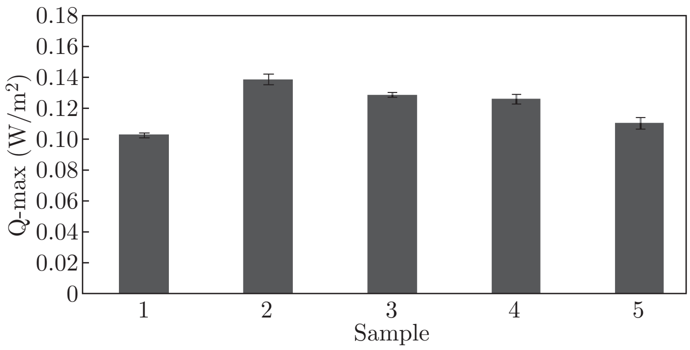
Fig. 4: Comparison of thicknesses of samples



(no significant differences between samples 1×3 and 5 and samples 2 and 4; significant differences at the 1% level for other sample pairs)

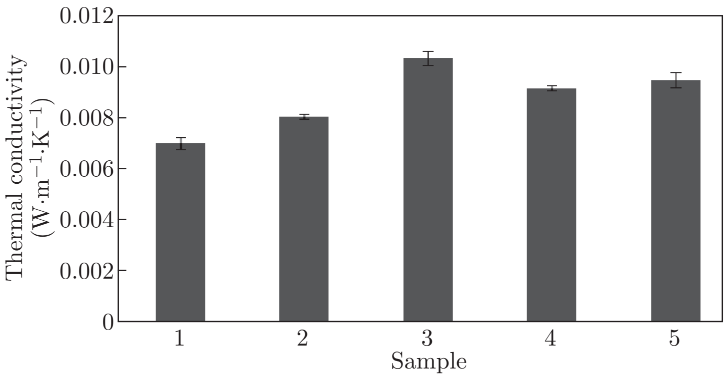
Fig. 5: Comparison of area densities of samples

Fig. 6 compares Q-max values of samples. The Q-max value of sample 1 was the smallest with a significant difference at the 5% level, revealing that sample 1 had a warmer contact feeling than the other samples. Fig. 7 compares the thermal conductivities of samples. Sample 1 had the lowest value among the samples with a significant difference at the 1% level. Fig. 8 compares the heat retentions of samples at a wind speed of 30 cm/s. Table 2 presents the significant differences in heat retention for sample pairs. Sample 1 had heat retention similar to that of the other samples. However, samples 1×2, 1×3, and 1×4 had heat retention much higher than that of other samples with significant differences at the 1% level. Fabric that is much warmer than the



(no significant difference between samples 3 and 4; significant differences at the 5% level between samples 1 and 5 and samples 2 and 3; significant differences at the 1% level for other sample pairs)

Fig. 6: Comparison of Q-max values of samples



(no significant difference between samples 4 and 5; significant differences at the 1% level for other sample pairs)

Fig. 7: Comparison of thermal conductivities of samples

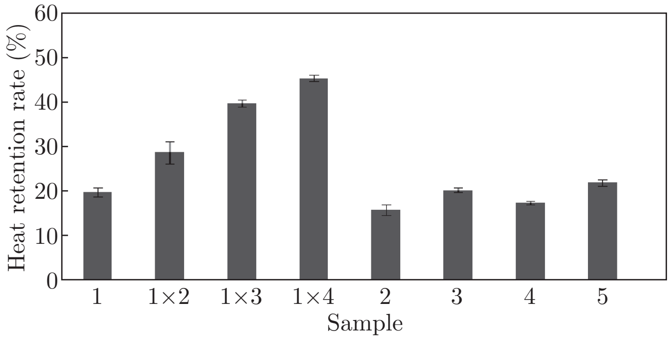


Fig. 8: Comparison of the heat retentions of samples at a wind speed of 30 cm/s

Table 2: Significant differences in heat retention between sample pairs (*5%, **1%)

