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Thermal Comfort Properties of a Bi-layer Knitted Fabric Structure for Volleyball Sportswear

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Abstract
The thermal comfort properties of different knitted fabric structures made from modal, polypropylene and micro denier polyester were studied for volleyball sportswear. Eleven knitted fabrics were produced, in which three samples were single jersey, two plated and six bi-layer knitted structures. The air permeability, water vapour permeability, thermal conductivity, wicking and drying ability of bi-layer knitted fabric made up of polypropylene as the inner layer and modal as the outer layer with one tuck point of repeat were found to be higher as compared to other bi-layer, plated and single jersey structures. Both the objective and subjective results show that bi-layer knitted fabric with polypropylene as the inner layer and modal as the outer layer with one tuck point of repeat is mostly suitable for sportswear. The results are discussed together with multivariate ANOVA test results at a 95% significance level.

Key words: *bi-layer, performance, sportswear, thermal comfort, subjective analysis.*

Introduction

Active sportswear is a kind of sportswear which requires higher moisture transfer properties than commercial sportswear [1]. Sportspersons are much more conscious of sportswear and demand more specific functions to be performed by it. As a result, a few fibres and fabrics are emerging to satisfy the stringent needs and developments arising mainly in the areas of comfort and aesthetic acceptability [2, 3]. Sports garments are worn next to the skin and are key to the physiological comfort of an athlete, and their attributes in this aspect are critical to his or her performance [4]. In traditional sportswear, players face many problems such as sweating, feeling hot while run and improper strechability. The main functional requirements of volleyball are sweat absorption, fast drying and cooling [5]. Sportswear's foremost property is to evaporate perspiration from the skin surface, and the secondary property is to transfer the moisture to the atmosphere [6]. High active sportswear should have stretch and elastic recovery to provide sufficient fit and freedom of movement to the wearer [7]. Sports clothing should be capable of maintaining heat balance between the excess heat produced by the wearer due to the increased metabolic rate, on the one hand, and the capacity of the clothing to dissipate body heat and perspiration on the other [8].

The wear comfort of active sportswear can be achieved by thermo-physiological, skin sensorial, ergonomic wear and psychological comfort. Liquid transporting and the drying rate of fabrics are two vital factors affecting the physiological comfort of garments [9, 10, 11]. Regional distribution of sweat takes place on the human body and it has been reported that back area sweat is substantially higher than the chest area of players [12]. The performance of layered fabric in thermo-physiological regulation is better than for a single layer structure [13, 14, 15, 16, 17].

For doubled layer fabric, it is recommended that the inner layer, which touches the skin, is made from synthetic materials that have good moisture transfer properties, such as polyester, acrylic, nylon and polypropylene. For the outer layer, materials that have good moisture absorption properties such as cotton, wool, viscose or their blends are recommended [18].

The aim of this study was to develop a bi-layer knitted fabric that will achieve a high level of clothing comfort for sports and active wear. Characteristics of this special knitted structure concern the existence of two different fabric surfaces: the outer surface is the absorption layer with hydrophilic properties, in which modal yarn was used due to its high moisture absorption property; the inner surface is considered as the separation layer with hydrophobic synthetic fibre; polypropylene was used due to its high water transfer capillarity, lightweight and easy care properties, and micro-denier polyester was used, which is ideal for wicking perspiration away from the skin.

Materials and methods

Yarn

Three different types of yarns, namely modal, texturised polypropylene and micro denier polyester (M/s. Sumukha Impex, Coimbatore, Tamilnadu India) were used for sample preparation. The yarn linear density for modal and polypropylene is 147 Decitex and for micro denier polyester – 167 Decitex.

Fabric

Bi-layer knitted fabrics were developed on an interlock jacquard knitting machine (Mayer & Cie – OVJA36), with a machine diameter of 30 inch, machine gauge of 20, total number of needles of 3744 and number of feeder of 36. Eleven samples were knitted, in which three samples were plain single jersey structures, two samples single jersey plated structures, and six samples were bi-layer knitted structures (***Table 1***, see page 76).

