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Effect of Biaxial Stretch and Domestic Washing on Air Permeability of Elastic Knitted Fabrics for Sportswear

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Abstract: This paper introduces a non-automatic device to apply biaxial stretch and investigates the effect of biaxial stretch and domestic washing on air permeability of polyamide-elastane knitted fabrics for sportswear. Air permeability of the selected fabrics significantly increased upon biaxial stretch, regardless the fabric type and stretch level (5 % or 10 %) applied. Generally, air permeability of relaxed fabrics decreased due to slight shrinkage that occurred upon washing, but domestic washing was not found to have a statistical significant influence on air permeability of the selected fabrics. The manual device proposed applies stretch in one or two directions, it is robust and easy to handle, and fabric preparation is quite straightforward. The fabric holder used in this study is particularly suited to the head of the air permeability tester and the level of stretch applied depends on type of fabric.

Keywords: Sportswear, Stretch knitted fabrics, Biaxial stretch, Domestic washing, Air permeability

Introduction

Clothing designed for leisure and sport undergoes different levels of stretch during use. A reasonable level of fabric extension is necessary to accommodate body changes upon movement and facilitate tight garment donning, wearer comfort, range of motion and generic garment sizing. Fabrics with elevated stretch and fit are used for casual tight apparel, intimate wear and are worn by athletes in many sport disciplines among which cycling, rowing, swimming. Knitted stretch fabrics with various levels of stretch are most suitable for such applications.

Humans produce heat continuously in their bodies during any activity because of metabolic processes and the heat produced shall be transported away from the body to preserve wearer comfort. Fabrics containing Outlast® and Coolmax® yarns for sportswear application were analyzed by applying principal components analysis and selected the most significant properties influencing thermo-physiological comfort, namely slowness of drying, intrinsic fabric thermal insulation, fabric air permeability and wicking [1]. Thermo-physiological comfort of various knitted fabrics for summer cycling clothing were investigated [2] and a warp knitted Rachel fabric was selected due to its good air permeability, low thermal and water vapor resistance and good moisture management properties. Dry and evaporative heat losses of clothed people are highly affected by the air exchange between the clothing microclimate and the environment (clothing ventilation) and this is highly affected by the air permeability of the fabric and clothing design. Combined highly air permeable fabrics and appropriate clothing apertures can induce the proper dry and evaporative heat loss to remain for keeping comfortable under light-work condition [3].

Considering the strong relationship between fabric air permeability and garment thermo-physiological comfort, a lot of studies looked at influence of fabric structure on air permeability. Due to their loop structure that accommodates more pores, knitted fabrics are more air permeable than woven fabrics [4]. Thermal properties, diffusion ability, air and water vapor permeability are affected by raw material and fabric structure [5]. Air permeability plays an important role in transporting moisture vapor from the skin to the outside atmosphere and its highly fabric structure-dependent [6]. The amount of air passing through the fabric increases when the fabrics get finer [7] and fabrics with lowest course per centimeter and yarn number (tex) have the highest air permeability [8]. Dimensional characteristics of knitted fabrics i.e. loop length, structure compactness and structure type have an important influence on their air permeability [9]. Air permeability and porosity are strongly related to each other, meaning that a fabric with high porosity is assumed to be permeable. [4] Air permeability of single jersey is inversely proportional with fabric thickness and tightness factor and directly proportional with its porosity [10]. Loop length, fabric thickness, mass per unit area density have the highest influence on air permeability of cotton/polyester blended double layer interlock knitted fabrics [11].

Another group of studies investigated air permeability as function of elastane content and stretch level. Elastane fibers, better known under their trade names such as Lycra, Spandex and Dorlastan, designate elastomeric fabrics which have an extension-at-break greater than 200 % and also

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show rapid recovery when the tension is released [12]. Elastane is used in all areas where high degree of permanent elasticity is required (i.e. tights, sportswear, swimwear, corsetry, etc.) and is a prerequisite for fashionable or functional apparel intended to cling the body, while at the same time remaining comfortable. It was stated [13] that air permeability of cotton fabrics was higher than those of cotton-spandex fabrics. Spandex-containing fabrics tend to be tighter, their weight and thickness are higher but their air permeability is lower. Similarly, it was found [14] that upon increase of elastane proportion and level of elastane stretch fabrics become heavier and thicker and show improved thermal resistance but lower air and water permeability as well as poor moisture management properties. Higher twist results in better air and vapour permeability but lower thermal resistance and wicking. Knits with Lycra® yarns are thicker and tighter and less permeable to air than knits from natural yarns and knits with textured polyamide [15]. Elastic yarns cannot absorb water and sweat and have reduced thermo-physiological comfort [16]. Woven fabrics with core-spun elastic yarn DOW XLA™ with polyester/cotton blend in sheet has shown better sensorial comfort with improved hand feel and similar thermal comfort which remain persistent with washing cycles [17].

