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Study on Improving the Thermal-Wet Comfort of Clothing during Exercise with an Assembly of Fabrics

Abstract
The thermal and moisture sensations are widely recognised as the most important factors contributing to the discomfort of subjects during exercise. The aim of this work is to find a new method of assembling different kinds of fabrics in clothing to achieve maximum thermal-wet comfort during exercise. The thermal-wet comfort of ten T-shirts made of ten kinds of hygroscopic fibres, such as cotton, wool, lyocell, model, soybean, bamboo and their blends, was investigated in wear trials in a standard environmental chamber. The experimental results show that the thermal-wet comfort of the ten kinds of T-shirt is varied due to the fibre types, which mainly influence the heat and moisture transfer during exercise. The temperature and humidity distribution of different sections of the human body are significantly different, resulting in different requirements for thermal-wet comfort during exercise. Based on the experimental results, a new method of assembling optimal fabrics with a certain thermal-wet comfort to match different sections of the human body to improve the thermal-wet comfort of the clothing system during exercise is given and validated in comparison wear trials.

Key words: *wear trial, thermal-wet comfort, fabric assemble, subjective evaluation, infrared image, clothing.*

Introduction

Various consumers consider comfort as one of the most important attributes in their purchase of apparel products, therefore companies tend to focus on the comfort of apparel products. Slater defined comfort as "a pleasant state of physiological, psychological and physical harmony between a human being and the environment" [1]. Comfort researchers recognise that clothing comfort has two main aspects that combine to create a subjective perception of satisfactory performance: thermo-physiological and sensorial comfort. The first relates to the way clothing buffers and dissipates metabolic heat and moisture [2 - 6], whereas the latter relates to the interaction of clothing with the senses of the wearer, particularly with the tactile response of the skin, which includes moisture sensation on the skin [7 - 10]. Wong and Li found that thermal-wet comfort, tactile comfort and pressure comfort were the three main sensations perceived by subjects during exercise, thermal-wet comfort being strongest [11]. Hence, the development of effective techniques and methods to improve the thermal-wet comfort of clothing during exercise is the main issue discussed in this paper.

Thermal-wet comfort is mainly determined by the heat and moisture transport of fabric, which is related to fibre characteristics as well as yarn and fabric construction and fabric finish, recognising that the extent of their relationship to comfort perception in clothing is also influenced by garment design, cut and fit [12]. Hollies performed a series of 21 knit fabric variations that were compared in wear trials in order to produce a more comfortable garment, and Shinjung found that the water wicking treatment of aramid and aramid/FR rayon blend fabrics shows higher rates of sweat uptake and a lower clammy sensation during exercise [13, 14]. Stana-Kleinschek changed pore characteristics, significantly influencing the water capacity and absorbency of fibres, which led to a change in the moisture sorption characteristics of fibres. Kongdee studied the influence of wet/dry treatment on the pore structure and correlation of the pore parameters, water retention and moisture regain values of fibre [15, 16]. Kim investigated inner and outer layer fabrics to evaluate the heat and moisture transfer of the layer assemble of different fabrics [17]. In previous researches, methods to improve the thermal-wet comfort of clothing focused on fabric finish, fibre construction, fibre blending and novel fibre development.

In this paper, a new method is proposed to improve the thermal-wet comfort of clothing by applying fabric with certain heat and moisture transfer properties to meet the special demand for thermal-wet comfort in different sections of the human body during exercise. The fabrics chosen in this experiment include natural fabrics such as cotton and wool, as well as regenerated cellulosic fibres, such as lyocell and modal, and also another two newly developed cellulosic fibres: soybean fibre and bamboo fibre.