The prerequisites of ideal sportswear are rapid transport of perspiration away from the body and then its rapid evaporation to keep the fabric dry. This is achieved by a bi-layer knitted fabric construction in which the inner layer is made of polypropylene or micro- denier polyester filament yarn, which is hydrophobic and

Sample code	Cam and needle order
S1, S2, S3, S4 and S5	(see grid below)
S6 and S7	(see grid below)
S8 and S9	(see grid below)
S10 and S11	By changing the tuck frequency of S6 or S7 in every odd feeders

S1, S2, S3, S4 and S5:

X	X
X	X

S6 and S7:

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
DN1	o	X	-	X	-	-	X	-	X	-
DN2	-	X	-	X	-	o	X	-	X	-
CN1	o	-	X	-	X	-	-	X	o	X
CN2	-	-	X	-	X	o	-	X	-	X

S8 and S9:

	F1	F2	F3	F4	F5	F6	F7	F8	... F36
DN1	X	-	X	-	X	-	X	-	-
DN2	X	-	X	-	X	-	X	-	-
CN1	-	X	-	X	-	X	-	X	X
CN2	-	X	-	X	-	X	-	X	X
CN3	o	X	-	X	-	X	-	X	X

Dial needles: Two tracks
DN1-Dial Needles Track 1; DN2-Dial Needles Track 2
Cylinder needles: Three tracks
CN1-Cylinder Needles Track 1; CN2-Cylinder Needles Track 2;
CN3- Cylinder Needles Track 3
F1, F2, F3,.......F35, F36-Number of feeders; X-Knit stitch; o-Tuck stitch; - -Miss stitch

Figure 1. *Cam and needle order of fabrics.*

Table 1. *Fabric sample code details*

Sample Code	Details
S1	100% Modal – Single Jersey Fabric
S2	100% Polypropylene – Single Jersey Fabric
S3	100% Micro Denier Polyester – Single Jersey Fabric
S4	40% Modal and 60% Micro Denier Polyester – Plated Fabric
S5	40% Modal and 60% Polypropylene – Plated Fabric
S6	40% Modal and 60% Polypropylene – Bi-Layer (five tuck point)
S7	40% Modal and 60% Micro Denier Polyester – Bi-Layer Fabric (five tuck point)
S8	40% Modal and 60% Polypropylene – Bi-Layer Fabric (one tuck point)
S9	40% Modal and 60% Micro Denier Polyester – Bi-Layer (one tuck point)
S10	40% Modal and 60% Polypropylene – Bi-Layer Fabric (seven tuck point)
S11	40% Modal and 60% Micro Denier Polyester – Bi-Layer (seven tuck point)

has a good wicking rate. The outer layer is made up of regenerated fibre such as modal, which has more absorption and rapid evaporation. The fabric which has to form the inner layer is fed in the dial needle and the outer layer in the cylinder needle. The cam and needle order is shown in ***Figure 1***.

More heat dissipation occurs across the back, under the arm, as well as at the shoulder, waist line and crotch level. Due to heat generation, sweat is accumulated in sportswear, leading to an uncomfortable situation for players and affecting their performance. Sweat generated in the micro climate part should be transferred and evaporated to the atmosphere to keep the fabric dry. This can be achieved by the development of a bi-layer structure in which the inner layer is made up of hydrophobic characteristic yarn and the outer layer of hydrophilic characteristic yarn.

Physical characteristics of samples

The course density and wale density were measured according to the ASTM D3887 standard [19]. The fabric weight per unit area and fabric thickness was measured according to the ASTM D3776 [20] and ASTM D1777-96 [21] standards, respectively. The tightness factor of the knitted structures was determined using the following equation:

$$\text{Tightness factor (K)} = \sqrt{T / l} \qquad (1)$$

Where T is the yarn liner density in tex and l is the loop length of the fabric in cm.

