Mishra *et al. Fash Text (2021) 8:40*
https://doi.org/10.1186/s40691-021-00266-5

Fashion and Textiles

RESEARCH

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Thermo physiological comfort of single jersey knitted fabric derivatives

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Abstract

The main aim of this study is to determine the thermo-physiological comfort properties of single knit fabrics and their derivatives. As the Single Jersey knitted fabrics are the most widely used fabrics in the apparel sector, they have been selected for the analysis purpose. Derivatives of single jersey are developed and compared in order to understand the influence of structural variations. Physical properties e.g. thickness and areal density were evaluated for all knitted fabrics with 100% cotton yarn having three different yarn linear densities and after different stages of relaxation. Various thermo-physiological properties have been studied by changing the combed cotton yarn linear density as well as the structure of single knit fabric. Air permeability, thermal insulation and relative water vapor permeability of the fabrics were observed and investigated under wet relaxed states. It is determined that fabric physical properties are affected by changing yarn linear density and by the dry or wet relaxation stages. The percentage/number of tuck stitches (NTS), location of tuck stitches (LTS) and ratio of tuck to knit stitches (RTKS) have strong influence on physical and thermo-physiological properties of single knit fabrics, even though other knitting parameters remained the same.

Keywords: Single knit derivatives, Tuck stitch, Air permeability, Thermal resistance, Relative water vapor permeability

Introduction

A dominant segment of consumer market is occupied by knitted fabrics due to their exceptional properties like light weight, economic production and excellent elasticity. As knitted garments provide excellent comfort and high flexibility, their application is wide spread to versatile areas like medical, protection, sports and geo applications. Different types of weft knitted structures are produced e.g. single jersey and double jersey. Single jersey is widely used for regular and sports t-shirts, leggings and for other garments. Its derivatives can be produced by changing types of stitches and their arrangements for design purposes (Islam, 2014; Kane et al., 2007).

The understanding of fabric properties and their relationship with end use becomes a basis for research, classification, quality control and selection of fabrics used for apparel. Most important component of the clothing functionality is thermo-physiological comfort. It is of great significance because of tremendous growth in the active leisure time of the human civilization at present. The comfort in clothing is a complex phenomenon which is derived from various factors affecting physical and non-physical stimuli during wearing of a person under specific environmental conditions. Among basic variables, fabric construction influences the comfort by a great deal. A number of thermo physiological comfort properties, such as thermal resistance, liquid water resistance, air permeability, absorbency, water vapor permeability, rate of drying, wickability etc. can be changed by varying fabric construction parameters (Bivainyte & Mikucioniene, 2011; Dubrovski, 2004; Kane et al., 2007). Knitted fabrics provide better stretch and recovery properties which help to maintain a proper pressure on the human body. They are best suitable for moisture management properties especially in terms of moisture transfer from body to the environment. This property enhances their applications in active sportswear. In case of performance apparels, the requirements can be functional and specifically linked with wicking, moisture transmission, water proofing, thermal and flame resistance. The requirements of properties as functional apparel are dependent on a vast range of end uses. The behavior and performance of functional apparel is critically governed by various internal as well as external factors. The internal factors are fiber/yarn movement, fineness of fiber and yarn, fabric density and thickness. The external factors are cold or hot weather conditions, wind, exposure to sunlight, rain and humidity etc.

It has been reported that fiber type and fabric structure play a crucial role in determining the comfort properties of textile fabric (Erdumlu & Saricam, 2013; Holcombe & Hoschke 1983; Uttam et al., 2013). The properties of transfer of water and heat through textile fabrics are the measures to determine thermal comfort experienced by the wearer. The water vapor and thermal resistance are required to access the amount of heat exchanged by human body and the environment which defines how humans perceive comfort (McCullough et al., 2004; Watkins & Slater, 1981).

Air permeability is an important functional property of apparel textiles. The geometrical characteristics of knitted textile fabrics are very important for evaluating and simulating a lot of functional properties, one of which is air permeability. The fabrics with larger surface area or dimensions of pores allow more air movement which provides a cooling effect to the wearer. A number of authors, e.g. (Backer, 1951; Havlová, 2005; Mishra et al., 2015; Szosland, 1999; Walde-Armstrong et al., 1996; Zupin et al., 2011) have dealt with the possibility to predict the value of the permeability of fabrics based on their structural parameters. In the modern apparel industry, moisture management is among the key performance indicators to define comfort level of a fabric. A garment which evaporates and transports moisture provides the wearer with cooling effect. Moisture management is defined as a controlled movement of water vapor and human perspiration from skin, through fabric, to the external environment. Good management of moisture means how quickly moisture is transported after absorption to provide comfort. This action prevents perspiration to remain on the skin thus resulting in dry skin instead of wet. When body can cool itself efficiently, the human body perspires lesser and there are lower chances of dehydration leading to better performance for a longer period. Literature showed that, yarn and fabric structural parameters are important in determining the fabrics moisture management properties (Frackiewicz-Kaczmarek et al., 2015; Marmarali, 2003). Relative water vapor permeability also provides information about absorption level of moisture.

The thermal comfort properties, fabric recovery, total hand value (THV), moisture management parameters, and air permeability of cotton single jersey knitted fabrics (SJKF) produced from cotton/spandex yarns at different Lycra states were investigated. The obtained values of air permeability, THV, and overall moisture management capacity of stretched SJKF are lower than 100% cotton fabric sample (Khalil et al., 2020; Kundu & Chowdhary, 2020). The thermal properties of cotton and polyester based single jersey of 1 × 1 rib and interlock structures were statistically investigated. The thermal properties of samples were measured using Alambeta and Permetest devices. The results indicate that each knitted structure shows different thermal comfort properties. Interlock and 1 × 1 rib fabrics have high thermal conductivity and thermal resistance. On the other hand, single jersey fabrics have higher relative water vapor permeability values than 1 × 1 rib and interlock fabrics (Oğlakcioğlu & Marmarali, 2007).

Box and Behnken, a three level three variable factorial design technique was used to study the interaction effects of the variables on the thermal characteristics of single jersey fabrics made from recycled polyester and cotton blends. The influence of the variables on thermal comfort properties of fabrics and response surface equations were derived and design variables were optimized. Fabric becomes thinner, lighter and more porous with the increase in recycled polyester in blend ratio and loop length, whereas thicker, heavier and less porous fabric is resulted with the increase in linear density. The increase of linear density results in thicker, heavier and less porous fabric with higher thermal conductivity, lower air permeability and thermal resistance and high relative water–vapor permeability at medium linear densities. Loose structure results in thinner, lighter and more porous fabric with higher thermal resistance, air permeability and relative water–vapor permeability, and lower thermal conductivity (Vadicherla & Saravanan, 2017). The influence of the knitting structure, loop length, tightness factor, fiber type and yarn properties on the mechanical and comfort properties of single jersey knitted fabrics has ben reported. The changes in the properties of weft knits as a function of the structure and density was investigated and relationships between the hand, knit structure and density was established. Statistical analysis indicated that the results were significant for the air permeability and water vapor permeability of the fabrics (Celep & Yuksekkaya, 2017; Çoruh, 2015).

The thermal comfort properties of flat knitted acrylic fabrics differing in terms of knit structure, tightness, thickness and porosity were investigated in winter wear products. Permetest and Alambeta devices were used for the thermal comfort properties, namely thermoregulation characteristics, breathability and thermo-physiological characteristics, and their relationship with fabric structural parameters were investigated statistically. The results indicated that rib 2 × 2 structures provide the optimum condition in terms of thermoregulation, breathability and thermo-physiological comfort, whose thickness and porosity values should be adjusted accordingly, since the thickness improves thermal insulation and porosity improves breathability (Ajmeri & Bhattacharya, 2017; Erdumlu & Saricam, 2017).

