STUDY ON THE INFLUENCE OF UNDERWEAR ON LOCAL THERMAL AND MOISTURE COMFORT OF HUMAN BODY

by

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Original scientific paper
https://doi.org/10.2298/TSCI190310229C

In order to study the influence of underwear on human thermal and moisture comfort in different sports conditions, the objective and subjective evaluation of underwear (including undershirt and underpants) made of three kinds of fabrics were carried out, and the underwear comfort model was established by CFD, and the application prospect of CFD technology in the field of clothing comfort research was prospected. The results show that the underwear combination of different fabrics has certain influence on the thermal and moisture comfort of human body, and the thermal and moisture of fabric of composite fiber is better than that of fabric of single fiber, the temperature and humidity of chest, back, hip, and thighs of the human body in different motion states change, and the temperature and humidity of the chest and back change greatly, and CFD can accurately predict human skin temperature.

Key words: *male underwear, thermal and moisture comfort, objective evaluation, subjective evaluation, CFD*

Introduction

Any physiological activity of human body can not be separated from proper temperature. At the same time, under comfortable conditions, the tissues and organs of the human body must keep a temperature close to a constant about 37 °C ±0.5 °C, beyond which the human body will feel uncomfortable. Based on this standard, the maximum deviation of the internal temperature is 2 °C, which leads to excessive heat and convulsion, and ventricular fibrillation when the temperature is too low [1, 2]. The regulating function of human body itself is limited, but it can regulate body temperature physiologically within a certain range. With the expansion of mankind into outer space, the protection of human body, especially under the condition of thermal load, has become more and more important. The temperature in different environments and the forms of human body temperature regulation are pointed out. The body temperature regulation includes behavioral regulation and physiological regulation. The so-called behavioral regulation is to take protective measures, such as adding or subtracting clothes or wearing specific clothes, while physiological regulation refers to regulating blood flow through vasoconstriction and relaxation, sweating and dissipating heat, and chattering and generating heat.

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The main function of ordinary clothing is to bring comfort to people. Therefore, comfort has always been a research hotspot in the field of clothing, and it is a key factor that can not be ignored for human body function or health. High temperature and high humidity are not conducive to the heat balance of the body. If the heat is not dissipated in time, high temperature will easily cause the decline of human muscle function and lead to fatigue. Higher humidity will prevent sweat from evaporating and destroy the heat balance. Heat and humidity are reflected in clothing, and they are inseparable and coexist.

Especially underwear (undershirt and underpants) as close-fitting clothing, its thermal comfort is related to human health. The thermal and moisture properties of underwear (undershirt and underpants) are very important for men's private parts. According to medical research reports, inappropriate thermal and wet conditions can easily breed molds and cause unnecessary inflammation of men, such as rotten crotch and eczema [3-5].

There must be a certain limit to the degree of heat and humidity of underwear, otherwise, there will be no comfort, but it will affect human health. However, at present, most researches on the influence of thermal and wet comfort of underwear on physiological activities only focus on the thermal and wet properties of fabrics [6-12], which does not involve the thermal and wet state of human body when wearing underwear. Even if some scholars have studied the thermal and wet comfort of underwear, they only use a kind of fabric or only study the static thermal and wet comfort. The measured comfort performance under steady-state conditions can not fully reflect the actual feeling of human body when wearing. Therefore, it is necessary to study the dynamic thermal and wet comfort of fabrics.

To sum up, in order to better explore the effect of underwear on the local thermal and moisture comfort of human body, this paper uses no fabric to make underwear, and uses different matching of upper and lower clothes to study the dynamic and static thermal and wet comfort state of human body, which can provide design guidance for underwear design. Mainly through subjective evaluation of thermal sensation and wet sensation, objective evaluation of skin temperature and humidity of related parts measured by thermal and wet testing system. The reasons for adopting the two evaluation methods: although subjective test takes into account many factors such as physics, physiology and psychology, and has strong applicability, especially for the evaluation of contact comfort and visual comfort, it also has certain defects, such as the subjective evaluation accuracy will be greatly affected by whether the subjects can reasonably judge the thermal comfort, or the result of subjective evaluation of thermal comfort is subjective. Therefore, the combination of subjective and objective evaluation is a more scientific method for the evaluation system of thermal and wet comfort. Finally, CFD is used to simulate the change of human skin temperature, and realize the visualization of human body temperature distribution when wearing underwear. At present, CFD is widely used in heat transfer, human thermal comfort, heat stress assessment, material model and flow model exploration [13-19]. Experiments show that the model established by CFD has good stability, reliability and accuracy.

Experiment

Participants

The participants were five young men, all of whom were healthy. Before the experiment, the participants were asked not to smoke, drink alcohol and take stimulating drugs. Tell them the process and danger of the test truthfully, but do not tell the subjects about the test fabric, so as to prevent the physiological and psychological influences of the subjects.

In order to ensure the validity of the body shape of the subjects (because of the difference in body shape, it will also affect the thermal comfort of underwear [20, 21], which will be studied in the next step), the subjects with relatively close body shapes are selected, as shown in tab. 1.

