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

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The thermal comfort characteristics of bi-layer knitted fabrics have been studied for shuttle badminton sportswear. Bi-layer knitted fabrics are developed by changing tuck position in course direction such as 6, 10, 14 and 18 course repeat, keeping the tuck on 12th wale the same. It is observed that the greater the distance between successive tuck points, the better will be the air, heat and moisture transfer properties. Bi-layer knitted fabric with slack structure facilitates lower thickness and mass per unit area, and exhibits better thermal comfort characteristics. By wear trial method, bi-layer knitted fabric with tuck on 18th course and 12th wale shows good rating compared to other bi-layer knitted fabrics. The results are discussed at 95% significant level with ANOVA analysis and Friedman one-way analysis of variance.

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

1 Introduction

The important quality decisive factor that affects performance, efficiency and well-being of sportswear is the wear comfort. As a result, few fibres and fabrics are emerging out for satisfying the stringent needs, and the developments are being made mainly in the areas of comfort and aesthetic acceptability. When the body temperature rises above 37^{0}C due to strenuous activity, the excess heat is liberated to the outer environment by means of heat loss mechanism process (radiation, convection, conduction and evaporation)[1]. In active participation of sports or exercise, the body liberates heat ranges between 100W at rest period and 1000W during strenuous activity[2,3]. In such environment, garment worn should not impede the perspiration to evaporate and therefore clothing plays a major role in permeable to air, [illegible] environment is achieved through a dry flux such as conduction, convection and radiation, and a latent flux is produced by perspiration. The dry flux depends on the thermal insulation property of the garment worn, while the latent flux depends on the garment moisture transport properties[4-6]. Comfort in fabrics is related to three main factors, namely thermo-physiological, sensorial and physiological[7,8]. Thermo-physiological comfort is a general expression of factors such as the thermal properties, water vapour transmission, sweat absorption and drying ability of fabrics[9,10]. The heat and moisture transmission behaviour of a clothing assembly plays a very important role in influencing its efficiency with respect to both thermo-physiological and sensorial body comfort[11,12]. The moisture management properties of a fabric are critical to wearer's comfort, especially for sportswear and protective garments in which intensive physical activities occur[13-15]. Many studies have focused on layered knitted structures to achieve high level of comfort[16-18]. The performance of layered fabric in thermo-physiological regulation is better than single layer textile structure[19-22].

A simple double-face construction is preferred, in which the inner layer is made of a synthetic filament yarn that is hydrophobic and has a good capillary action; the outer layer is made from a hydrophilic [illegible]oisture and allows it to evaporate[illegible]. Cellulosic fibres like cotton and viscose absorb moisture easily and retain the moisture, thus making liquid transportation difficult[24]. Hydrophilic fibres like viscose can absorb liquids into the fibre structure thus preventing the spread of liquids, including sweat, along the fabrics[25]. 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[26,27].

The moisture management properties of the fabrics were analyzed by using different types of yarns in

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the inner and outer layer of multilayered fabrics[15]. A textile material with asymmetric wettability was also developed by fabricating one surface of fabric to be hydrophobic and the opposite surface to be hydrophilic[28]. The moisture content of one layer is not only dependent on its own material properties but also on the material properties of neighbouring layer[21]. Two layer fabrics made up of 30% tencel and 70% polyester in the outer layer give better moisture compared to 100% polyester. Fabric knitted with polypropylene filament on the inner side and facing the skin can be preferred for summer, active and sportswear when combined with viscose and cotton on the outer side of fabric[29]. Combinations of polyester with thermo-regulating viscose Outlast gives better wicking ability but poor drying capability[30]. Blending wool with polyester or wool with bamboo has improved moisture management properties of the fabrics in comparison to 100% wool and 100% bamboo fabrics[31]. Moisture management properties of wool/polyester and wool/bamboo viscose blended fabrics has better moisture management properties than 100% wool and 100% bamboo fabrics[32,33].

The aim of this investigation is to study the effect of placement of tuck stitch in course direction on thermal comfort characteristics of sportswear. Four bi-layer knitted structures were developed with micro-fibre polyester as inner layer and modal as outer layer. From objective evaluation and wear trial assessment of bi-layer knitted fabrics, the suitable bi-layer fabric with tuck position in course has been suggested for 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 with the variation in placement of tuck stitch on course. The fabrics were developed in circular weft knitting machine having the specifications circular multi-track rib knitting machine (Kemyoung-KILM-72AV) with 68 feeders, 18 gauge, 3168 needles and 28 inch diameter.