Sample pairs	Significant difference	Sample pairs	Significant difference	Sample pairs	Significant difference	Sample pairs	Significant difference
1–(1×2)	**	(1×2)–(1×3)	**	(1×3)–2	**	(1×4)–5	**
1–(1×3)	**	(1×2)–(1×4)	**	(1×3)–3	**	2–3	*
1–(1×4)	**	(1×2)–2	**	(1×3)–4	**	2–4	
1–2	*	(1×2)–3	**	(1×3)–5	**	2–5	**
1–3		(1×2)–4	**	(1×4)–2	**	3–4	
1–4		(1×2)–5	**	(1×4)–3	**	3–5	
1–5		(1×3)–(1×4)	**	(1×4)–4	**	4–5	*

fabrics of commercially available inner wear can be obtained by layering sample 1 with lighter mass. The higher air content of sample 1, as shown in Table 1, affects the heat retention of the non-twisted hollow yarn. It is therefore found that the knitted fabric made of cotton non-twisted hollow yarn is warmer to the touch than the commercial inner wear fabric. Warmer inner wear will be made by layering the knitted fabric.

Fig. 9 shows a comparison of the ventilation resistance of samples and the significant differences in ventilation resistance between sample pairs are shown in Table 3. The ventilation resistance of sample 1 was the lowest among all samples. However, by layering samples 1, the ventilation resistance became similar to ones of the commercial cotton inner wear fabrics. Therefore, ventilation

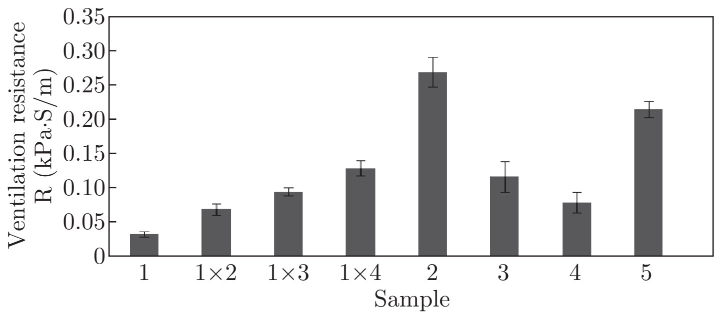


Fig. 9: Comparison of the ventilation resistance of samples

Table 3: Significant differences in ventilation resistance between sample pairs (*5%, ** 1%)

Sample pairs	Significant difference	Sample pairs	Significant difference	Sample pairs	Significant difference	Sample pairs	Significant difference
1–(1×2)		(1×2)–(1×3)		(1×3)–2	**	(1×4)–5	**
1–(1×3)	**	(1×2)–(1×4)	*	(1×3)–3		2–3	**
1–(1×4)	**	(1×2)–2	**	(1×3)–4		2–4	**
1–2	**	(1×2)–3	*	(1×3)–5	**	2–5	*
1–3	**	(1×2)–4		(1×4)–2	**	3–4	
1–4	*	(1×2)–5	*	(1×4)–3		3–5	**
1–5	**	(1×3)–(1×4)		(1×4)–4	*	4–5	**

resistance will be controlled by layering samples 1.

Fig. 10 shows the elongation at 20 gf/cm of samples. In wale direction, the elongation at 20 gf/cm of sample 1 is the second-highest value next to sample 2. In the course direction, the elongation at 20 gf/cm of sample 1 is over 30%. Therefore, sample 1 is a very stretchable fabric that will be comfortable for wearing.

Figs. 11-13 shows the shear properties of samples. Shear stiffness of sample 1 is higher than sample 2 in wale and course directions as shown in Fig. 11. However, those are lower than the other samples. Shear hysteresis of sample 1 is similar to ones of the samples 3 and 4 as shown in Figs. 12 and 13.

