

SINGLE-SIDED JACQUARD KNIT FABRIC DEVELOPMENT AND SEAMLESS SKI UNDERWEAR ZONING DESIGN BASED ON BODY MAPPING SPORTSWEAR

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Abstract:

In order to meet the functional requirements of professional skiers for ski underwear, such as warmth, breathability, moisture absorption, sweat drainage, and stretch elasticity, six single-sided jacquard knit fabric structures were designed and then knitted with polyester and DRYARN. Then, 12 fabrics were acquired and ranked comprehensively by the one-way analysis of variance and grey correlative analysis based on entropy. According to the fabric properties and sweat distribution on the human skin surface, the professional ski underwear was zoning designed and the wearing experiment and evaluation were carried out on the "Newton" sweated manikin system. The analysis results show that the fabric with DRYARN® material has better air permeability and moisture permeability. Thermal resistance, Clo value, and permeability play important roles in comprehensive evaluation. The results of wearing experiment show that the seamless professional ski underwear woven based on body mapping sportswear has superior function and reasonable design, which can provide technical support for the design of professional seamless ski underwear.

Keywords:

Seamless ski underwear, fabric properties, body mapping sportswear, zoning design, grey correlative analysis

1. Introduction

Body mapping sportswear (BMS) refers to the sportswear with mapping design according to the distribution rule of sweat on the surface of human skin [1]. However, the mechanism of sweat secretion of human body is extremely complex and subject to testing conditions. At present, there are still many differences in studies on physiological indicators related to sweat secretion and their effects [2]. Some scholars proposed that sweat rates of different parts of human body are significantly different in the same environment, i.e. the trunk (particularly the waist) has a higher sweat volume, and limbs show the lowest [3,4]. On the contrary, it was found that compared with the anterior trunk, the posterior trunk has a lower sweating rate [5]. The sweating volumes of the upper, middle, and lower parts of the trunk decrease in turn in the same state [6]. The sweat volume of male athletes when the exercise intensity is 55% and 75%, respectively, with the maximum oxygen uptake, is measured and the results show that middle and lower back and the head all have larger sweat volume, and that of the limbs is the least [7]. In addition, the local sweating rate of more than 80 parts of the body of 9 male athletes is completely measured, including head, neck, torso, hands, and limbs, by using the sweat patch system, and draw a detailed sweating distribution map of human body to study the effects of core temperature, exercise intensity, heart rate, sweating rate, and skin temperature on the

regulation mechanism of human sweating [8]. In general, except for the head, the area with most sweating volume of the human body is on the back. Compared with the upper back, the sweating rate of the middle and lower back is larger, and it gradually decreases from the trunk to the limbs. Moreover, the sweating rate of the limbs is the lowest [9].

At present, most of the sportswear studies related to mapping design focus on the stitching of different fabrics, fabric structure, and micro-climate on the human skin surface [10]; however, there is few discussion on the effects of changed fabric structure on fabric properties. A novel type of sportswear with different fabric stitching at different positions was designed according to the heat and humidity distribution rules of human body [11]. The results show that the indicators of the new sportswear were better than those of ten sportswear made of single fabric. The influence of T-shirt designed based on human sweat map on human thermal physiological performance in a thermal environment was discussed [12]. It was found that compared with traditional T-shirt, the designed T-shirt reduced the increase in skin temperature and the clothing microclimate growth (relative humidity) on the chest, shoulder, and back of ten male subjects, which has significant thermal physiological benefits. Researcher evaluated the sportswear based on the BMS concept using the sweated manikin system [13]. Then the research results show that the clothing has advantages in the running of the thermal stress, especially during the stationary phase.

To sum up, the development methods of sportswear based on the BMS concept can be divided into three categories:

The first two authors contributed equally to this work.



(1) sportswear designed by stitching fabrics with different materials; (2) sportswear obtained by using the same material and different fabric structures according to the difference in heat and humidity distribution of human body and the concavity of body surface (e.g. the area with high dominant sweating and the area with normal temperature and humidity); and (3) sportswear combined with the first two types [14]. Compared with the traditional sportswear, the sportswear based on the concept of BMS can provide better comfort for human body. On the basis of seamless knitting, changing the knitting structure used for different regions of human body can successfully avoid the contact discomfort of the patchwork and play clothing zoning functional at the same time.

During skiing, a kind of cold environment, with the character of high oxygen consumption of which, the body metabolism and physiological indicators such as heat production and sweating will grow with the increase in activity intensity. And it is found that, when exercising in a cold environment, it is not necessary to wear more clothes, because wearing too much clothes can cause the body to heat and get more sweat volume. When sweat wets clothes, evaporation will quickly take away the heat, resulting in heat loss at a very fast rate [15]. Thus, it is necessary to deeply discuss the method used for fabric structure corresponding to different sweat areas of human body, so as to better design high-performance ski underwear based on sweat distribution characters and improve its wearing comfort.

Combined with the functional requirements of 71 professional skiing athletes to ski underwear including keeping warm, having good moisture absorption, perspiration, and tensile elastic, six kinds of single-sided jacquard fabrics were designed using polyester and DRYARN, respectively, and therefore, a total of 12 fabrics were developed by using SANTONI single-sided electronic jacquard knitting machine. Then one-way analysis of variance (ANOVA) and grey correlation degree of

entropy weight were carried out to discuss the influence of fabric structure on fabric properties. Finally, the use areas of fabric with different organizational structures were reasonably allocated based on the characteristics of local sweat and sweat evaporation difference of human body [16], in order to provide better local comfort for professional skiers.

2. Fabric development and performance testing

SANTONI single-sided electronic jacquard knitting machine with 16 inch/1,440 needles was selected as the equipment for fabric development and seamless ski underwear development. The fabric has a surface layer and an interior layer, with the inside layer contacting the wearer's skin and the outside layer contacting the environment. In addition, the face yarn is fed to No. 5 knitting feeder and knitted as a fabric surface layer, while the base yarn is knitted as the inner layer of the fabric through the No. 3 knitting feeder.