Table 1. Participants size parameter

Participants	Age	Height [cm]	Bust girth [cm]	Waist girth [cm]	Hip girth [cm]	Neck-waist length [cm]	Front waist length [cm]	BMI	Human surface area [m^2]
B1	18	173.1	85	71.4	86.7	42.8	43.0	21.9	1.69
B2	20	172.0	89	74.76	92.2	42.5	43.2	22.9	1.81
B3	21	174.3	88	73.92	90.6	43.1	43.3	22.2	1.75
B4	23	173.4	85	71.4	89.5	42.8	42.9	21.1	1.69
B5	24	175.5	87	73.08	94.1	43.3	43.6	21.9	1.77
Minimum value	18	172	85	71.4	86.7	42.5	43	21.1	1.69
Maximum value	24	175.5	89	74.8	94.1	43.3	44	22.9	1.81
Mean	21.2	173.66	86.8	72.912	90.62	42.9	43.2	22	1.742
Standard deviation	2.387	1.3164	1.789	1.5026	2.7941	0.3082	0.274	0.6481	0.0522
Skewness	–0.206	0.315	0.052	0.052	–0.297	0.085	0.609	0.009	0.164
Coefficient of variance	0.1126	0.0076	0.0206	0.0206	0.0308	0.0072	0.0063	0.0295	0.0299

Among them, the BMI index in tab. 1 refers to the index obtained by dividing the weight by the square of the height, that is, the body mass index, which is a standard commonly used in the world to measure the degree of obesity and health. Body mass index BMI = weight [kg]/height^2 [m], as shown in tab. 2.

Table 2. Body mass index value

BMI	Interval	≤18.5	18.5-23.9	24.0-27.9	28.0-32.0	≥32
	Morphology	thin	normal	overweight	obese	very obese

It can be seen from tab. 1 that the skewness coefficient is small, which means that it is close to symmetrical distribution, and the coefficient of variation is small, which means that the data distribution is concentrated and the size of subjects is relatively close.

Experimental clothing

Using the different fabric to make the underwear (including undershirts and underpants) according to the average body shape of the five participants. The underwear's fabric parameters and styles are seen in tabs. 3-6, and figs. 1 and 2.

During the experiment, the testers randomly selected undershirts and underpants to wear, and there were nine combinations, namely (S1, P1), (S1, P2), (S1, P3), (S2, P1), (S2, P2), (S2, P3), (S3, P1), (S3, P2), (S3, P3).

Table 3. The undershirts' fabric parameters and styles

No.	Fabric	*Fd* [gm^{-2}]	*WL*	*CL*	*T* [mm]	*M* [$gm^{-2}h^{-1}$]	*MR* [$°CPW^{-1}$]	*WH* [cm per 10 minute]	*TR* [$°CmW^{-1}$]	HPR [%]	HTC [$Wm^2 °C^{-1}$]	*AP* [mms^{-1}]
S1	100% cotton	147.31	110	72	0.56	531.051	2.5125	1.5	0.102	25.98	26.04	1780.6
S2	100% bamboo fiber	121.65	201	227	0.40	561.337	1.858	6.1	0.084	27.86	26.78	2193.7
S3	78% cotton 17% tencel 5% spandex	283	125	90	0.82	526.572	3.1030	5.2	0.036	0.582 6	26.39	1582.3

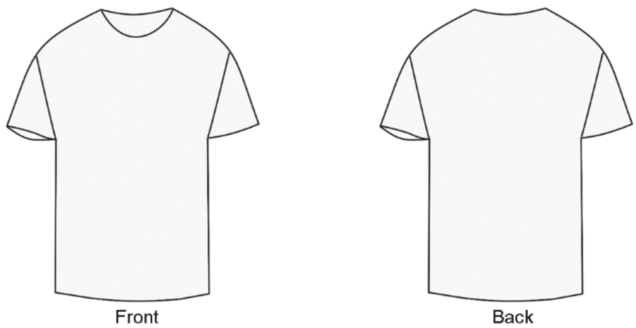

Figure 1. Style structure of the male underwear

Table 4. The size of male undershirts

Part	*L* [cm]	*BG* [cm]	*WG* [cm]	*SW* [cm]	*SL* [cm]	*NW* [cm]
Size	65	93	37	36	18	20

Note: *Fd* – fabric density, *WL* – the number of wales per unit length, *CL* – the number of courses per unit length, *T* – thickness, *M* – moisture permeability, *MR* – moisture resistance, *WH* – wicking height, *TR* – thermal resistance, HPR – heat preservation rate, HTC – heat transfer coefficient, *AP* – air permeability, *L* – length, *BG* – bust girth, *WG* – waist girth, *SW* – shoulder width, *SL* – sleeve length, *NW* – neck width. Fabric parameters were conducted with some instruments or equipment shown in the Detection of underwear parameters according to related standards, experimental environment by GB/T6529-2008 (ISO 139:2005): temperature (20±2) °C. humidity (65±4)% .

The undershirts and underpants are made by three-needle five-thread flat-seam (HW782T-01X356/UTD/AK, HIKARI (Shanghai) Sewing Machine Making Co., Ltd.) as shown in fig. 3.

Experimental procedure

Experimental requirements

Half an hour before the experiment, participants should enter to the artificial climate room with constant temperature and humidity. the ambient temperature was (25 ±2) ℃ (simulate daily temperature), the relative humidity was (65 ±5)%, and the wind speed ≤ 0.1 m/s. The study was ethically approved by the university and institute's ethics committees, and all the participants provided written informed consent.

In addition, the whole experimental process must be carried out in strict accordance with the following requirements:

– the test personnel only wore the experimental undershirt and underpants for the experiment,

- before each experiment, make sure that all undershirts and underpants for experiment are restored to its original state and placed in the artificial climate room for 24 hours,
- the tester randomly selects and tries on each undershirt and underpants in turn without being informed of the underwear fabric for the experiment, and
- each experimental link is strictly carried out in accordance with relevant standards (as shown in tab. 7), and the measurement shall be carried out after being taken off and put on again during the next measurement.