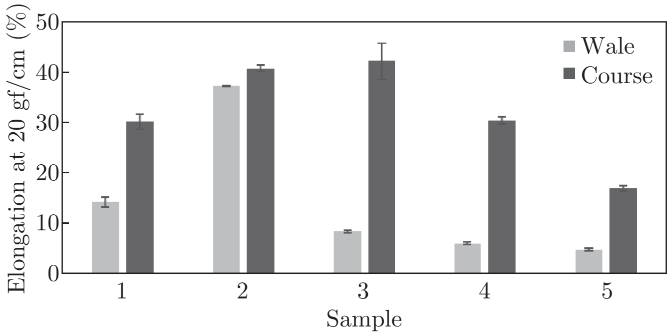


Fig. 10: Elongation at 20 gf/cm (%) of samples

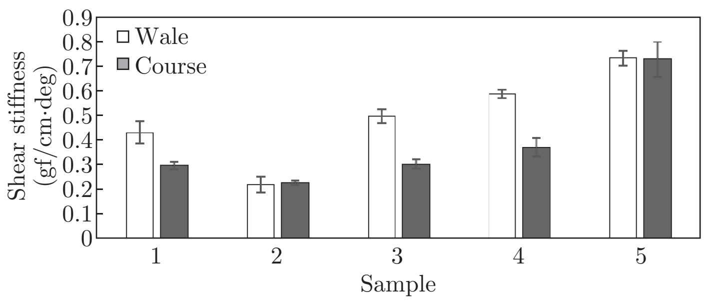


Fig. 11: Comparison of shear stiffness of samples (no significant differences between samples 1 and 3 in wale direction, significant differences at 5% level between samples 3 and 5 in wale direction, significant differences at 1% level for other sample pairs; significant differences at 1% level between samples 1 and 5, samples 2 and 4, samples 2 and 5, samples 3 and 5 and samples 4 and 5 in course)

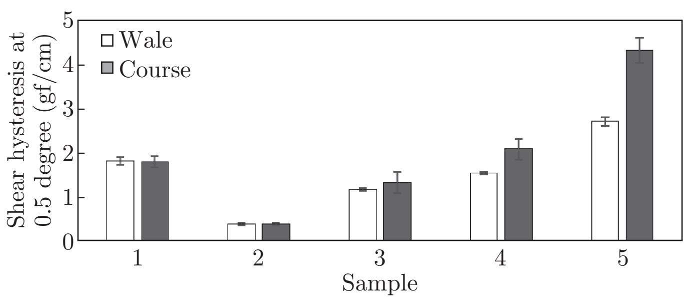


Fig. 12: Comparison of shear hysteresis at 0.5 degree (2HG) of samples (significant differences at 1% level for all sample pairs in wale direction; no significant differences between samples 1 and 3, and samples 1 and 4 in course; significant differences at 5% level between samples 3 and 4, significant differences at 1% level for other sample pairs in course)

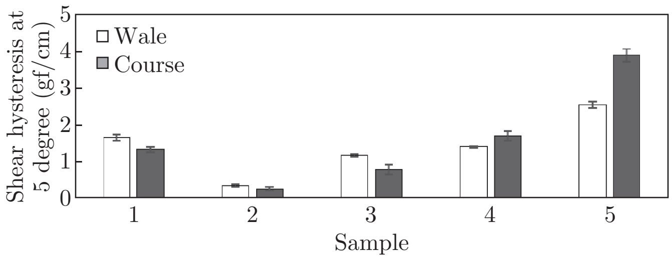


Fig. 13: Comparison of shear hysteresis at 5 degree (2HG5) of samples (significant differences at 5% level between samples 3 and 4 in wale direction, significant differences at 1% level for all other sample pairs; significant differences at 5% level between samples 1 and 4 in course, significant differences at 1% level for other sample pairs)

Figs. 14 and 15 show the bending properties of samples. Bending rigidity of sample 1 is lower than the ones of samples 3, 4 and 5. Bending hysteresis of sample 1 is also lower than ones of samples 3, 4 and 5.

Figs. 16-18 shows the surface properties of samples; frictional coefficient (MIU), an average of frictional coefficient (MMD), and surface roughness (SMD). Table 4 shows significant differences in surface roughness SMD between sample pairs. Although there are some significant differences among some sample pairs, there is no large differences.

