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Evaluation of Surface Characteristics of Fabrics Suitable for Skin Layer of Firefighters' Protective Clothing

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Abstract

Sensorial comfort, usually described as “fabric hand or feel”, is the sensation of how the fabric feels when it is worn next to the skin. This feeling deals with properties of the fabric such as prickling, itching, stiffness or smoothness. It can also be related to its attributes related to physiological comfort, as for instance when a fabric is wet its sensorial properties change and fabric may cling to the skin. Wet feeling and wet clinging can be a major source of sensorial discomfort in situations of profuse sweating like in firefighters' working environment. For the objective evaluation of this aspect of comfort Kawabata Evaluation System (KES) was used for the present study. Seven commercially available knitted fabrics of different fibre blends in different knitted structures suitable for skin layer of firefighters' protective clothing were evaluated in virgin (original non-treated) state and then in wet state. The influence of fabric physical parameters, fibre content, fabric construction and moisture content on fabric surface properties were determined. For statistical evaluation of results student's-test was carried out to predict the level of significance on coefficient of friction (MIU) and geometrical surface roughness (SMD) due to presence of moisture. Pearson correlation coefficients were also calculated between MIU and SMD in virgin state and in wet state.

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1. Introduction

The skin sensorial comfort characterizes the sensations, which a textile causes in direct mechanical contact with skin. These sensations may be pleasant like smoothness or softness, or be unpleasant, if a

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textile is scratchy, too stiff or clinging to a sweat-wetted skin. Textiles with poor skin sensorial wear comfort may even lead to mechanically induced skin irritations when worn next to skin [1].

The most commonly used objective evaluation of this aspect of comfort in fabrics and materials is carried out by the utilisation of four modules of the Kawabata System (KES) for measuring the tensile and shearing characteristics, bending and compression characteristics and the measurement of surface characteristics [2-3]. For the evaluation of sensorial comfort of fabrics and materials the friction between the fabric and the skin and also the fabric surface geometrical roughness are the two important components. LaMotte reported that the sensation of roughness or smoothness is evoked during the contact of fabrics with the skin. From these sensations, people judge the feel and comfort of clothing and tend to select the fabrics or materials acceptable to them in that sense [4]. In general the frictional force is higher for the fabric with rough surface and is lower for the fabric with the smooth surface [5]. The force required to move the fabric along the skin during the fabric-skin contact is opposed by the frictional force created by that contact. When the applied force exceeds the frictional force, movement of fabric against the skin occurs. Frictional characteristics of sliding surfaces are often described by the coefficient of friction which is defined as the ratio of the drag force (parallel to one surface) to the normal force pressing on the contacting surface [6]. The presence of moisture on fabric-skin contact has been found to be positively correlated with the frictional force and thus with the perception of roughness. Moisture at the skin surface can alter the intensity of the perceived fabric roughness: as the moisture content increases, the friction and displacement of the skin increases as well activating more touch receptors. Therefore, a fabric that is perceived to be comfortable under low humidity conditions may be perceived to be uncomfortable under high humidity or sweating conditions [7].

Different studies have been carried out to understand the relationship between fabric physical properties (protruding fibres, fibre and yarn diameters, fabric thickness, stiffness, etc.) and sensorial feelings generated on the skin. Fabric surface characteristics have been reported to be affected by numerous factors such as fabric structure and density, the type of fibre used, fibre blend ratio, and yarn structure. Ajayi studied the effect of fabric structure on fabric friction properties by changing the fabric structure from plain woven fabric to pile fabrics (velveteen and corduroy) and concluded that in case of pile fabrics, the frictional force was approximately double of that of plain weave structures. Also for woven fabrics frictional properties were very similar on both sides of the fabric but for pile fabrics the force on face to face contact was significantly higher than on back to back contact in all pile fabrics [8]. He further studied the effect of yarn surface properties on the fabric hand and concluded that yarn structure and fabric friction are positively correlated: with fabric structure and finishing treatment being constant, yarns with higher coefficient of friction will yield fabrics with the higher coefficient of friction [9].

