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Influence of tuck stitch in wale direction on thermal comfort characteristics of layered knitted fabrics

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Thermo-physiological comfort of the clothing has been studied considering the ability to manage heat and to transfer sensible and insensible perspiration to the environment. Four bi-layer knitted fabrics are developed by changing the tuck stitch placement in four different points on wale, such as tuck on 4th, 8th, 12th and 16th wale with same course. It is observed that the bi-layer knitted fabric with tuck on 12th wale exhibits better air, heat and moisture transfer as compared to those with tuck on 4th, 8th, and 16th wales. The lower thickness and low mass per unit area exhibit better thermal conductivity, air permeability, water vapour permeability, wicking, moisture absorbency, drying rate and moisture management properties. The less number of tuck stitch shows better thermal comfort characteristics considering both objective and wear trial method. The results are discussed with 95% significant level with ANOVA analysis and Friedman one-way analysis of variance.

Keywords: Bi-layer knitted fabric, Micro fibre, Polyester, Sportswear, Thermal comfort, Tuck stitch, Wear trial

1 Introduction

The changes in lifestyle of human, era of population, increase of participation in sports and health consciousness have created tremendous demand for functional sportswear. The human body strives to keep its core temperature at 37°C, and the metabolic heat generation for a person engaged in physical activity is found in the range of 800-1300W. During normal activity, insensible perspiration is evaporated from the body, whereas during strenuous activity, sensible perspiration is evaporated. A heat loss of 2.4 kJ occurs for every gram of water being evaporated. In comfort aspects of clothing, the sweat must be transported away from the human body which is formed as a thin film on the skin's surface, and the transportation of sweat may be in the form of liquid or vapour. Sweat generation can go as high as 2.5L/h and hence the main functional requirement of high active sportswear is sweat absorbing, fast drying and cooling[1-5].

In hot environment or high activity levels, evaporation of sweat becomes a significant factor of body heat loss and fabrics must allow water vapour escape in time to maintain the relative humidity between the skin and the first layer of clothing at about 50% (refs 6,7). Advances in fibre science, yarn, fabric production technologies, and finishing techniques are the contributing factors for developing active sportswear fabrics[8].

The thermo-physiological comfort depends on thermal, moisture and air permeability properties[9]. Fabric knitted with micro-denier polyester yarn is reported to have better moisture vapour transmission, faster heat transfer and cooler feeling at initial touch as compared to spun polyester, polyester/cotton and 100% cotton[4,10]. The comfort properties of single-layered and double-layered fabrics made of lyocell/polyester blended yarns on the face of the fabric and polyester as the skin contact layer was analyzed[11]. The comfort properties of bamboo / micro polyester / lyocell combination fabrics were also studied[12]. Slack structures of 2×2 rib, 1×1 rib, interlock and single jersey knits have higher transfer wicking ratios when compared with their tight structures[13].

Fabric thickness values play an important role in the properties evaluation, such as air permeability and thermal resistance[14-16]. The moisture transfer and quick dry behavior of textiles mainly depend on the capillary capability and moisture absorbency of the fibres[12]. The performance of layered fabrics in thermo-physiological regulation is better than single layer textile structure[17]. Each layer has a distinct function to perform, for

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example the layer next to the skin is to wick away the perspiration rapidly to the outer layer, which absorbs and dissipates it rapidly to the atmosphere by evaporation. On inside, a synthetic material with good moisture transfer properties and good capillary action, e.g. polyester, nylon, acrylic or polypropylene is used, whereas on the outside, a material which is a good absorber of moisture, e.g. cotton, wool, viscose rayon or their blends can be placed[9,18].

Bi-layer knitted fabric with polypropylene (inner-side) and cotton (outer-side) shows the best moisture management properties[19]. Double-layered weft fabrics knitted from cotton or man-made bamboo yarns and synthetic polyamide, polypropylene and polyester threads combination in three different knitting patterns were investigated[20]. Polypropylene/cotton combination gives best moisture management properties followed by polyester/cotton and polyamide/cotton combinations[21]. The effect of yarn linear density on moisture management characteristics of cotton/polypropylene double layer knitted fabric was also investigated[22]. The polyester fabric with interlock jacquard and double face weaves shows better thermal comfort performance according to objective and subjective measurements[23]. The wettability characteristics of polyester, cotton and multilayered polyester/cotton fabrics to manage human perspiration were analyzed[24,25].

In this investigation, the influence of tuck stitch in wale direction on thermal comfort characteristics of bi-layer knitted fabrics has been studied for shuttle badminton sportswear. The effects are studied by changing the tuck stitch position in the wale direction, keeping the tuck stitch same(18 course). The objective and subjective evaluations have been analyzed to find out the suitable fabric for shuttle badminton sportswear.