Researches have mostly focused on the influence of yarn, fiber and fabric constructional variables on comfort properties of different knitted structures. The type of knit structure has an effect on extensibility and strength of knitted fabrics as investigated by other researchers (Mikučionienė et al., 2010). However, there are limited studies focused on the comfort properties of single jersey derivatives. Three basic knit stitches are Tuck, Miss and Knit respectively. Some fabrics have a combination of two or even three of the loop types. As might be expected, fabric properties change as different loop types are knitted. In this study an attempt has been made to analyze the physical and thermo-physiological comfort properties with respect to change in linear density, relaxation stage and stitch type. As the Single Jersey knitted fabrics are the most widely used fabrics in the apparel sector due to ease of production as well as their economy, they have been selected for the analysis purpose. Derivatives of single jersey are developed and compared in order to understand the influence of structural variations.

Method

Materials

100% combed cotton grey knitted samples were made on circular knitting machine of Fukhura, Japan with three linear densities 29.5 tex (20's Ne), 24.6 tex (24's Ne), and 19.7 tex (30's Ne).

Single jersey fabrics and their derivatives were made from each linear density of yarn. The actual yarn fineness was checked and mentioned in Table 1. Yarn fineness, was determined according to ASTM D1059-01 (2010). A constant tightness factor (14 ± 1) was maintained for all the structures, with the help of positive feed device and cam setting on the machine. All the fabric structures developed for this study are shown in Table 2.

Scouring and bleaching/wet processing: applied treatment

Scouring and bleaching was carried out in a laboratory model soft flow machine of 8–10 kg capacity (mini Jet Dyeing Machine) where all sample processing was carried out within the bath by stitching all the samples end to end. Scouring/bleaching was done for 60 min. at 100 °C. Recipe used for bleaching was: Hydrogen peroxide (H_2O_2) 8 g/L, Caustic soda (NaOH) 6 g/L, stabilizer, wetting agent and sequestering agent. The bleaching process was carried out in order to remove foreign particles/ materials that result in bringing characteristics of natural hydrophobicity in cotton. Subsequently, the fabrics were hydro-extracted and dried under standard atmospheric conditions.

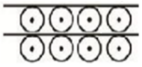
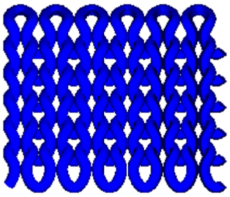
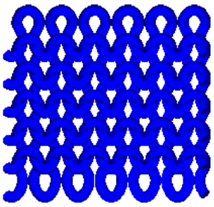
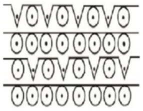
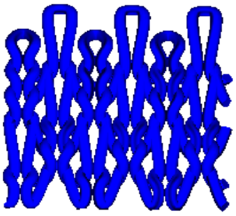
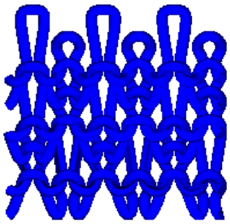
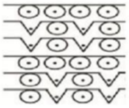
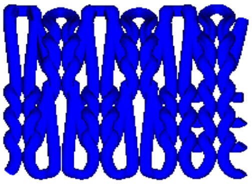
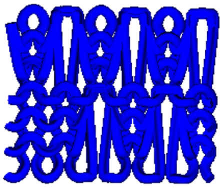
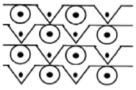
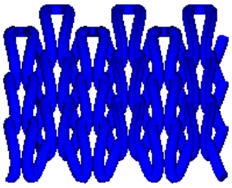
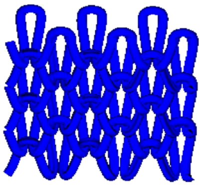
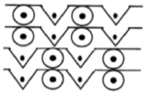
Evaluation of comfort related properties

Comfort related properties were evaluated only for bleached knitted fabrics. Measurements were carried out for samples in wet relaxation state as reported in literature

Table 1 Properties of yarns used for knitted fabric samples

No	Nominal yarn fineness *Ne*	Actual yarn fineness *Ne*	Actual Yarn tex T_t, tex
1	20	19.83	29.77
2	24	24.26	24.34
3	30	30.14	19.59

Table 2 The sample codes, needle diagrams and line diagrams

Sample code	Graphic Notation	Needle Diagram	Fabric face side Line diagram	Fabric back side Line diagram
Single Jersey (SJ)	X X X X X X X X			
Single Lacoste (SL)	X X X . X . X X			
Double Lacoste (DL)	X X X X . . X . . X X X			
Single Pique (SP)	. X . X X . X .			
Double Pique (DP)	. . X X X X . .			

(Marmarali, 2003; Mishra et al., 2012). Thermo-physiological comfort properties such as air permeability, thermal resistance and relative water vapor permeability were evaluated.

Air permeability

Air permeability is the measure of airflow passing through a given area of the fabric. This parameter influences the thermal comfort properties of fabrics to a large extent. It is generally accepted that the air permeability of a fabric depends on its air porosity, which in turn influences its openness. With higher porosity, more air permeability is observed. It was measured on SDL Atlas Air Permeability Tester, M021A according to standard ASTM-D737/ISO 9237.

The principle of air permeability instrument depends on the measurement of air flow passing through the fabric at a certain pressure gradient Δp. In this instrument any part of the fabric can be placed between the sensing circular clamps (discs) without the garment destruction. As the fabric fixes firmly on its circumference (to prevent the air from escaping), the fabric dimensions doesn't play any role. There is also enough space between the clamps and the instrument frame, which allows the measurement on large samples (Arumugam et al., 2017; Venkataraman et al., 2014).

The rate of air flow perpendicular through the fabric was measured at the temperature of 20 ± 2 °C, relative humidity 65 ± 4%,with 20 cm^2 area of fabric and with air pressure of 100 Pa. Ten measurements were performed for each sample and their mean and standard deviations were calculated.

Thermal resistance/insulation

The Alambeta instrument was used to measure the thermal properties like thermal conductivity and thermal resistance of the knitted samples. Thermal conductivity, λ, is a measure of the rate at which heat is transferred through unit area of the fabric across unit thickness under a specified temperature gradient. Thermal resistance is defined as the ratio of the temperature difference between the two faces of a material to the rate of heat flow per unit area. Thermal resistance determines the heat insulation property of a textile material. The higher the thermal resistance, the lower is the heat loss. The thermal resistance, R, is the ratio of fabric thickness, h, to thermal conductivity, λ (Arumugam et al., 2017; Venkataraman et al., 2014, 2015a, 2015b).

This computer controlled semi-automatic instrument called Alambeta calculates all the statistical parameters of the measurement. To simulate the real conditions of warm-cool feeling evaluation, the instrument measuring head was heated to 36 °C, which correspond to the average human skin temperature, while the fabric is kept at the room temperature 25 °C. Similarly, the time constant of the heat flow sensor, which measures directly the heat flow between the automatically moving measuring head and the fabrics, exhibits similar value (0.07 s), as the human skin. For each sample, 10 measurements were carried out and the mean (m) and standard deviation (σ) were calculated.

Relative water vapor permeability%

PERMETEST determines the fabric capability to transfer water vapor by measurement of absolute vapor resistance and relative water vapor permeability%. The instrument for this test is based on heat flux sensing principle same as skin model. The fabric sample is placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1 m/s. The temperature of the measuring head is maintained at room temperature for isothermal conditions. When water flows into the measuring head, some amount of heat is lost. This instrument measures the heat loss from the measuring head due to the evaporation of water in bare condition and when covered by the fabric. PERMETEST instrument enables the determination of relative water vapor permeability (RWVP)% and evaporation resistance, R_{et} [m^2.Pa/W] of fabrics which were measured according to EN ISO 11092 standard (Arumugam et al., 2017; Venkataraman et al., 2014). For each sample, 10 measurements were carried out and the mean (m) and standard deviation (σ) were calculated.