Later on in another study, Kondo used six different materials: cotton, wool, silk, rayon, polyester and nylon 6 in the study into the relationship of frictional properties between fabrics and human skin. All the experimental fabrics were constructed using plain weave. Cotton and wool fabrics were made of spun yarns and remaining fabrics - with filament yarns. It was found that coefficient of friction (MIU) of spun yarn fabrics were higher than the fabrics made of filament yarns [10]. Further investigation into frictional characteristics of polyester/cotton and polyester/viscose blended fabrics revealed that fabric material compositions have different frictional properties which influence the frictional properties of the resultant fabrics. Fabrics made of spun yarns demonstrated higher fabric-to-fabric friction than continuous filament 100% polyester or 100% viscose fabric-to-fabric friction: in polyester/cotton blended fabrics the frictional force increased with the increase of the cotton fibre component; and in polyester/viscose blended fabrics this occurred with the increase of the viscose fibre component. The difference in the type of fibre, the surface fibre population, and their length distribution and low load-compressible properties of the respective fabrics may cause these differences in the frictional properties of the P/C and P/V blend fabrics [11].

It was also observed that different fabric treatments such as bleaching, dyeing and finishing cause an increase in friction and roughness of cotton knitted fabrics through the increased disturbance in surface fibres as well as fabric surface irregularities [12]. Laundering also affects surface properties of different materials but depends more on fabric structural parameters rather than on laundering temperature [13].

Therefore surface characteristics and physical attributes of the fabric surface are of high importance in the overall aspect of fabric sensorial (tactile) comfort. The objective of the present study is to investigate and compare the surface characteristics of seven knitted fabrics suitable for the skin layers of firefighters' protective clothing. Furthermore, this study examines and evaluates the effects of the fabric composition, construction, its physical structural parameters and presence of moisture on the fabric surface characteristics.

2. Experimental

The physical parameters and surface properties of the selected seven knitted fabrics were tested. The surface properties were tested in virgin state and then also in wet state to determine the effect of moisture on their surface properties.

The resultant data for all the sample fabrics is presented using bar charts having error bars. These bars are indicating standard deviation of the individual fabrics to show variation of surface properties in each sample fabric. Student's-t-test was carried out to predict the level of significance on coefficient of friction (MIU) and (SMD) due to presence of moisture. P – Values in the data table under the bar charts are indicating the level of significance after t-test. The Pearson Coefficients of correlation between the coefficient of friction and surface roughness were also calculated to find the correlation between these two variables for the sample fabrics studied.

3. Materials

Seven commercially available knitted fabrics SJ1-IM2 (Table 1) of different constructions and fiber blends were studied. SJ2 and SJ4 (Table 1) are two fabrics having intimate fiber blending in yarns used and then knitted into the fabrics using single jersey construction. IM2 has yarn blending of 100% wool yarn with 100% Biophyl™ yarn in fabric structure where the face side of the fabric is constructed of Biophyl™ yarn and its back side (used next to skin) is constructed of wool yarn. The back side of the fabric is constructed as “half-needle” interlock which causes slightly ribbed surface topography. To examine the effect of moisture on surface properties, the fabrics were wetted by following a developed procedure: fabric samples were dried to the moisture content of 0% to determine their dry weight and then completely wetted by immersion in water. The excess moisture was then squeezed out by passing the samples one by one through squeezing rollers of the padder mechanism at constant roller pressure twice so that the fabric felt wet but not dripping with moisture before testing. The fabric samples were weighed again to determine the moisture pick up as a percentage of their dry weight (Figure 3). After weighing, each fabric was enclosed in a polyethylene bag to avoid any moisture loss and then tested one by one for surface properties, therefore simulating the condition when fabric is next to the wearer's skin and is saturated with perspiration.

4. Test methods

4.1. Fabric physical parameters

Fabric mass per unit area: five specimens of 100mm×100mm from the fabric samples were prepared and each of the specimens was weighed by measuring balance. The mass per unit area was calculated as the mean mass per unit area [14]. *Fabric thickness* : the thickness of fabric samples was measured as the

distance between the reference plate and parallel presser foot of the thickness tester [15]. *Fabric density*: the number of courses and wales in an accurately measured length of fabric were counted along a line at right angles to the warp or weft direction being considered [16].

4.2. Fabric Surface Properties

The coefficient of friction (MIU) and surface roughness (SMD) are the parameters that characterise the fabric surface properties. MIU and SMD were determined for sample fabrics on their sides that would be in contact with the skin during wear. To measure the fabric surface properties corresponding to the human senses of “Numeri”(smoothness) and “Zaratsuki” (roughness) [2-3] the KESFB4-A, Kato Tech Co.Ltd. Evaluation System was used.