Table 5. Underpants fabric parameters and styles

No.	Fabric	*Fd* [gm^{-2}]	*WL*	*CL*	*T* [mm]	*M* [$gm^{-2}h^{-1}$]	*MR* [$°CPaW^{-1}$]	*WH* [cm per 10 minutes]	*TR* [$°Cm^2W^{-1}$]	HPR [%]	HTC [$Wm^{2}°C^{-1}$]	*AP* [mms–1]
P1	78%cotton 17%tencel 5%spandex	283	125	90	0.82	2.4952	3.1030	5.2	0.036	0.5826	26.39	1582.36
P2	55%/bamboo fiber 45%cotton	157	100	80	0.76	2.3547	3.3395	5.8	0.021	0.5831	18.05	2283.57
P3	75%/bamboo fiber 20%cotton 5%spandex	110	115	98	0.71	1.7836	2.378	4.6	0.023	0.6097	23.49	1492.84

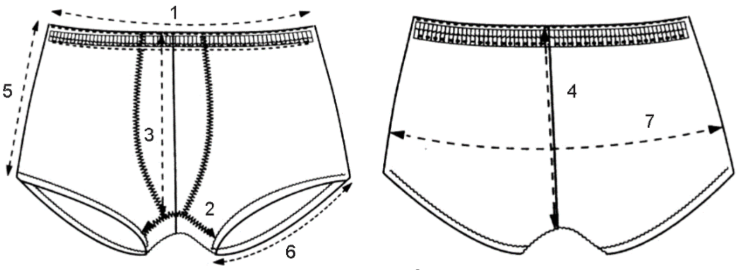

Figure 2. Style structure of male underwear

Table 6. The size of male underpants

No.	Part	Size [cm]	No.	Part	Size [cm]
1	Waist girth/2	34.0	5	Side seam length	25.0
2	Crotch width	13.5	6	Foot opening/2	21.0
3	Front middle length	20.5	7	Hip girth/2	42.0
4	Rear middle length	21.5			

Note: *Fd* – fabric density, *WL* – the number of wales per unit length, *CL* – the number of courses per unit length, *T* – thickness, *M* – moisture permeability, *MR* – moisture resistance, *WH* – wicking height, *TR* – thermal resistance, HPR – heat preservation rate, HTC – heat transfer coefficient, *AP* – air permeability.Fabric parameters were conducted with some instruments or equipment shown in the Detection of underwear parameters according to related standards, experimental environment by GB/T6529-2008 (ISO 139:2005): temperature (20±2) °C, humidity (65±4)%.

Dynamic and static evaluation indexes

During the exercise, the experimenter enters the artificial climate room (as shown in fig. 4) and stands still for 20 minutes to adapt to the environment. The experimenter moves according to the experimental posture shown in tab. 7 (*i.e.* sitting 10 minutes → stand still

Figure 3. Flat-seam machine

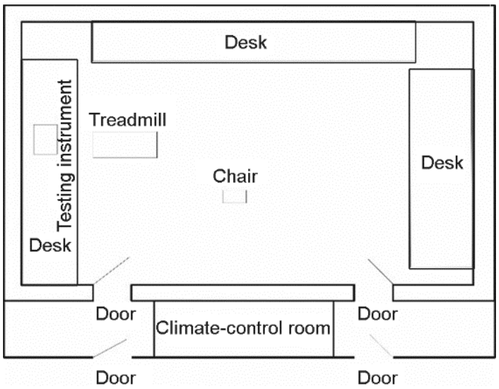

Figure 4. Climate chamber structure

5 minutes → squat 3 minutes → lift leg 2.5 minutes → jogging 20 minutes → rest 10 minutes). The data collector asks the experimenter about heat-moisture comfort of designated body parts to calculate the subjective value and records the relevant data of objective according to fig. 5.

Table 7. Experimental posture

No.	Posture	Posture description
S1	Sitting position	The sitting posture is maintained for 10 minutes
S2	Standing posture	Stand still for 5 minutes
S3	Squat	Squat down completely for 3 minutes
S4	Leg lift	Lift the leg to 90°, keep it down after 15 seconds, and lift the left and right legs once each, lift each leg 5 times.
S5	Jogging	Jogging on the treadmill for 20 minutes (speed control at 6.5km/h)
S6	Rest	10 minutes

Dynamic and static evaluation indexes

During the exercise, the experimenter enters the artificial climate room (as shown in fig. 4) and stands still for 20 minutes to adapt to the environment. The experimenter moves according to the experimental posture shown in tab. 7 (*i. e.* sitting 10 minutes → stand still 5 minutes → squat 3 minutes → lift leg 2.5 minutes → jogging 20 minutes → rest 10 minutes). The data collector asks the experimenter about heat-moisture comfort of designated body parts to calculate the subjective value and records the relevant data of objective according to fig. 5.

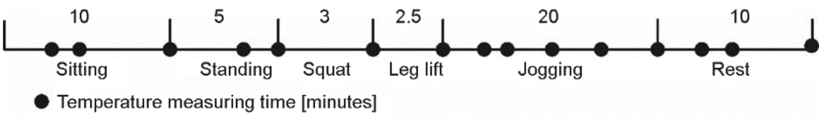

Figure 5. Time distribution of thermal and humidity measurement in human body parts

Detection of underwear parameters

The experiments were conducted with Sweat Hot Plate Tester (Northwest Testing Technology Company of the United States), YG(B)606E Fabric thermal insulation tester (Wenzhou Darong Textile Instrument Co., Ltd.), YG(B) 461D-II digital fabric air permeability tester (Wenzhou Darong Textile Instrument Co., Ltd.), YG (B) 216-II fabric moisture permeability tester (Wenzhou Darong Textile Instrument Co., Ltd.), YG (B) 141D digital fabric thickness meter (Wenzhou Darong Textile Instrument Co., Ltd.), Y(B)802G constant temperature oven (Wenzhou Darong Textile Instrument Co., Ltd.), LCK-800 Textile capillary effect tester (Shandong Textile Science Research Institute), the results are shown in tabs. 3 and 5.