Table 1. *Basic properties of fabrics; fabric structure - jersey.*

Fibre type	Fibre composition,%	Yarn count, tex	Fabric weight, g/m²	Fabric thickness, mm
Soybean/Modal	50/50	15	120	0.63
Soybean/Cotton	50/50	15	120	0.62
Soybean	100	16	120	0.67
Bamboo /Cotton	50/50	16	130	0.72
Bamboo	100	15	120	0.62
Lyocell	100	15	120	0.64
Model	100	15	120	0.66
Cotton	100	16	130	0.73
Wool	100	17	140	0.78
Wool/Soybean	50/50	16	130	0.72

Table 2. *Mean features of the subjects.*

No.	Age, years Mean ± SD	Weight, kg Mean ± SD	Height, m Mean ± SD	Surface area, m² Mean ± SD
25	21.3 ± 2.4	50.4 ± 5.6	160.1 ± 0.08	1.62 ± 0.135

Regenerated cellulosic fibres offer many advantages over synthetic ones, comprising a significant share of the man-made textiles market; cotton and wool possess high performance properties that are popular in the textile market.

Experimental

Test fabrics and subjects

Table 1 gives the basic properties of the knitted fabrics selected. Wear trials were designed to investigate the thermal and humidity comfort of these fabrics during sweating in wear conditions, and to establish optimal combinations of multiple fabrics to achieve maximum thermal and humidity comfort during wearing.

The fabrics were put together to produce matching long-sleeved round neck T-shirts in sizes to fit the subjects. During the trials, all subjects wore the same underpants, trousers, and socks. The T-shirts were of the same colour to ensure that the subjects could not visually distinguish between the garments.

25 female subjects were selected from a pool of volunteers for the experiment: all subjects wore clothing of the same size. Physical characteristics of the subjects are presented in ***Table 2***.

Experimental Procedure

The subjects entered an environmental chamber, put on the test clothing and at the moment recorded the subjective rating of coolness to the touch sensation of the test clothing, and then rested for 15 minutes to equilibrate to the ambient atmosphere. Conditions in the chamber were 24 ± 1 °C and 55 ± 4% RH. At the end of this rest period, they exercised on a treadmill at a running speed of 5.5 km/hour for 25 minutes, and then rested for 5 minutes in the environmental chamber. During the exercise, the temperature of the clothing surface was recorded by an infrared temperature measurement device, and infrared images were obtained every minute. According to previous research of subjective evaluation, subjective perception indices include hotness, dampness, stickiness, after-chill, and coolness to the touch [18]. The subjective comfort rating, such as dampness, stickiness, after-chill, coolness to the touch, were recorded on a five-point intensity scale, 1 (none) to 5 (extremely), and the thermal sensation was recorded on a seven-point scale, respectively[19], shown in ***Figure 1***. Subjective evaluation values were recorded every five minutes. After a preliminary acclimatisation trial, each subject completed ten trials for ten test items of clothing made of different knitted fabrics in a random order, the length of each exercise period being 30 minutes.

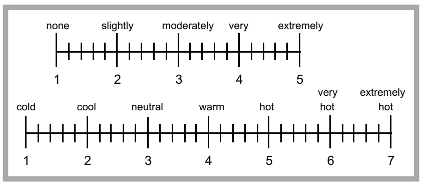

Figure 1. *Subjective rating scales for subjective sensations.*

Experimental results and discussion

Figure 2 shows the mean subjective rating of the damp sensation from subjects for ten T-shirts during the wear trials. A damp sensation was clearly perceived from 20 minutes after exercise; cotton and wool have much more dampness than others after 25 minutes, but wool decreases quickly after a period of rest, whereas cotton exhibited the highest dampness continuance. Soybean, bamboo and modal show a lower damp sensation, and lyocell was between the two but closer to the soybean at 30 minutes. The bamboo and model showed a higher damp sensation than soybean and lyocell after a period of rest. The soybean/model was much lower than the other three kinds of blend fabrics, and the cotton blend produced a less damp sensation than cotton fabric. Behmann found that the higher sorption capacity of wool delayed the onset of the perception of sweating and dampness [20]. However, wool was much damper than regenerated cellulosic fibres in our trials, which maybe due to the regenerated cellulosic fabrics chosen for the experiment, which have a higher sorption capacity and lower thermal resistance resulting in considerably more heat loss than that of wool during exercise. Another factor was the heavier exercise of the subjects in our trials.