The yarn fed into the dial needle forms inner layer and the yarn fed into the cylinder needle forms outer layer. Micro-fibre polyester yarn is fed into the dial needle and the modal yarn is fed into the cylinder needle. Here the dial needle knit on all odd feeders, cylinder needles knit on all even feeders and the cylinder needle tuck on odd feeders such as 13th, 21th, 29th and 37th feeders produce four different bi-layer knitted structures. For all the developed samples, tuck cam was placed in 1st feeder and with respect to course repeat, tuck cam was placed in next consecutive feeders.

Bi-layer knitted fabric with 6 course repeat was developed by the placement of tuck stitch in every 12th wale and consecutive 6th course. Dial needles knit on all odd feeders and cylinder needles knit on all even feeders. Cylinder needles tuck on odd feeders such as 1, 13, 25, 37, 49 and 51. Ten course repeat bi-layer knitted fabric structure was developed by placing tuck cam in third track of cylinder in 1st, 21st and the selective odd feeders. Bi-layer knitted fabric with 14 course repeat was developed by placing tuck cam in third cam track of 1st, 29th and the selective odd feeders. 18 course repeat fabric was developed by the placement of tuck stitch in every 12th wale and consecutive 18th course. The placement of tuck cam is taken in third track of 1st, 37th and the selective odd feeders. The cam and needle set out of all developed bi-layer knitted fabrics is shown in Table 1. The entire bi-layer knitted fabrics 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 ^{o}C. The bi-layer knitted fabrics were measured for their loop length, stitch density (ASTM D3887:1996: RA 2004), thickness (ASTM D1777:1996), porosity and areal density (ASTM D3776).

Air permeability, thermal conductivity, water vapour permeability, vertical wicking, transverse wicking, moisture management properties, and subjective evaluation by wear & trial methods were determined using BS 5636:1990, ASTM D1518, BS 7209:1990, BS 3424, AATCC 198-2011, AATCC 195, and ISO 10551:1995 respectively.

2.3 Statistical Analysis

Analysis of variance (ANOVA) tests were used to examine significant difference between the thermal properties of samples. Subjective evaluation for thermal sensation was evaluated using Friedman one-way analysis of variance by ranks[34].

3 Results and Discussion

The physical and thermal comfort properties of four layered knitted fabrics have been measured and the findings are given in Table 2.

Table 1 — Cam set out of bi-layer knitted fabric structure

S6

Feeders	1	2	3	4	5	6	7	8	9	10	11	12
Dial	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
	O	X	-	X	-	X	-	X	-	X	-	X

S10

Feeders	1	2	3	4	5	6	7	8	9	10	11	12	13	14	19	20
Dial	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
	O	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X

S14

Feeders	1	2	3	4	5	6	7	8	9	10	11	12	13	14	27	28
Dial	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
	O	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X

S18

Feeders	1	2	3	4	5	6	7	8	9	10	11	12	13	14	35	36
Dial	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
	O	X	-	X	-	X	-	X	-	X	-	X	-	X	-	X

Needle set out:
Dial needle: ABAB……..
Cylinder needle: ABABABABABAC………
X-Knit; O-Tuck; -Miss

3.1 Thermal Conductivity

The thermal insulation value of bi-layer knitted fabric is given in Table 2. Thermal conductivity is found high for S18 fabric followed by S14, S10 and S6 bi-layer knitted fabrics. With the same fibre type in inner layer (micro-fibre polyester), and outer layer (modal), the entrapped air influences the thermal characteristics of bi-layer knitted fabric. It is observed that the increase in thermal conductivity of S18 bi-layer knitted fabric is due to lower thickness and mass per unit area. The lower the thickness, the lesser will be the entrapped air in the bi-layer knitted structure. S6 possesses lowest thermal conductivity due to higher thickness and mass per unit area. The thickness of the air gap gets increased when more number of tuck stitches are introduced per unit area. The difference in thickness is due to the accumulation of tuck stitch on fabric structure. The air entrapment between the inner and outer layer is found high in S6 as compared to that in other structures. On the other hand, in S18 bi-layer knitted fabric, the inner and outer layers are joined by tuck stitch in every 18th course on 12th wale. The number of tuck stitches is less in S18 as compared to other bi-layer fabrics. This may lead to lesser air gap thickness and entrapment of air, thereby increasing the thermal conductivity or heat transfer through the bi-layer knitted fabric. It is clear that the thermal conductivity of bi-layer knitted fabrics mainly depends on number of tuck stitches, thickness and mass per unit area. The significant difference is found between the bi-layer knitted fabrics using one-way ANOVA (F_{actual} = 277.4902 in comparison with $F_{critical}$=3.24) at degree of freedom 3 & 16.