2.1. Fabric development

The impact of 3D knitted garments orientated by map on thermo-regulation using an infrared scanning imager was investigated [17]. Temperature changes from the skin and outside of the garment indicated that the raised fabric structure will regulate the individual skin temperature by changing the microclimate of the torso area, with better skin temperature regulation ability than ordinary knitted fabric. In addition, in the preliminary experiment, it was found that the heat and moisture properties of single-sided jacquard fabric were similar to those of double-sided jacquard fabric, but the knitting process of single-sided jacquard fabric was simple and efficient, which was beneficial to production. Therefore, in this study, six kinds of three-dimensional single-sided jacquard fabrics were developed

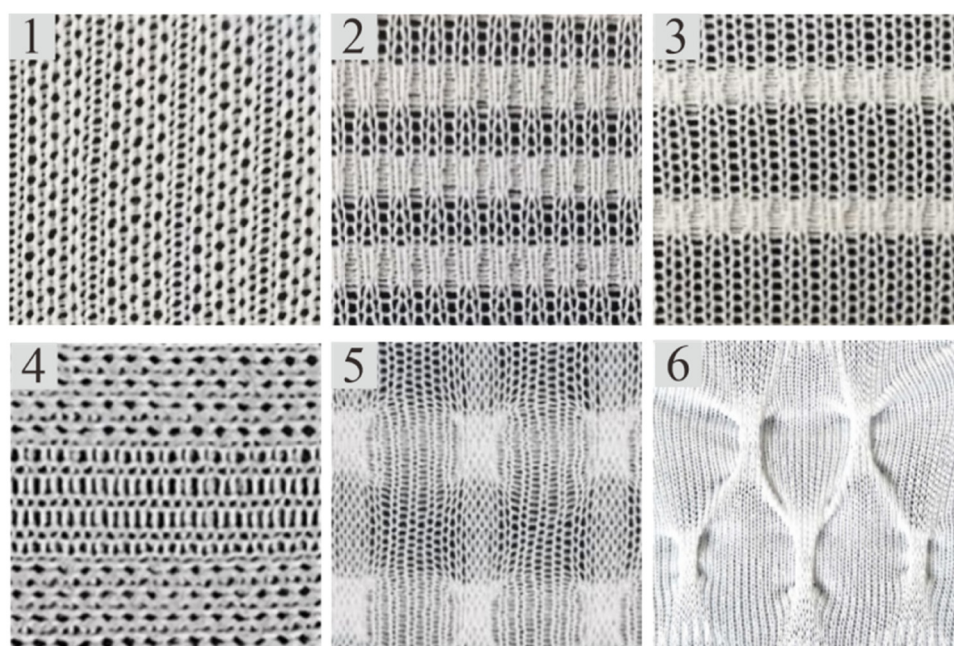


Figure 1. Single-sided jacquard structures of No. 1–6.

and marked from No. 1 to No. 6, respectively, as shown in Figure 1. Then they were knitted, respectively, by using 100 dtex polyester as face yarn, 30 dtex polyester covered 20 dtex spandex as base yarn, double 75 dtex DRYARN® as face yarn, 50 dtex DRYARN® covered 17 dtex spandex as base yarn, and in the end, a total of 12 fabrics were developed for two groups (group T₁ and group T₂). The surface density, thickness, horizontal density, vertical density, gramme per square meter (GSM), and other specifications of the 12 fabrics are shown in Table 1.

2.2. Performance testing

2.2.1. Method

According to ISO 9237-1995 Textiles – Determination of the permeability of fabrics to air, YG4616G automatic air permeability tester was used to test the air permeability of fabric, and ten different parts of the same fabric were selected for measurement.

The moisture permeability of fabric was tested using M261 moisture permeability tester according to ASTM E96/E96M-16 Standard Test Methods for Water Vapor Transmission of Materials. Cut three samples of each fabric with a diameter of 88 mm and ensure that there were no creases on the sample surface. Before the test, the sample was balanced in a constant temperature and a humidity chamber for 24 h.

The thermal resistance of fabric was measured by YG606E thermal resistance tester with reference to ISO 11092:2014 Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test). Three samples of each fabric with specifications of 35 cm × 35 cm were cut, and the hot plate temperature was set at 35°C.

The tensile properties of fabric in this research were determined by the elastic recovery rate, which is tested by HD026N + electronic fabric strength machine according to ASTM D2594-04 Standard Test Method for Stretch Properties of Knitted Fabrics Having Low Power.

2.3. Results

The experimental test results of 12 fabrics are listed in Table 2, including the permeability (I), moisture permeability (II), heat preservation rate (III), warp elastic recovery rate (IV), weft elastic recovery rate (V), thermal resistance (VI), heat transfer coefficient (VII), and Clo value (VIII).

3. Analysis of fabric performance

It can be inferred from Table 2 that the yarn materials and fabric structures have a certain influence on the results. To clarify the extent of influence, this section is discussed in detail.