Objective evaluation

Skin temperature is an important physiological parameter that reflects the degree of cold and heat stress of human body and the state of heat exchange between human body and environment. The existing studies basically regard skin temperature as a human physiological parameter closely related to thermal comfort and thermal sensation [22]. In the thermal comfort determination part of human comfort model, skin temperature is used as the physiological index of human thermal comfort determination in this paper. According to the mechanism of thermal comfort and thermal sensation, human skin receptors play an important role in the generation of thermal comfort and thermal sensation. Huizenga *et al.* [23] established the models of local thermal sensation, local thermal comfort, global thermal sensation and global thermal comfort according to the skin temperature of each part and its change rate. Sun [24] established the relationship between thermal sensation and skin temperature through a large number of subjective sensory experiments. Tong *et al.* [25] studied the relationship between average skin temperature and heat sensation.

One of the three conditions for human thermal comfort proposed by Fanger [26] is that the average skin temperature should meet the given comfort requirements. Bulcao *et al.* [27] studied the influence of skin temperature and body temperature on human thermal comfort, and thought that human thermal comfort depended on skin temperature to a great extent. Because the subjects in this paper only wear customized jackets and underpants, the body temperature collection sites mainly include chest, back, hip, and thighs.

Therefore, in order to study the influence of underwear on the local thermal and humidity comfort of human body, the chest, back, hip, and thighs are selected as the measuring points of temperature and humidity. Use physiological measurement system AMI 3179TU (Japan AMI Techno Co., Ltd.) to measure thermal and humidity of human, and the instrument is shown in fig. 6. The dynamic and static dressing experiments mainly focus on the effects of heat and moisture comfort produced by various parts of underwear. Each part can be scored separately, and finally the average value of all the participants is calculated as the overall evaluation value.

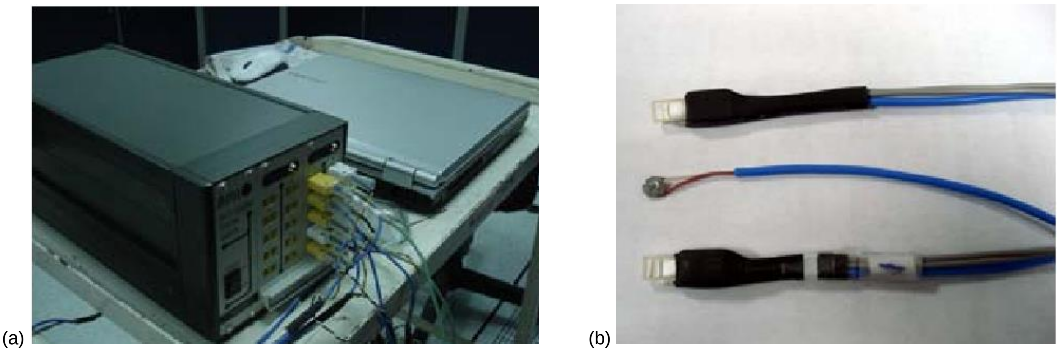

Figure 6. Heat and moisture measuring system; (a) measuring system and (b) sensor

Subjective evaluation

Subjective thermal sensation evaluation according to ISO 10551-2001, *Ergonomics of Thermal Environment Evaluates Impact of Thermal Environment by Subjective Judgment Scale*, overall subjective evaluation is carried out, as shown in fig. 7.

The subjective evaluation scale of moisture feeling adopts a five-level scale (as shown in fig. 8), with a minimum score 0 and a maximum score 4. The greater the score is, the more obvious the moisture feeling is. According to the wet feeling of chest, back, hip, thighs, *etc.*, the overall score is made according to the scale.

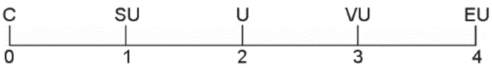

Figure 7. Subjective evaluation scale of thermal feeling; *level 0 comfortable (C), level 1 slightly uncomfortable (SU), level 2 uncomfortable (U), level 3 very uncomfortable (VU), and level 4 extremely uncomfortable (EU)*

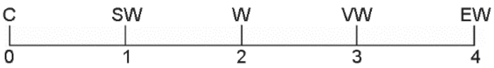

Figure 8. Subjective evaluation scale of moisture feeling; *level 0 comfortable (C), level 1 slightly wet (SW), level 2 wet (W), level 3 very wet (VW), and level 4 extremely wet (EW)*

In addition, in order to ensure the validity of subjective evaluation, Kendall correlation coefficient (KCC) test is used to test whether the subjective evaluation among five subjects is consistent.

Kendall correlation coefficient test of subjective evaluation results

In order to verify the consistency of the evaluation results among the five evaluators (*i.e.* 5 testers), Kendall is used to analyze whether the judgment criteria of the evaluators are consistent and fair. The KCC also known as harmony coefficient, is a method to express the correlation degree of multi-rank variables:

$$k = \frac{12\sum_{i=1}^{\beta} R_i^2 - 3\alpha^2\beta(\beta+1)^2}{\alpha^2\beta(\beta^2-1)} \tag{1}$$

where α is the number of judges or testers, β – the number of observation objects or observation indicators, and R_i – the sum of the ranks of the i observation object.