Air permeability of knitted fabrics is usually measured on un-stretched fabrics which then indicates their ability to allow air to pass through them when they are not in use. Nevertheless, in most of occasions when metabolic processes are in peak, the garments are stretched and these (sport-specific) body movements induce changes in the structure of stretch fabrics which, in response, considerably affect, their air permeability among others. It is therefore important to know air permeability in actual use, under various levels of stretch. Unfortunately, most of the studies investigated air permeability in relaxed state and there are only a limited number of studies that address the relationship stretch-air permeability. Other researchers [18] investigated handle, fit and pressure comfort of silk/hybrid yarn woven stretch fabrics. Air permeability of the plain, sateen and crepe woven stretched fabrics was analyzed in normal state and in stretched conditions. Depending on fabric weave, stretch of about 50 % applied in weft direction with the hand, lead to an increase of air permeability between 110-200 %, the lowest values being recorded for plain fabrics, followed by sateen and crepe weave. An automatic fabric stretching device, mounted on the air permeability tester, was developed [19] and employed to assess the influence of 10-40 % unidirectional stretch applied dynamically, on air permeability of fabrics with various structures and yarns spinning systems [20]. Among the fabrics investigated, core spun jersey and pique structures showed the lowest air permeability values but, unlike the other structures, these fabrics uniformly showed an increase in their air permeability as the stretch progressed.

Moreover air permeability undergoes changes upon various treatments. Other research [21] investigated the effects of oxygen and atmospheric plasma on air and water vapor permeability of single jersey bamboo fabric and the outcomes showed that water vapor permeability increased while air permeability decreased along with the plasma treatments. Worn next-to-the-skin sportswear are often subjected to domestic washing which affect fabric dimensional stability and comfort-related parameters in response. It was found that after washing relaxation the knitted fabrics became tighter, their weight and thickness was higher, while their air permeability was lower [22]. Recent research studied the influence of 5-15 washing cycles on compression, comfort and mechanical properties of stretchable knitted fabrics and bi-stretch woven fabrics with various structures and weaves [23]. They did not investigate the effect of washing on air permeability but found that bi-stretch woven fabrics preserved well their compression capacity and durability after washing and repeated uses.

As can be deducted from the literature above, the number of studies that investigated changes of fabric air permeability after washing [22] and upon unidirectional stretch applied by hand [18] or by an automatic fabric stretching device [19, 20] is limited. This study attempts to fill in this gap and examines the influence of biaxial stretch and domestic washing on air permeability of stretch knitted fabrics for sportswear worn next-to-the-skin. A non-automatic, easy to handle device developed to apply prescribed biaxial stretched is introduced and fabric dimensional and structural changes upon washing and stretch are discussed in relationship with their air permeability.

Experimental

Materials

In this study, five commercially available polyamide-elastane knitted fabrics typically used for swimwear were used. Their structural parameters, fiber content, mass per unit area, thickness and porosity are listed in Table 1. Fabric ID 1, 2 and 4 are weft knitted jersey structures and fabrics ID3 and ID5 are warp knitted fabrics.

Mass Per Unit Area

Fabric mass per unit area was assessed according to ISO 3801-1977. Average value of ten measurements was expressed to the nearest 0.1 g m^{-2}.

Thickness

Thickness of the fabrics was assessed according to ISO 5084-1996. Average value of ten measurements was expressed to the nearest 0.1 mm.

Bulk Density

Bulk density of the fabrics ($kg \cdot m^{-3}$) was calculated as ratio

Table 1. Structural and physical parameters (mean and standard deviation SD) of the selected fabrics

ID	Fibre composition (% PA6.6/ EL)	Courses (cm)	Wales (cm)	Mas per unit area (SD) (g m^{-2})	Thickness (SD) (mm)	Bulk density (SD) (kg m^{-3})	Porosity (%)
1	67/33	37	18	267.5 (3.45)	0.7 (0.02)	382.1	66.6
2	75/25	44	28	162.2 (0.93)	0.5 (0.01)	324.4	71.6
3	64/36	58	40	188.0 (4.87)	0.5 (0.00)	376.0	67.1
4	75/25	41	28	151.8 (3.99)	0.5 (0.00)	303.6	73.4
5	58/42	62	36	143.0 (5.48)	0.4 (0.00)	357.5	68.8

of fabric mass per unit area (g·m^{-2}) and thickness (mm).