Table 3 Experimental factors and levels

No	Factors	Factors levels				
		1	2	3	4	5
1	Yarn fineness (*tex*)	29.77	24.34	19.59	–	–
2	Relaxation stage	Dry	Wet	–	–	–
3	Knitting structure	Single Jersey	Single Lacoste	Double Lacoste	Single Pique	Double Pique

Table 4 Design of experiment (DoE)

Sample No	Sample ID	Fabric structure	Ne (tex)
1	SJ20	Single Jersey	20 (29.5)
2	SL20	Single Lacoste	20 (29.5)
3	DL20	Double Lacoste	20 (29.5)
4	SP20	Single Pique	20 (29.5)
5	DP20	Double Pique	20 (29.5)
6	SJ24	Single Jersey	24 (24.6)
7	SL24	Single Lacoste	24 (24.6)
8	DL24	Double Lacoste	24 (24.6)
9	SP24	Single Pique	24 (24.6)
10	DP24	Double Pique	24 (24.6)
11	SJ30	Single Jersey	30 (19.7)
12	SL30	Single Lacoste	30 (19.7)
13	DL30	Double Lacoste	30 (19.7)
14	SP30	Single Pique	30 (19.7)
15	DP30	Double Pique	30 (19.7)

All samples were further available as dry and wet relaxed samples

Statistical analysis of the dependent parameters

The full factorial Design of experiment (DoE) was used for the number of samples prepared (Behera et al., 2008; Crina et al., 2013; Jamshaid et al., 2016). Factors and their levels are mentioned in Table 3. The Design of experiment (DOE) for the samples developed is given in Table 4.

Analysis of variance (ANOVA)

Analysis of variance method is well known statistical method and is employed to recognize the influential process parameter in the multi-response optimization model. The significance of model terms is judged in terms of F-value or p-value. The F-value is the ratio of factor mean square to the mean square error. Usually, a factor with larger F-value has significant effect on dependent parameter (Behera et al., 2008; Crina et al., 2013; Jamshaid et al., 2016). The significance of the model parameters can also be identified by the use of p-value which is less than α level of significance (5% theoretically). ANOVA is employed to the values of input parameters in order to identify the significant influence on all the dependent parameters of thermo-physiological comfort for which the p-value is less than level of significance, 5% in this study. The statistical analysis of data was carried out using Minitab 17 software.

Results and Discussion

Structural parameters and physical properties

Relevant structural parameters, namely loop length, courses/cm, wales/cm etc. were recorded after conditioning the samples. All the parameters were measured and mentioned in Table 5.

Physical properties

Effect of stitch parameters on fabric areal density

Areal density and thickness were measured and compared on the basis of yarn fineness, structural variation and dimensional stability as shown in Fig. 1.

In the samples developed, areal density/GSM is affected by yarn fineness, relaxation stage and stitch type of knitted fabrics. The yarn linear density (yarn count) has direct relationship with fabric areal density. The areal density of knitted fabric for same type of fabric decreases as the yarn becomes finer and increases as the yarn becomes coarser. As yarn becomes finer, the number of fibers per cross-section decrease and thus the weight decreases. Areal density of wet relaxed /bleached fabrics are higher than dry

Table 5 Structural parameters of developed knitted fabrics

Sample ID	Fabric structure and yarn fineness		Nominal loop length (cm)	Actual loop length (cm)	Courses/cm		Wales/cm	
	Fabric structure	Ne (tex)			Dry relaxed	Bleach relaxed	Dry relaxed	Bleach relaxed
SJ20	Single Jersey	20 (29.5)	0.39	0.38	12.99	13.38	9.84	12.59
SL20	Single Lacoste	20 (29.5)	0.39	0.39	8.66	9.84	7.87	8.66
DL20	Double Lacoste	20 (29.5)	0.39	0.39	9.84	11.41	7.87	9.44
SP20	Single Pique	20 (29.5)	0.39	0.38	9.44	10.62	7.48	9.84
DP20	Double Pique	20 (29.5)	0.39	0.39	9.44	11.02	8.27	9.44
SJ24	Single Jersey	24 (24.6)	0.36	0.36	14.17	14.56	9.84	13.77
SL24	Single Lacoste	24 (24.6)	0.36	0.36	9.84	10.23	7.87	9.44
DL24	Double Lacoste	24 (24.6)	0.36	0.36	11.02	11.81	7.48	10.62
SP24	Single Pique	24 (24.6)	0.36	0.35	10.23	11.02	7.48	10.23
DP24	Double Pique	24 (24.6)	0.36	0.35	10.62	11.81	8.26	10.62
SJ30	Single Jersey	30 (19.7)	0.32	0.31	17.32	15.74	10.23	15.35
SL30	Single Lacoste	30 (19.7)	0.32	0.32	11.02	11.41	6.69	12.20
DL30	Double Lacoste	30 (19.7)	0.32	0.32	12.59	14.17	7.87	12.99
SP30	Single Pique	30 (19.7)	0.32	0.32	11.81	11.02	8.26	12.59
DP30	Double Pique	30 (19.7)	0.32	0.32	11.81	11.81	8.66	12.41

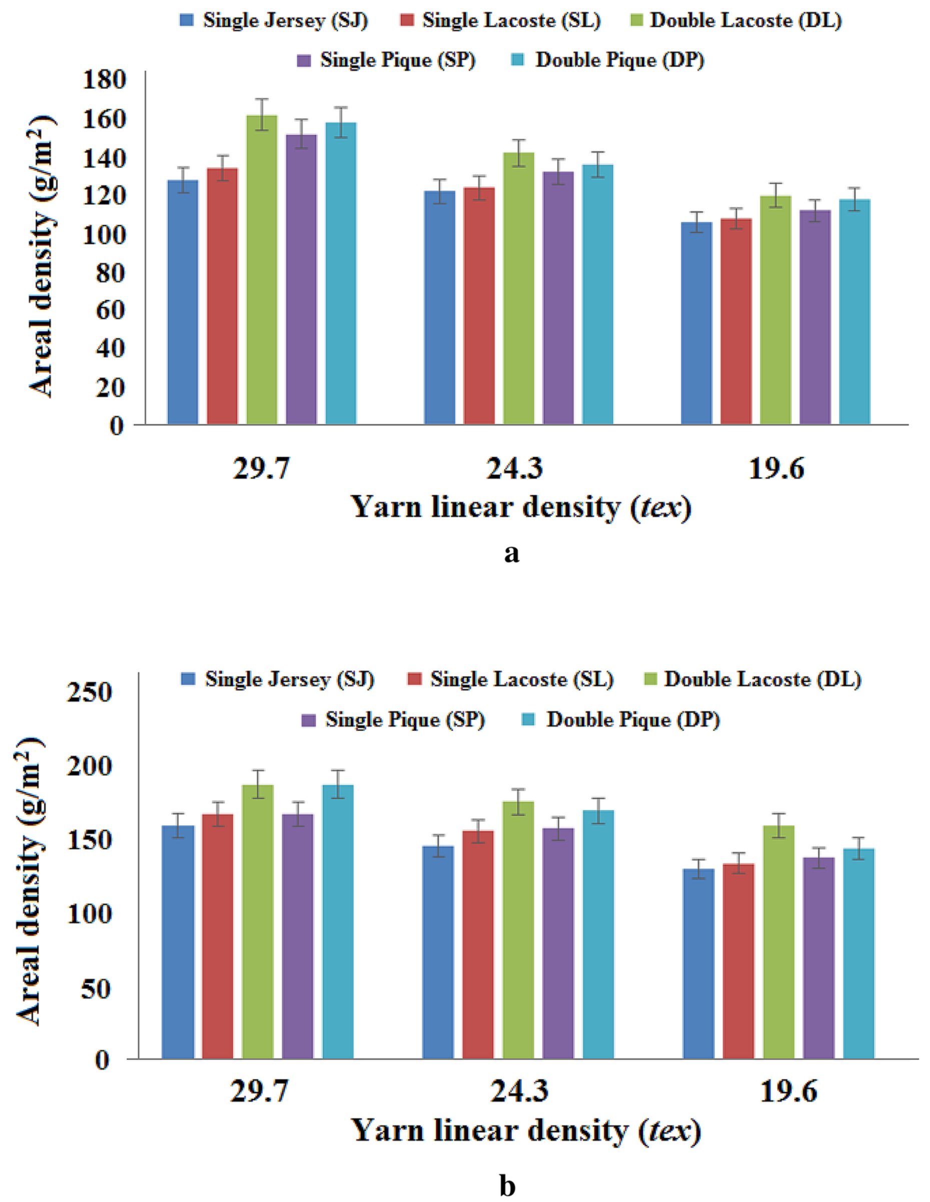


Fig. 1 Areal density of all knit derivatives. **a** Dry relaxed state. **b** Bleached state