The system acquires data from two sensors measuring the frictional coefficient and the roughness of the fabric surface simultaneously in three different areas within a fabric sample of 20cm x20cm. The frictional coefficient MIU is calculated by averaging the output over the distance between 0 to 20mm using an integrator. The low-cut filter removes the frequency components lower than 1mm/sec assuming that they are the signals that can not be sensed by a human skin. Frictional coefficient is defined as:

$$MIU=F/P \quad (1)$$

where F - frictional force, N

P - sensor load, N

As the sample travels at a speed of 1mm/sec in the same way as in the friction test, the differential transformer detects the up-and-down movement of the contact probe caused by asperity of the fabric surface. The geometrical Surface Roughness Mean deviation (SMD) is the value obtained by eliminating the low frequency harmonic wave by filtering the measurement curve through the low-cut filter, extracting the frequency components higher than 1mm/sec and by integrating over the absolute value of the distance moved from the standard position along the path taken by the sensor. Surface roughness SMD is expressed as follows:

$$SMD=1/L_{max} \int_0^{L_{max}} |Z_0-Z| dL, \quad (2)$$

where L_{max} is the distance travelled by the sensor over the fabric, and Z_0 is the standard sensor position.

The value of the friction coefficient (MIU), and the roughness signal are recorded individually and simultaneously for the “go and return” stroke. Measurements were taken in the wales and courses directions.

All the fabrics were tested on the side which is next to skin during the practical use of the garments.

The evaluation of the fabrics was carried out having particulars that:

- The value of MIU ranges from 0 to 1 and its approaching value of 1 is interpreted as increasing friction and decreasing smoothness.
- The value of SMD ranges between 0 and 20 and as its approaching value of 20 is interpreted as the increase in the surface roughness and surface irregularities.

The standard deviation for MIU and SMD of each individual sample was calculated to demonstrate the variation in their individual surface properties. In addition Student's T-Test was performed to determine whether a statistically significant difference exists between fabrics of different groups being studied.

5. Results

5.1. Physical Attributes and Moisture Pick up %

Physical properties of sample fabrics (Table 1) demonstrate that sample fabric SJ2 is 12% heavier than SJ1 which is most likely due to the higher density of SJ2 being a blend of wool and bamboo fibers where bamboo fiber is comparatively denser than wool. SJ3 has more open structure in comparison to SJ1 and SJ2 due to its different stitch density. Higher thickness and mass/unit area of SJ4 is greater due to blending of wool with continuous filament elastomeric fibers which contributes to the compactness of the finished fabric. IM2 is the heaviest and thickest fabric among all the sample fabrics of this study, and has different wales/courses stitch densities which is all due to the double jersey construction, use of coarser yarns and coarser knitting machine gauge. IM1 has uniform and compact fabric structure due to having equal stitch densities of wales and courses.

Table 1. Physical and structural attributes of sample fabrics

Fabric code	Fibre composition	Construction	Mean fabric mass/unit area [g/m ²]	Mean fabric thickness [mm]	Mean no. of Wales/cm	Mean no. of Courses /cm
SJ1	100% Merino wool	Single Jersey	139	0.35	18	18
SJ2	60% Merino Wool/ 40% Bamboo	Single Jersey	156	0.34	18	18
SJ3	100% Cotton	Single Jersey	149	0.47	16	20
SJ4	94% Merino wool/ 6% Elastane	Single Jersey	185	0.55	18	20
SJ5	100% Bamboo	Single Jersey	185	0.50	22	16
IM1	100% Polyester	Interlock based mock mesh	168	0.61	16	16
IM2	52% Merino wool / 48% Biophyl TM	Interlock based mock mesh, “half-needle back”	216	0.97	12	16

Figure 1 demonstrates that 100% wool (SJ1), different wool blends (SJ2, SJ4 and IM2) and 100% polyester (IM1) fabrics picked up less moisture in comparison to 100% cotton or 100% bamboo fabrics (SJ3, SJ5). SJ2 being a blend of wool and bamboo has higher moisture pick up than SJ1, SJ4 and IM2. This is due to the presence of bamboo fibres in SJ2 which have very higher than wool fibre moisture absorbency similar to other regenerated cellulosic fibres for example viscose rayon.