3.1. Influence of the materials on fabric performance

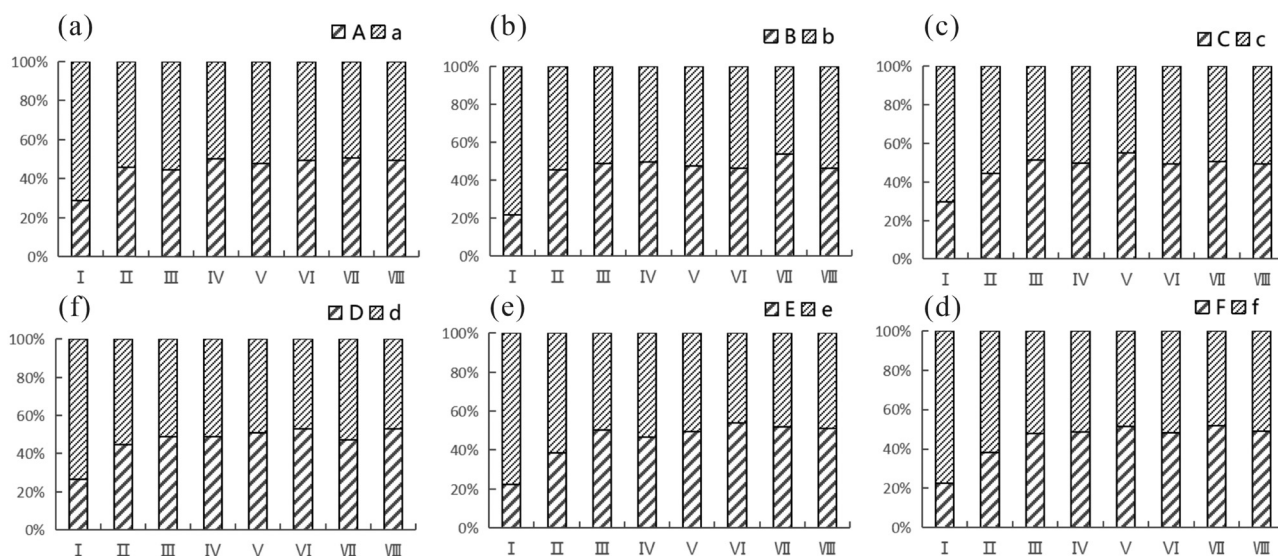
Figure 2 shows the performance differences of fabrics with the same structure in different groups. According to Figure 2, for the same single-sided jacquard structure, the air permeability and moisture permeability of fabrics in group T₂ are significantly better than those of group T₁, which is related to the yarn material. Among them, the main material of yarn used in group T₁ fabric is polyester and that used in group T₂ is DRYARN, of which DRYARN is the ultra-fine polypropylene fibre developed by Italian manufacturer Aquafil using metallocene polypropylene. Due to the use of Avant M catalyst [18], its relative

Table 1. Fabric parameters

Group	Fabric	Material		Thickness (mm)	Fabric density (g m ⁻²)	Density (yarn number [5 cm ⁻¹])		Weight (g)
		Yarn material select	Structure			Horizontal	Vertical	
T ₁	A	100 dtex polyester as face yarn, 30 dtex polyester covered 20 dtex Spandex as base yarn	1	1.7132	213.3	100	60	2.31
	B		2	2.4294	284.7	85	100	3.081
	C		3	2.2694	228.2	115	92.5	2.47
	D		4	2.015	198.4	85	75	2.153
	E		5	3.4242	307.9	105	90	3.33
	F		6	3.6158	530.2	160	111	3.408
T ₂	a	Double 75 dtex DRYARN® as face yarn, 50 dtex DRYARN® covered 17 dtex Spandex as base yarn	1	1.547	216.8	140	110	2.346
	b		2	2.1352	273.4	140	85	2.959
	c		3	2.0792	220.1	90	65	2.382
	d		4	1.6668	181.3	90	55	1.96
	e		5	2.8508	266.7	125	100	2.886
	f		6	3.056	490.8	151	126	3.075

Table 2. Text results of fabric physical performance index

Group	Fabric	I (mm s^{-1})	II ($\text{g}/[\text{m}^2 \cdot 24\text{h}]$)	III (%)	IV (%)	V (%)	VI ($\text{m}^2 \text{K W}^{-1}$)	VII ($\text{W m}^{-2} \text{°C}^{-1}$)	VIII (clo)
T_1	A	145.27	749.54	41.18	80.18	73.19	43.99	22.75	283.75
	B	142.50	709.63	43.07	88.06	75.47	48.355	20.68	311.9
	C	215.34	731.54	53.89	76.59	97.68	63.435	15.775	409.2
	D	151.34	819.03	51.49	82.72	83.61	58	17.265	374.15
	E	240.58	587.66	56.01	74.93	84.68	101.975	12.363	587.71
	F	260.35	539.20	58.94	75.31	93.26	109.37	10.69	657.9
T_2	a	361.33	895.16	51.00	79.23	79.53	45.08	22.185	290.85
	b	516.35	861.16	45.26	89.37	83.94	56.345	17.75	363.5
	c	514.73	920.30	50.74	77.62	79.51	64.8	15.445	418
	d	419.25	1017.13	54.27	85.99	80.07	51.89	19.275	334.75
	e	840.82	946.91	55.78	85.17	85.97	87.9	11.38	567.05
	f	886.72	870.58	64.12	79.61	88.31	117.53	9.87	683.2

**Figure 2.** Effects of different yarn materials on fabric properties.

molecular weight distribution is narrow so that it has excellent air permeability, radiation resistance, and insulation performance. Therefore, the a–f fabrics of group T_2 have better air permeability and moisture permeability, which can better help human body to absorb moisture and sweat and enhance human comfort. From the point of view of tensile properties and thermal insulation properties, for the same single-sided jacquard structure, the properties of group T_1 fabrics and group T_2 fabrics are similar to little difference. To sum up, the fabric made of DRYARN material has superior functional performance, in terms of comprehensive moisture absorption and perspiration releasing performance, tensile performance, and thermal insulation performance.

3.2. Influence of the fabric structure on fabric performance

3.2.1. One-way ANOVA

One-way ANOVA is used to analyse the influence of the fabric structure on the fabric performance. Six kinds of single-sided jacquard fabric structures were used as control variables, and air permeability, moisture permeability, heat preservation rate, warp elastic recovery rate, and weft elastic recovery rate were used as observation variables to explore whether different organizational structures had an effect on the fabric function. Before one-way ANOVA, it is necessary to test the homogeneity of variance among data. In this study, the homogeneity

test method based on mean value is adopted. Table 3 shows its results.