relaxed fabric similar to other researchers (Uyanik et al., 2016). The reason behind this is the fabric shrinkage after washing which increases the loop density. Due to increased loop density, more number of stitches accumulate in a particular area that ultimately increases the areal weight of the fabric. The variation in areal density of different knit structures for the same yarn fineness is also observed. This is due to the variation in number/percentage of tuck stitches (NTS), ratio of tuck to knit stitches (RTKS), and location/positioning of tuck stitches (LTS). Pattern also has some effect, but in present study all structures have same pattern i.e. zigzag (Tyagi et al., 2009). Figure 1 shows that all the fabrics having tuck stitches have higher weight compared to single jersey knitted fabric due to accumulation of yarn at tucking places. DP samples have higher percentage of tuck stitches i.e. 50% as compared to 33% in DL samples. However, DP samples show lower areal density. This can be explained on the basis of LTS. DL has no plain courses as in DP, although both of them have 2 successive tucks in the wales. The courses with tuck stitches squeeze between the plain courses in the lengthwise direction. Thus there is an increase of courses/cm in Lacoste samples which leads to increase in areal density. But for SP and SL this is not followed, as percentage of tuck stitches is double in SP as compared to SL i.e. (50% and 25% respectively). The tuck stitches do not get squeezed in these samples. Both the SP and DP samples have same percentage of knit and tuck stitch i.e. 50%. But DP has higher areal density than SP because the ratio of tuck to knit stitches (RTKS) is different. DP has 2 tuck stitches per 2 knit stitches, while in SP this ratio is 1 tuck stitch per 2 knit stitches. This ultimately results in higher areal density in DP than SP. The combination of knit and tuck loops is the best option to increase the areal density of knitted fabrics.

Under real wearing conditions, as the knitted apparel fits the body, there can be substantial changes in areal density. It might increase or decrease depending upon the multiaxial stretch and resulting compression. The structure of knit is responsible to determine the level of deformation and corresponding change of areal density. Once a knitted structure has been stretched in use, a fabric should contract or recover to its original dimension. It was noticed that, when the structure has tuck stitch, there is a significant increase in width-wise extensibility values, but a significant decrease in length-wise extensibility values. The results show that single jersey structure has higher extensibility and recovery value as compared to its derivatives. This is due to the geometry or shape of the knitted loop and its arrangement, which makes the fabric highly extensible and recoverable, than tuck loop structure. Comparatively, single pique has higher width-wise extensibility and recovery values but lower length-wise extensibility and recovery value. This is due to the fact that, tuck loops reduce fabric length and length-wise elasticity because of the higher yarn tension on the tuck and held loops that cause them to rob yarn from adjacent knitted loops, making them smaller. Therefore, the fabric width is increased because of tuck loops pulling the held loops downward, causing them to spread outwards and make extra yarn available for width-wise extensibility and recovery. Single jersey derivatives with tuck loop are also thicker than plain single jersey due to tucked yarn over the held loop, which increases fabric thickness than a normal knitted loop (Assefa & Govindan, 2020).

Effect of stitch parameters on fabric thickness

Figure 2 shows a comparison of thickness for all the knitted samples with effect of yarn fineness, relaxation stage and stitch type. As yarn becomes finer, thickness decreases due to decrease of number of fibers/cross section.

As the fabric samples undergo wet treatment, thickness increased due to increase of stitch density. Because of the increase in stitch density higher weight and thickness are obtained for all fabric samples. This effect is not very significant for thickness, as the fabric samples are compressed and lose their bulk/porosity during the finishing process.

The thickness of DL fabric sample is higher than that of all other fabrics. It is followed by DP, SP, SL and SJ respectively as is the trend for areal density. Lowest value of thickness is observed for SJ fabric. This shows that thickness of fabric increases with

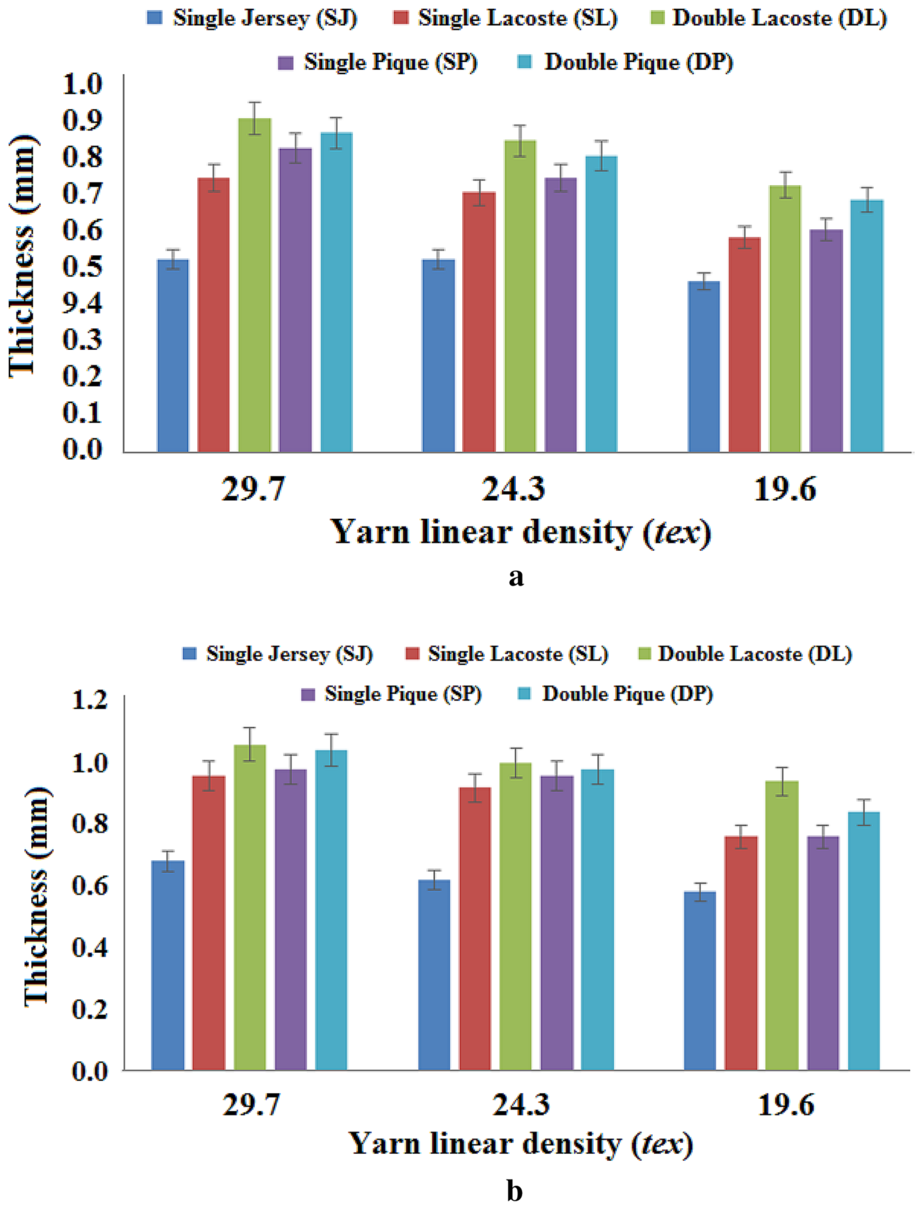


Fig. 2 Thickness of all knit derivatives. **a** Dry relaxed state. **b** Bleached state

increasing the tuck stitch. The tucked yarn over the held loop increases fabric thickness as compared to a normal knitted loop.