2 Materials and Methods

2.1 Materials

The four bi-layer knitted fabrics were developed in which inner layer is made-up of micro-fibre polyester (150 denier) and outer layer is made-up of modal yarn (132 denier). Bi-layer knitted fabrics were produced by the variation in placement of tuck stitch on wale, keeping the placement of tuck stitch in course the same (18^{th} course). The yarn to form inner layer was fed into dial needle and that to form outer layer is fed into cylinder needle. S4 bi-layer knitted fabric was developed by placing tuck stitch in every 4^{th} consecutive wale. Similarly, other bi-layer knitted structures S8, S12 and S16 were developed by placing tuck stitch in 8^{th}, 12^{th} and 16^{th} consecutive wale respectively. The tuck stich placement in wale was changed by changing needle order which run in third track of cylinder cam. All the bi-layer knitted samples were produced in circular multi-track rib knitting machine (Kumyong-KILM-72AV) with 68 feeders, 18 gauge, 3168 needles and 28 inch diameter using constant setting values. The cam and needle set out of all developed bi-layer knitted fabrics is shown in Table 1. The entire bi-layer knitted fabrics photograph is shown in Fig 1.

2.2 Testing Methods

The testing of bi-layer knitted fabrics was carried out under standard atmospheric conditions of 65% RH and 27±2 °C. The bi-layer knitted fabrics were measured for their loop length, stitch density, thickness, porosity and areal density. The thermal comfort properties were analyzed and its respective standards are given in Table 2.

2.3 Statistical Analysis

Analysis of variance (ANOVA) tests were used to examine significant difference between the thermal properties of samples. In order to infer whether the parameters were significant or not, p values were examined. If the 'p' value of a parameter is greater than 0.05 ($p>0.05$), the parameter was not significant and should not be investigated. Subjective evaluation for thermal sensation was evaluated using Friedman One-Way

Table 1 — Cam set out of bi-layer knitted fabrics S4

Feeders	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			19	20	21	22	23	24	25	26	27	28	29	30	31		36	
Dial	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-
	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-
Cylinder	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X
	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X
	O	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X

Analysis of Variance by Ranks[26]. It is non-parametric analysis, used to find out the significant difference between the rankings of five subjective judgement scales.

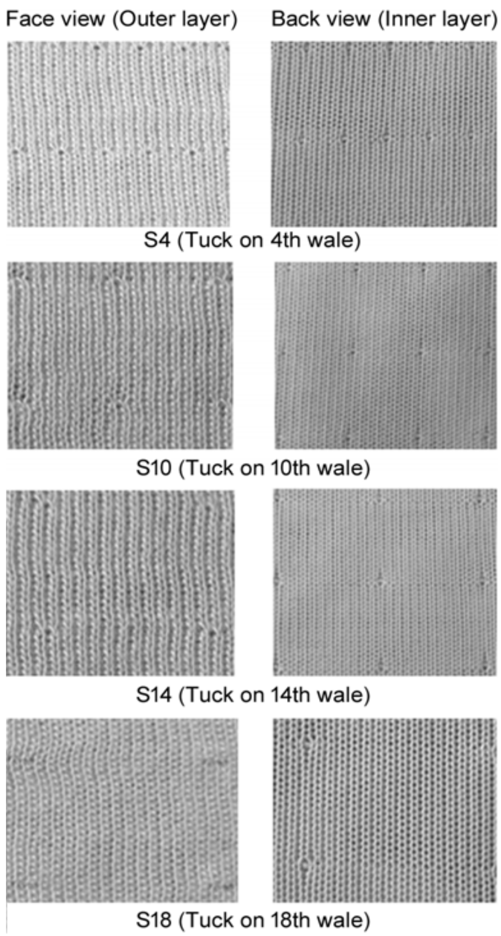

Fig 1 — Photographs of bi-layer knitted fabrics (Inner layer- Microfibre polyester and Outer layer: Modal)

3 Results and Discussion

The physical and thermal comfort properties of four layered knitted fabrics have been measured and are given in Table 3.

3.1 Thermal Conductivity

Table 3 shows that among bi-layer knitted fabrics with 18 course repeat, S12 shows lower Clo value than other fabrics. The reason is lower thickness which entraps less air between the pores of fabric and thereby increases the thermal conductivity[6]. In the next case, consecutively the thermal conductivity is high for S16 followed by S8 and S4 bi-layer fabrics. The amount of volume of dead air in the textile fabrics increases with the increase in thickness of fabric. In S4 bi-layer fabric, the volume of dead air within the structure is high and leads to lower thermal conductivity. The thickness of the fabric contributes to the air entrapment within the bi-layer knitted structure. S12 bi-layer fabric shows higher thermal conductivity, because the thickness of the fabric is lower than other fabrics. The number of tuck loops per repeat is less as tuck loop is present in every 12th consecutive wale. This leads to lower thickness and mass per unit area and higher thermal conductivity. In S16 bi-layer fabric, tuck loop is present at every 16th consecutive wale but the thickness remains same and it shows smaller variation in mass per unit area value. Thermal conductivity is lower than that of S12 fabric, because the tuck frequency beyond 12th wale does not shows marked effect on thermal conductivity. It is important to note that placement of tuck stitch in 4th wale shows lower thermal conductivity than in 8th wale.