For group T_1 , the P values of air permeability, heat preservation rate, and warp elastic recovery rate are greater than the significance level of 0.05. Thus, it is concluded that there is no significant difference in the overall variance of air permeability, thermal insulation rate, and elastic recovery rate under different organizational structures, which meets the prerequisite requirements of variance analysis. Then the same applies to the group T_2 . Therefore, in the single factor ANOVA, the observed variables of group T_1 should be air permeability, warmth retention rate, and warp elastic recovery rate, while for group T_2 , they should be air permeability, warmth retention rate, and weft elastic recovery rate. Table 4 shows the results of one-way ANOVA.

According to the results of one-way ANOVA in Table 4, for the fabrics in group T_1 , the P value of the air permeability and the warp elastic recovery rate is less than 0.05, so it can be considered that different organizational structures have a significant impact on them. While in group T_2 , the P value is less than 0.05 at the same. Thus, it is also thought that organization structure has significant influences on the air permeability, heat preservation rate, and weft elastic recovery rate. Furthermore, multiple comparative analysis

is needed on the basis of one-way ANOVA structure in order to clarify which organizational structure has a more significant effect. Figure 3 shows the results of multiple comparative analysis, that is, the influence degree of fabric structure on the air permeability, heat preservation rate, and weft and warp elastic recovery rate in groups of T_1 and T_2 .

As can be seen from Figure 3, for the fabrics of group T_1 , the mean value of air permeability of single-sided jacquard tissues 1, 2, and 4 is significantly different from that of tissues 3, 5, and 6, forming three similar subsets, that is to say, compared with the structures 1, 2, and 4, the tissues 3, 5, and 6 have more significant influence on fabric air permeability. Similarly, the six single-sided jacquard structures all have an impact on the thermal insulation rate of the fabric. Compared with the 2, 4, 6 single-sided jacquard structures, structures of tissues 1, 3, and 5 have a more significant impact on the elastic recovery rate. In addition, single jacquard tissue 6 has the best air permeability and heat preservation rate; however, the rate of warp recovery is low. Single-sided jacquard tissue 2 has the best warp elastic recovery, but the air permeability and heat preservation rate are not ideal.

For group T_2 , according to the results of multiple comparison, it can be found that it formed three similar subsets in the air permeability which are the single-sided jacquard tissues 1 and 4, tissues 2 and 3, and tissues 5 and 6. In addition, the fabric structures of tissues 5 and 6 have the most significant influence on fabric air permeability and tissues 1 and 2 have the least significant in the same way. Similarly, the six single-sided jacquard structures all have an effect on the thermal insulation rate of the fabric, but the six single-sided jacquard structures have a similar effect on the weft elastic recovery rate of the fabric. In addition, single jacquard tissue 6 has the best air permeability insulation rate and weft elastic recovery rate.

3.2.2. Grey correlation analysis based on entropy weight

Grey correlation analysis technique has progressively become a widely used approach in assessment since the birth and development of grey system theory, although some academics consider that the evaluation accuracy of grey evaluation method is low [19], and the determination of weight is an important influencing factor. Therefore, according to the variation degree of each index value, the calculated entropy value can be used to determine the weight of each target, and then all indexes can be weighted, so as to obtain a relatively objective comprehensive evaluation result [20]. To summarize, in order to comprehensively evaluate the influence of organizational structure on fabric properties, the entropy method was introduced into the weight calculation of grey correlation analysis to improve its evaluation accuracy in this work.

3.2.2.1. Determination of index weight coefficient

This study mainly evaluates the thermal and wet comfort performance of fabrics. The total evaluation set $U = \{U_1, U_2, U_3, U_4, U_5, U_6\}$, whose factors, respectively, represent permeability (U_1), moisture permeability (U_2), heat preservation

Table 3. Homogeneity test of variance

Group	Observation variables	Significance
T_1	I	0.153
	II	0.000
	III	0.216
	IV	0.067
	V	0.007
T_2	I	0.070
	II	0.002
	III	0.324
	IV	0.006
	V	0.076

Table 4. Results of one-way ANOVA

Group	Observation variables	Significance
T_1	I	0.000
	III	0.000
	IV	0.012
T_2	I	0.000
	III	0.000
	V	0.039