Porosity

Relative porosity P was calculated using the equation bellow (equation (1)):

$$P = \left(1 - \frac{m}{\rho \times d}\right) \times 100 \tag{1}$$

where m is fabric mass per unit area (g·m^{-2}), ρ is the fiber density (g·m^{-3}) and d is fabric thickness (m).

Fiber density ρ was calculated depending on the fabric fibrous mixture PA6.6-elastane using the equation bellow (equation (2)):

$$\rho = a_1 \times \rho_1 + a_2 \times \rho_2 \tag{2}$$

where $a_{1,2}$ and $\rho_{1,2}$ are the percentage respective fiber density of elastane (1.14 g·cm^{-3}) and PA6.6 (1.15 g·cm^{-3}).

Air Permeability

Preparation of Biaxial Stretched Samples

A mechanical device (Figure 1) capable of applying unidirectional or biaxial stretch was developed and employed. A square sample of 21.5 cm×21.5 cm (1) is attached to the metal part with three screws (2) on each of the four edges (Figure 1(a)). To apply unidirectional stretch two mobile parts (3) are displaced along the x-axis or y-axis. To apply biaxial stretch, the four mobile parts (3) foreseen by metallic pins underneath are successively displaced to the appropriate hole (4) in the metal frame, corresponding to the prescribed stretch percentage (5). The applied stretch is preserved into the fabric by means of a square metallic fabric holder with sharp, thin pins (6) which is pressed against the fabric until the pins penetrate it and preserve the stretch applied. The fabric holder on which the fabric is attached is then mounted on the testing head of the air permeability tester (Figure 1(b)).

The level of stretch applied may be limited by type of fabric construction, stretch, tightness, and thickness among others. Coatings may also prevent the pins of the fabric holder to penetrate the fabric and retain applied stretch. Knitted fabrics elastane used in this this study amount 25-43 %. Some of the fabrics used in this study could accommodate large levels of biaxial stretched but, to allow comparisons, the biaxial stretch applied to all fabrics was 5 % (SL5) respectively 10 % (SL10).

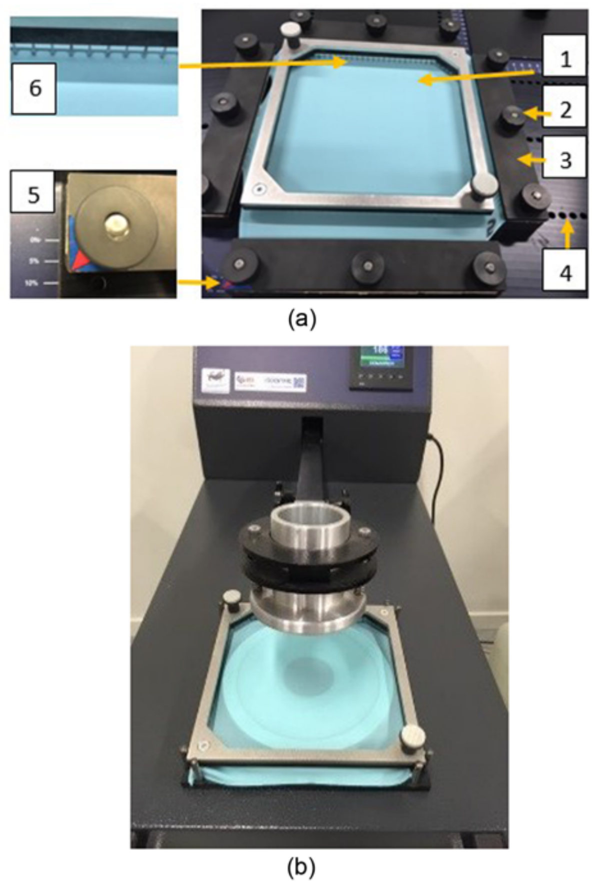

Figure 1. Module for applying biaxial stretching showing (a) details of the sample holder and (b) biaxial stretched fabric and holder mounted on the air permeability tester.

Air Permeability of Relaxed and Stretched Fabrics

Air permeability (mm/s) of relaxed (RS) and biaxial stretched fabrics (SL5, SL10) was determined as velocity of an air flow passing perpendicularly through a test specimen under specified conditions of test area, pressure drop and time (ISO 9237-1995). Air permeability of the fabrics was measured at air pressure drop of 100 N on a fabric test surface of 20 cm^2 using an air permeability tester (EMI Development, France). Mean value of ten measurements is expressed to the nearest 0.1 %.