Thermal comfort characteristics of samples

The air permeability of the knitted fabric structures were measured using KES–F8 AP1, with the Air Permeability Tester following the BS 5636 1990 standard [22]. Thermal conductivity is an intrinsic property of material that indicates its ability to conduct heat. Lee's disk instrument was used to measure the thermal conductivity according to Standard ASTM D7340 [23]. The evaporative dish method based on BS 7209:1990 [24] was used to determine the water vapour permeability of the fabrics. A strip of 20 cm × 2.5 cm test fabric at 20°C & 65% RH was suspended vertically with its lower edge (0.5 cm) immersed in a reservoir of distilled water. The rate of rise of the leading edge of the water was then monitored for longitudinal wicking [25]. The static immersion method, which follows Standard BS 3449 [26] was used to evaluate the amount of water absorbed by the fabric. The drying behaviour of the fabric was tested as a continuous process from absorption process. The fabrics were wetted according to the static immersion method and were dried in a drying oven at 30°C for 30 minutes to simulate natural drying [25].

Subjective evaluation of fabrics

15 male players with a mean and standard deviation age of 23 years (1 year), body mass 55.9 kg (2.9 kg), and height 1.7 m (0.03 m) participated in this study. All participants provided written consent to participate. The survey was carried out for 8 days and followed a standardized procedure when approaching participants, and proper directions were given to them. Subjective evaluation was conducted at the following conditions: Temperature – 26°C, RH – approximately 76%, approximate wind velocity – 9.36 km/hr and time of play – 5.30 pm. The purpose of subjective evaluation is to know the suitability of sports activity with respect to the product design and

climatic conditions. The sportswear was given to the volleyball players in hot climatic conditions. Parameters such as the clamminess, dampness and thermal sensations were chosen for subjective evaluation. The subjective evaluation is purely based on the psychological feeling of the sports person, which is rated using Hollie's subjective comfort rating scale [27]. While playing, each subject has to rate the sportswear for selected comfort sensations like stiffness, stickiness, non-absorbence, dampness, clamminess, coldness, roughness and scratchiness. The comfort descriptor is rated using the intensity scale: 4 (partially), 3 (mildly), 2 (definitely) and 1 (totally) [28].

Statistical analysis

The relationship between the structures was analysed using ANOVA at a 95% confidence level. The coefficient of correlation obtained on the basis of rank is called Spearman's Rank Correlation. The Spearman's Rank Correlation (r) is a crude method of computing the correlation between two characteristics. In this method, various items are assigned ranks according to the two characteristics and a correlation is computed between these ranks.

Table 2. *Fabric geometric parameters of samples developed.*

Sample Code	Stitch density	Areal density $g.m^{-2}$	Loop length mm	Thickness mm	Tightness factor (K)
S1	2264	112	2.9	0.58	13.26
S2	1906	91	3.1	0.56	13.42
S3	1760	85	3.3	0.53	13.82
S4	1974	123	3.1	1.00	11.46
S5	2112	141	2.9	1.20	11.84
S6	3392	143	3.1	0.87	12.48
S7	3674	152	2.9	0.91	12.54
S8	2016	118	3.1	0.69	12.12
S9	2444	126	2.9	0.72	12.28
S10	3968	158	2.9	0.97	12.64
S11	3080	136	3.1	0.84	12.34

Table 3. *Thermal comfort properties of samples developed.*

Sample Code	Air permeability, $cm^3.s^{-1}.cm^{-2}$		Water vapour permeability, $g.m^{-2}.day^{-1}$	Coefficient of thermal conductivity, $W.m^{-1}.K^{-1}$	Longitudinal wicking, cm	Moisture absorbency, percentage	Drying behaviour, minutes
	Dry	Wet					
S1	182	122	1224	0.024	4.5	55.6	14.3
S2	191	146	1424	0.021	4.8	52.3	12.6
S3	242	161	1325	0.019	4.3	61.8	13.8
S4	253	184	1116	0.018	5.8	72.6	11.8
S5	196	156	1254	0.038	4.2	78.1	10.9
S6	964	724	1892	0.026	8.5	88.7	8.6
S7	826	622	1745	0.031	8.2	93.1	9.1
S8	1244	884	2450	0.052	9.8	80.5	6.5
S9	1210	851	2116	0.045	9.2	82.2	11.2
S10	815	642	1834	0.032	7.9	95.4	7.2
S11	986	785	1926	0.028	7.1	85.9	10.3

Results and discussion

Fabric geometric parameters

Table 2 below shows the geometrical properties of all eleven samples developed. The areal density of the fabric varies according to the fabric structure.