The reason is tuck stitch placed in nearby wale leads to closer construction of bi-layer fabric and

Table 2 — Testing properties and its standards

Property	Instrument	Standards
Stich density	-	ASTM D 3887: 1996 (RA 2004)
Thickness	-	ASTM D1777-96
Fabric areal density	-	ASTM D3776
Air permeability	KES–F8 AP1 Air Permeability Tester	BS 5636 1990
Thermal conductivity	TF 130 Flat plate thermal conductivity tester	ASTM D1518
Water vapour permeability	Shirley water vapour permeability tester	BS 7209:1990[31]
Vertical wicking	Vertical suspension	BS 3424
Transverse wicking	-	AATCC 198-2011
Moisture management properties	Moisture management tester	AATCC Test Method 195
Subjective evaluation by wear trial method	Ergonomics of thermal environment — Assessment of influence of thermal environment using subjective judgment scales	ISO 10551 (1995)

Table 3 — Physical and thermal comfort properties of bi-layer knitted fabrics

Property	S4	S8	S12	S16
Physical properties				
Stitch density, loops/cm^2	240	220	197	189
Weight, g/m^2	202	195	182	185
Thickness, mm	0.66	0.63	0.58	0.58
Loop length, cm	0.30	0.30	0.30	0.30
Porosity, %	75.75	77.85	80.12	78.75
Tightness factor	12.6	12.6	12.6	12.6
Thermal comfort properties				
Air permeability, cm^3/s/cm^2				
Dry	241.38	269.59	423.64	372.31
Wet	158.89	176.23	276.37	245.23
Thermal insulation, Clo	0.26	0.18	0.08	0.11
Water vapour permeability, g/m^2/day	1459.90	1530.43	1745.59	1709.11
Vertical wicking (30 min)				
Wale-wise, cm	14.1	15.2	17.3	15.9
Course-wise, cm	12.4	13.0	16.8	15.1
Transverse wicking, mm^2/s	6.1	6.9	9.2	7.8
Moisture absorbency, %	277.17	268.16	251.89	261.17
Drying rate, g/h/m^2	36	47	71.4	62

increases the thickness and stitch density of the fabric. Greater space between the tuck stitch in the consecutive wale leads to higher the thermal conductivity of fabric. But among S12 and S16 fabrics, S12 shows good thermal conductivity than S16. The reason is, tuck placement after 12th wale leads to structure with lower slacke and lower thermal conductivity. The significant difference was found between the bi-layer knitted fabrics using one-way ANOVA (F_{actual} = 165.2641 in comparison with $F_{critical}$=3.24) at degree of freedom 3 & 16.

3.2 Air Permeability

Air permeability is one of the most important properties of knitted fabrics for sportswear application[25]. Table 3 shows that S12 fabric has higher air permeability value in both dry and wet states than S16, S8 and S4. The reason is, thickness and mass per unit area of S12 is found lower than other bi-layer knitted fabrics. The decrease in number of loops per unit area also increases the free flow of air from inner to outer layer of fabric. The tuck stitch is placed in every 12th wale, and because of this the force exerted on loops is less and the fabric seems slacker than S4, S8 and S16 bi-layer fabrics. This causes decrease in stitch density and thickness and increase in air permeability of fabric. In S4 fabric, tuck stitch is placed in every 4th consecutive wale and the fabric seems tighter. The placement of tuck stitch in nearby wale pulls the wale together and increases the thickness and mass per unit area. The porosity of the bi-layer fabric is also lower than other fabrics. In the S8 fabric, the distance between the tuck stitches is twice than that of S4 bi-layer fabric, thereby decreasing the stitch density and increasing the porosity of bi-layer knitted fabric. Hence, the air permeability of S8 fabric is higher than that of S4 bi-layer knitted fabric.

When the tuck stitch is placed in every 16th consecutive wale, the fabric becomes tighter than S12 bi-layer fabric. The distance between two tuck stitches in S16 is higher than in S12 and it causes lower air permeability than in S12 and higher air permeability than S4 and S8 bi-layer knitted fabrics. S12 and S16 bi-layer fabrics can be used for sportswear because of higher air permeability in dry and wet state. The significant difference is found between the air permeability of bi-layer knitted fabrics in both wet and dry state using one-way ANOVA (Dry: F_{actual} = 9196.523 in comparison with $F_{critical}$=3.24; Wet: F_{actual} = 3381.876 in comparison with $F_{critical}$=3.24) at degree of freedom 3 &16.