Domestic Washing

The influence of five, ten and fifteen domestic washing cycles (WC) on air permeability of the fabrics in relaxed and stretched state was furthermore investigated. Domestic washing (40 °C) was carried out according to ISO 6330-2012, washing procedure 4N using detergent type 3. After each washing cycle the fabrics were flat dried at chamber temperature. Air permeability of dry fabrics was subsequently assessed in relaxed (RS) and stretched state (SL5, SL10). Mean value of five measurements is expressed to the nearest 0.1 %.

Fabric Structural and Dimensional Changes

Fabric structural changes upon biaxial stretch were analysed by a stereo microscope Nikon SMZ 800 (zooming range 1-8 x), equipped with a Digital microscopy software (Motic Images Plus 2.0 ML).

Fabric dimensional changes upon 5, 10, 15 washing cycles and drying were assessed (ISO 5077-2007) using equation bellow (equation (3))

$$\frac{X_t - X_0}{X_0} \times 100 \qquad (3)$$

where X_0 is the original dimension and X_t is the dimension measured after washing and drying. Mean value of five measurements was expressed to the nearest 0.5 %.

Prior testing, all samples were placed for at least 24 hours in a conditioning chamber, controlled at 21±2 °C and relative humidity of 65±4 % (ISO 139-2005).

Results and Discussion

As shown in Table 2 the average air permeability of unwashed fabrics (WC0) in relaxed state (RS) varied between 57.8 mm/s (heaviest/thicker fabric 1, 267.5 g·m^{-2}) and 484.6 mm/s (lightest/thinnest fabric 5, 143 g·m^{-2}). Fabric 1 with a single jersey structure exhibited the lowest porosity (66.6 %) which partially contributes to its low air permeability. However warp knitted fabric 5 was not the most porous fabric (68.8 %) but exhibited the lowest thickness and mass per unit area. This is line with other work [10] that found that air permeability of single jersey is inversely proportional with fabric thickness and tightness factor and directly proportional with its porosity and also Afzal *et al.* [11] found that air permeability cotton/polyester blended double layer interlock knitted fabrics is inversely proportional with thickness and mass per unit area.

Influence of Stretch on Air Permeability and Fabric Structural Changes

Air permeability of all the fabrics (RS) increased due to biaxial stretch of 5 % (SL5) and 10 % (SL10) regardless the number of washing cycles (Figure 2(a)-(d)), especially for the single jersey fabrics 1, 2 and 4. For instance, air permeability of heaviest/thickest fabric 1 increased most upon biaxial stretch from 57.8 mm/s (SR) to 239.4 mm/s (SL5), respectively to 475.4 mm/s (SL10), which represents an increase of 314 % (SL5) and 722 % (SL10) respectively. The thinnest/lightest fabric 5 had the highest air permeability (484.6 mm/s) and this further increased upon biaxial stretching with 98 % (SL5) respectively 180 % (SL10). This is in agreement with work of Kumar *et al.* [20] who found that core spun jersey and piqué structures uniformly show an increase in their air permeability as the unidirectional stretch progresses. Increase of air permeability of woven fabrics with crepe weave upon stretch was also reported by Vargese *et al.* [18].

An one-way ANOVA (IBM SPSS Statistics 25) test was applied and identified statistical significant differences between the air permeability of each fabric upon biaxial stretch (RS, SL5, SL10), regardless the washing cycles (WC0, WC5, WC10, WC15). A post-hoc Tukey test was applied that identified the significant different pairs of fabrics, with respect of their air permeability upon all biaxial stretch levels, regardless the washing cycles. In Table 3 and Table 4 an example is given for the ANOVA and post-hoc Tukey respectively for unwashed fabrics (WC0).

Upon biaxial stretch the knitted structure became more open and air could pass faster through the fabric. Structure changes responsible for elevated air permeability as consequence of biaxial stretch were investigated by a stereo microscope Nikon SMZ 800 (zooming range 1-8 x), equipped with a Digital microscopy software (Motic Images Plus 2.0 ML). In Figure 3 changes can be observed in the

Table 2. Average air permeability (mm/s) of the fabrics

	WC0			WC5			WC10			WC15		
	RS	SL5	SL10	RS	SL5	SL10	RS	SL5	SL10	RS	SL5	SL10
Fabric 1	57.8	239.4	475.4	50.4	245.6	532.0	50.0	286.4	569.6	49.0	254.4	551.2
Fabric 2	174.0	489.6	784.0	151.8	499.8	855.0	154.2	468.4	855.8	145.4	441.6	808.2
Fabric 3	227.8	581.4	864.4	218.2	613.0	992.6	204.0	615.8	962.0	203.8	597.8	979.8
Fabric 4	255.2	646.4	1098.2	242.0	658.4	1037.6	232.0	611.6	962.0	222.6	581.2	1015.2
Fabric 5	484.6	958.2	1358.8	495.6	1059.4	1441.4	474.6	1042.4	1446.0	479.6	1076.4	1484.4

WC: washing cycle (0-5-10-15), RS: relaxed state, SL: stretch level (5 %; 10 %).