Air permeability

The air permeability value of bi-layer fabric with one tuck point in S8 and S9 was greater than for the other fabrics due to the structural variation and decrease in stitch density, as shown in ***Table 2*** and ***Table 3***. A lower air permeability value was observed in single jersey and plated structures, because loops are very closely packed, becoming closer than in bi-layer structures. The air permeability value was lower for S6, S7, S10 and S11 due to the presence of more tuck points, higher thickness and increased number of loops present in the unit area. The air flow principle states that the flow of air will be less in thicker fabric and more in thinner fabric. Even though the thickness is less for single jersey structures S1, S2 and S3, the presence of more tuck stitches in S8 and S9 increases the passage of air from one side of the fabric surface to the other. As a result, the air permeability of bi-layer knitted fabrics can decrease with increased stitch density and thickness.

During activity, usually the sports person's body dissipates heat, leading to the formation of sweat. In this wet state, fabric should have enough air permeability so that vapour transfer will be strong enough. If air permeability in the wet state is not sufficient, it leads to the accumulation of sweat on the skin. It is observed that fabrics S8 and S9 have more air permeability in a wet state, followed by S11 and S6. In a wet state the modal absorbs moisture and swells, which decreases the air permeability. Thus the air permeability of fabric in a wet state was comparatively lower than for fabric in a dry state due to water present in a free liquid state between yarns also trapping air movement through the fabric.

Water vapour permeability

The bi-layer knitted structures of fabrics S8 and S9 had higher water vapour transport than the other fabrics because their thickness and weight were lower than for the others (***Table 3***). This is because, in a steady state, moisture vapour transport through fabrics is controlled by the diffusion process, which is influenced by the fabric structure, thickness and openness. Fabric S7 had the lowest air permeability value because of its higher thickness. Fibre-related factors, such as the cross-sectional shape and moisture absorbing properties, do not play a significant role. The fabric of low moisture vapour permeability is unable to pass sufficient perspiration, leading to sweat accumulation in the clothing, and hence discomfort.

Thermal conductivity

Thermal conductivity is a function of fabric material, thickness and structure. The highest thermal conductivity value was observed for the S8 fabric, as shown in ***Table 3***, whereas the lowest was observed for the S6 fabric. The reason is that fabric S8 had the lowest thickness, and the higher the volume of dead air within a textile structure, the lower the thermal conductivity will be. Even though bi-layer fabrics S8 and S9 possess high air permeability due to thickness and structural variation, it was found that they possess higher thermal conductivity.