3.3 Water Vapour Permeability

Water vapour permeability is one of the important properties of thermal comfort that determines the capability of transporting perspiration through a textile material. Table 3 shows that the S12 fabric has higher water vapour permeability followed by S16, S8 and S4 bi-layer knitted fabrics. Moisture vapour transmission through S12 bi-layer knitted fabric is predominantly controlled by the geometric properties such as thickness and porosity[27]. Here, the thickness plays a vital role, because this ensures the distance through which the liquid moisture has to move from inner layer to outer layer. The distance between successive tuck stitch in S12 is higher than in S4 and S8 bi-layer knitted fabrics, thereby exhibiting lowest thickness and stitch density. This is because, the force exerted on loops will be less due to less number of tuck points in S12 bi-layer knitted fabric. The structures of S12 and S16 are slacker than S4 and S8 which is a compact structure. The reason is, with the same course repeat the distance between successive tuck stitches is high which seems unfastened, whereas in S4 bi-layer fabric, the distance between the successive tuck stitch is less and the fabric becomes tighter. This leads to higher thickness and mass per unit area and lower water vapour permeability. In S8 bi-layer knitted fabric, the number of tuck stitch per unit area is lower than in S4 bi-layer fabric. The S8 fabric seems less compact and hence shows higher water vapour permeability than S4 fabric.

The S16 bi-layer fabric shows lower water vapour permeability than S12 and higher water vapour permeability than S4 and S8 bi-layer fabrics. The reason is, distance between successive tuck stitches beyond 12 wales does not show increasing trend in water vapour permeability. This is because, the force exerted on loops due to tuck stitch is very less. The fabric porosity also plays a vital role which is lower for S4 fabric. ANOVA results show that there is a significant difference among bi-layer knitted fabrics [F_{actual}= 1550.915> $F_{critical}$=3.24 ($p<0.05$)].

3.4 Wicking

Vertical Wicking

The wickability of the fabric mainly depends upon the fibre type, yarn regularity, fabric construction and thickness of material[28]. The wicking rate of bi-layer knitted fabric is shown in Fig. 2. The vertical wicking height is increased for all the fabric types for the given period of 30 min. S12 bi-layer fabric shows higher wicking height than other bi-layer fabrics. This is due to its lowest stitch density and thickness followed by S16, S8 and S4 bi-layer knitted fabrics. It is observed that, when the tuck stitch is placed nearby on wales, it decreases the capillary action due to higher thickness and mass per unit area. In S4 bi-layer fabric, the placement of tuck stitch is on every 4th wale and it increases the thickness and mass per unit area. In S12 bi-layer knitted fabric, distance between successive tuck stitches is high and possess lower thickness and mass per unit area.

The vertical wicking in wale-wise direction is higher than in course-wise direction for all bi-layer knitted fabrics. Initially for first 5 min, all the fabrics show equally increasing trend in vertical wicking and after consecutive 5 min till 30 min bi-layer knitted fabrics attain different wicking height in both wale and course directions. The lesser the number of tuck stitch per unit area, the higher will be the vertical wicking for S12 and S16 bi-layer knitted fabrics. Even though with the same course repeat of 18, the placement of tuck stitch in different positions on wale has greatest influence on geometrical properties of bi-layer knitted fabric. The vertical wicking value of bi-layer knitted fabrics has significant difference between the structures (F_{actual}= 359.6768 > $F_{critical}$=3.24 in wale-wise; and F_{actual}= 1140.396 > $F_{critical}$=3.24 in course-wise).

Transverse Wicking

Table 3 shows that the transverse wicking is higher for the structure with tuck on 12th wale and 18 course

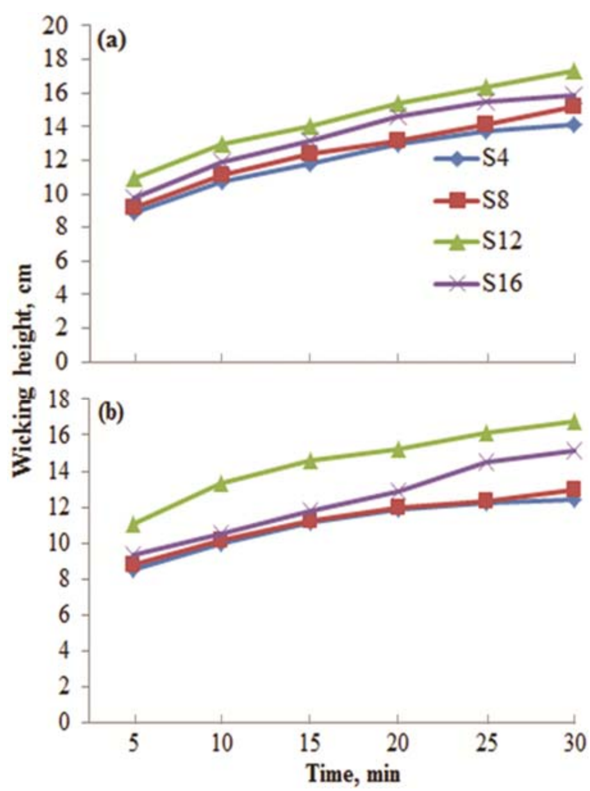

Fig. 2 — Vertical wicking in (a) wale and (b) course directions of bi-layer knitted fabric