Figure 3 (see page 48) is a plot of the thermal sensation rating during exercise. Wool fabric and cotton fabric produce a much stronger thermal sensation than other fabrics, and subjects wearing T-shirts made of bamboo, soybean and model fabrics perceived a low thermal sensation, whereas those wearing lyocell felt a moderate thermal sensation. The blend fabrics represented a moderate thermal sensation. The thermal rating of all T-shirts showed a rapid rise and decreased swiftly after stopping exercise due to the heat loss of sweating and moisture evaporation; similar thermal responses appeared during exercise in the wear trial studies [21].

Subjective ratings for a sticky sensation are shown in ***Figure 4*** (see page 48). Variations in the sticky sensation for all the kinds of T-shirt became slightly apparent from the moment of 15 minutes after starting exercise. Wool and bamboo tend to be less sticky than soybean and lyocell; the sensation rating of cotton and model are the highest, but the rating of model declines swiftly after stopping exercise. Wool/soybean is less sticky than other blend fabrics, and variation in the sticky sensation of blend fabrics is less significant than that of a single fabric before being blended.

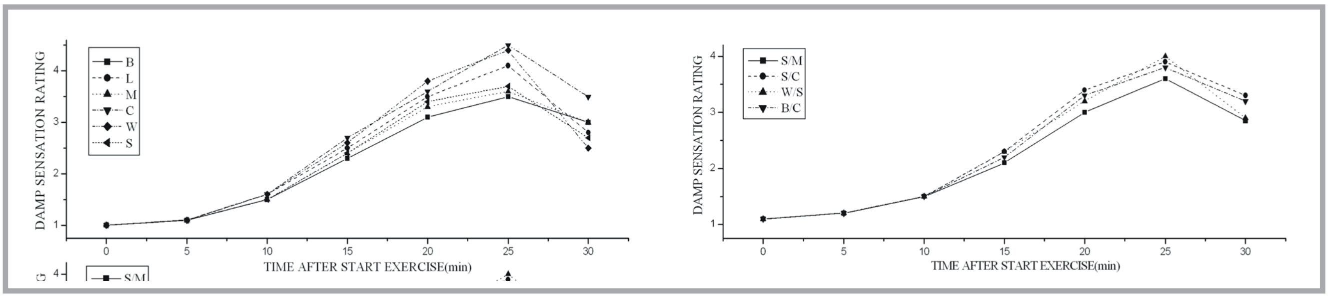

Figure 2. *Subjective rating for a damp sensation during exercise.*

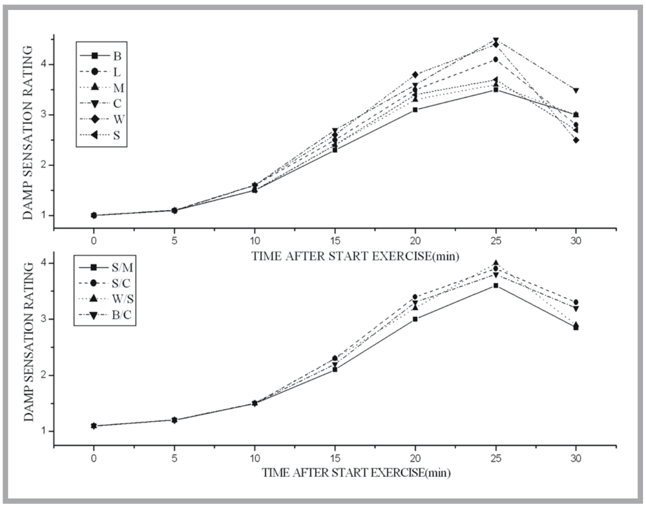

Figure 3. *Subjective rating for thermal sensation during exercise.*

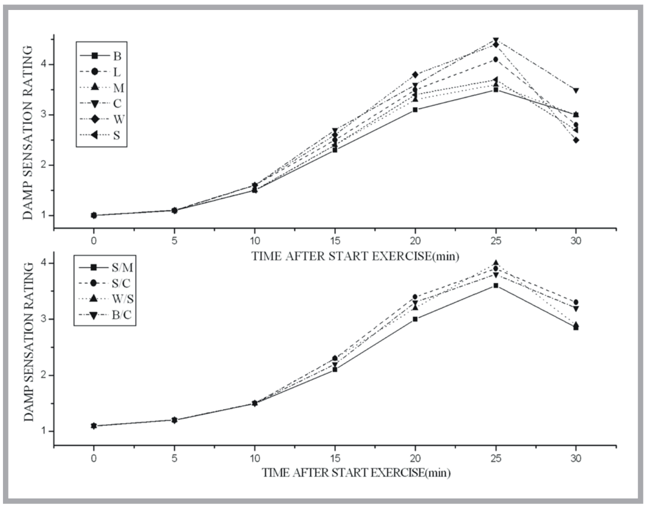

Figure 4. *Subjective rating for sticky sensation during exercise.*

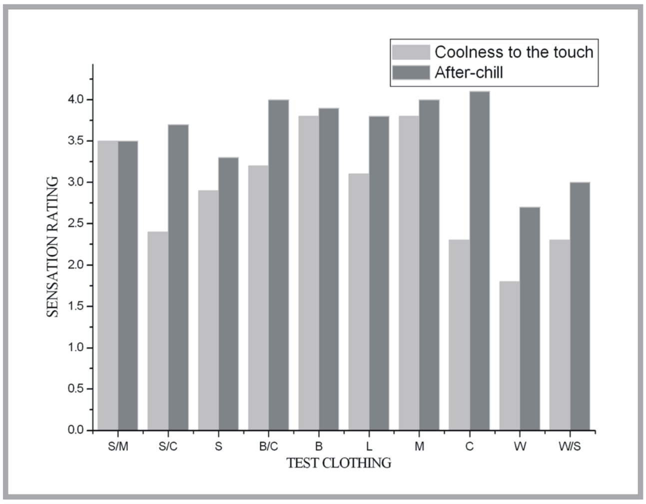

Figure 5. *Subjective rating for coolness to the touch and after-chill.*

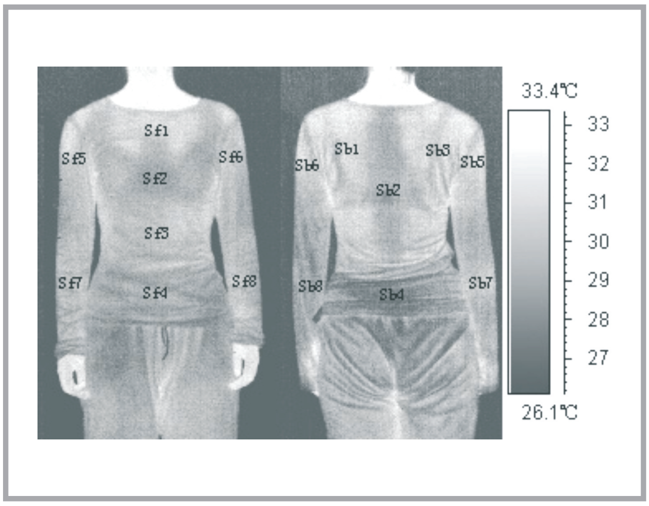

Figure 6. *Infrared images of outer surface after exercise.*

Figure 5 is the subjective rating for coolness to the touch and after-chill. Subjects perceived a much stronger coolness to the touch with soybean/model, bamboo and model. Perspiration from the human body may build up with clothing, and the evaporation of water can cause "after-chill" discomfort [22]. Cotton exhibited the highest moisture after exercise: wool the lowest. The others are between the two, whereas bamboo/cotton, model and bamboo are closer to the cotton.