IM2 has the lowest moisture pick up among all the fabrics indicating that it might not be able take up skin moisture to produce comfortable sensation during high-rate sweating. Blending of wool fibre with BiophylTM could be a possible reason for reduced moisture pick up as BiophylTM being a synthetic fibre has less absorbency than wool. Moisture pick up% of SJ5 is higher than that of all other sample fabrics of the study except for the 100% cotton SJ3, which exhibits its ability to take up more moisture than 100%wool or wool blended samples under the same conditions.

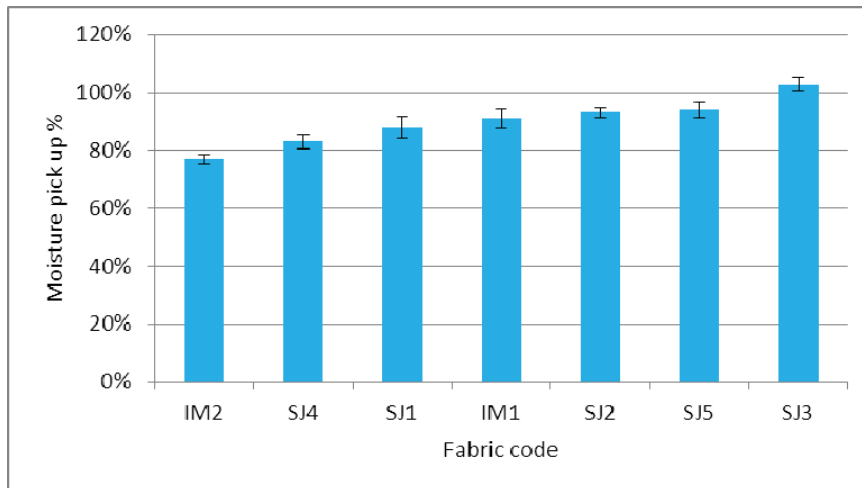


Fig. 1. Moisture pick up % of the sample fabrics

5.2. Surface properties

Fig. 2 and 3 demonstrate the mean values of MIU and SMD of the sample fabrics in virgin state and wet state where the error bars are displaying the standard deviation within each sample fabric. It was observed that significant differences exist, as indicated by the p-values, between the values of coefficients of friction MIU for all fabrics except SJ1 and IM2, and SMD for fabrics SJ1, SJ3 and SJ5 at the 10% level of significance indicating that wetting treatment influenced these characteristics of the fabrics in majority of cases for MIU and in some for SMD.

Blending of wool with bamboo In SJ2 in comparison with SJ1 seems to reduce MIU of the resultant fabric in virgin state. In wet state MIU of SJ2 increased 28% of the virgin state while for SJ1 there is a negligible increase as shown in Fig. 2. It is expected that SJ1 will be providing better sensorial comfort than SJ2 in wet state in terms of friction, which is advantageous in hot conditions. SJ3 has higher MIU than sample fabrics SJ1, SJ2 and SJ4 (Fig. 2). Moisture raised MIU of SJ3 by 50% in comparison to MIU in virgin state and in addition SJ3 has the highest moisture pick up% among all the fabrics of the study. The only difference between sample fabrics SJ1, SJ2 and SJ3 is their fibre composition so it would be right to assume that this parameter is causing the variation in their respective MIU. In virgin state MIU of SJ4 is 17% greater than that of SJ2 but closer to SJ1. Wetness of SJ4 did not significantly affect the MIU which is not the case for SJ2. SJ5 has the highest MIU among all samples of single jersey structures. It could be due to the higher number of available contact points comparing to the surfaces of other fabrics : bamboo fibres are of a plastic nature rather than elastic like wool and polyester fibres, so they would be bent down very easily on contact, and this would increase the area of contact leading to increase in MIU. For samples SJ3 and SJ5 presence of moisture leads to increase in MIU by 48% and 33% respectively in comparison to their virgin state; this could be due to the high moisture pick up% of these samples and also due to the non-elastic nature of these fibres that become even more in-elastic when wet, leading to increased contact area.