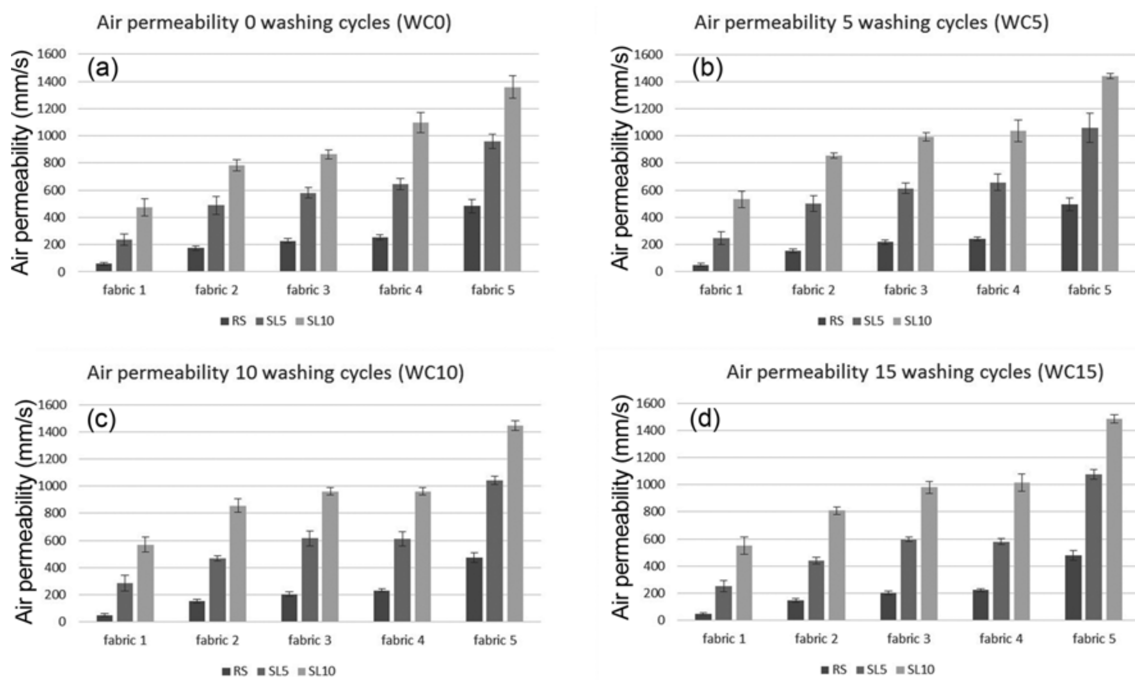

Figure 2. Influence of biaxial stretch (SL5, SL10) on air permeability of the fabrics (a) before washing and after (b) 5, (c) 10 and (d) 15 washing cycles.

Table 3. Influence of stretch level (SL5, SL10) on air permeability of the fabrics 1-5: ANOVA results for untreated fabrics (WC0)

		Sum of squares	df	Mean square	F	Sig.
Fabric 1	Between groups	438440.53	2	219220.27	112.19	0.00
	Within groups	23447.20	12	1953.93		
	Total	461887.73	14			
Fabric 2	Between groups	930624.53	2	465312.27	222.22	0.00
	Within groups	25127.20	12	2093.93		
	Total	955751.73	14			
Fabric 3	Between groups	1017302.53	2	508651.27	528.05	0.00
	Within groups	11559.20	12	963.27		
	Total	1028861.73	14			
Fabric 4	Between groups	1779682.80	2	889841.40	363.56	0.00
	Within groups	29370.80	12	2447.57		
	Total	1809053.60	14			
Fabric 5	Between groups	1915004.93	2	957502.47	245.38	0.00
	Within groups	46824.80	12	3902.07		
	Total	1961829.73	14			

Significant difference for Sig.<0.05.

structure of (a) relaxed fabric 1 (267.5 g m^{-2}) upon (b) 5 % biaxial stretching and (c) 10 % respectively. The fabric stretched in two direction has a more open structure and differences are particularly visible for 10 % SL. For this fabric, average size of wales/course of 211/468 micrometres (RS) increased to 231/480 micrometres (SL5) and to 255/497 micrometres (SL10) respectively. The open space available for air movement explains the larger air permeability of biaxial stretched fabrics.