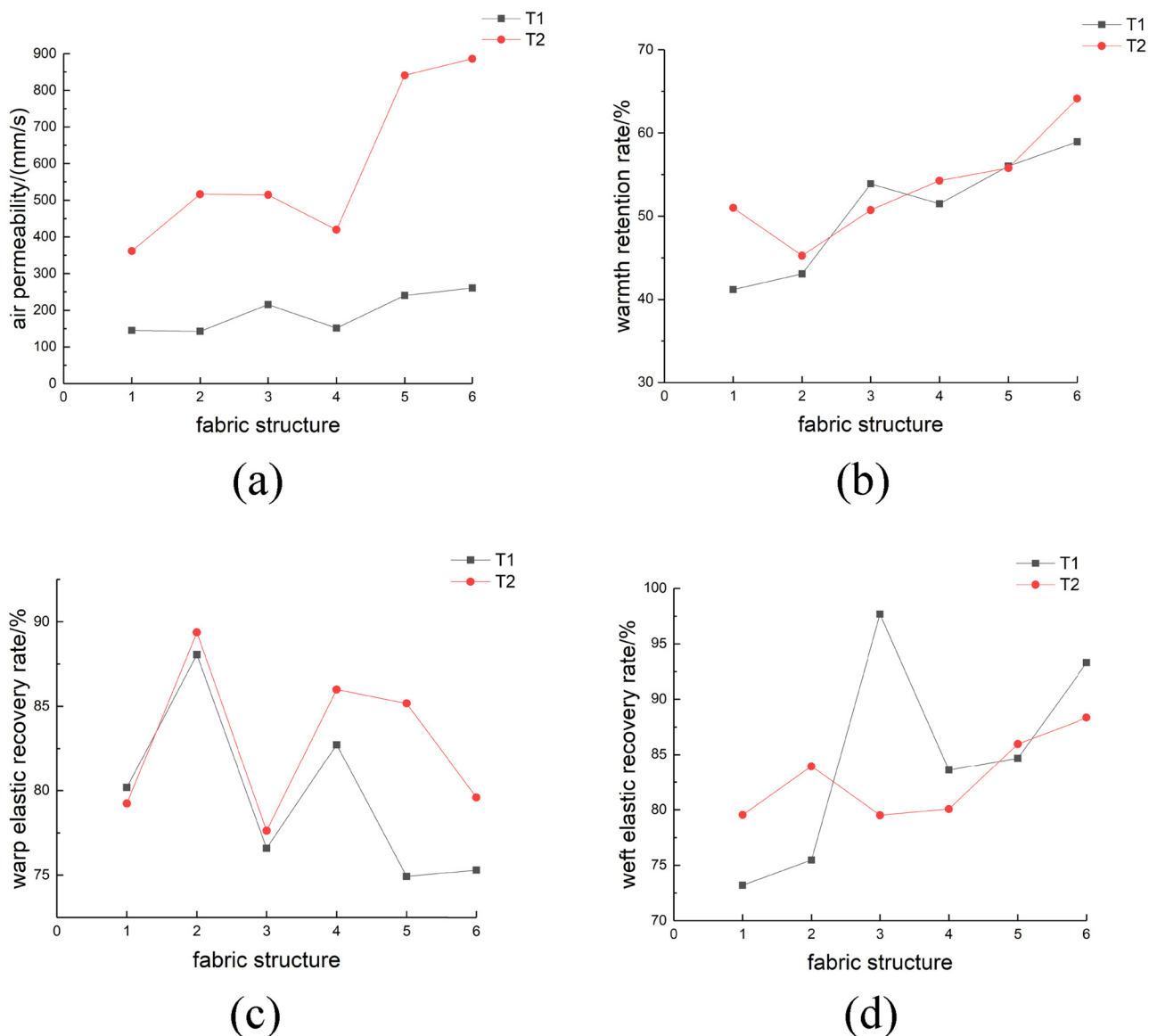


Figure 3. The influence degree of fabric structure on the air permeability, heat preservation rate, and weft and weft elastic recovery rate in groups of T_1 and T_2 .

rate (U_3), thermal resistance (U_4), heat transfer coefficient (U_5), and Clo value (U_6). Since the dimensions and units of each index are different, they cannot be directly compared and calculated. Therefore, before the weight calculation of each

index, range standardization should be carried out to obtain the evaluation matrix R as shown in formula (1). In formula (2), the larger the value is, the better the index will be; while in formula (3), the smaller the value, the better the index.

$$R = \begin{bmatrix} 0.003722 & 0 & 0.097874 & 0.011878 & 0.131789 & 0.158354 & 0.294039 & 0.502338 & 0.500161 & 0.371866 & 0.938325 & 1 \\ 0.440106 & 0.3566 & 0.410936 & 0.585504 & 0.101396 & 0 & 0.744795 & 0.673655 & 0.797397 & 1 & 0.853075 & 0.693365 \\ 0 & 0.098082 & 0.554054 & 0.449433 & 0.646469 & 0.774194 & 0.428073 & 0.177855 & 0.416739 & 0.570619 & 0.636443 & 1 \\ 0 & 0.059355 & 0.264414 & 0.190509 & 0.788482 & 0.88904 & 0.014822 & 0.168004 & 0.282975 & 0.107425 & 0.59709 & 1 \\ 1 & 0.839286 & 0.458463 & 0.574146 & 0.193556 & 0.063665 & 0.956134 & 0.611801 & 0.432842 & 0.730202 & 0.117236 & 0 \\ 0 & 0.070472 & 0.314057 & 0.226311 & 0.760946 & 0.936663 & 0.017774 & 0.19965 & 0.336087 & 0.127676 & 0.709225 & 1 \end{bmatrix}, \quad (1)$$

$$x'_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}, \quad (2)$$

$$x'_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}}. \quad (3)$$

Using the specific gravity method as shown in formula (4), dimensionless treatment was made to formula (1), and formula (5) was obtained.

$$y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^n x'_{ij}}, \quad (4)$$

$R' =$

$$\begin{bmatrix} 0.062692 & 0.06246 & 0.068573 & 0.063202 & 0.070691 & 0.07235 & 0.080825 & 0.093835 & 0.093699 & 0.085686 & 0.121067 & 0.124919 \\ 0.077069 & 0.0726 & 0.071833 & 0.08485 & 0.058942 & 0.053516 & 0.093374 & 0.089567 & 0.09619 & 0.107032 & 0.099169 & 0.090622 \\ 0.056332 & 0.061857 & 0.087543 & 0.081649 & 0.092749 & 0.099944 & 0.080446 & 0.066351 & 0.079807 & 0.088476 & 0.092184 & 0.112664 \\ 0.061117 & 0.064744 & 0.077277 & 0.07276 & 0.109306 & 0.115452 & 0.062023 & 0.071385 & 0.078411 & 0.067682 & 0.097609 & 0.122234 \\ 0.111251 & 0.102311 & 0.081128 & 0.087563 & 0.066392 & 0.059167 & 0.108811 & 0.089657 & 0.079703 & 0.096244 & 0.062147 & 0.055626 \\ 0.059884 & 0.064104 & 0.078691 & 0.073437 & 0.105453 & 0.115976 & 0.060949 & 0.07184 & 0.080011 & 0.06753 & 0.102356 & 0.119769 \end{bmatrix}. \quad (5)$$

In this study, the entropy method was selected to calculate the weight of each indicator, which is an objective weighting method. The information entropy is obtained through the calculation of indicators, and the influence of indicators on the system is measured by the difference between them according to the change rule of indicators. The greater the difference, the heavier the weight will be [21]. This method has obvious advantages when the index system is relatively complex and can reduce the subjectivity brought by subjective weight assignment when determining the weight; thus, it is more objective and scientific to calculate the information entropy of each index. According to the definition of information entropy in information theory, the indexes in formula (5) were normalized, and the entropy value of the j th-item index was calculated by using formula (6), where $j = 1, 2, \dots, p$.