It is generally believed that Kendall co-ordination coefficient < 0.2, it indicates poor consistency. Between 0.2 and 0.4, the consistency degree is general. The consistency between 0.4 and 0.6 is moderate. Between 0.6 and 0.8, the consistency degree is strong. Between 0.8 and 1.0, the consistency is very strong.

Results and discussion

The experiment lasted 50.5 minutes, and the whole process data was recorded and connected into a curve chart. In this paper, taking (S1,P1) and (S2,P2) as examples, the objective and subjective evaluation results of the temperature and humidity at the measuring points on the body surface in the wearing experiment were analyzed.

Results and discussion of objective evaluation

Thermal comfort

It can be seen from fig. 9 that under the conditions of sitting, standing, squat and leg lift, the combination of undershirts and underpants of different fabrics has little difference in

Figure 9. Temperatures in different motion states; CT – chest temperature, BT – back temperature, HT – hip temperature, and TT – thigh temperature

skin temperature. There is a certain difference in temperature in jogging state, which shows that there is no obvious difference in the influence of underwear combination of different fabrics on human skin temperature in static or light exercise state, but there is a big difference in strenuous exercise (running state). Therefore, when studying the thermal comfort of underwear fabrics, it should be studied in dynamic state to have certain accuracy.

Specific difference analysis is as follows.

– During the period of sitting and standing, because the human body is in a stable and peaceful physiological state, the temperature changes in the hip and thighs are relatively stable, and the temperature in the back is higher and the temperature in the thighs is the lowest in the measured parts. Taking S1,P1 as an example, the highest temperature in the back reaches 35.77 ℃, and the thigh temperature ranges from 32.25 ℃ to 32.36 ℃. The chest temperature decreased in the first 10 minutes and then increased, indicating that the chest has gradually adapted to the environment.
– During the period of squat and leg lift, the temperature of thigh rises obviously at the beginning of squatting, because after squatting, the pressure of thigh is too high, the blood flow speed increases rapidly, which accelerates the metabolism of human body and generates more heat.
– After entering the jogging stage, the temperature of hip and thighs showed an upward trend, with little increase. For example, when wearing S1,P1, the temperature of hip at the beginning of running was 33.26 ℃, and the temperature at the end of running was 34.37 ℃. The thigh temperature at the beginning of running is 33.81 ℃, and the temperature at the end of running is 35.59 ℃, because more heat generated by human body movement causes the skin temperature to rise. However, the temperature of chest and back rises first and then drops, which is because the chest and back are affected by the heat generated by human exercise, but the skin temperature of these two parts decreases with time, because the sweat glands in chest and back are concentrated, and exercise produces a lot of sweat, which evaporates and takes away some heat. At the same time, with the increase of human exercise time, the skin temperature gradually reaches a stable state, that is, when the body temperature rises to the self-regulation point, In order to maintain body temperature, the human body began to dissipate heat by sweating. At this time, sweat evaporated and lost to the external environment, which took away a lot of heat, so the body surface temperature began to drop. Because if there is not enough heat dissipation by skin, it will increase the heat dissi-

pation in the form of sweating to keep the body temperature constant. Generally speaking, when the heat in the body accumulates rapidly due to exercise, the excess heat generated by the human body needs to be lost through sweating, which is one of the main forms of the body's spontaneous thermoregulation reaction. The average temperature of chest, back, hips, and thighs during the whole running process is 35.66 ℃, 35.88 ℃, 33.93 ℃ and 34.91 ℃. It can be seen that the temperature of chest is the highest, followed by back.

– During the rest period, the metabolism of human body stops producing heat, but sweat is still evaporating, which means that the heat of human body is still losing. However, as time goes by, the temperature of human body drops to a certain state, and human body functions will play a role again, producing a certain amount of heat to supplement the lost heat. This is the self-regulation of human body function. The reason why the temperature of chest and back drops rapidly is mainly due to the concentrated distribution of sweat glands in chest and back, as shown in humidity, fig. 13. Because a large amount of sweat accumulated in chest and back is still evaporating and losing, the temperature of body surface continues to drop for a certain period of time, and then gradually rises to the temperature when sitting quietly. When the subjects wear S1,P1, the temperature of chest and back drops greatly, because cotton is easy to absorb moisture, but it is not suitable for moisture removal, so cotton underwear is always in a wet state, which leads to lower skin temperature.

During the whole experiment, the temperature of chest, back, hip, and thighs changed with the change of exercise state. Among them, the temperature of the back is higher than that of other parts, and the temperature of the front chest surface changes more than that of the back. Therefore, when designing underwear, we can focus on the design of thermal comfort on the back.

Moisture comfort

It can be seen from fig. 10 that during the period of sitting and leg lift, the change trend of the relative humidity of the subjects' body surface is also consistent, and the relative humidity is maintained at 35-40%, and the body surface humidity does not rise immediately after the beginning of jogging, indicating that the heat generated by exercise at this time is mainly dissipated by skin radiation and evaporation. This is because the body temperature has not yet reached the sweating adjustment point. With the increase of exercise, the accumulated