Figure 6 is an infrared image of the outer surface of a T-shirt worn by a subjects at about 20 minutes after exercise. ***Figure 7*** is the surface temperature of 16 sections of ten kinds of test clothing during exercise. The surface temperature of different sections of the human body is statistically significant, and all kinds of T-shirts show a similar temperature distribution, though the temperature on the same section of ten T-shirts is different due to various fabric characteristics. Changes in the surface temperature of clothing involves four possible heat components: direct heat transfer from the skin surface to the fabric; the heat of adsorption; the heat of evaporation; the heat of condensation. The inner and outer surface temperature showed similar changes [17].

Before exercise the temperature of 16 sections are equal statistically, and at the begin of exercise, the sections that are tightly close to skin show a high temperature due to direct heat transfer from the skin. The temperature of those sections where a thick air layer exists between the clothing and skin is much lower due to the low heat transfer coefficient of air in a steady-state. Furthermore, the temperature at about 5 minutes is lower than before exercise owing to forced convection with the microclimate and convection at the clothing surface. But at about 10 minutes the temperature is higher than that before exercise due to heat liberation of the metabolism during exercise, which increases rapidly. The temperature of 16 sections changes significantly during heavy sweating, and the uneven surface of the human body, clothing structure, and the thickness of the layer of air result in different heat and moisture transfer, which contributes to variations in temperature. Depending on the temperature, the surface is divided into 8 sections based on the temperature difference for the front: Sf1, Sf2, Sf3, Sf4, Sf5, Sf6, Sf7, Sf8 and back: Sb1, Sb2, Sb3, Sb4, Sb5, Sb6, Sb7 and Sb8, respectively.

The surface temperature of the 16 sections was divided into several clusters using cluster statistical analysis, shown in ***Figure 8***. The 16 sections were gradually clustered and then divided into 4 basic clusters: Sf4, Sf5, Sf6, Sb4, Sb5, Sb6; Sf7, Sf8, Sb7, Sb8; Sf2, Sf3, Sb2; Sf1, Sb1, Sb3 became four separate clusters.

The first cluster of six sections, such as Sf5, Sf6, Sb5, Sb6, Sf4 and Sb4, Sf5, Sf6, Sb5, Sb6 are of the upper arm of the human body, where clothing close to the arm is of moderate temperature and humidity during exercise. Lyocell, soybean/cotton and bamboo/cotton with a moderate thermal and sticky sensation are suitable fabrics for these sections. Sf4 and Sb4 are the abdomen and waist-hip sections of the back with a high humidity and lower temperature, where plenty of moisture is collected due to the vapour that is delayed in evaporating, which then condenses on the skin's surface and clothing surface, resulting in moisture build up in those two sections. Furthermore, Sf4 and Sb4 are not directly close to the skin in underwear and trousers, and the moisture diffuses much more slowly in a two layer fabric than one with a single layer. Although model is very sticky and wool/soybean shows little high thermal sensation, both thermal and stickiness are not the main factors of concern for those sections that are not directly close to the skin, being of lower temperature during exercise. Both model and wool/soybean, with a less damp sensation during exercise, are optimal fabrics for these two sections.

Sf7, Sf8, Sb7, Sb8 represent the lower arm of the human body, with a lower temperature and humidity because of heat and moisture loss due to convection from the placket cuff during exercise; all kinds of hygroscopic fibres chosen for these wear trials are appropriate. The temperature of Sf2, Sf3, Sb2 increased swiftly after the start of exercise, but heat loss via evaporation occurred when,there was plenty of water buildup due to the uneven surface of the human body. Sweating results in high humidity, therefore bamboo and soybean, which have a lower thermal and damp sensation as well as a moderate sticky sensation during exercise, are appropriate. But the subjects wearing bamboo perceived a much damper sensation than with soybean after stopping exercise, which caused a chill sensation. The temperature of Sb1, Sb3 & Sf1 are the highest when tight to the skin with mass heat transfer, but with a moderate humidity. With the lowest thermal and sticky sensation, bamboo and soybean/model are the best for these sections.