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^n y_{ij} \ln y_{ij}. \quad (6)$$

Formula (7) is used to calculate the difference coefficient of item j , where $j = 1, 2, \dots, p$.

$$g_j = 1 - e_j. \quad (7)$$

Formula (8) is used to calculate the weight coefficient of item j , where $j = 1, 2, \dots, p$. The calculation results are shown in Table 5.

$$\omega_j = \frac{g_j}{\sum_{j=1}^p g_j}. \quad (8)$$

Table 5. Entropy weight method calculates the information entropy, difference coefficient, and weight of each factor

Factor	e_j	g_j	ω_j
U_1	0.988219	0.011781	0.195022
U_2	0.992802	0.007198	0.119163
U_3	0.992991	0.007009	0.116024
U_4	0.987791	0.012209	0.202119
U_5	0.989889	0.010111	0.167384
U_6	0.987901	0.012099	0.200288

3.2.2.2. Grey relational analysis

After determining the index weight coefficients as shown in Table 5, the grey relational degree analysis was carried out. The first step was to build the ideal fabric composed of the best indicators. Then, the ideal fabric and each tested fabric were composed of correlation coefficient matrix, and the correlation coefficient between each fabric and the performance of the ideal fabric was calculated. Finally, fabric properties were sorted according to the correlation coefficient, so as to judge the quality of fabric properties. The specific steps are as follows:

- (1) Compute the absolute difference between a comparison sequence and a reference sequence. The maximum value of each index was used to form the optimal value x_{0j} , and the difference between each index of the tested fabric and that of the ideal fabric were calculated. The formula is shown in the following equation:

$$(|x_{ij} - x_{0j}| \triangleq \Delta_{0i}(j))_{n \times p}, \quad i = 1, 2, \dots, n, \quad j = 1, 2, \dots, p. \quad (9)$$

- (2) Calculate the correlation coefficient between each index of the tested fabrics and each performance index of the ideal fabrics, as shown in the following equation:

$$\zeta_{0i}(j) = \frac{\min \Delta_{0i}(j) + \rho \max \Delta_{0i}(j)}{\Delta_{0i}(j) + \rho \max \Delta_{0i}(j)}, \quad (10)$$

where ρ is the resolution coefficient, usually 0.5.

- (3) Calculate the grey relational degree of each tested fabric. The calculation formula of comprehensive grey correlation degree in formula (11) was obtained by weighted average of grey correlation coefficient and the weight of entropy method, and the results are shown in Table 6. The larger the correlation degree is, the closer the corresponding target sequence is to the optimal one.

$$r_{0i} = \sum_{j=1}^p \omega_j \zeta_{0i}(j), \quad i = 1, \dots, n. \quad (11)$$

It can be seen from Table 6 that the correlation degrees of fabrics a–f are higher than those of fabrics A–F corresponding to the same organizational structure. According to the calculation result of grey correlation analysis, in group T_2 , the grey comprehensive evaluation result of fabric f is the best. The reason is that the number of concave holes and the hole on the surface of the fabric layer formed by the hollow channel system constitute the warmth and sweat-wicking system. After contacting with human skin, it can form a certain interval space so that it can retain more still air to increase the thermal performance. At the same time, it can accelerate the sweat excretion and evaporation when the human body sweats. This is consistent with the conclusion of Kinnicutt et al. [17]. Combined with the functional superfine polypropylene fiber, the functional superiority of yarn and fabric structure can be further maximized. Then the evaluation results of e and F fabrics were second best with the E and d fabric as follows. The fabrics with relative correlation degree less than 0.5 are mainly concentrated in group T_1 which are fabrics A, B, C, and D, and their grey comprehensive evaluation results are general. Therefore, group T_2 is used as a yarn material set for knitting seamless ski underwear.

To sum up, through the factor ANOVA and grey correlation analysis based on entropy weight, the influences of fabric structures on fabric function property were cleared and the sorting

results of the performance differences of 12 fabrics were obtained, which provides a theoretical basis for the zoning design of ski underwear.

4. Zoning design of seamless ski underwear based on BMS

4.1. Theoretical analysis

The human sweating map was analysed and produced [7], which served as a guide for sports apparel functional zoning design. Because different sections of the upper body are vulnerable to cold and sweat in different ways, different single-sided jacquard tissues should be used for different body parts. The thickness and microstructure of jacquard fabric can adjust the heat and moisture transfer of the human body, so jacquard fabric with excellent air permeability and moisture permeability is suitable for high temperature and high humidity parts, while some fabrics with outstanding thermal performance and good tensile performance can be used for parts with high cold sensitivity and concentrated muscle group distribution to make the underwear have better wearing. In order to reasonably design the organization division of functional ski underwear, a questionnaire survey was conducted about skiing sports experience and functional requirements of ski underwear on 71 professional skiers [22], including 24 international athletes, 12 athletes, 12 first-level athletes, 8 second-level athletes, and 15 third-level athletes. Then the statistical analysis was carried out on the functional requirements of various parts of ski underwear for professional skiers, and the results are shown in Table 7.

The abdomen, joints, and back are the body components of elite skiers that demand high warmth and air permeability, as shown in Table 7. The back, armpits, and chest had the highest requirement for moisture permeability and perspiration.