Fabric samples with tuck loop are thicker than fabric having knit loop due to accumulation of yarn at the tucking place in a repeat. The percentage of knit and tuck loops in the structure of knitted fabric has significant effect on thickness. If there are 100% knit loops then yarn accumulation will be minimum and loop lies on two dimensions i.e. in length and width directions only. This means that no yarn will lie in the third direction and as a result the thickness of fabric will be reduced. But as the percentage of tuck stitch increases in combination with knit stitch, the fabric thickness also increases. If we check the thickness value of DL and DP fabrics, it can be seen that DL has higher value of thickness as compared to DP, because of positioning/location (LTS) of tuck stitches (LTS). Similar trends are observed as for the areal density in other structures. In real life condition, as the knitted apparel fits the wearer body, there can be decrease in thickness. Based on the resistance to mechanical deformation, the corresponding changes in thickness will occur. Among the knitted structures, single jersey structure is mechanically less resistant as compared to tuck-knit combinations. Therefore, the decrease of thickness can be higher with respect to undeformed state.

Effect of stitch parameters on knitted fabric comfort properties

Air permeability of knitted single jersey and derivatives

Air permeability is very sensitive indicator for a fabric comfort. It is ability of fabric to allow air/wind to pass through it. It can affect apparel fabric performance in many ways. It defines fabric properties like protection against wind, keeping warm, rate of quickest heat loss etc. (Haghi, 2004; Vigneswaran et al., 2009). Air permeability depends on a number of factors like material properties, dimensional properties and finishing treatment. An in-depth study of the structural factors, that influence air permeability, assumes that air flow occurs through the spaces in between the yarn. Thus, the pores between adjacent yarns contribute to pore volume of fabric. The total airflow is also affected by pores enclosed within the yarn. Air permeability depends upon tightness factors, but in our study tightness factor was kept constant i.e. approximately 14. Comparative analysis of air permeability is shown in Fig. 3.

It can be observed from Fig. 3a, as yarn becomes finer, it results in increase in air permeability, which is due to a smaller number of fibers/cross section. In finer yarns, higher fabric porosity occurs due to low packing factor. Air permeability increases as pores between loops become bigger, which results in higher air transmission. In case of coarser yarns, there are smaller spaces between yarns as well as less air space within yarn which causes lower permeability of air. Air permeability increases for the fabrics made from finer yarns as expected in present study. Finer yarns have lower hairiness values which may be another factor for higher air permeability. In this study, combed yarns were used which show much lower hairiness responsible to block the pores and restrict airflow.

From Fig. 3b it is clear that SJ fabrics show lowest airflow permeability. With all knit stitches, the fabric becomes compact and the spaces between loops reduce, making the fabric air resistant. When tuck stitches are introduced in the fabric structure, it becomes more open and porous. SP structure has maximum NTS, thus it exhibits highest air permeability value followed by DL and SL. The inter-yarn pore is the most important parameter influencing the openness of the fabric structure. The fabric pore chartertics and their distribution in knitted fabric affect the air permeability. In Lacoste structures, there are courses of knit structure which squeeze the tuck stitches. Thus the pore size decreases which leads to lower air permeability as compared to SP knits which have an effect of LTS. Although DP has higher percentage of tuck stitches like SP, but DP has ratio of 2 tuck stitches to 2 knit stitches (RTKS) i.e. double overlapping of yarn in double tuck loops, while in SP it is 1 to 1. Therefore, more accumulation of yarn occurs and ultimately results in higher thickness, which leads to reduction of air permeability. In the current analysis the major

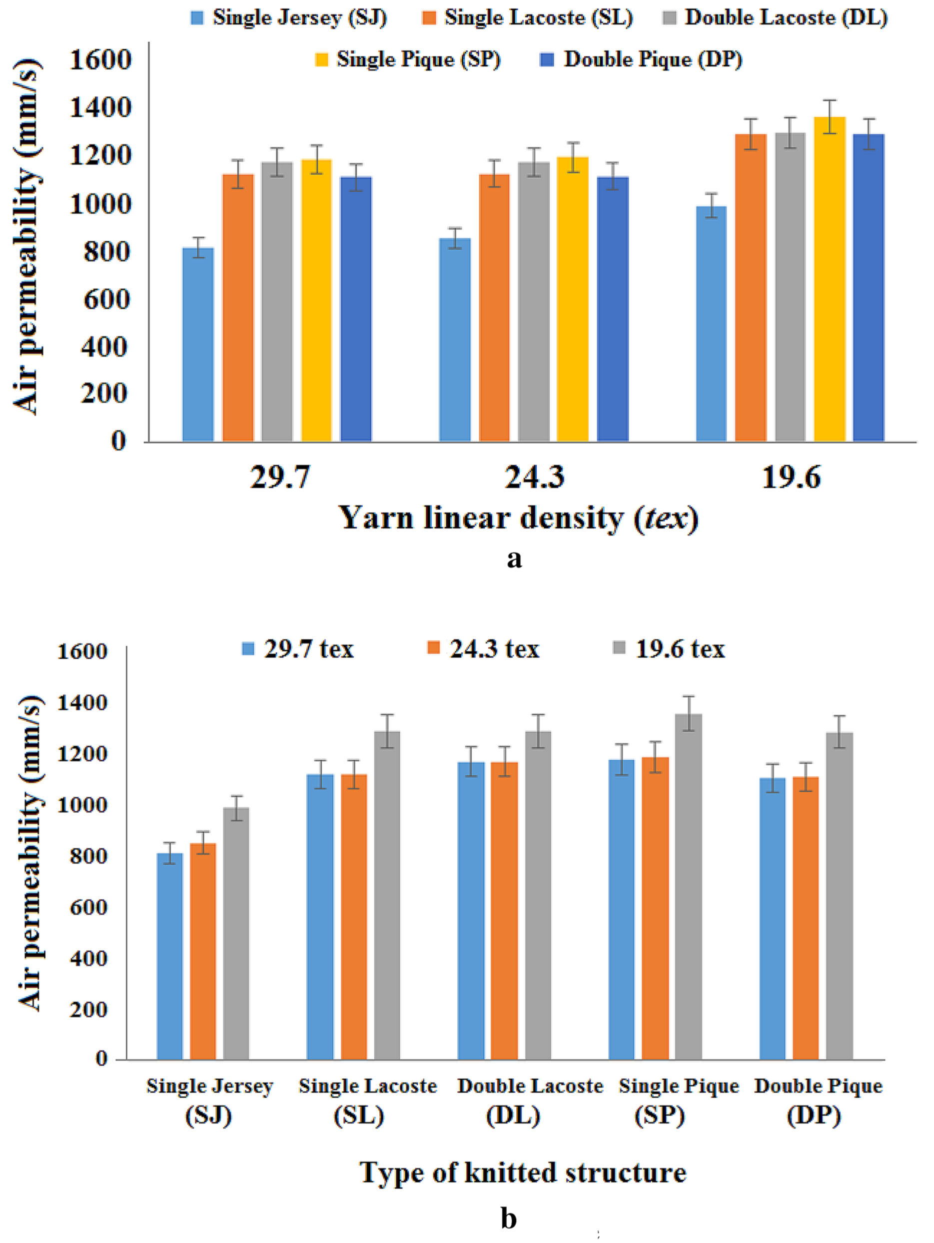


Fig. 3 Comparison of air permeability for different single jersey fabrics and derivatives. **a** Effect of linear density. **b** Effect of knit structure

factor which affects the air permeability in the loop type. The combination of alternate tuck and knit stitch is the best option for higher air permeability. Under real wearing conditions, as the knitted apparel fits the body, there can be variations in areal density and thickness. These changes will certainly influence the resultant air permeability for the apparel in real use. In most cases, the stretching would cause increase of inter loop spaces and thus an increase of air permeability.