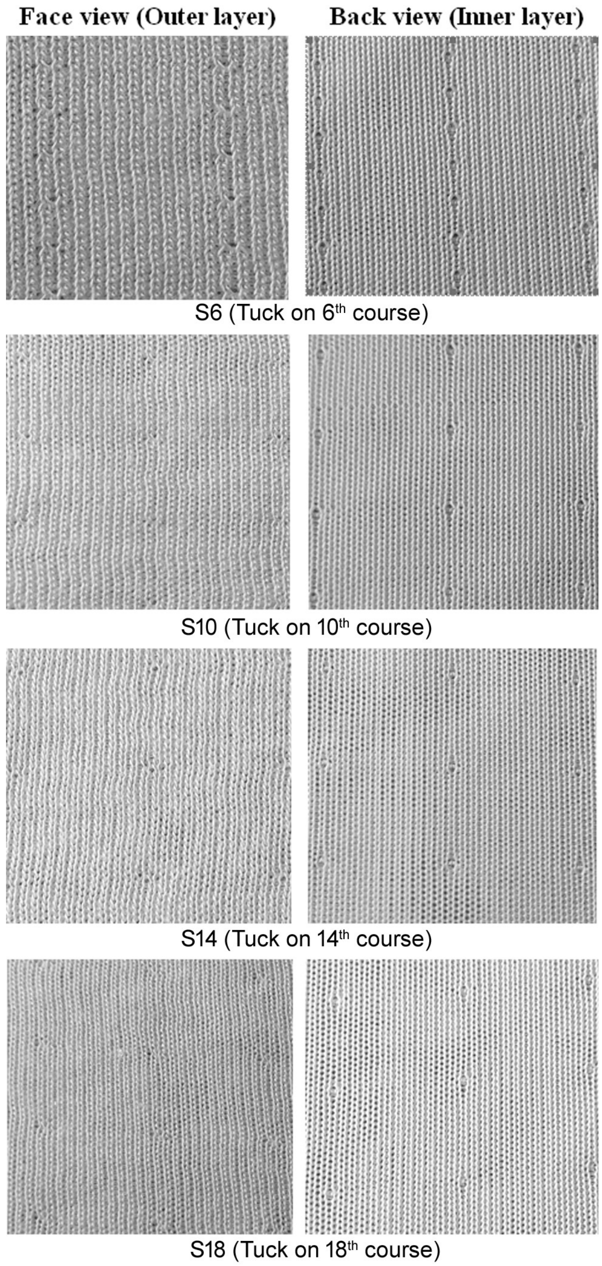

Fig. 1 — Photographs of bi-layer knitted fabric structure (inner layer: microfibre polyester and outer layer: modal)

3.2 Air Permeability

Air permeability is the most important property of knitted fabrics for sportswear application. Table 2 shows that S18 bi-layer knitted fabric possesses greater value of air permeability than S14, S10 and S6 bi-layer fabric. Among bi-layer knitted structures, the decrease in number of loops increases the air permeability of the fabric in both dry and wet state. S18 bi-layer knitted fabric is a 18 course repeat and tuck stitch is introduced for joining of two layers by cylinder needle on odd feeder. This leads to more pores in the structure and the structure seems slacker than other layered fabrics[35]. The lower the thickness and higher porosity of bi-layer knitted fabric, the greater will be the air flow through the fabric. In case of S6 bi-layer knitted fabric, the thickness and mass per unit area are higher than other bi-layer knitted fabrics. It causes lower permeability to air in both dry and wet state. The higher thickness value is due to the presence of tuck stitch per 4 course repeat on 12th wale. It pulls the wales together and the fabric seems less slack than other bi-layer knitted fabrics.

S10 bi-layer knitted fabric exhibits higher permeability to air than S6 and lower permeability to air than S14 and S18 bi-layer knitted fabrics, because the placement of tuck stitch is on every 10th course and 12th wale. Hence, it shows lower thickness than S6 and higher thickness than S14 and S18. It is similar for S14 bi-layer knitted fabric, which possesses higher permeability to air in both dry and wet states than in other bi-layer knitted fabrics except for S18. S18 bi-layer knitted fabric shows higher air permeability both in dry and wet state and provides good ventilation to the micro-climate, and thus making the wearer to feel more comfortable. The significant difference is found between the air permeability of bi-layer knitted fabrics in both wet and dry states using one-way ANOVA (dry– F_{actual} : 10047.87 in comparison with $F_{critical}$=3.24; wet– F_{actual} : 1594.674 in comparison with $F_{critical}$=3.24) at degree of freedom 3 & 16.