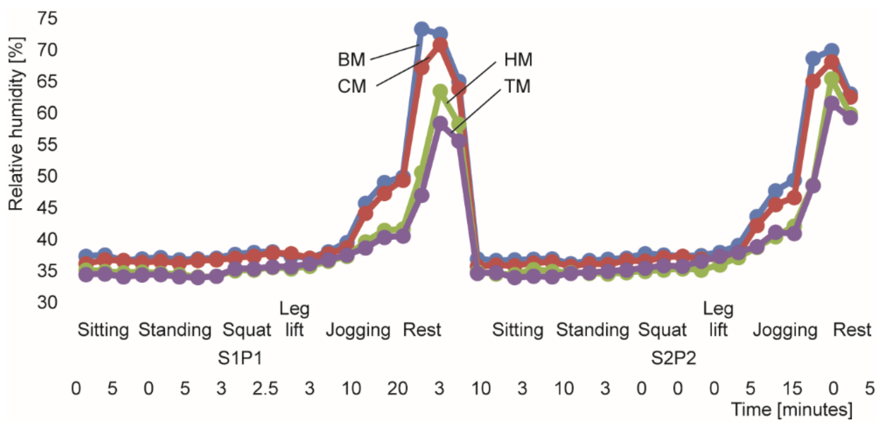

Figure 10. Moisture in different motion states; CM – chest moisture, BM – back moisture, HM – hip moisture, TM – thigh moisture

heat in the body increases, the body temperature rises beyond the sweating adjustment point, and the skin begins to sweat. At this time, the relative humidity of the body surface begins to rise. After stopping exercise, the relative humidity continued to rise and reached the maximum value, then began to decline slowly, and finally returned to the body surface humidity during meditation. This is because when people stop exercising, all the thermogenic functions in the body will not stop immediately, so the sweating behavior of the human body will lag for a few minutes before it weakens and stops gradually. With the gradual decrease of sweating, the humidity on the body surface decreases and gradually returns to its original size.

Specific difference analysis is as follows.

During the period of sitting and leg lift, the relative humidity of human chest, back, hip, and thighs is relatively stable, indicating that there is no exercise or slight exercise, which has no obvious influence on human humidity comfort. During the period of jogging, the accumulated heat in the body makes the body temperature rise. At this time, it is not enough to adjust the body temperature only by convection and conduction, and the human body will dissipate heat in the form of sweating. If the clothing fabric fails to transfer heat and moisture to the external environment in time, the body surface temperature and relative humidity, especially relative humidity, will rise rapidly, and the wearer will feel uncomfortable, such as sultry, damp, and even sticky. Sweat transfer mainly depends on the moisture transfer ability of clothing fabrics, so the feeling of thermal and wet comfort is mainly affected by the moisture transfer ability of clothing fabrics. Because of the differences in the properties of different underwear fabrics, when wearing different combinations of underwear (tops and underpants), the humidity of the subjects is different, and the relative humidity rises in order, but the trends are the same. The subjects began to exercise, and with the accumulation of heat in the body, the human body began to sweat. The relative humidity of chest and back when wearing cotton jacket was higher than that when wearing bamboo fiber. With the increase of sweat, sweat enters the inner surface of the fabric, is transported to the outer surface of the fabric through the gaps and holes between yarns and fibers in the fabric, and then evaporates into water vapor, which diffuses and moves to the outer space. The moisture transfer in the clothing mainly depends on the capillary channel of the fabric, and depends on the wettability and wicking ability of the fabric. Therefore, when the subjects wear clothes with good liquid water conductivity, they can transfer the gaseous and liquid sweat generated by heat accumulation in the body in time, so the relative humidity on the body surface will be kept at a low level. Taking S1,P1 as an example, the relative humidity of chest, back, hip, and thighs all showed an upward trend, and the relative humidity of back was the highest, followed by chest, with humidity change rates of 0.5850% per minute and 0.4800% per minute, respectively. The subjects stopped exercising and started to sit still. The residual heat in the body made the human body sweat for a short time, and a large amount of liquid sweat remained on the body surface. The humidity of the subjects' body surface mainly depends on the water absorption and moisture conductivity of the fabric. Although cotton fiber fabric has good water absorption, due to its poor moisture conductivity, the moisture can not be transferred to the external environment of the garment in time, so the body surface humidity value of the subject is higher when wearing the jacket. Taking the subject wearing S1,P1 as an example, the relative humidity of chest, back, hip, and thigh is above 45%.

During the whole experiment, wearing underwear with different fabrics, although the highest humidity reached by different parts of the subjects is different, the humidity change trend is the same. Generally, the sweat glands on the back of the human body are distributed in a larger density and sweat is also large, so the highest humidity reached by the back is higher than that of the chest, and the humidity change of the back can better reflect the difference of thermal and wet comfort of different fabrics.

In a word, the thermal humidity values of chest, back, hip, and thighs of human body change with the change of exercise state. Different underwear fabrics have different thermal humidity values. When wearing S2,P2, the body surface temperature decreases with the increase of humidity during exercise, and the body temperature quickly recovers with the decrease of humidity after stopping exercise. When wearing S1,P1, the body surface temperature drops slowly, and the high humidity on the body surface lasts for a long time. In the final analysis, the thermal humidity value of fabric mainly lies in the fiber, and the moisture absorption of fiber is mainly reflected in the inner layer of fabric, which has a significant impact on the heat and moisture transfer process of fabric: after the fiber absorbs moisture, the thermal conductivity of fiber increases and the heat transfer of fabric is strengthened, after the fiber absorbs moisture, the water vapor concentration in the surrounding air is reduced, and the moisture transmission in the inner layer of the fabric is strengthened, while that in the outer layer is reduced, and moisture absorption and heat release from fiber moisture absorption significantly increases the surrounding temperature, which slows down the heat transfer from the inner layer to the outside to a certain extent. Meanwhile, the increase of temperature increases the water vapor diffusion coefficient and strengthens the water vapor transfer.