The different temperature distribution of the human body during exercise, combined with the subjective thermal-wet comfort of ten kinds of test clothing in real wearing conditions were correspondingly analyzed to establish an optimal fabric for the different sections of the human body. A new method of clothing design by applying optimal fabric to different sections is proposed to improve the thermal-wet comfort of clothing during exercise.

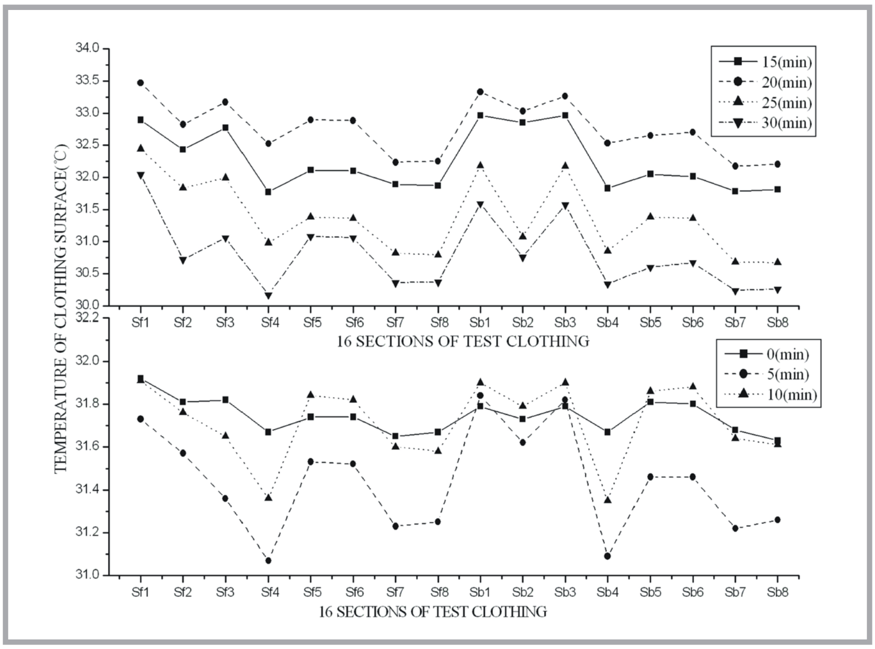

Figure 7. Temperature of the 16 sections during exercise. ***Note:*** *The straight lines do not presents dependences, only join measuring points of the particular sections.*

Comparison of experimental results

Design of fabric assembly

Depending on the results of wear trials, a new method to achieve optimal thermal-wet comfort during exercise with fabrics assembled into clothing is proposed. According to the analysis above, many kinds of fabrics meet the thermal-wet comfort demand of the same section, and one kind of fabric corresponding to each section was chosen to create new test clothing in order to verify experimental results; the matching fabric chosen for each section is shown in ***Table 3***. The four fabrics were assembled to make a long-sleeved round neck T-shirt with three-thread overlock seams on a three-thread overlock machine using cotton thread, the colour of the fabrics being the same. In order to compare the experimental results precisely, the subjects were asked to repeat the experiment in the same environmental chamber with a new T-shirt assembled from four kinds of fabrics wearing the same underpants, trousers and socks as before.

Comparison of experimental results

Figure 9 (see page 50) is the subjective rating for sticky, damp and thermal sensations during exercise. Compared with the lowest thermal sensation among the ten test items of clothing (see ***Figure 3***), the thermal sensation of a new T-shirt tends to be slightly higher at the moment of starting exercise, but increases gradually with the exercise time due to matching the fabrics with the lowest thermal sensation for the high temperature sec-

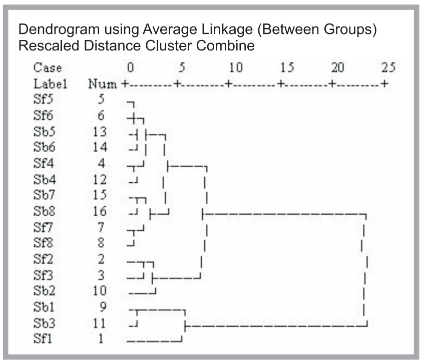

Figure 8. Result of cluster analysis of 16 sections.