3.3 Water Vapour Permeability

The diffusion of vapour molecules through air space in a fabric is a major contributor to total water vapour transport[36]. From Table 2, it is apparent that S18 has higher water vapour permeability than all other bi-layer knitted fabrics. The thickness of S18 is lower than other fabrics and it is a vital feature. It establishes the distance through which moisture vapour pass through from one side of the fabric to the other side. The mass per unit area and porosity are also the contributing factors of water vapour permeability[34]. The structure of bi-layer knitted fabric (S18) is a 18 course repeat with less number of tuck stitch present per unit area. S6 bi-layer knitted fabric is a 6 course repeat with more number of tuck stitches present per unit area as compared to other bi-layer knitted fabrics. The accumulation of more tuck stitches in the structure facilitates higher thickness and mass per unit area.

Table 2 — Physical and thermal comfort properties of bi-layer knitted fabrics

Property	S6	S10	S14	S18
Physical properties				
Stitch density, loops/cm^2	234	225	213	197
Weight, g/m^2	202	196	191	182
Thickness, mm	0.65	0.63	0.61	0.58
Loop length, cm	0.30	0.30	0.30	0.30
Porosity %	74.15	76.4	78.26	80.12
Tightness factor	12.6	12.6	12.6	12.6
Thermal comfort properties				
Air permeability, cm^3/s/cm^2				
dry	253.15	289.65	312.94	423.64
wet	165.55	189.27	205.41	276.37
Thermal insulation, Clo	0.22	0.19	0.1	0.08
Water vapour permeability, g/m^2/day	1474.10	1565.98	1647.38	1745.59
Vertical wicking (30 min), cm				
wale-wise	13.1	14.0	15.5	17.3
course-wise	11.6	12.6	13.2	16.8
Transverse wicking, mm^2/s	6.4	7.3	8.1	9.2
Moisture absorbency, %	290.33	286.38	272.55	251.89
Drying rate, g/h/m^2	38.7	48.6	64.28	71.43

Next to S18 bi-layer knitted fabric, S14 followed by S10 and S6 possess good water vapour permeability. The more number of pores in the structure possesses less air entrapped than the other fabrics and causes good water vapour permeability. As the course repeat decreases, the force exerted on loops will be higher due to tuck stitch in the structure. The bi-layer knitted fabrics become narrower, thickness of bi-layer knitted fabrics gets increased and it reduces water vapour permeability. The increased water vapour permeability of S18 bi-layer knitted fabric results in high fabric breathability. The stage of high physical activity causes increased sweating and the increased permeability of the water vapour provides better comfort to the wearer. ANOVA results show that there is a significant difference between bi-layer knitted fabrics [F_{actual}= 1448.717> $F_{critical}$=3.24 ($p<0.05$)].

3.4 Wicking

Vertical Wicking

Wicking is the spontaneous flow of liquid in a textile material, driven by capillary forces caused by wetting. All the bi-layer knitted fabrics show increasing trend in vertical wicking height for first 5 min. Figure 2 shows that vertical wicking height is higher for S18 followed by S14, S10 and S6 bi-layer knitted fabrics. The initial rate of water take-up in vertical wicking is higher for fabrics with less number of tuck stitch per unit area. S18 bi-layer knitted fabric with lower stitch density and thickness shows higher amount of water take-up compared to other bi-layer fabrics. The fabric characteristics and structure are the determining factors of the amount of water take-up.

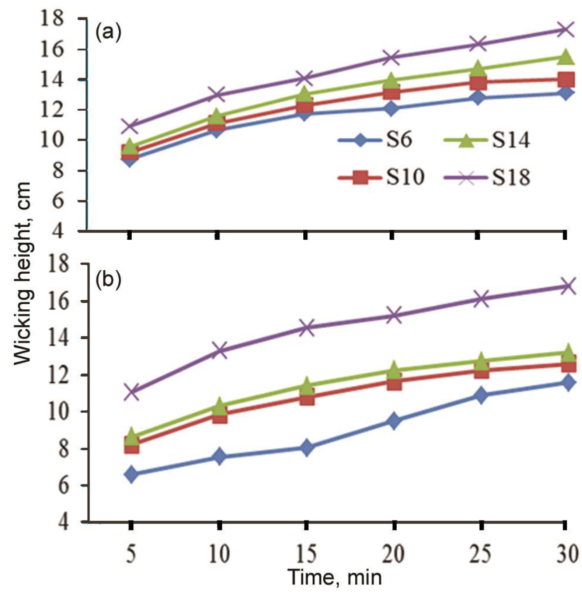

Fig. 2 — Vertical wicking in (a) wale and (b) course directions of bi-layer knitted fabric