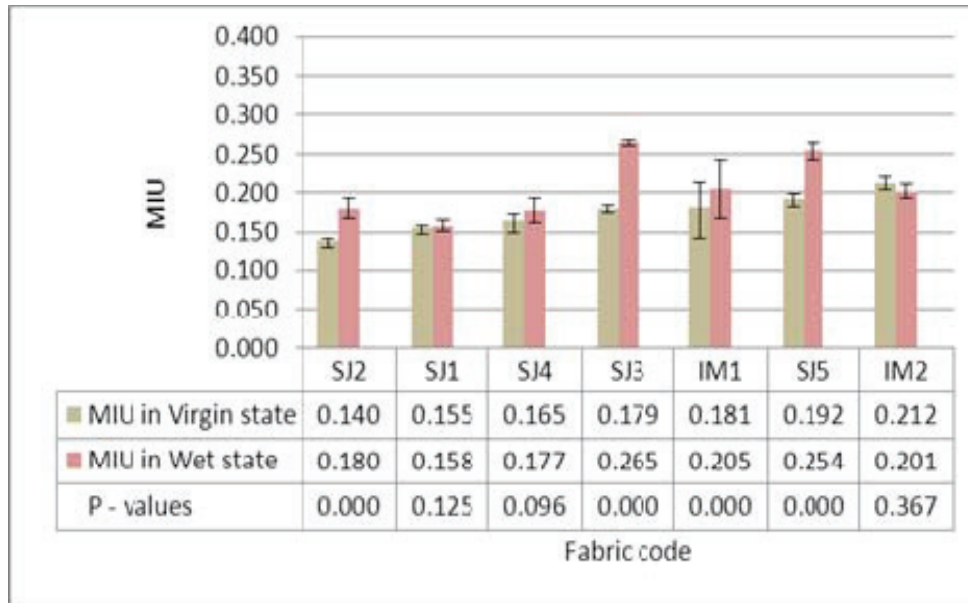


Fig. 2. MIU of sample fabrics in virgin and wet states

IM2 has the highest MIU among all the sample fabrics of the study and is 17% greater than IM1- another double jersey fabric (Fig. 2). IM2 being a yarn, rather than intimate blend of 100% wool yarn with 100% Biophyl™ yarn within the fabric structure, where the face side of the fabric is constructed of Biophyl™ yarn and its back side (used next to skin) is constructed of wool yarn as a “half-needle” interlock which causes slightly ribbed surface topography. Due to this non- uniform surface topography IM2 has an irregular 100% wool next-to-skin surface compare to single jersey fabrics such as for example SJ1. It is possible to conclude that such increased MIU is due to the fabric structure

Sample IM1 has uniform stitch density in wale and course directions which produces homogeneous balanced surface comparing to fabrics with differential stitch density in wale and course directions. Higher MIU of IM1 compared to single jersey structures could be to its double jersey construction. In wet state MIU of IM1 increased slightly while MIU of IM2 slightly dropped, which in addition is statistically non-significant at 10% level of significance. But these two fabrics already have the highest MIU values than the other sample fabrics of the study, and higher MIU values are usually irritating due high frictional force when used next to skin. The standard deviation of MIU for all the sample fabrics in virgin state is in the interval of 0.002 – 0.031 and in wet state it is 0.004 -0 .038.

In virgin state all the single jersey construction (SJ1- SJ5) have lower SMD except for SJ4 only (Fig. 3). IM1 has SMD very close to SJ3 and IM2 has 136% higher SMD than IM1 in virgin state. This is most likely due to the fact that IM1 is constructed with continuous filament yarns and IM2 with spun yarns being on the next-to-skin side and in addition fabric IM2 having a ribbed structure.