Influence of Washing on Fabric Air Permeability and Dimensional Stability

Some variation of the air permeability due to the washing can be observed for all the fabrics (Figure 4). For instance, in

Table 4. Significant differences between unstretched (RS) and stretched fabrics (SL5, SL10): Tukey Post hoc test for unwashed fabrics (WC0)

Dependent variable	(I) Stretch level	(J) Stretch level	Mean difference (I-J)	Std. error	Sig.	95 % confidence interval	
						Lower bound	Upper bound
Fabric 1	0	5	-181.60000*	27.96	0.00	-256.18	-107.02
		10	-417.60000*	27.96	0.00	-492.18	-343.02
	5	0	181.60000*	27.96	0.00	107.02	256.18
		10	-236.00000*	27.96	0.00	-310.58	-161.42
	10	0	417.60000*	27.96	0.00	343.02	492.18
		5	236.00000*	27.96	0.00	161.42	310.58
Fabric 2	0	5	-315.60000*	28.94	0.00	-392.81	-238.39
		10	-610.00000*	28.94	0.00	-687.21	-532.79
	5	0	315.60000*	28.94	0.00	238.39	392.81
		10	-294.40000*	28.94	0.00	-371.61	-217.19
	10	0	610.00000*	28.94	0.00	532.79	687.21
		5	294.40000*	28.94	0.00	217.19	371.61
Fabric 3	0	5	-353.60000*	19.63	0.00	-405.97	-301.23
		10	-636.60000*	19.63	0.00	-688.97	-584.23
	5	0	353.60000*	19.63	0.00	301.23	405.97
		10	-283.00000*	19.63	0.00	-335.37	-230.63
	10	0	636.60000*	19.63	0.00	584.23	688.97
		5	283.00000*	19.63	0.00	230.63	335.37
Fabric 4	0	5	-391.20000*	31.29	0.00	-474.68	-307.72
		10	-843.00000*	31.29	0.00	-926.48	-759.52
	5	0	391.20000*	31.29	0.00	307.72	474.68
		10	-451.80000*	31.29	0.00	-535.28	-368.32
	10	0	843.00000*	31.29	0.00	759.52	926.48
		5	451.80000*	31.29	0.00	368.32	535.28
Fabric 5	0	5	-473.60000*	39.51	0.00	-579.00	-368.20
		10	-874.20000*	39.51	0.00	-979.60	-768.80
	5	0	473.60000*	39.51	0.00	368.20	579.00
		10	-400.60000*	39.51	0.00	-506.00	-295.20
	10	0	874.20000*	39.51	0.00	768.80	979.60
		5	400.60000*	39.51	0.00	295.20	506.00

*The mean difference is significant at the 0.05 level.

Figure 3. Changes in the structure of (a) the unwashed jersey fabric 1 (RS) upon (b) biaxial SL5 and (c) SRl10 (technical face, magnification 3x).