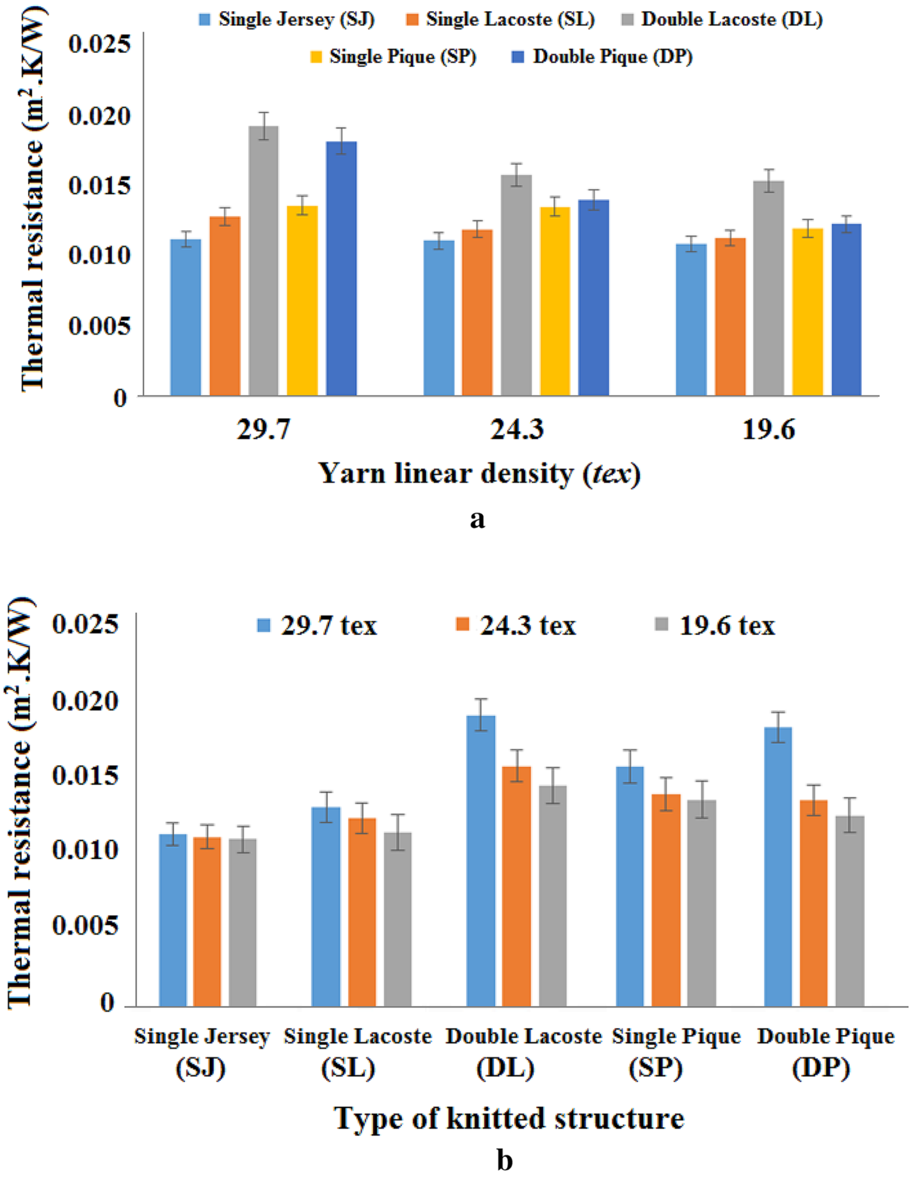


Fig. 4 Comparison of thermal resistance of different single jersey knitted fabrics and derivatives. **a** Effect of linear density. **b** Effect of knit structure

Thermal resistance/insulation of knitted single jersey and derivatives

Thermal insulation is the ability of a material to resist heat flow through it. With a low thermal resistance a gradual loss of heat energy results in cold feeling. The term thermal resistance, refers to value of fabric thermal insulation and it is inversely proportional to thermal conductivity. The thermal resistance is dependent upon thermal resistance of fiber and resistance offered by air trapped within the fabric structure. Effect of yarn linear density and knitted structures on thermal resistance of fabrics was investigated in the present study. Results are shown in Fig. 4.

As shown in Fig. 4a, coarser yarns result in higher thermal resistance due to increase in total pore volume which leads to increase air pockets in the knitted fabric structure. The thermal conductivity of stagnant air is 0.025 $\mathrm{Wm}^{-1}\ \mathrm{K}^{-1}$ which is much lower than any fiber material. The amount of stagnant air pockets influences the overall resistance of fabrics. When hairiness increases, more air is entrapped in air pores resulting in increased value of thermal insulation.

Thermal properties are influenced by microscopic, mesoscopic and macroscopic porosity. Fabrics from tuck-knit stitch combinations showed higher thermal resistance values than the fabrics from 100% knit stitches. DL fabric exhibits a higher value than the others due to its higher thickness. It is decreased in the order DP, SP, SL and SJ, respectively. The plain courses in DL squeeze tucks between them which changes the pore size due to LTS. So the amount of stagnant air pockets increases which very much influences the overall thermal resistance of the fabric. But in SL structures, pore size increases due to RTKS. In DP structure, due to double tuck loop or in other words due to RTKS, more accumulation of yarn leads to higher thickness and thus a higher thermal resistance. The thermal resistance is highly correlated with thickness in present study as shown in Fig. 6. Similar observations are reported by other researchers in a dry fabric which entirely depends on thickness and, to a lesser extent, on fabric construction and fiber conductivity (Arumugam et al., 2017; Venkataraman et al., 2015a, 2015b).

Under real wearing conditions, as the knitted apparel fits the body, there can be variations in areal density and thickness. These changes will certainly influence the resultant thermal properties. The thickness decrease will result in reduction of thermal insulation. However, the extent of decrease will further depend on corresponding change of areal density. Among the knitted structures, single jersey structure is mechanically less resistant as compared to tuck-knit combinations. Therefore, the thermal insulation will also reduce substantially.

Relative water vapor permeability (RWVP%) of knitted single jersey and derivatives

It is the term used for ability to transfer water vapors through fabric to the external environment which defines transfer of sweat from wearer's body to environment through fabric. It is a percentage of vapor transfer through the fabric in comparison with equivalent thickness of air.

From the Fig. 5, it is clear that as the yarn linear density increases, RWVP% increases. RWVP% is largely dependent upon the formulation and arrangement of fibers within the yarn. Finer yarn has lower packing fraction, lower diameter, increasing number of pores or spaces between loops and thus contribute to higher RWVP%. A layer having coarser cotton yarn will take more time in transferring water vapor.