repeat (S12). This is due to the fact that lower thickness of fabric provides more space to accommodate water, which leads to more water transfer when the capillary pressure is large enough to activate wicking[29]. Next to that, S16 exhibits good wicking rate followed by S8 and S4 bi-layer knitted fabrics. With the same course repeat and changes in tuck stitch placement on wale, there is difference in wicking rate. S4 bi-layer knitted fabric shows lower wicking rate than other fabrics due to higher thickness and mass per unit area. Comparatively higher thickness and stitch density of S8 fabric shows good wicking rate than S4 bi-layer knitted fabric. S16 shows lowest wicking rate than S12. This may be due to the fact that the placement of tuck stitch in beyond 12th wale decreases the wicking rate.

The closer the tuck stitch in wale, the higher is the thickness and mass per unit area. But in case of S16 bi-layer knitted fabric, it shows decreasing trend in wicking rate compared to that in case of S12 bi-layer fabric. This is due to the fact that the force exerted on tuck stitch is very less than in S12 fabric. The tuck stitch present in the structure pulls the wale together and causes higher thickness and mass per unit area. It is also found that there is a significant difference in between the transverse wicking of bi-layer knitted fabrics [F_{actual}= 348.3951> $F_{critical}$=3.24 ($p<0.05$)].

3.5 Moisture Absorbency

When the sportswear is subjected to heavy sweating conditions, to prevent the wearer from feeling wet and clammy the moisture should be stored in the fabric[30]. Table 3 shows that the moisture absorbency is found high for S4 followed by S8, S16 and S12 bi-layer knitted fabrics. The increase in thickness and mass per unit area increases the moisture absorbency of the bi-layer knitted fabric. S12 fabric shows lowest moisture absorbency due to lower thickness and mass per unit area. With the same course repeat, the decrease in distance between consecutive tuck stitches in wale increases the moisture absorbency of the bi-layer knitted fabric. The more number of tuck stitches per unit area absorbs more moisture on its surface of bi-layer fabric. The higher number of tuck stitches leads to accumulation of more loops on the fabric structure. This causes higher thickness and mass per unit area. In S4 bi-layer knitted fabric, the accumulation of loops will be higher and hence it absorbs more moisture.

In S8 bi-layer fabric, accumulation of loops is lower than in S4 and hence it absorbs less moisture, whereas in S12 bi-layer knitted fabric, the distance between the successive tuck stitch is high and hence it absorbs less moisture. The lesser the accumulation of tuck stitch, lower will be the thickness and mass per unit area, thereby indicating lower moisture absorbency. Even though the accumulation of tuck stitch for S16 is lower than that for S12, the moisture absorbency of S16 is lower than that of S12. The reason is, the distance between the successive tuck stitch is high and it does not influence the moisture absorbency characteristics of fabric to a greater extent. The moisture absorbency of bi-layer knitted fabrics shows significant difference between them (F_{actual} = 24.801> $F_{critical}$=3.24) at degrees of freedom 3 & 16.

3.6 Drying Behavior

Among four bi-layer knitted fabrics, tuck on 12th wale & 18 course repeat shows good drying rate than tuck on 4th, 8th and 16th wale (Table 3). The reason is that the lower thickness, lower mass per unit area and higher moisture vapour transmission of S12 fabric facilitate faster drying ability. S12 bi-layer knitted fabrics require less time to reach initial dry mass of fabric. The least drying rate is found for S4 bi-layer knitted fabric due to highest thickness and mass per unit area. S8 bi-layer knitted fabric shows good drying ability than S4 fabric due to its lowest thickness and mass per unit area. The reason is that the distance between successive tuck stitch is higher than in S4 bi-layer fabric. It is observed that S16 fabric requires more time to reach initial dry mass than S12 bi-layer fabric. The reason is that the placement of tuck stitches is far away from each other. Therefore, the water vapour transmission and drying ability are lower in S16 fabric than in S12 bi-layer knitted fabric. It can be concluded that the drying ability of bi-layer knitted fabrics is primarily affected by knitted structure parameters and then by mass per unit area and thickness. It is also found that there is a significant difference between the drying ability of bi-layer knitted fabrics [F_{actual}= 1262.57> $F_{critical}$=3.24 ($p<0.05$)].