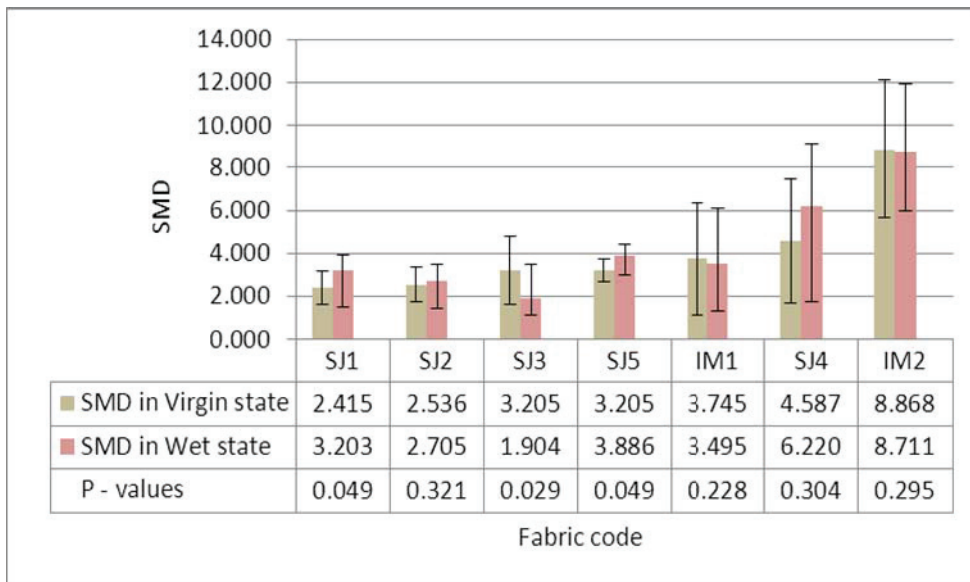


Fig. 3. SMD of sample fabrics in virgin state and wet state

For the sample fabrics SJ4, IM1 and IM2 the roughness pattern is not constant indicating that the height of the irregularities for these fabrics surface are not even and regular. Differences in fabric physical parameters and constructional features (fabric structure) could cause variation in height and magnitude of fabric irregularities. These fabrics have higher variability of results with standard deviations of 2.890, 2.625 and 3.229 respectively within each fabric (Fig. 3). The standard deviation of SMD for all sample fabrics is in virgin state is in the interval of 0.508 – 3.229 and in wet state it is in the interval of 0.764 – 4.445 indicating a high level of variation in roughness pattern of the sample fabrics.

In wet state SMD of SJ1, SJ2, SJ5, IM1 and IM2 increased negligibly. For SJ3 there was a slight decrease. For SJ4, presence of moisture increased SMD by 35 % of the virgin state but is statistically non-significant at 10% level of significance due to very high variation in results. SJ4 and IM2 have higher SMD in virgin state in comparison to the other sample fabrics of the study.

Pearson coefficient of correlation was calculated between MIU and SMD of the sample fabrics. It was 0.747 in virgin state indicating a strong positive linear relationship between two variables for all the sample fabrics. In wet state it was – 0.184 indicating a negative linear relationship between these two variables. This relationship demonstrates that wetness, washing or another applied treatment may change MIU and SMD in a random pattern for the set fabrics in the present study.

6. Discussions and Conclusion

The main objective of the study was to investigate the surface properties of different knitted fabrics suitable for skin layers of firefighters’ protective clothing. For that purpose 100% wool, 100% cotton, 100% polyester and different wool blends were studied in virgin state and then in wet state. From the results it is clear that wool fibre and wool fibre blends can be considered to perform better in terms of

sensorial comfort in single jersey constructions. Wool is an elastic and resilient fibre due to having inherent fibre crimp and its micro-structure with scales compared to bamboo, cotton or polyester. It seems to provide better sensorial comfort due to its resiliency when used next to skin in single jersey structure. Though moisture increased MIU of SJ2 in wet state but it might be possible that SJ2 is quicker in absorbing moisture than SJ1 and helps in keeping skin dry due to blending of wool with bamboo. If it is able to keep skin dry it might be able to provide comfortable sensations when used next to skin in firefighting situation where body sweats heavily in liquid form. For physiological and sensorial comfort moisture pick up% as well as the other moisture management attributes are important but these are beyond the scope of the present study. In case of IM1 it has textured filament yarns which are creating a smoother surface but this could generate a clinging sensation on the skin. Cotton and bamboo (SJ4 and SJ5) having protruding fibre ends with less resilience as compared to wool are not as comfortable as wool or wool blends, especially when fabrics are wetted.

Therefore from the present study it can be concluded that fibre content and fabric structure are the most critical parameters to influence the fabric surface properties relevant to sensorial comfort. This study revealed that single jersey structures are the best to be used next to skin and 100% wool and wool blended with bamboo provides better sensorial comfort as compared to 100% cotton, or 100% polyester.

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