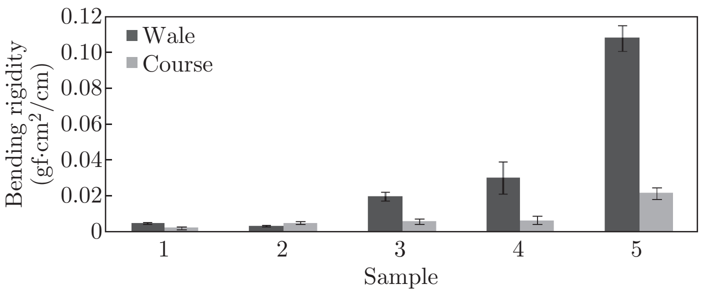


Fig. 14: Comparison of bending rigidity of samples (no significant differences between samples 1 and 2, samples 3 and 4 in wale direction, significant differences at 5% level between samples 1 and 3 and samples 2 and 3 in wale direction, significant differences at 1% level for other sample pairs; significant differences at 1% level between samples 1 and 5, samples 2 and 5, samples 3 and 5, and samples 4 and 5)

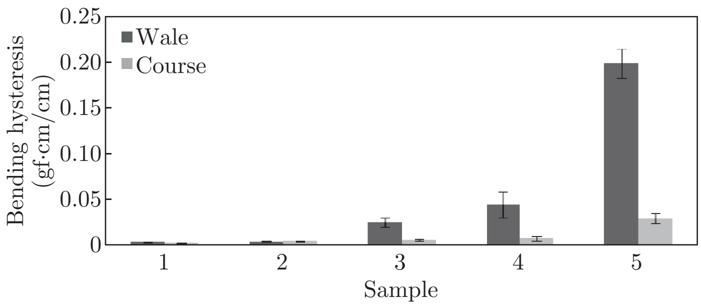


Fig. 15: Comparison of bending hysteresis of samples (significant differences at 1% level between samples 1 and 4, samples 1 and 5, samples 2 and 4, samples 2 and 5, samples 3 and 5, samples 4 and 5 in wale direction, significant differences at 1% level between samples 1 and 5, samples 2 and 5, samples 3 and 5, and samples 4 and 5 in course)

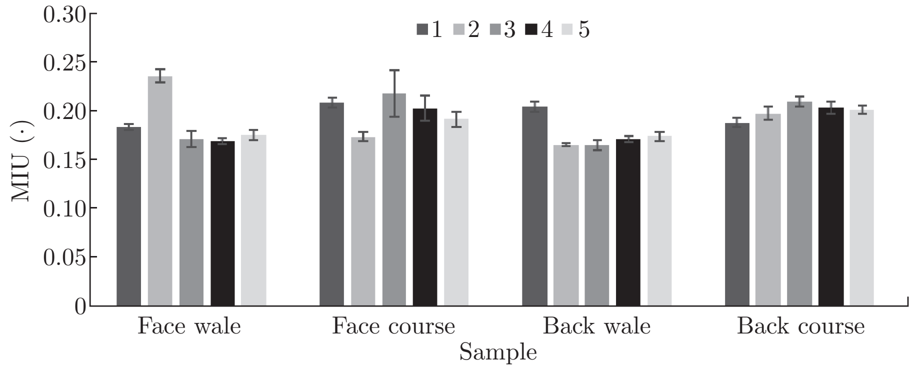


Fig. 16: Comparison of frictional coefficientMIUof samples (significant differences at 1% level between samples 1 and 2, samples 2 and 3, samples 2 and 4, and samples 2 and 5 in face-wale, significant differences at 5% level between samples 2 and 4 in face wale; significant differences at 1% level between samples 1 and 2 in face-course, significant differences at 5% level between samples 2 and 3 in face-course; significant differences at 1% level between samples 1 and 2, samples 1 and 3, samples 1 and 4, and samples 1 and 5 in back-wale; significant differences at 1% level between samples 1 and 3 in back course, significant differences at 5% level between samples 1 and 4 in back-course)