Table 6. Results of grey correlation analysis

Group	Fabric	Correlation degree	Rank
T_1	A	0.461578	8
	B	0.425369	12
	C	0.433674	10
	D	0.432092	11
	E	0.523434	4
	F	0.593777	3
T_2	a	0.503364	6
	b	0.46083	9
	c	0.483385	7
	d	0.522282	5
	e	0.631977	2
	f	0.843112	1

Table 7. Results of professional skiers' functional requirements for ski underwear

Body part	Frequency					
	I	ii	iii	iv	v	vi
Shoulder–neck	28	8	27	6	27	3
Chest	32	13	18	11	22	2
Back	33	26	9	15	17	5
Waist–hip	27	6	21	8	21	8
Abdomen	39	11	14	8	24	0
Body sides	24	11	22	8	19	5
Arms	24	5	24	4	21	9
Joints	34	5	27	6	16	10
Armpit	26	15	20	12	21	11

Note: i is the heat preservation and air permeability; ii is the moisture permeability; iii is the tensile elasticity; iv is the quick drying; v is the soft and comfort; vi is the good abrasion resistance.

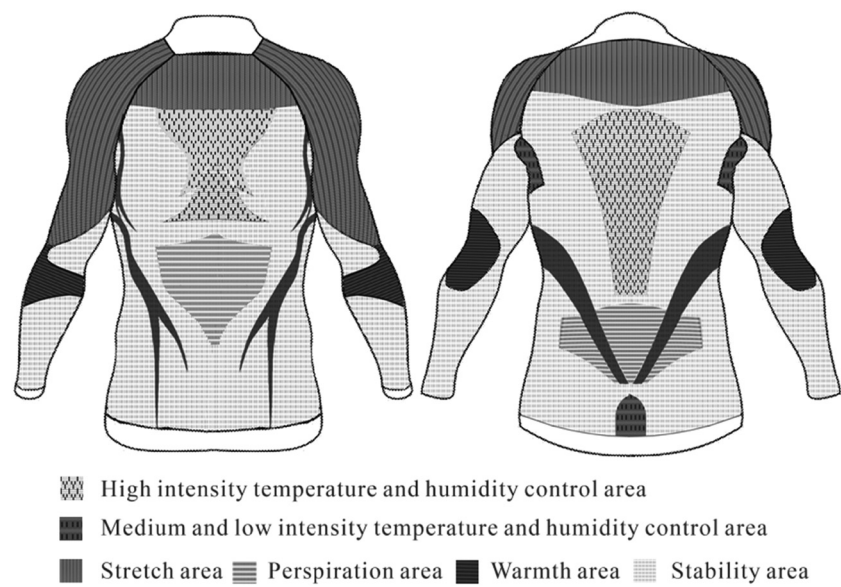


Figure 4. Zoning design of professional ski underwear.

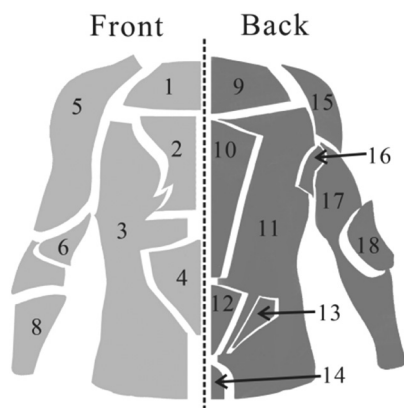


Figure 5. Functional area planning for professional ski underwear.

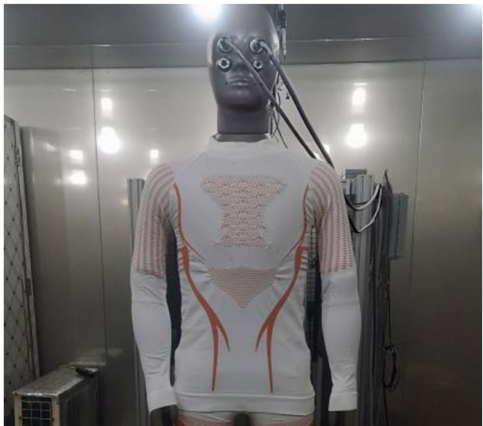


Figure 6. "Newton" sweated manikin system.

Furthermore, the shoulder–neck, joints, and arms require greater tensile strength.

4.2. Zoning design of seamless ski underwear

Functional regions of ski underwear were divided, and the optimized functional ski underwear was designed as shown in Figure 4, which could be divided into high, medium, and low

intensity temperature and humidity control areas, as well as warmth area, perspiration area, stretch area, and stability area, based on professional skiers' demand for ski underwear and distribution characteristics of human sweat rate.

Among them, the high intensity temperature and humidity control area correspond to the part with high sweat volume in the regional sweat diagram of male athletes, which is suitable for

Table 8. Fabric matching recommendations for ski underwear with zoning design

Function zoning	Sections	Fabric structure
High intensity temperature and humidity control area	(2), (10)	6
Medium and low intensity temperature and humidity control area	(14), (16)	5
Perspiration area	(4), (12), (13)	3
Stretch area	(1), (5), (9), (15)	4
Warmth area	(7), (18)	2
Stability area	(3), (6), (8), (11), (17)	1

filling the fabric with tissue structure of strong concave and convex sense. In addition, the fabric should have good moisture absorption and sweat drainage and excellent heat preservation performance. The middle and low intensity temperature and humidity control area correspond to the part with high dominant sweating rate, the fabric of which need to inhibit sweat formation and achieve effective cooling. The solar plexus located under the 12th thoracic vertebra in the abdominal cavity is more sensitive to cold, so the filled fabric not only need to have better warmth and air permeability but also have certain requirements for moisture absorption, sweat drainage, and stretching. The warmth area is corresponding to the joint of human body, that is, the part with the largest demand for thermal insulation in the underwear demand survey of professional skiers. In this area, the organizational fabric structure with strong concave and convex sense, moderate thickness, and good tensile performance should be selected. The stretch area is accompanied by the deformation of human skin in the process of exercise, so the filled fabric needs to have good tensile performance and reduce muscle tremor. The stable area covers a large area of human body, which can be used in parts that are not sensitive to the cold degree. The fabric with general warmth preservation is used to assist the circulation of fresh air from the outside.