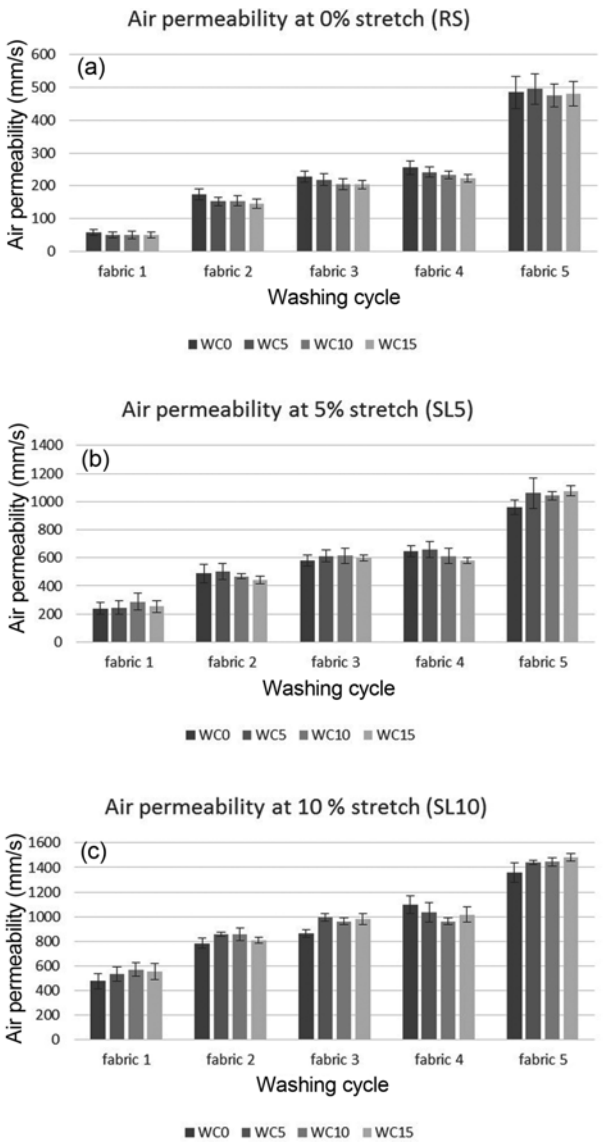

Figure 4. Influence of washing cycles WC (5, 10, 15) on air permeability of (a) fabrics in relaxed state RS, (b) 5 % biaxial stretch SL5, and (c) 10 % biaxial stretch SL10.

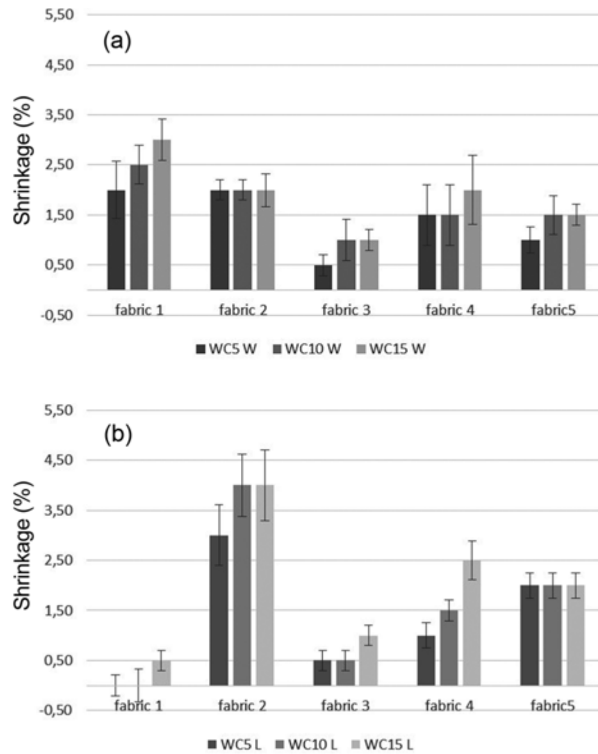

Figure 5. Shrinkage of the fabrics (a) in widthwise (W) and (b) lengthwise (L) direction after 5, 10 and 15 washing cycles (WC).

relaxed state RS (Figure 4(a)), air permeability of fabrics 1-4 slightly decreased with increasing number of washing cycles. This is in good agreement with findings of Mavruz and Ogulata [22] who pointed out that after washing relaxation the knitted fabrics in their study became tighter, heavier and thicker and exhibited lower air permeability. Nevertheless, unlike fabrics 1-4, fabric 5 showed a less clear trend, but also exhibits larger variances of air permeability. As it can be also seen further in Figure 5, unlike other fabrics, fabric 5 seems to be barely affected by shrinkage, especially not after five washing cycles WC5 and in widthwise direction.

Decrease of air permeability upon washing can be attributed to some shrinkage occurred during washing. As shown in Figure 5, most of the fabrics exhibited an average shrinkage below 2.5 % upon washing. Fabric 2 reduced its dimensions in lengthwise direction depending on number of washing cycles with 3 % (WCL 5) respectively 4 % (WCL 10, WCL 15). Unlike most of the fabrics, fabric 1 also showed a higher shrinkage of 3 % in widthwise direction after 15 washing cycles (WC15). Shrinkage increased with number of washing cycles regardless the fabric, which generally lead to lower air permeability after 15 washing cycles (WC15) as compared with 10 washing cycles (WC10). However, the effect of stretch applied seems to overcome the effect shrinkage and slightly higher air permeability can be noticed for all the fabrics biaxial stretched with 5 % SL5 (Figure 4(b)) or 10 % SL10 (Figure 4(c)) after 5 washing cycles (WC5) and depending on fabric, also after 10 washing cycles (WC10). However, an ANOVA test showed that the observed changes after washing have no statistically significant ($p>0.05$) influence on air permeability of the fabrics.