Fabric RWVP% is the replacement of fabric–air interface with fabric–water interface. More porous structure offers lower resistance to water vapor. SJ structures exhibit highest RWVP% followed by knit-tuck stitch combinations. In SJ, the structure comprising of knit stitches only, increases the flow of moisture vapor. Another reason may be the lowest thickness in case of SJ fabric structure. Also SJ structure consists of knit loops only as compared to other structures which consist of a combination of knit-and-tuck loops. In SJ, the loop leg orientation is only in the vertical wale direction which helps in better

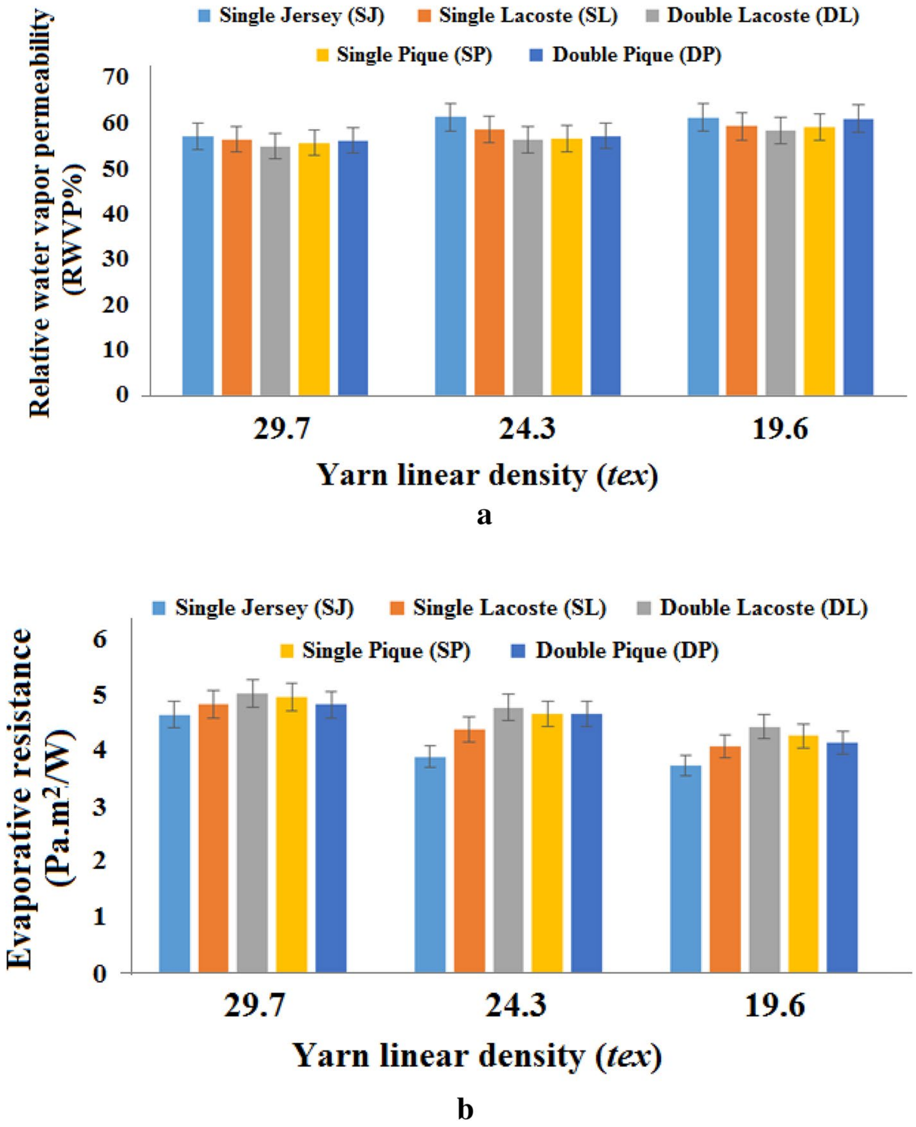


Fig. 5 Comparison of RWVP% & EvR for different single jersey fabrics and derivatives. **a** Relative water vapor permeability %. **b** Evaporative resistance

wicking. Faster liquid dispersion in fibrous materials is facilitated by small, uniformly distributed and interconnected pores (Behera & Mishra, 2007).

Due to more porous structures (high total pore volume) the tuck stitches have high liquid retention. Water vapor permeability of SL fabrics is maximum among all the knit–tuck combinations due to minimum percentage of tuck stitches. DL structures exhibit lowest RWVP% due to LTS (tuck stitch squeeze between plain courses). This leads to small pores which are not interconnected. Although it is good for liquid movement due to high capillary pressure, but flow in capillary spaces may stop when geometric irregularities allow the meniscus to reach an edge and flatten. This limits the liquid advancement in the thickness direction (Das et al., 2009; Hsieh, 1995).

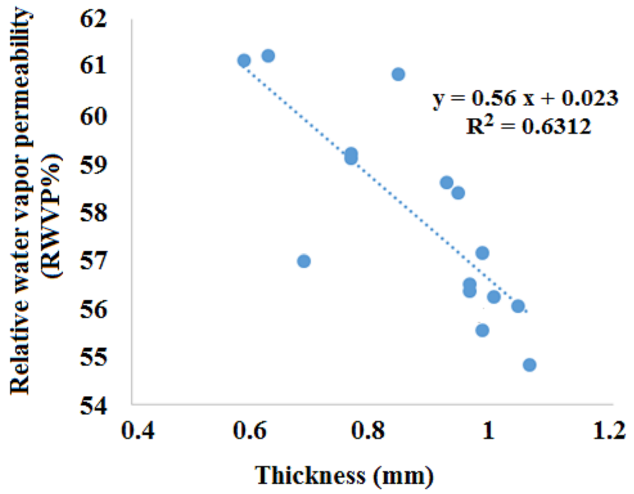


Fig. 6 Correlation of thickness and relative water vapor permeability

A combination of high thermal resistance and low relative water–vapor permeability can cause uncomfortable situation to the wearer as the heat stored in the body cannot be dissipated. Increase in RWVP can be attributed to lower fabric density and thickness. Such observations are depicted in Fig. 6.

Water vapor resistance/evaporative resistance

A higher value of water vapor resistance is an indicator of bad moisture transportation and fabric being less breathable to vapor transmission. A fabric having lower water vapor resistance means it takes less time during transportation of moisture thus resulting in drier skin and improved comfort. Due to increase of yarn linear density, fabric thickness increases and thereby increasing evaporative resistance. The knitted fabrics in present research show considerably lower water vapor resistance in the range of 3–5 m^2 Pa/W, which indicates these fabrics can provide satisfactory level of comfort to the wearer. As compared to all other structures DL, the thickest fabric shows highest evaporative resistance and lowest relative water vapor permeability. When density of fabrics increases, the resistance to water spreading also increases. So evaporative resistance of DL is highest followed by DP, SP, SL and SJ.

Relation between RWVP% and air permeability

The air permeability trends are compared vis-à-vis relative water vapor permeability (RWVP%) of the single knit derivative fabric as given in Fig. 7. It can be observed that the trends are almost opposite to each other. This is due to replacement of fabric–air interface with fabric–water interface, and thus due to presence of more stagnant air, more resistance for water to evaporate is resulted.

Under real wearing conditions, as the knitted apparel fits the body, there can be variations in density and porosity. These changes will certainly influence the moisture