Results and discussion of subjective evaluation

During the wearing experiment, the subjects made subjective evaluation on the thermal and wet comfort of different combinations of underwear, and the average scores of various thermal and wet sensory factors are shown in tab. 3. Because evaluation adjectives are negative descriptions of comfort, the higher the score of each factor, the worse the thermal and wet comfort.

In addition, KCC analysis was carried out on all subjective evaluation results of five subjects, the results show that asymptotics significance value = 0.000 < 0.05. Because the original hypothesis KCC is 0, *i. e.* completely inconsistent, the original hypothesis is not valid (obviously not equal to 0), whereas it shows Kendall consistency. The KCC (Kendall W^a) is greater than 0.7, indicating that the comfort evaluation of underwear by five professionals has a high consistency level and the data are reliable, that is, the subjective evaluation results of five subjects are valid.

Therefore, the average value of subjective evaluation results of five subjects on wearing experimental underwear can be used as the final subjective evaluation value of overall thermal humidity of experimental underwear.

The subjective evaluation results of thermal and humidity comfort still take (S1,P1) and (S2,P2) as examples, and the overall subjective evaluation values of thermal and humidity are shown in tab. 8.

It can be seen from tab. 8 that the trend of subjective evaluation results of subjects heat and humidity is the same, that is, the heat feeling is the worst just after exercise, and the heat feeling is better at the evaluation time after rest. Wet feeling is most obvious during rest.

Specific difference analysis is as follows.

During sitting, because the human body is in a stable and peaceful physiological state, the subjective feeling of the human body is relatively comfortable as a whole, and there is no difference in the temperature and humidity feeling of each part, that is, the heat and humidity feeling of the subject's body surface is stable, that is, there is no obvious uncomforta-

Table 8. Subjective evaluation of overall thermal and moisture comfort in S1,P1 and S2,P2

	Subjective evaluation of thermal sensation		Subjective evaluation of moisture sensation	
	S1,P1	S2,P2	S1,P1	S2,P2
Sitting position	0.1	0.1	0.1	0.1
Standing posture	0.3	0.2	0.2	0.2
Squat	1.6	1.1	1.2	1.5
Leg lift	2.2	2.1	1.5	1.8
Jogging	3.6	3.0	3.3	3.0
Rest	2.2	1.8	3.7	3.1

ble feeling of heat and humidity, which is consistent with the objective evaluation results. In the process of squatting-leg lifting-jogging, the heat and humidity are in the rising stage, and the heat and relative humidity are obviously higher than those during meditation. At this time, the body temperature rises due to exercise, so the human body has obvious heat and humidity feeling. The heat and humidity feeling of wearing S1,P1 is stronger than that of wearing S2,P2. The reason why the temperature of S2,P2 is lower than that of S1,P1 in motion state is that the main way of heat dissipation of human body in motion state is the evaporation and heat absorption of liquid sweat on skin or clothing surface, so the liquid water transfer (moisture conductivity) of fabric has an important influence on it. After a period of rest, the body surface humidity reaches the highest level. Although the body surface temperature drops due to sweating, there is still a lot of heat generated during exercise in the body. At this time, the body temperature is still high, and a lot of sweat accumulated on the skin surface makes people feel uncomfortable. At the end of the rest, the heat generated by exercise has basically been transferred to the external environment through clothing, and the temperature of the body surface has also risen, so the subjects no longer feel uncomfortable like sultry and damp, but the wet feeling is still obvious, among which the wet feeling of chest and back is the strongest. Especially, the wet feeling of wearing S1,P1 is more obvious, which may be due to the wet feeling of cotton jacket affecting the whole wet feeling. Because of cotton fabric, although cotton fabric has good hygroscopicity, its moisture conductivity is poor, and cotton fabric absorbs a lot of water, resulting in a strong sticky wet feeling. The S2,P2 fabric has good moisture conductivity, which makes heat loss and humidity transfer faster, thus reducing the humidity of the whole sportswear. It shows that underwear fabric has certain influence on heat and humidity feeling, and the specific influence mechanism needs to be modeled for in-depth analysis. It also shows that the moisture and heat conductivity of single fiber is not as good as that of composite fiber, because the thermal properties of single material fabric are closely related to the material characteristics and lack the ability to change. The thermal properties of composite fabric with multiple materials can combine the characteristics of different materials and show better adaptability to heat and moisture conduction.

In a word, the subjective evaluation of overall heat and humidity is basically consistent with the objective data, and the higher the temperature and humidity, the worse the subjective comfort of heat and humidity. However, in the subjective evaluation of heat and humidity in static state, the subjects think that the temperature and humidity of each part are basically the same, and can not clearly distinguish the difference of temperature and humidity of each part. According to the subjective evaluation results, the subjects subjectively think that the temperature of chest, back, hip, and thighs after jogging is higher than that after sitting quietly. In fact, because the body sweat takes away heat after jogging, the temperature is lower than that after walking, which is obviously different from the subjective evaluation of thermal sensation.

The fabric of underwear has a significant impact on the thermal and wet comfort of dynamic human body. The CFD is used to simulate the temperature change of human skin and realize the visualization of human temperature distribution when wearing underwear.

The CFD model

Heat and moisture transfer principle

When human body metabolizes and produces heat during exercise, it also produces gaseous sweat and liquid sweat, which exchange heat and moisture with the surrounding environment, thus ensuring the heat balance of human body. However, the processes of heat transfer and moisture transfer in fabrics are coupled with each other, and the processes are very complex. Many complex phenomena occur in the process of heat transfer and moisture transfer. One common feature of these phenomena is displacement or movement, so it can be called transport phenomenon. In essence, the transport phenomenon is mass transfer and force transfer, that is, mass transfer and momentum transfer. Because mass transfer and momentum transfer are inseparable from energy transfer, the transfer of heat and moisture in the air layer is bound to be accompanied by energy transport. Because the experimental underwear is custom-made clothing, and the underwear is fitted to the body, the microclimate between underwear and human body can be ignored, and the heat and moisture transfer process is shown in fig. 11.