Conclusion

During use, stretch sportswear are subjected to deformations in more directions. Depending on fabric structure, these deformations significantly affect fabric structural parameters and, in response, its comfort-related parameters among which air permeability. Worn next-to-the-skin sportswear are often subjected to domestic washing which affects fabric dimensional stability and thus contributes to changes in comfort-related parameters. In the absence of data about influence of biaxial stretch on fabric properties, this paper investigated the effect of biaxial stretch and domestic washing on air permeability of five polyamide-elastane knitted fabrics. A non-automatic, easy to handle device to apply biaxial stretched is proposed and dimensional and structural changes of fabrics upon several washing cycles and stretch levels are discussed in relationship with their air permeability. It was found that air permeability of the selected fabrics significantly increased ($p<0.05$) upon biaxial stretched applied, regardless the fabric type and stretch level (5 % or 10 %) applied and that was in good agreement with the fabric structural changes upon biaxial stretch. In contrast, washing seems to have some influence on air permeability but that was not found statistical significant ($p>0.05$). Generally, air permeability of relaxed fabrics decreased for single jersey due to slight shrinkage of about 2 % that occurred after washing. Nevertheless, once the fabrics were stretched no clear trend could be observed anymore. The device proposed applies prescribed stretch in one or two directions, is easy to handle, robust and fabric preparation is quite straightforward. However the level of stretch applied may depend on type of fabric (woven or knitted fabric), its thickness and level of stretch. Changes of fabric comfort-related properties such as moisture management, water vapor permeability, drying time upon stretching are of particular interest for sport fabrics. The fabric holder used in this study was designed to particularly suit the head of the air permeability tester and additional fabric holders shall be designed for the purpose of other investigations. Manufacturers of fabrics, sportswear or compression clothing need knowledge about variation of air permeability under biaxial stretch in designing or selecting the fabrics for sportswear respectively. Unlike the fabrics used in this study, depending on fabric construction, the air permeability of some fabrics may decrease upon stretch and this should be avoided at any time as it jeopardises the thermo-physiological comfort of the wearer, and this is especially critical during high-intensity activities.

References

1. E. Onofrei, *Ind. Text.,* **63**, 91 (2012).
2. E. T. Őzkan and B. Meriç, *Text. Res. J.,* **85**, 62 (2015).
3. H. Ueda and G. Havenith, in "Environmental Ergonomics, The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment" (Y. Tochihara and T. Ohnaka Eds.), Vol. 3, pp.343-346, Elsevier Ergonomics Book Series, 2005.
4. R. T. Ogulata and S. Mavruz, *Fibres Text. East. Eur.*, **5**, 71 (2010).
5. E. Onofrei, A. Rocha, and A. Catarino, *J. Eng. Fibr. Fabr.*, **6**, 10 (2011).
6. B. Karaguzel, MSc Dissertation, North Carolina State University, 2004.
7. G. Ertekin and A. Marmali, *Tekstil ve Kofeksiyon*, **21**, 369 (2011).
8. R. Oinuma, *J. Text. Machin. Soc. Japan*, **36**, 91 (1990).
9. A. Bivainyte, D. Mikucioniene, and P. Kerpauskas, *Mat. Scs.*, **18**, 167 (2012).
10. S. S. Bhattacharya and J. R. Ajmery, *Int. J. Eng. Res. and Develop.*, **5**, 48 (2013).
11. A. Afzal, H. Tanveer, M. H. Malik, A. Rasheed, S. Ahmad, A. Basit, and A. Nazir, *Fiber. Polym.*, **15**, 1539 (2014).
12. M. Senthilkumar, N. Anbumani, and J. Hayavadana, *Ind. J. Fib. Text. Res.,* **36**, 300 (2011).
13. A. B. Marmali, *Tex. Res. J.*, **73**, 1539 (2003).
14. M. Manshahia and A. Das, *Ind. J. Fib. Text. Res.*, **39**, 441 (2014).
15. R. Čiukas and J. Abralavičiūtė, *Fibres Text. East. Eur.,* **18**, 84 (2010).
16. V. T. Bartles, "Textile in Sport Part 3: Sportswear and Comfort", Woodhead Publication, Cambridge, UK, 2005.
17. P. Verdu, J. M. Rego, J. Nieto, and M. Blanes, *Text. Res. J.*, **79**, 14 (2009).
18. N. Varghese and G. Thilagavathi, *Fiber. Polym.*, **17**, 484 (2016).
19. K. V. Kumar, V. R. Sampath, and C. Prakash, *J. Text. Inst.,* **107**, 1213 (2016).
20. K. V. Kulmar, V. R. Sampath, and C. Prakash, *Int. J. Cloth. Sci. Technol.,* **29**, 754 (2017).
21. C. Prakash, G. Ramakrishhnan, S. Chinnandurai, S. Vignesh, and M. Senthilkumar, *Int. J. Thermophysics*, **34**, 2173 (2013).
22. S. Mavruz and R. T. Ogulata, *J. Text. Inst.*, **102**, 57 (2011).
23. M. Maqsood, Y. Nawab, J. Umar, M. Umair, and K. Shaker, *J. Text. Inst.,* **108**, 822 (2017).