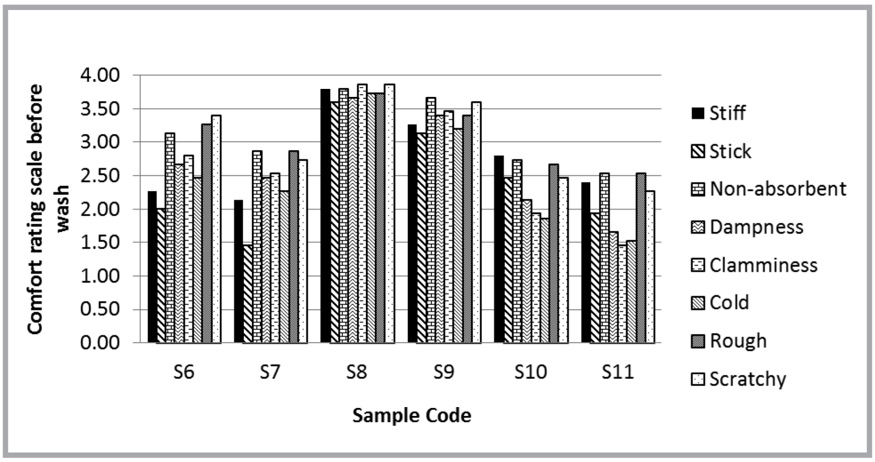

Figure 2. *Comfort descriptor rating before washing.*

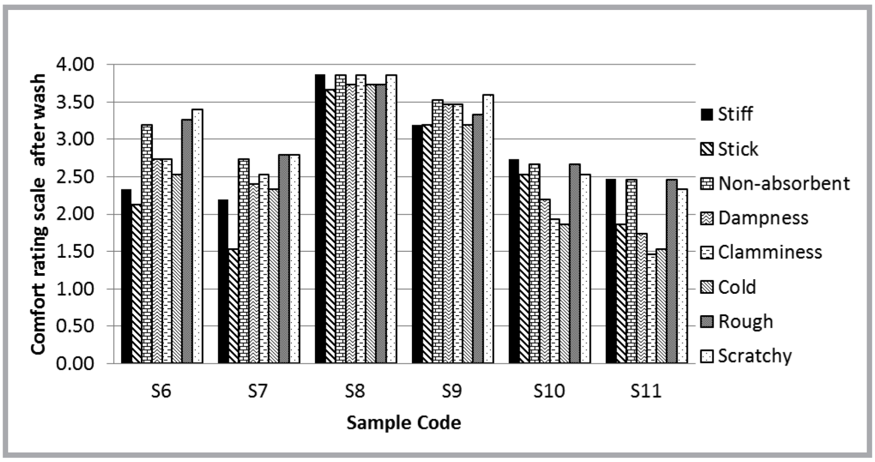

Figure 3. *Comfort descriptor rating after wash.*

Fabrics S6, S7, S10 and S11 had greater variation than the bi-layer fabrics with one tuck point. It is important to note that the higher number of tuck points and consequent increase in thickness shows a comparatively lower thickness than for one tuck point bi-layer fabrics. The presence of polypropylene in S8 proved to be beneficial due to its very good thermal characteristics, keeping the wearer warm in cold weather and cool in warm weather.

Wicking

Wicking is the spontaneous flow of liquid in a porous substrate, driven by capillary forces. The capillary forces caused by wetting is wicking [29]. The longitudinal wicking height determines the liquid transporting ability, and the faster the rate of wicking, the better the sweat transporting ability will be, hence the fabric feels more comfortable to wear [30]. Longitudinal wicking was observed only on the polypropylene side since it is well known that the wicking of modal is very low as compared to polypropylene. The longitudinal wicking height is increased for all fabric types for a given period of 5 minutes. Among the bi-layer knitted fabrics, S8 and S9 had a higher wicking rate due to their lowest stitch density and thickness, followed by fabrics S6, S7, S10 and S11 (***Table 3***). Plated fabrics S4 and S5 had the lowest wicking rate compared to bi-layer fabrics due to having a higher thickness than bi-layer fabrics. Bi-layer fabrics S10 and S11 had the lowest wicking ability due to higher thickness and the presence of a greater number of tuck loops.

Absorbency

When fabric is subjected to heavy sweating conditions, not all the sweat absorbed by the fabric can be given off to the atmosphere instantaneously. Thus to prevent the wearer from feeling wet and clammy moisture should be stored in the fabric. Maximum absorbency was found to be high in S10 and S7, followed by the other samples. From ***Table 3***, it is clearly shown that the bi-layer knitted structures have a high amount of water absorbency when compared to the plated structure. The higher the stitch density, the more the amount of moisture that can be stored by the fabric, and the better the performance of the fabric would be under moderate to heavy sweating conditions. Bi-layer fabrics with five and seven tuck points had higher absorbency than one-tuck point bi-layer fabrics because their thickness and weight were higher than for S8 and S9.

Drying behaviour

Moisture transfer is a critical factor for the thermoregulation of body heat. Moisture on the skin or clothing increases the heat loss of the body and also affects its overall performance and endurance. Therefore clothing should have a quick drying ability property. S8 had a higher

Table 4. *ANOVA multivariate data analysis of thermal comfort properties.*

Thermal comfort properties	Between single jersey and plated fabrics				Between bi-layer knitted fabrics			
	Sum of square value (SS)	F_{actual}	$F_{critical}$	P_{value}	Sum of square value (SS)	F_{actual}	$F_{critical}$	P_{value}
Air permeability in dry state	20464.24	2144.61	2.87	<0.0001	844498.71	62166.88	2.62	<0.0001
Air permeability in wet state	10213.43	1234.5	2.87	<0.0001	367875.46	23229.44	2.62	<0.0001
Water vapour permeability	240682	31.41	2.87	<0.0001	1626791.45	65724.14	2.62	<0.0001
Thermal conductivity	0.00112	157.94	2.87	<0.0001	0.0032	183.07	2.62	<0.0001
Longitudinal wicking	7.84	614.38	2.87	<0.0001	24.26	244.05	2.62	<0.0001
Moisture absorbency	2443.21	8901.41	2.87	<0.0001	1112.84	833.5	2.62	<0.0001
Drying behaviour	41.72	492.28	2.87	<0.0001	79.08	698.15	2.62	<0.0001

Table 5. Spearman's coefficient of rank correlation before and after washing.