The functional area decomposition diagram of front and back professional ski underwear is shown in Figure 5. It can be seen that professional ski underwear is divided into 18 sections. The (1)–(4) are the front body, zoning (9)–(14) are the back body. Then the zoning (5)–(8) are the front ply of sleeves, and zoning (15)–(18) are for the back ply of sleeve. The matching of functional zonings and fabrics of ski underwear is shown in Table 8.

4.3. Performance testing of seamless ski underwear

In order to verify the rationality of the zoning design method of seamless ski underwear proposed in this research, “Newton” sweated manikin system as shown in Figure 6 was used to perform wearing evaluation experiment, and thermal resistance index of the garment was obtained. The experimental conditions and process are as follows: according to ISO 15831 (2004), constant skin temperature model (T_{manikin} is 35°C) was adopted, and the thermal resistance of clothing was measured under constant temperature and humidity. The air temperature is $(20 \pm 0.5^{\circ}\text{C})$, the relative humidity is $(65 \pm 5\%)$, and the wind speed is $(0.4 \pm 0.1 \text{ m s}^{-1})$. Formula (13) is used to calculate the inherent thermal resistance (I_{cl}). Since the clothing studied is fitted clothing, f_{cl} has little influence on the inherent thermal resistance of clothing, so it is assumed that f_{cl} is 1.

$$I_t = \frac{6.45 \times (\bar{T}_{sk} - T_a)}{\sum A_i H_i / A}, \quad (12)$$

$$I_{cl} = I_t - I_a/f_{cl}, \quad (13)$$

where I_t and I_a are the total thermal resistance of clothing and boundary air layer, respectively, and I_{cl} is the inherent thermal resistance of clothing. $\bar{T}_{sk}$ and T_a are mean skin temperature

Table 9. Thermal resistance index of the overall and each part

Thermal resistance index of each part												
I_{cl}/clo	I_{cl}/clo	R/L up arm Fr	R/L up arm Bk	R/L forearm Fr	R/L forearm Bk	Upper chest	Shoulders	Stomach	Mid back	Waist	Lower back	
0.701	0.256	0.045	0.021	0.038	0.014	0.102	0.076	0.099	0.062	0.061	0.065	

Note: Fr-Front; Bk-Back.

and ambient temperature, respectively. H_i is the heat dissipation of the i th clothing part; A_i is the surface area of the i th body paragraph. The A is the total skin surface area. The f_{cl} is the clothing area factor.

Table 9 shows the overall thermal resistance index of the clothing and the thermal resistance index of each section. According to this result, the seamless ski underwear designed in this study has excellent performance, which can provide certain technical support for the design of professional seamless ski underwear.

4.4. Error analysis

Table 1 shows that thickness and density of the 12 fabrics are different due to the different organizational structure, as a result, the fabric thickness and density of fabrics will produce certain error to further affect the result of the study. In order to quantify this error, the Pearson correlation coefficient was selected to measure the linear relationship between fabric thickness, gram weight, and fabric. Table 9 shows the analysis results.

As can be seen from it, for A–F fabrics of group T_1 , fabric thickness is highly positively correlated with thermal insulation rate, moderately positively correlated with air permeability, and negatively correlated with moisture permeability and warp elastic recovery rate.

For group a–f fabrics of group T_2 , fabric thickness is highly positively correlated with air permeability and heat preservation rate, and moderately correlated with latitudinal elastic recovery rate. As is shown in Table 10, there was a moderate positive correlation between the fabric gram weight and the air permeability insulation rate, and a moderate negative correlation between the fabric gram weight and the moisture permeability.

Table 10. Results of Pearson correlation analysis

Group	Performance	Correlation coefficient	
		Thickness	GSM
T_1	I	0.735	0.467
	II	−0.460	−0.560
	III	0.826	0.451
	IV	−0.325	−0.044
	V	0.150	−0.090
T_2	I	0.979	0.650
	II	−0.055	−0.579
	III	0.954	0.546
	IV	0.244	−0.019
	V	0.682	0.627

5. Conclusion

In this study, 6 kinds of single-sided jacquard fabrics were designed, and 12 kinds of fabrics were developed by using two kinds of materials of polyester and DRYARN, respectively. The effect of fabric structure on fabric properties was clarified by one-way ANOVA and grey correlation analysis based on entropy weight, and the fabric with better overall wear performance and its specification parameters were obtained. Then zoning optimization of professional ski underwear was designed based on the new concept of BMS, combined with the needs of professional skiers for sports underwear, and the conclusions are as follows:

- 1) Yarn material has a certain influence on heat, moisture, and tensile properties of fabric. Under the same organizational structure, the fabric with face yarn using DRYARN and base yarn using DRYARN-covered spandex has better moisture permeability than that of fabric with face yarn using polyester and base yarn using Polyester-covered spandex.
- 2) The structure has an impact on the permeability of fabric, moisture permeability of insulation, and weft and warp elongation. In the evaluation of comprehensive wearing performance, the three indexes of thermal resistance Clo value and permeability have a greater weight, that is, these three indexes play a greater role in the comprehensive evaluation.
- 3) According to the needs of professional skiers for ski underwear, the functional ski underwear area is divided into six zoning in combination with BMS: high intensity temperature and humidity control area, medium and low intensity temperature and humidity control area, perspiration area, stretch area, warmth area and stability area. Single jacquard tissue with different properties was applied to the correct part of underwear according to the difference of heat and humidity in different parts of human body to maximize the garment performance. On the basis of aesthetics and fashion, it improves the rationality and scientificity of design, so that the single jacquard organization corresponding to each part meets the requirements of professional skiers for thermal and wet comfort performance of sports underwear.
- 4) “Newton” sweated manikin system with 34 sections was used to evaluate the designed professional ski underwear based on BMS. And it is found from the warmth results of the experiment that, in this study, the zoning optimization design of seamless ski underwear is reasonable, playing an obvious role in thermal regulation. It provides a reasonable theoretical basis for the zoning design of seamless ski underwear and provides some technical reference for the product development and design of seamless clothing in the future.

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