S6 shows lowest wicking height than other fabrics, because the thickness and mass per unit area are higher than other fabrics. The presence of tuck stitch in the structure restricts the capillary action in both wale-wise and course-wise. This is due to accumulation of more tuck stitch per unit area in S6 fabric. S10 bi-layer knitted fabric shows higher wicking height in wale and course than S6 and lower wicking height than S14 and S18 bi-layer fabrics. The reason is placement of tuck stitch on every 12th wale on 10 course repeat and the fabric becomes slacker than S6 and tighter than S14 and S18. S18 bi-layer knitted structure with good capillary action will transfer the sweat generated during strenuous physical activity through the inner layer to outer layer. The vertical wicking value of bi-layer knitted fabrics has significant difference between the structures [F_{actual}= 778.9333> $F_{critical}$=3.24 in wale-wise; F_{actual}= 756.4571> $F_{critical}$=3.24 in course-wise].

Transverse Wicking

Analysis of transverse wicking characteristics of bi-layer knitted fabric is more important than vertical wicking because perspiration transfer from the skin involves its movement through the lateral direction of fabric. Table 2 shows that the wickability is more for S18 followed by S14, S10 and S6 bi-layer fabrics. S18 fabric due to lesser accumulation of tuck stitch on its surface shows increase in the spreading rate in both wale–wise and course–wise manner. In S6 bi-layer fabric, the accumulation of tuck stitches is more and thereby the spreading of moisture in wale and course direction is less. The lesser the course repeat of bi-layer knitted fabric, the lower will be the wicking rate in bi-layer knitted fabric. When a liquid is dropped on the surface of bi-layer fabric, the tuck stitch absorbs the moisture rather than spreading it. However, in S10 bi-layer fabric, the accumulation of tuck stitches is lower than in S4 but higher than in S14 and S18. This causes high and low wicking rate than S6 and other two (S14 and S18) bi-layer knitted fabrics respectively. S14 also exhibits the same characteristics. The increase in number of tuck points increases the thickness and mass per unit area of fabric. If the capillary pressure is high, the thickness of fabric provides more space to accommodate water, which leads to more transfer of water. It is also found that there is a significant difference in between the transverse wicking of bi-layer knitted fabrics [F_{actual}= 299.6275> $F_{critical}$=3.24 ($p<0.05$)].

3.5 Moisture Absorbency

Table 2 shows that the moisture absorbency is high for S6 bi-layer knitted fabric due to more number of tuck stitches per unit area in the fabric structure. Next to that, maximum absorbency is found in S10 followed by S14 and S18 bi-layer knitted fabrics. The thickness and mass per unit area are higher for S6 fabric and hence it absorbs more percentage of moisture than its dry weight. S18 fabric shows lowest moisture absorbency due to lower thickness and mass per unit area.

The accumulation of tuck stitch at a particular place absorbs more moisture as tuck stitch is placed above the head of knit stitch. This facilitates higher thickness and mass per unit area. The lesser number of tuck stitch reduces the force exerted on loops and the fabric seems slacker. The thickness and mass per unit area is also lower. It can be concluded that lesser course repeat with tuck stitch on 12th wale exhibits good moisture absorbency. The higher the thickness of bi-layer knitted fabric the greater will be the moisture absorbency of bi-layer knitted fabric. The moisture absorbency of bi-layer knitted fabrics shows significant difference between them (F_{actual} = 59.67476> $F_{critical}$=3.24) at degrees of freedom 3 &16.

3.6 Drying Behavior

It can be inferred from Table 2 that bi-layer knitted fabric with 18 course repeat possesses good drying rate than 14, 10, 6 course repeat bi-layer knitted fabrics. This is due to variation in placement of tuck stitch per unit area. Being with the tuck stitch on same wale, the changes in course repeat influences the drying ability of bi-layer fabrics. The lower thickness and mass per unit area is found for S18 bi-layer knitted fabric. Hence, these properties facilitate quick drying capability of bi-layer knitted fabric. In the next case, S6 bi-layer knitted fabric exhibits lower drying rate than other fabrics. This is due to highest thickness and mass per unit area[37]. The increase of number of tuck stitches in the bi-layer knitted structure increases the force exerted on loops and becomes less slack. S6 bi-layer knitted fabric requires more time to reach initial dry mass than other bi-layer knitted fabrics. On the other hand, S18 bi-layer knitted fabric requires less time to reach initial dry mass due to its good drying rate. The fabric structure and geometrical properties of bi-layer knitted fabrics greatly influences the drying ability of fabric. It is also found that there is a significant difference between the drying ability of bi-layer knitted fabrics [F_{actual}= 619.695> $F_{critical}$=3.24 ($p<0.05$)].