Sample code	Coefficient of rank correlation before and after wash (r)
S6	0.994
S7	0.946
S8	0.930
S9	0.932
S10	0.994
S11	0.982

rate of drying ability, followed by S10 and S6 (***Table 3***). The drying ability of bi-layer and plated fabrics was greatly influenced by the thickness and weight of the fabrics, as a result of which there was lower thickness and the presence of a layer structure which has the ability to transfer perspiration from the inner layer (Polypropylene) of the fabric to the outer layer (Modal), which it easily gets evaporated and dried.

Effect of thermal comfort properties on single jersey, plated and bi-layer knitted fabrics using ANOVA multivariate analysis

In this section, one-way ANOVA is analysed, with a selected value of significance for all statistical tests in the study of 0.05. The degree of freedom for analysing single jersey and plated structures is 4 & 20, and the $F_{critical}$ is 2.87. The degree of freedom for bi-layer fabric is 5,25, and the $F_{critical}$ is 2.62. The results of ANOVA are listed in ***Table 4***, which analyses the significant difference between the thermal comfort properties of single jersey, plated and bi-layer knitted fabrics. The value of $F_{critical} < F_{actual}$ proves that changes in the surface layer structures and types of fibre between single jersey and plated fabrics show a significant difference with respect to thermal comfort properties. Similarly between the bi-layer structures, $F_{critical} < F_{actual}$ shows that changes in the surface structure and fibre type are highly significant for the above-mentioned thermal comfort properties.

Subjective analysis

From the objective test conducted for all eleven samples, S6, S7, S8, S9, S10 and S11 show better results than other samples, the reason being high air permeability, thermal conductivity and water vapour permeability as well as good absorbency. Thermalcomfort is mainly achieved by the above-mentioned fabric properties. Hence only samples showing better results were taken for the garment making process. After garment production, a questionnaire was prepared and given to the 15 players. The sportswear was given to them before washing and after washing. The average comfort rating of the comfort descriptor before and after washing is shown in ***Figure 2*** and ***Figure 3***, respectively.

Spearman's rank correlation is used to find out the correlation between the responses of players, which can be inferred from ***Table 5***, where the correlation value between before washing and after washing of volleyball sportswear is positive; hence there is the same level of ranking among the 15 players. From the subjective analysis, it can be concluded that S8 is more comfortable to wear while playing volleyball compared to other bi-layer structures.

Conclusion

The research work mainly focuses on the thermal comfort properties of single jersey, plated and bi-layer knitted structures. The air permeability and thermal conductivity of bi-layer fabric with one tuck point are greatly influenced by the thickness of the fabric. The water vapour permeability of the bi-layer fabric increases with a decrease in the thickness and presence of openness in the fabric. The structure of bi-layer fabric has the greatest impact on the water permeability of the knitted fabrics.

Among the different bi-layer knitted fabrics, the wicking characteristics of the bi-layer fabric with one tuck point shows an increasing trend when the stitch density and thickness decrease. It is observed that the moisture absorbency of the bi-layer knitted structure increases with an increase in the stitch density and tightness factor. The drying ability of bi-layer fabric with one tuck point is primarily influenced by the thickness and weight. It has the ability to transfers perspiration from the inner layer of the fabric to the outer layer, and it easily gets evaporated and dried. The primary requirement of volleyball sportswear is the quick transport of perspiration away from the body and to keep the fabric dry as long as possible. This can be achieved by a bi-layer knitted fabric structure made up of polypropylene as the inner layer and modal as the outer layer, recommended as sportswear for volleyball players.

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