3.7 Moisture Management Properties

Wetting Time

Wetting time, top and bottom, are respectively the time periods in which the top and bottom surfaces of the tested fabric begin to wet after the commencement of the test[31]. From Table 4, it can be seen that among all bi-layer knitted fabrics, S12 bi-layer fabric has the

Table 4 — Moisture management test results of bi-layer knitted fabrics

Moisture management indices	S4	S8	S12	S16
Wetting time of top surface, s	3.463	3.37	1.685	2.672
Wetting time of bottom surface, s	3.182	3.276	1.527	2.125
Absorption rates on top surfaces, %/s	28.867	26.782	28.127	27.197
Absorption rates on bottom surfaces, %/s	37.71	38.011	41.58	40.356
Maximum wetted radius at top bottom surfaces, mm	20	20	25	20
Maximum wetted radius at bottom surfaces, mm	25	25	25	25
Top surface spreading speed, mm/s	4.021	4.159	6.217	4.111
Bottom surface spreading speed, mm/s	4.312	4.289	6.966	4.222
One-way liquid transport capacity, %	228.271	252.623	348.363	274.607
Overall moisture management capacity	0.647	0.672	0.78	0.7

fastest wetting time in both top and bottom surfaces. S12 bi-layer fabric with tuck stitch on every consecutive 12th wale and 18 course repeat shows that the time period in which the bottom surface of the fabric gets wetted is shorter than the top surface of the fabric. Lower thickness of S12 bi-layer knitted fabric facilitates the shorter wetting time on top and bottom surfaces. This is because the accumulation of tuck stitches in S12 bi-layer fabric is lesser than in S4 and S8, and it quickly transfers water to the bottom surface. It has a good capillary action than other bi-layer knitted fabrics.

On the other hand, in S16 bi-layer fabric longer wetting time is found on top surface while shorter wetting time on bottom surface followed by S8 and S4 bi-layer knitted fabric. S4 bi-layer knitted fabrics has taken longer time to wet on the top and bottom surfaces. This is due to higher thickness and mass per unit area. The presence of more number of tuck stitches and higher thickness value of S4 and S8 shows longer wetting time on top and bottom surface. The result shows that among four bi-layer knitted fabrics, S12 bi-layer knitted fabric will stay dry during the period of physical activity.

Absorption Rates

It can be observed from Table 4 that the top absorption rate is lower than bottom absorption rate for all bi-layer knitted fabrics. In S12 and S16 bi-layer knitted fabrics, the bottom absorption rate is higher than other bi-layer knitted fabrics. This is due to lower stitch density and thickness value of S12 and S16 fabrics. This would quickly act as a capillary channel to transport moisture to the bottom surface. For S4 bi-layer knitted fabric, the thickness and stitch density are high which possess lower bottom absorption rate than other bi-layer knitted fabric. Because of higher thickness, the transfer of water from top to bottom surface would take longer time and thereby reduces the bottom absorption rate[32]. If the sweat is slowly transferred to the bottom surface of fabric, it causes the collection of sweat on the skin surface and affects the performance of wearer, like in the case of S4 and S8 bi-layer knitted fabrics. It can be concluded that S12 and S16 bi-layer knitted fabric transmit the sweat quickly through better capillary action from top surface to bottom surface by diffusion. When a person is engaged in any strenuous physical activity, the generated sweat has to be transferred and absorbed by the bi-layer knitted fabric.

Maximum Wetted Radius

In general, the increase of maximum wetted radius decreases the drying time of the layered knitted fabric. The maximum wetted radius on the top and bottom surface was found high for S12 bi-layer knitted fabric (Table 4). S4, S8 and S16 bi-layer knitted fabrics exhibit lower maximum wetted radius on top surface and higher maximum wetted radius on bottom surface. Therefore, with the same 18 course repeat, the tuck stitch on 4th, 8th and 16th wale exhibits comparatively good maximum wetted radius.

Higher maximum wetted radius on top and bottom surface of S12 fabric indicates the ability of liquid spreading and evaporation over a larger surface area[21]. The reason for maximum wetted radius is lower thickness and mass per unit area. This is due to less number of tuck stitches per unit area as compared to other bi-layer knitted fabrics. The bi-layer knitted fabric with relatively large wetted radius on the top and bottom surface indicates that the liquid can be spreaded from top to bottom surface more quickly. When the sweat is evaporated from the skin surface, the body losses heat and the instant heat loss increases the clammy feel of the wearer. In order to avoid this, the bi-layer knitted structure which has good capillary affect can take the moisture away from the skin surface.

Spreading Speed

Table 4 shows the highest spreading speed for S12 fabric followed by S16, S8 and S4 bi-layer knitted fabrics. This is due to the lower mass per unit area and thickness of S12 bi-layer knitted fabric, and hence less air is entrapped within the fabric. The higher the maximum wetted radius and spreading speed on bottom surface of bi-layer fabric S12, the greater is the evaporation from the bottom layer and lesser is the time taken by fabric to dry. Spreading speed is lower for the bi-layer knitted fabric with more number of tuck stitches per unit area. This is due to the reasons: (i) top and bottom surface of fabric are joined by tuck stitch, (ii) the more number of tuck stitches are used for layer binding, (iii) lower will be the spreading speed and (iv) more time is required to dry the fabric. Because of this, the thickness and mass per unit area are higher for S4 and S8 bi-layer knitted fabrics and they exhibit lower spreading speed than S12 bi-layer fabric. For a sports person, the generated sweat should get transmitted to the environment through the garment worn. This can be achieved by the bi-layer knitted fabric S12 which possesses higher bottom spreading speed. It reduces the drying time of fabric and is one of the most important physiological parameters for sportswear comfort.