3.7 Moisture Management Properties

Wetting Time

It can be observed from Table 3 that the wetting time of the bi-layer knitted fabric is different for each type of fabric. The top wetting time is higher than bottom wetting time for all bi-layer knitted fabrics. When the liquid drops on the top surface of the bi-layer knitted fabric, S18 fabric followed by S14, S10 and S6 bi-layer knitted fabrics require less time to wet on the top surface. S18 bi-layer knitted fabric wet on top surface quickly and immediately it gets wet in the bottom surface. This

Table 3 — Moisture management test results of bi-layer knitted fabrics

Parameter	S6	S10	S14	S18
Wetting time, s				
top surface	3.931	3.557	2.808	1.685
bottom surface	3.369	3.37	2.714	1.527
Absorption rates, %/s				
top surface	27.43	27.312	24.595	28.127
bottom surface	36.085	38.509	39.81	41.58
Maximum wetted radius, mm				
top surface	20	20	20	25
bottom surface	25	25	20	25
Spreading speed, mm/s				
top surface	4.327	4.118	3.687	6.217
bottom surface	4.462	4.347	3.829	6.966
One-way liquid transport capacity, %	226.009	238.025	260.361	348.363
Overall moisture management capacity	0.629	0.649	0.652	0.78

is due to the presence of less accumulation of tuck stitch, which transfers liquid to the bottom surface. S6 bi-layer knitted fabric requires longer time to wet on top and bottom surface than other bi-layer knitted fabrics. When the liquid drops on the top surface of S6 bi-layer knitted fabric, it requires more time to wet on the top surface due to the presence of tuck stitch which absorbs moisture and takes longer time to wet on bottom surface. Here, the thickness and mass per unit area plays a major role. The lower the thickness and mass per unit area, the shorter is the time taken to wet top and bottom surface. The liquid can easily transfer to the bottom surface of S18 fabric because of decrease in fabric thickness and mass per unit area.

In general, sitting, standing or normal walking (at about 4 km/h), produce metabolic heat production of approximately 90, 165 or 280W respectively[11,38], and this will be increased to values of 1000W or more by activities such as running or biking. It is very important for sportswear to dissipate body heat and to transfer water vapour to the outer environment. This can be achieved by S18 bi-layer knitted fabric in which top and bottom wetting time is faster than other bi-layer knitted fabrics and will stay dry soon.

Absorption Rates

It is clearly shown in Table 3 that the top absorption rate is lower than bottom absorption rate for all bi-layer knitted fabrics. The bottom absorption rate is higher for S18 followed by S14, S10 and S6 bi-layer knitted fabric. In S18 fabric the top absorption of liquid is less but the bottom surface absorbs more moisture than top surface. When the sweat is generated from the human body, it is transferred or less absorbed by the top surface and more absorbed by the bottom surface. In the case of S6 bi-layer knitted fabric, when the sweat is released from the micro-climate it is less transferred by the top surface and it is absorbed less by the bottom surface than S18 fabric.

The higher thickness of S6 bi-layer knitted fabrics reduces moisture transfer to the bottom surface and shows less absorption by bottom surface. S10 and S14 bi-layer knitted fabrics exhibit same result as in S6 fabric. S18 bi-layer knitted fabric due to lower thickness and mass per unit area, leads to less accumulation of moisture in the micro-climate and the wearer will stay dry in the time period of action. Comparatively in S6 bi-layer knitted fabric, sweat is not quickly transferred to the bottom of the fabric as it causes accumulation of moisture in the micro-climate and thus causes discomfort to the wearer than other bi-layer knitted fabrics.

Maximum Wetted Radius (MWR)

It is observed from Table 3 that S18 bi-layer knitted fabric has the maximum top and bottom wetting radius than other bi-layer knitted fabric. Here the test liquid is not absorbed by the fibres because of micro-fibre polyester yarn and it is transferred easily to the bottom surface through the capillary force of micro-fibre polyester. The bi-layer knitted fabric with lowest thickness shows better MWR. It indicates that the higher the bottom wetted radius of the fabric, the greater will be the evaporation from the bottom layer, and the lesser is the time required by fabric to dry[39,40]. MWR value is comparatively less for S6, S10 and S14 bi-layer knitted fabrics due to the presence of more number of tuck stitches on the surface of fabric, which increases the thickness of fabric. When the human is subjected to kinetic activity, the metabolic heat rate is produced from 3.0 met to 8.7 met[41]. The heat is transferred to the environment by respiration and perspiration. In S18 bi-layer fabric, being the hydrophobic fibre ensembles (micro-fibre polyester), moisture is quickly diffused into the molecular network without chemically attracted by the fibre molecules and finally dissipates to the outer environment[11]. The maximum wetted radius is influenced by thickness, porosity and mass per unit area and these parameters are controlled by placement of tuck stitch in different course repeat.