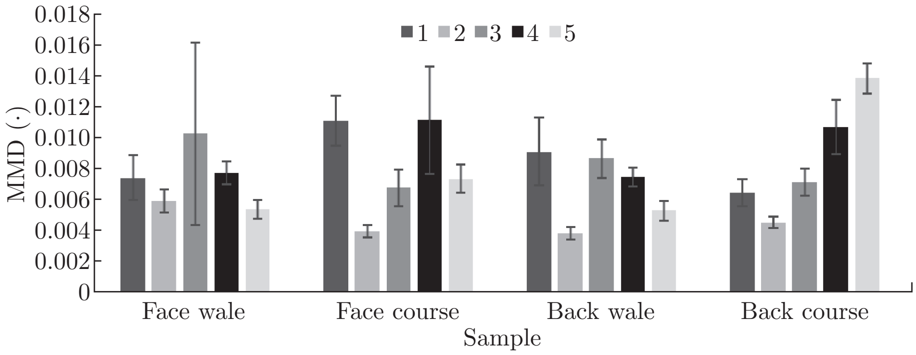


Fig. 17: Comparison of average of frictional coefficient MMD of samples (significant differences at 1% level between samples 1 and 2 and samples 2 and 4 in face-course; significant differences at 1% level between samples 1 and 2 and samples 2 and 3 in back-wale, significant differences at 5% level between samples 1 and 5, samples 2 and 4, samples 1 and 5 and samples 3 and 5 in back-wale; significant differences at 1% level between samples 1 and 4, samples 1 and 5, samples 2 and 4, samples 2 and 5, samples 3 and 5 in back-course, significant differences at 5% level between samples 3 and 4, and samples 4 and 5 in back-course)

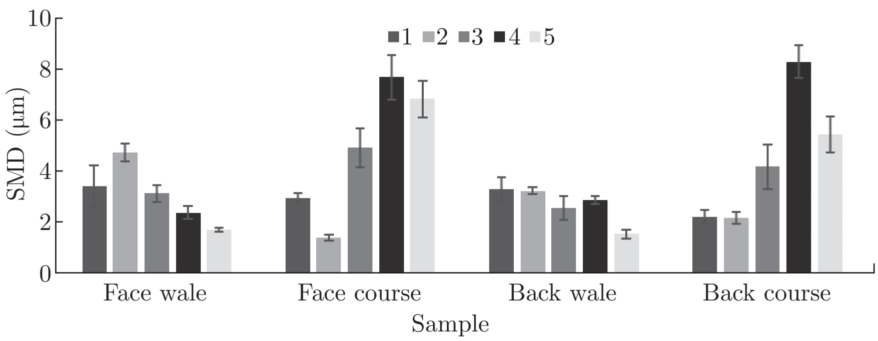


Fig. 18: Comparison of surface roughness SMD of samples

Table 4: Significant differences in surface roughness SMD between sample pairs (* 5%, ** 1%)

Face wale		Face course		Back wale		Back course	
Sample pairs	Significant difference	Sample pairs	Significant difference	Sample pairs	Significant difference	Sample pairs	Significant difference
1-2	*	1-2		1-2		1-2	
1-3		1-3	*	1-3		1-3	*
1-4		1-4	**	1-4	**	1-4	**
1-5	**	1-5	**	1-5	**	1-5	**
2-3	*	2-3	**	2-3		2-3	**
2-4	**	2-4	**	2-4	**	2-4	**
2-5	**	2-5	**	2-5	**	2-5	**
3-4		3-4	**	3-4	**	3-4	**
3-5	*	3-5	*	3-5	*	3-5	
4-5		4-5		4-5	**	4-5	**

4 Conclusion

We compared structural, thermal and mechanical characteristics of a knitted fabric made of a new cotton non-twist hollow yarn and four fabrics of commercially available inner wear. The knitted fabric made of cotton non-twisted hollow yarn is lighter and fuller than the commercially available inner wear fabrics. The fabric is also warmer in touch as indicated by the Q-max value and in wearing by the thermal conductivity lower than those of commercially available inner wear fabrics. The layered fabric has a higher heat retention ratio with lighter mass than fabrics of commercially available inner wear. The layered fabric also has a similar ventilation resistance to fabrics of commercially available inner wear.

The shear stiffness and bending rigidities of the new fabric were similar or lower than ones of commercially available cotton inner wear fabrics. The surface properties of the new fabric were similar to ones of commercially available inner wear fabrics. It is therefore found that the characteristics of the knitted fabric made of cotton non-twist hollow yarn are suitable for inner wear.

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