Overall Moisture Management Capacity (OMMC)

Table 4 shows the one-way transport capacity (OWTC) and OMMC values of bi-layer knitted fabrics. OWTC and OMMC are higher for S12 bi-layer knitted fabrics owing to higher bottom absorption rate and spreading speed. S12 fabric is classified as moisture management fabric with excellent grade for overall moisture management capacity. This fabric would feel dry next to skin due to low absorption rate of top layer, better evaporation of sweat from bottom layer due to its higher top maximum wetted radius and spreading speed. The geometrical properties such as thickness, mass per unit area and porosity are the governing factors in determining the moisture management properties of bi-layer knitted fabrics.

The geometrical properties are influenced by the number of tuck stitches used for binding the inner layer (next to skin) layer and outer (faces outer environment) layer. The lower moisture management properties are found for S4 bi-layer knitted fabric owing to lower bottom absorption rate, maximum wetted radius and spreading speed. The overall moisture management grade is given in Fig. 3. It is also found that there is a significant difference between the OWTC of bi-layer knitted fabrics [F_{actual}= 1000.785> $F_{critical}$=3.24 ($p<0.05$)]. The OMMC of bi-layer knitted fabrics shows significant difference between them (F_{actual} = 34.904> $F_{critical}$=3.24) at degrees of freedom 3 & 16.

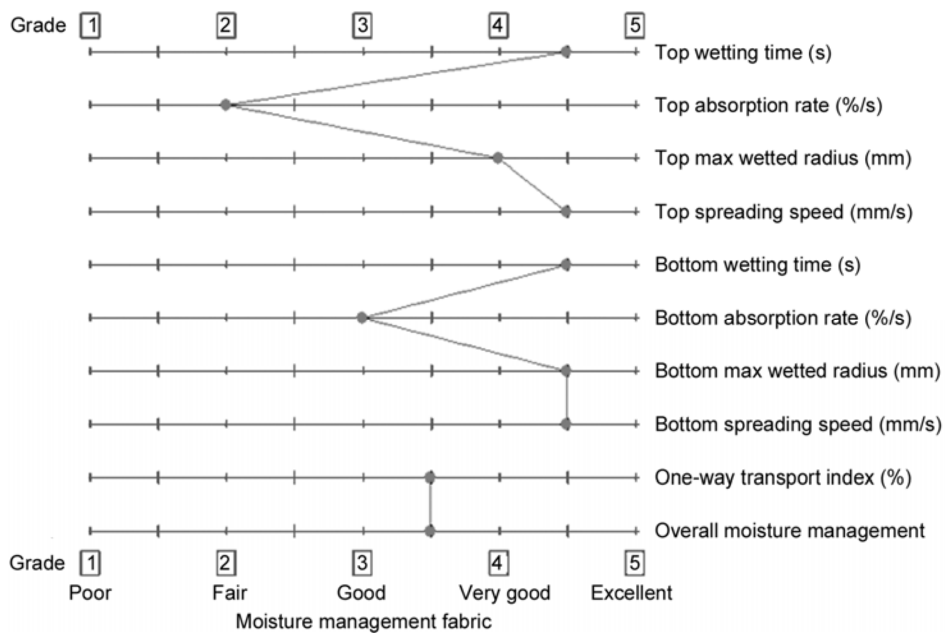

Fig. 3 — Finger print of moisture management properties of S12 bi-layer knitted fabric structure (average)

3.8 Subjective Analysis by Wear Trial

It is found that the bi-layer knitted fabric S12 shows good rating on subjective judgment scales followed by S16, S8 and S4 bi-layer knitted fabrics. The subjective judgment scale consists of five scales for evaluation of thermal comfort such as thermal perception, affective assessment, thermal preference, personal acceptability statement and tolerance. S12 is rated as cool on 9-point thermal perception scale, comfortable on 4-point affective assessment scale, slightly cooler on 7-point thermal preference scale, acceptable on two category statement of personal acceptability and perfectly bearable on personal tolerance scale. Next to that S18 rated as cool on 9-point thermal perception scale, slightly uncomfortable on 4-point affective assessment scale, no change on 7-point thermal preference scale, not acceptable on two category statement of personal acceptability and slightly difficult to bear on personal tolerance scale. Friedman one-way analysis of variance is used to find out the significant difference between the rankings. The selected confidence level is found 95%, the degree of freedom 3 and the F value 7.8. The obtained F value is less than the critical value of chi-square for all five scales, which proves that there is a significant difference in the rankings of bi-layer knitted fabrics.