Spreading Speed

Table 3 shows the top surface spreading speed and bottom surface spreading speed. The highest spreading speed was observed in S18 followed by S14, S10 and S6 bi-layer knitted fabrics. The reason is, more pores in the bi-layer fabric structure results in high porosity and increases the spreading speed. In addition to that, the mass per unit area and thickness of the fabric are found lower and less air is entrapped within the fabric. Maximum wetted radius is influenced by the spreading speed of the bi-layer knitted fabric due to better capillary action[42]. The result shows that, the higher the maximum wetted radius and spreading speed of bi-layer knitted fabrics, the greater will be the evaporation from the bottom layer, and the fabrics will take lesser time to evaporate. S18 bi-layer knitted fabric possesses quick absorbing and fast-drying ability. S6 bi-layer knitted fabric has lower top and bottom spreading speed within all fabric types. In this case, higher thickness and mass per unit area result in lower spreading speed. This shows that the liquid moisture is assembled in the inner layer (layer next to skin) of the fabric and not completely absorbed by the outer layer of bi-layer knitted fabric. It indicates that, the sweat cannot easily diffuse from the next-to-skin surface to opposite side and evaporate into the atmosphere.

Overall Moisture Management Capacity (OMMC)

The overall moisture management capacity is an index to indicate the overall capability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance, namely bottom absorption rate, one-way transport capacity (OWTC), the difference of cumulative moisture content between the two surface of fabric and bottom spreading speed[32]. Table 3 shows the OWTC and OMMC values of all bi-layer knitted fabrics. OWTC and OMMC values are higher for S18 bi-layer knitted fabric owing to higher bottom absorption rate and spreading speed. Next to that, S14 shows lower OWTC and OMMC followed by S10 and S6 because these fabrics possess lower bottom absorption rate and spreading speed. S4 bi-layer knitted fabric shows lowest OWTC and OMMC due to lowest bottom absorption rate and spreading speed. In this type of fabric, sweat is slowly diffused from the next-to-skin surface to the opposite side and will accumulate on the top surface of bi-layer knitted fabric. S18 fabric is classified as excellent grade for overall moisture management capacity. The fabric would dry next to skin due to lower top absorption rate and higher maximum top wetted radius and spreading speed in bottom surface. It is also found that there is a significant difference between the OWTC of bi-layer knitted fabrics [F_{actual}= 1451.348 > $F_{critical}$=3.24 ($p<0.05$)]. The OMMC of bi-layer knitted fabrics shows significant difference between them (F_{actual} = 74.66101> $F_{critical}$=3.24) at degrees of freedom 3 & 16.

3.8 Subjective Analysis by Wear Trial

The subjective wear trial was conducted for all the bi-layer knitted fabrics and the results are shown in Fig. 3. Fifteen subjects were rated for the garment

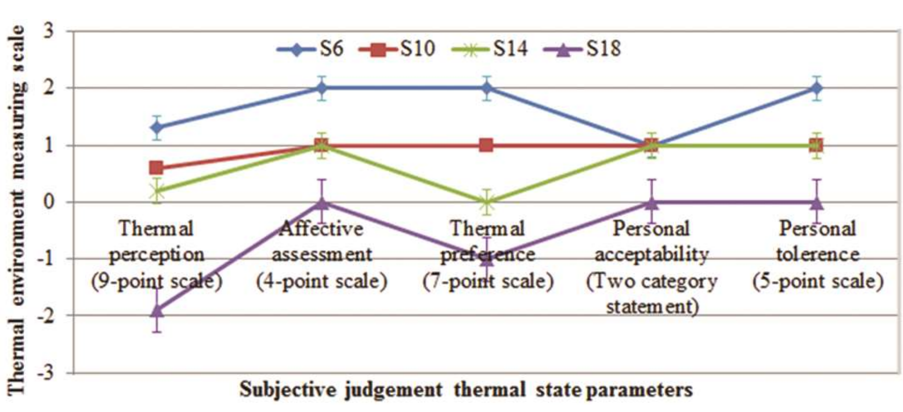

Fig. 3 — Subjective rating on thermal environment judgement scale

worn by them on subjective judgment scales. It is observed that the S18 bi-layer knitted fabric shows good result on thermal environment subjective judgment scale followed by S14, S10 and S6 bi-layer knitted fabrics. It 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.