Table 3. Matching fabric chosen for each section.

Sections of human body	Matching Fabrics
Tf5, Tf6, Tb5, Tb6	lyocell
Tf4, Tb4	model
Tf7, Tf8, Tb7, Tb8	lyocell
Tf2, Tf3, Tb2	soybean
Tb1, Tb3, Tf1	bamboo

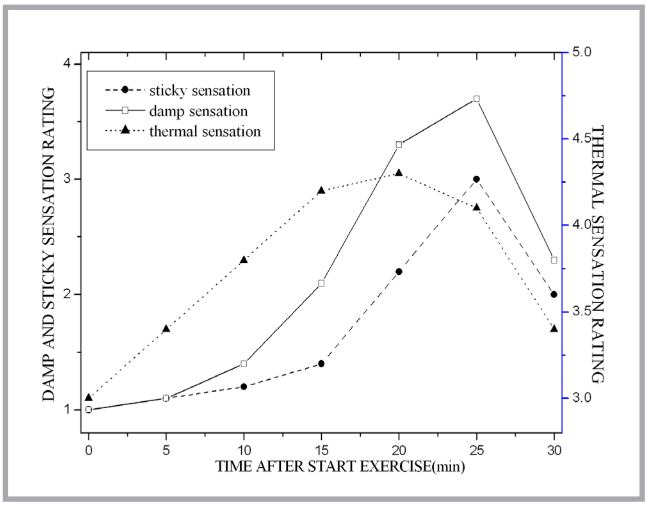

__Figure 9.__ Subjective rating for sticky, damp and thermal sensation of new T-shirt.

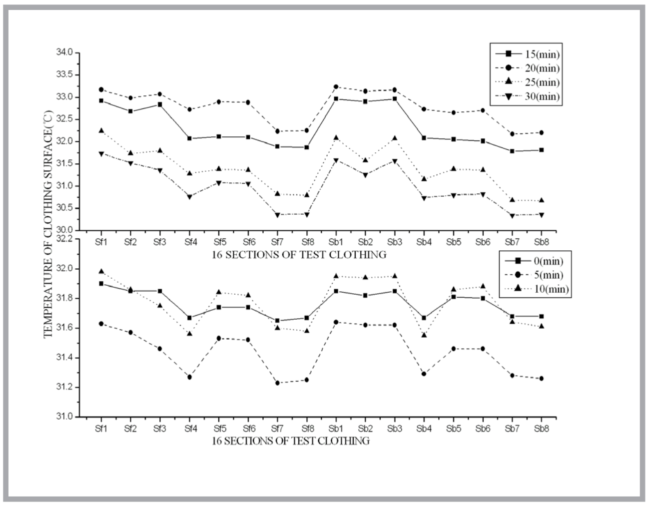

__Figure 10.__ Surface temperature of 16 sections of a new T-shirt. __Note:__ The straight lines do not presents dependences, only join measuring points of the particular sections.

tions. The thermal sensation increased quickly after stopping exercise. The plot of the damp sensation shows no apparent change; aat the first moment of exercise, the damp sensation of a new T-shirt is much lower than that of bamboo (see ***Figure 2*** - page 47), increasing swiftly from 20 minutes and reaching a peak at 25 minutes, but dropping quickly after stopping exercise. The subjects wearing a new T-shirt did not perceive a significant chill after stopping exercise. The sticky sensation rating of a new T-shirt is much lower than the ten T-shirts used in this research (see ***Figure 4*** - page 48), the difference being significant. The sticky sensation reached a peak at 25 minutes; the lowest rating of ten T-shits is 3.5, between moderately and very sticky, and the rating of a new T-shirt is 3, which is moderate.