From both objective and subjective results analysis of thermal comfort characteristics, it can be concluded that S12 bi-layer knitted fabric can be preferred for shuttle badminton sportswear. The coefficient of correlation is obtained between the objective and subjective test results. The subjective judgement scales shows positive correlation with thermal conductivity and moisture absorbency (Tables 5 and 6). All the five subjective scales exhibit negative correlation with air permeability, water vapour permeability, vertical wicking, transverse wicking, moisture absorbency, drying rate and overall moisture management capacity.

Table 5 — Coefficient of correlation between objective and subjective test results of bi-layer knitted fabrics for thermal conductivity

Parameter	Thermal perception	Affective assessment	Thermal preference	Personal acceptability	Personal tolerance	Air permeability		Thermal insulation	Vertical wicking	
						Wet	Dry		Wale-wise	Course-wise
Thermal perception	1.00	-	-	-	-	-	-	-	-	-
Affective assessment	0.88	1.00	-	-	-	-	-	-	-	-
Thermal preference	0.99	0.82	1.00	-	-	-	-	-	-	-
Personal acceptability	0.94	0.90	0.90	1.00	-	-	-	-	-	-
Personal tolerance	0.86	0.85	0.85	0.71	1.00	-	-	-	-	-
Air permeability										
Wet	-0.96	-0.97	-0.93	-0.96	-0.87	1.00	-	-	-	-
Dry	-0.97	-0.97	-0.93	-0.97	-0.86	1.00	1.00	-	-	-
Thermal insulation	0.99	0.88	0.99	0.90	0.92	-0.96	-0.96	1.00	-	-
Vertical wicking										
Wale-wise	-0.93	-0.94	-0.90	-0.84	-0.97	0.96	0.95	-0.96	1.00	-
Course-wise	-0.94	-0.99	-0.89	-0.93	-0.89	0.99	0.99	-0.94	0.97	1.00

Table 6 — Coefficient of correlation between objective and subjective test results of bi-layer knitted fabrics for moisture absorbency

Parameter	Thermal perception	Affective assessment	Thermal preference	Personal acceptability	Personal tolerance	Transverse wicking	Water vapour permeability	Moisture absorbency	Drying behavior	Over all moisture management capacity
Thermal perception	1.00	-	-	-	-	-	-	-	-	-
Affective assessment	0.88	1.00	-	-	-	-	-	-	-	-
Thermal preference	0.99	0.82	1.00	-	-	-	-	-	-	-
Personal acceptability	0.94	0.90	0.90	1.00	-	-	-	-	-	-
Personal tolerance	0.86	0.85	0.85	0.71	1.00	-	-	-	-	-
Transverse wicking	-0.93	-0.97	-0.89	-0.87	-0.95	1.00	-	-	-	-
Water vapour permeability	-0.99	-0.93	-0.97	-0.97	-0.85	0.94	1.00	-	-	-
Moisture absorbency	0.96	0.94	0.93	0.87	0.96	-0.99	-0.96	1.00	-	-
Drying behavior	-0.99	-0.95	-0.96	-0.96	-0.87	0.96	1.00	-0.97	1.00	-
Over all moisture management capacity	-0.85	-0.97	-0.80	-0.81	-0.94	0.99	0.88	-0.96	0.91	1.00

4 Conclusion

The effect of changing tuck stitch in wale direction on thermal comfort characteristics has been studied. The following conclusions are drawn from the study:

4.1 Thermal conductivity of the bi-layer knitted fabric is the function of thickness and mass per unit area. In tuck on 12th wale and 18th course bi-layer fabric, space between the tuck stitches in the consecutive wale leads to higher thermal conductivity. This fabric allows excess heat to dissipate during physical activity and it keeps the wearer dry.

4.2 In dry and wet states, the air flow through the bi-layer knitted fabric is higher for bi-layer knitted fabric with tuck stitch on 12th wale and lower for bi-layer knitted fabric with tuck stitch on 4th wale. The placement of tuck stitch has a significant effect on air passage through the bi-layer fabric with the same course repeat while playing shuttle badminton.

4.3 Water vapour transmission and moisture management capacity through the bi-layer knitted fabrics is predominantly controlled by the thickness and porosity. Water vapour permeability is high for bi-layer knitted fabric with tuck stitch on 12th wale than other fabrics which results in high fabric breathability for shuttle badminton sportspersons.

4.4 With the same course repeat, among four bi-layer knitted fabrics, tuck on 12th wale shows good drying rate than tuck on 16th, 8th and 4th wale. The reason is, lower thickness and mass per unit area of fabric facilitate faster drying ability while playing shuttle badminton.

4.5 Shuttle badminton players by wear trial method rate the bi-layer knitted fabric with tuck on 12th wale and 18th course as comfortable to wear on subjective judgement scale. Both objective and subjective test results show that the bi-layer knitted fabric with tuck on 12th and 18th wale exhibit good thermal comfort characteristics and can be preferred for shuttle badminton sportswear.

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