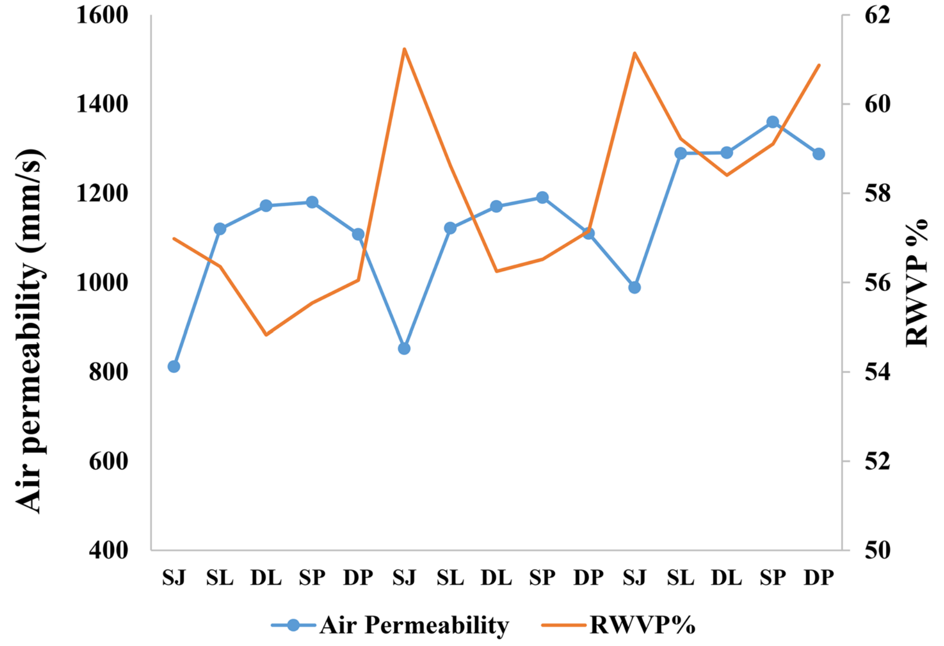


Fig. 7 Relation between air permeability and RWVP%

Table 6 ANOVA table of dependent variables

Model terms	Areal density	Thickness	Air permeability	Thermal resistance	RWVP%
R-sq (predicted) %	92.42	93.23	85.35	91.78	85.14
Sum of squares (SS)	5.54	5.86	5.07	5.82	4.23
Mean sum of squares (MS)	2.25	2.01	2.78	2.16	2.12
F-statistic	1.01	1.11	1.03	1.1	1.2
Error%	4.41	3.20	5.44	4.71	4.88
% contribution of Yarn fineness (*tex*)	54.23	60.74	42.86	46.28	39.14
% contribution of finishing/relaxation	22.18	18.43	32.14	28.94	28.74
% contribution of knitting structure	23.59	20.83	25.00	24.78	32.12
P value					
Yarn fineness (T)	0.000	0.012	0.000	0.001	0.002
Wet relaxation (R)	–	–	0.002	0.535	0.005
Knitted structure (S)	0.000	0.000	0.004	0.000	0.122
T * R	–	–	0.061	0.082	0.011
T * S	0.042	0.002	–	0.027	0.004
R * S	0.077	–	–	–	–

Values of areal density, thickness, air permeability and thermal resistance were expressed as g/m^2, mm, mm/s and m^2 K/W respectively. RWVP% represents Relative Water Vapor Permeability (%)

management and RWVP%. It will depend upon the nature of capillarity or distribution of pores under deformed state of the knitted apparel.

Analysis of variance

The ANOVA statistical technique was employed to investigate which input parameter has most significant effect on the thermo-physiological characteristic. The ANOVA analysis given in Table 6 shows the percentage contribution for each parameter on the thermo-physiological comfort.

The analysis of variance shows that the variables like yarn fineness, wet relaxation as well as the type of knitted structure have significant influence on the physical parameters e.g. areal density and thickness of single knit fabric derivatives. Further the yarn tex, wet treatment and change of structure by tuck-knit stitch combinations significantly influences the thermo-physiological properties e.g. air permeability, thermal insulation and relative water vapor permeability.

The yarn fineness has maximum contribution towards changing thickness and areal ensity, followed by knit structure. Further the yarn fineness is most influential factor to change the thermo-physiological properties. The wet relaxation induced structural changes seem to be slightly more influential than the knit structure itself to change the air permeability and thermal resistance. On the other hand RWVP% is rather dominated by the yarn fineness and the knit structure. These findings are in the same line as previous researchers (Arumugam et al., 2017; Celep & Yuksekkaya, 2017; Çoruh, 2015; Vadicherla & Saravanan, 2017).

Conclusions

The study mainly focused on effect of combed yarn linear density and loop pattern of single jersey knitted structures on their thermo-physiological comfort related properties. Combination/order of knit-tuck stitches plays an important role in determining all the physiological properties. Number/percentage of tuck stitches (NTS), ratio of tuck to knit stitches (RTKS), and location/positioning of tuck stitches (LTS) are important parameters which affect fabric properties. It was concluded from the study that, wet treatment processes such as bleaching increases fabric thickness and areal density. This phenomenon is found common to all five knitted structures. It was also inferred from this study that manufacturers can manage areal density by using knit- tuck combinations. Thickness is also affected by linear density, relaxation stage and knit/tuck stitches combination. During evaluation of experimental study findings with respect to comfort, it was observed that air permeability, thermal resistance and moisture management properties of single jersey knitted fabrics and derivatives are affected by the change of stitch type. Similar conclusions are supported by other researchers (Khalil et al., 2020; Kundu & Chowdhary, 2020). It was concluded from this study that, the increase in fabric porosity by increasing the tuck stitches percent consequently results in increase in fabric air permeability. Higher permeability can be achieved by alternate knit and tuck loop. The thermal resistance of fabric is primarily dependent on stagnant air that is enclosed inside the knitting structure. The most important factor affecting the thermal resistance and evaporative resistance is the thickness of the knitted fabric. Subjected to specific climatic conditions, a lower value of thermal resistance provides cooling effect due to gradual loss of heat energy from human body through the fabrics (Oğlakcioğlu & Marmarali, 2007). Similarly RWVP% is strongly dependent on physical properties e.g. thickness and areal density. Plain Single Jersey (SJ) structures exhibit lowest thermal resistance and highest RWVP% which makes them suitable for high physical activity in hot weather conditions. High physical activity in summer leads to rise of body temperature and wetness. The clothing material used in such weather conditions must have good moisture management and high wicking ability in order to transport liquid/ moisture without absorbing it. Different fabric structures are needed to be advised in accordance with activity to be performed and weather condition. A user or wearer performing low physical activity in a warm weather will not face too much wetness. Air permeability of fabric will be widely important in evaluating comfort. As the value of air permeability reaches higher values, heat loss will be quicker and vice versa. Structures with tuck stitches are recommended for summer wear as they allow cold air to penetrate through them, causing a cooling effect for the body as sweat will evaporate quickly. A higher air permeability results in quicker heat-loss obtained from a textile material. Single Pique (SP) structure is a good option which can provide the comfort needed under these conditions. While working in cold weather, low physical activity, structures with tuck stitches are better suited. Double Lacoste (DL) structures having highest thermal resistant with good air permeability and reasonably good overall moisture management capacity (OMMC) can serve the purpose needed. Statistical analysis indicated that the results of the single jersey knit fabrics and derivatives are significantly dependent on the yarn fineness, structural parameters and finishing stages (Celep & Yuksekkaya, 2017; Çoruh, 2015; Vadicherla & Saravanan, 2017). The performance under real wearing condition will vary depending on the mechanical response of the knitted structure to the loading conditions. From the results of investigation, it can be concluded that the type of knitted structures has strong influence on their comfort properties and further research areas shall be opened in this regard.

Acknowledgements
The work was supported by Internal grant agency of Faculty of Engineering, Czech University of Life Sciences Prague (no. 2021:31140/1312/3108), project: Optimization of performance and comfort properties of fire resistant knitwear (No. NRPU /HEC/8980), project: "Development of comfortable compression socks for treatment of varicose veins or chronic venous disease in legs" under HEC project Establishment of Technology Development Fund (TDF) (No.TDF03-149), and by Ministry of Education, Youth and Sports of the Czech Republic, the European Union (European Structural and Investment Funds—Operational Program Research, Development and Education) in the frames of the project "Modular platform for autonomous chassis of specialized electric vehicles for freight and equipment transportation", Reg. No. CZ.02.1.01/0.0/0.0/16_025/0007293.

Authors' contributions
All authors tested and analyzed the data. All authors read and approved the final manuscript.

Funding
The work was supported by Internal grant agency of Faculty of Engineering, Czech University of Life Sciences Prague (no. 2021:31140/1312/3108), project: Optimization of performance and comfort properties of fire resistant knitwear (No. NRPU /HEC/8980), project: "Development of comfortable compression socks for treatment of varicose veins or chronic venous disease in legs" under HEC project Establishment of Technology Development Fund (TDF) (No.TDF03-149), and by Ministry of Education, Youth and Sports of the Czech Republic, the European Union (European Structural and Investment Funds—Operational Program Research, Development and Education) in the frames of the project "Modular platform for autonomous chassis of specialized electric vehicles for freight and equipment transportation", Reg. No. CZ.02.1.01/0.0/0.0/16_025/0007293.

Availability of data and materials
All data generated or analyzed during this study are included in this published article. Further data and material relevant to this work can be provided on request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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Received: 15 November 2020 Accepted: 22 April 2021

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