The temperature of 16 sections of a new T-shirt during exercise is shown in ***Figure 10***. Compared with the graphics of the ten test items of clothing (see ***Figure 6*** - page 48), the significant difference is between the temperatures of sections Sf4, Sb4 and Sb2, which increase quickly at the begin of exercise due to the wool/soybean and soybean fabrics having a higher thermal sensation, but still remains below the Sf1, Sb1 and Sb3. The maximum difference occurs from 20 minutes. The temperature of Sf4, Sb4 and Sb2 is much higher with respect to the point shown in ***Figure 6*** - page 48. The temperature of other sections of the new T-shirt appeared similar to fabrics assembled before, such as Sf5, Sf6, Sb5, Sb6, Sf7, Sf8, Sb7, Sb8, which keep the same level as before. The temperature of Sf1, Sb1, Sb3 increases gradually and is lower than that of fabrics assembled before, but the difference is not significant. The thermal and moisture sensations are widely recognised as the most important factors contributing to the discomfort of subjects during exercise. The new T-shirt performed well during exercise, and optimal fabrics matched to the right sections improved the thermal-wet comfort of the clothing system.

Note: In order to eliminate all doubts concerning estimation devintions, the following should be stated. The parameter deviations of the subjective evaluation ratings shown in ***Figures 2, 3, 4,*** and ***5***, as well as of the temperature measurements presented in ***Figures 7*** and ***10*** were analysed, and we indicated that no significant differences occurred in the subjective evaluation ratings and temperatures of the subjects. The values shown in ***Figures 2, 3, 4, 5, 7*** and ***10*** are based in the average on data of 25 subjects. The deviation analysis was based on the middle step of the data processed, but it was not shown in this paper.

Depending on the wearing trials, the three kinds of sensation ratings of 25 subjects were recorded during every five minutes (as the subjects tested ten kinds of T-shirts), as well as 16 section temperatures of 25 subjects. These tests produced thousands of original data. All these data were analysed and dozens of statistical analysis forms were created. In order to shorter this paper, only the statistical analysis related to the moment of 30 minutes of thermal sensation ratings and the temperatures of Sf1 of 25 subjects (wearing T-shirts made of bamboo fabric) was presented as an example. The statistical results are given in ***Table 4*** (at 95% of confidence interval of the difference).

__Table 4.__ Statistical analyze results of the ratings and temperature of 25 subjects.

No.	Item	Mean	SD	SE	Sig. (2-tailed)
25	Thermal ratings	3.8	0.21213	0.15	0.00
	Damp ratings	3.0	0.07071	0.05	0.00
	Sticky ratings	2.6	0.36757	0.11624	0.00
	Coolness	3.8	0.26194	0.08731	0.01
	After chill	3.9	0.20276	0.06759	0.01
	Temperature, °C	32.3	0.07975	0.01994	0.00

Conclusion

In this study, we have investigated the thermal-wet comfort of ten T-shirts made of ten kinds of hygroscopic fibres during exercise using subjective evaluation and objective measurements in wear trials in an environmental chamber. Natural hygroscopic fibre, cotton and wool are much damper and more thermal than others; regenerated cellulosic fibres, bamboo, soybean and model are less thermal and damp during exercise, whereas model is very sticky and bamboo has a significant coolness to the touch. Lyocell shows a higher thermal sensation than other regenerated cellulosic fibres, with moderate dampness and stickiness. Test clothing made of blend fabrics exhibit moderate thermal-wet comfort. Furthermore, the study revealed that the surface temperature of clothing is distinguishable during heavy exercise. The 16 sections of the human body show certain thermal and moisture characteristics. Optimal fabrics matching certain sections of the human body are selected depending on the temperature and moisture characteristics of the sections, combined with the thermal-wet comfort of every kind of fabric. Subjects wearing the new T-shirt made of four fabrics perceived a low thermal sensation, and the temperature increased quickly after stopping exercise. The sticky sensation rating is much lower than before assembly, although the damp sensation shows no apparent change. The method of assembling different fabrics into clothing to improve the thermal-wet comfort of a clothing system is proposed and validated based on the comparative experimental investigation. The approach proposed in this paper can be applied in the practical design of sports wear, T-shirts and underwear etc. to achieve high performance during exercise or in a high temperature climate.

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