The least rating is found for S6 bi-layer knitted fabric; neutral 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 by ranks is used to find the significant difference between the bi-layer knitted fabrics on thermal environment using subjective judgment scales. The selected confidence level was 95%, the degree of freedom is 3 and the F value is 7.8. The obtained F value is less than the critical value of chi-square, which proves that there is a significant difference between the rankings of bi-layer knitted fabrics.

From the objective and subjective test results, it is found that bi-layer knitted fabric with tuck on 12th wale and 18th course (S18) exhibits good results. This is due to placement of tuck stitch in the structure and geometric properties of bi-layer knitted fabrics. The co-efficient of correlation (r) is obtained between objective and subjective evaluation. Both positive and negative correlation is obtained between objective and subjective test results. Positive correlation is found between subjective scales and thermal conductivity; and between subjective scales and moisture absorbency. Negative correlation is obtained between other thermal comfort characteristics and subjective judgement scales. The correlation matrix between objective and subjective test results is shown in Tables 4 and 5.

Table 4 — 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	0.98	1.00	-	-	-	-	-	-	-	-
Thermal preference	0.87	0.85	1.00	-	-	-	-	-	-	-
Personal acceptability	0.87	0.82	0.52	1.00	-	-	-	-	-	-
Personal tolerance	0.98	1.00	0.85	0.82	1.00	-	-	-	-	-
Air permeability										
wet	-0.98	-0.95	-0.78	-0.94	-0.95	1.00	-	-	-	-
dry	-0.99	-0.95	-0.78	-0.94	-0.95	1.00	1.00	-	-	-
Thermal insulation	0.91	0.84	0.96	0.66	0.84	-0.85	-0.86	1.00	-	-
Vertical wicking										
wale-wise	-0.99	-0.93	-0.89	-0.84	-0.93	0.97	0.97	-0.96	1.00	-
course-wise	-0.98	-0.94	-0.75	-0.96	-0.94	1.00	1.00	-0.83	0.96	1.00

Table 5 — 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	Transvers wicking	Water vapour permeability	Moisture absorbency	Drying behavior	Over all moisture management capacity
Thermal perception	1.00	-	-	-	-	-	-	-	-	-
Affective assessment	0.98	1.00	-	-	-	-	-	-	-	-
Thermal preference	0.87	0.85	1.00	-	-	-	-	-	-	-
Personal acceptability	0.87	0.82	0.52	1.00	-	-	-	-	-	-
Personal tolerance	0.98	1.00	0.85	0.82	1.00	-	-	-	-	-
Transverse wicking	-0.99	-0.96	-0.92	-0.81	-0.96	1.00	-	-	-	-
Water vapour permeability	-0.99	-0.96	-0.93	-0.79	-0.96	1.00	1.00	-	-	-
Moisture absorbency	0.86	0.90	0.75	0.90	0.90	-0.79	-0.78	1.00	-	-
Dryingbehavior	-0.95	-0.90	-0.97	-0.70	-0.90	0.98	0.99	-0.66	1.00	-
Over all moisture management capacity	-0.93	-0.89	-0.63	-0.99	-0.89	0.88	0.87	-0.93	0.79	1.00

4 Conclusion

In bi-layer knitted fabrics, the changes have been done in placement of tuck stitch in course-wise manner and the results have been analyzed. The following conclusions are drawn from the analysis:

4.1 Thermal conductivity of bi-layer knitted fabric is greatly influenced by thickness and mass per unit area. When playing shuttle badminton, bi-layer knitted fabric with higher course repeat possesses good permeability to air and water than bi-layer fabric with lesser course repeat. The decrease of course repeat increases the force exerted on loops due to the closer placement of tuck stitch per unit area.

4.2 The fabric characteristics and structure of the bi-layer knitted fabrics are the determining factors of the amount of water take-up. Bi-layer knitted fabric with tuck stitch on 6^{th} course and 12^{th} wale shows lowest moisture management property than other fabrics, because the thickness and mass per unit area are higher than other fabrics. The shuttle badminton sports person feels wet and clammy by wearing this bi-layer knitted fabric.

4.3 Among four bi-layer knitted fabrics, 18 course repeat fabric possesses good drying rate. Being with the tuck stitch on same wale, the changes in course repeat influences the drying ability of bi-layer knitted fabrics. This is due to the variation in placement of tuck stitch per unit area.

4.4 On thermal environment subjective judgment scale, bi-layer knitted fabrics with tuck stitch on 18^{th} course are rated as comfortable by shuttle badminton players to wear as compared to other bi-layer knitted fabrics. With the same fibre type in the inner layer (micro-fibre polyester), and outer layer (modal), the placement of tuck stitch in course influences the thermal characteristics of bi-layer knitted fabric suitable for shuttle badminton players.

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