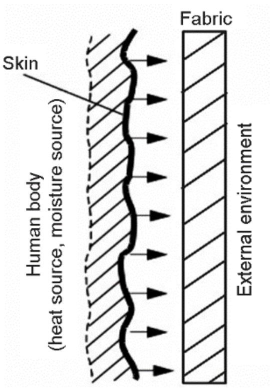

Figure 11. Schematic diagram of human-clothing-environment heat transfer

Establishment of CFD model

The main purpose of CFD is to carry out numerical simulation calculation of flow state. On the basis of 3-D geometric model of human body, a thermophysiological model of human body can be established, and on this basis, the heat and moisture generation and transfer process between human body, clothing and environment can be simulated by combining the heat and moisture transfer model of clothing materials, which is the basis of thermal functional design of clothing. At present, many researchers have applied CFD to the evaluation of clothing comfort and the design of functional clothing, such as the simulation of human physiology and blood flow process, and the simulation of heat and mass transfer process between human body, clothing and environment.

The CFD is a comprehensive subject which integrates fluid mechanics, computer science of numerical analysis of heat transfer and so on. The use of CFD is conducive to saving the experimental cost, and can predict the flow results under some difficult experimental conditions by CFD. Under the condition of ensuring the accuracy of the model and simulation results, the experimental cost can be greatly reduced. Moreover, CFD can complete some experiments which are difficult to carry out in reality (such as studying the heat transfer process), or which have unclear experimental results and need to be guessed by some means. In this paper, CFD model is used to explore the heat transfer mechanism of human body wearing underwear. To verify the effectiveness of this model, it is compared with the traditional experimental results. In addition, CFD simulation follows the laws of mass conservation, momentum conservation and energy conservation.

On the basis of dressing human body model and grid design, CFD calculation is carried out, and its flow chart is shown in fig. 12. After reading the files generated by pre-processing, ANSYS software solver checks the calculation domain unit and grid volume, sets the solver, determines the models and parameters of fluid and heat transfer, sets the boundary conditions of calculation domain, starts iterative calculation after initialization, and finally performs post-processing.

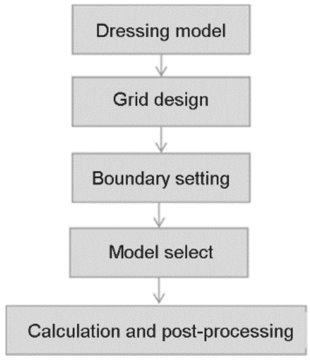

Figure 12. The CFD simulation process

Dressing model

According to the average body size data of the subjects, a human body model is established in combination with Poser and Solidework, and underwear (underwear) is made by ET according to body size. Finally, the human body model and underwear pattern are imported into CLO3D to design the dressing model. Naked model and figure for dressed model are shown in fig. 13.

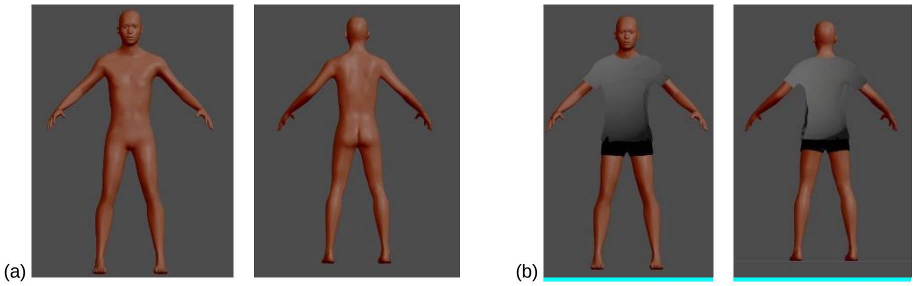

Figure 13. Human body model; (a) naked model and (b) dressed model

Grid design

The type and number of grids have an important impact on the speed and accuracy of solution. The number of grids should be balanced between calculation accuracy and solution time. Too many grids will cause a waste of computing resources. Grid division is the foundation of simulation and the most workload in the whole simulation work. Increasing the understanding of grid can help to improve the modeling level and simulation accuracy. Many problems, such as poor simulation results, large errors and difficult convergence, are related to the selection and division of grids. At present, the grid division software mainly includes Gambit, ANSYS ICEM and so on. In this paper, ICEM is adopted to realize grid design, because ICEM can efficiently partition complex geometric structures, and the computer can automatically generate grids after selecting parameters such as grid types after processing geometric structures, as shown in fig. 14. The dressed human body model is divided into tetrahedrons. In order to ensure the stability of the flow field, a multi-layer prismatic grid is set on the surface of the model, with a grid size of 50 mm and a total of 5982365 nodes. The Growth rate is 1.2.

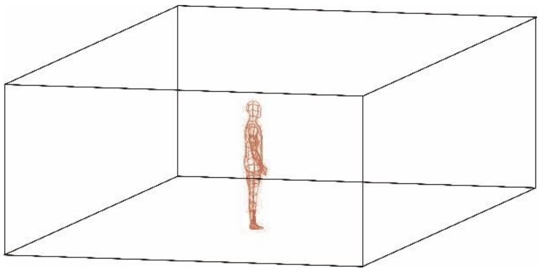

Figure 14. Division of grid area

Boundary setting

The boundary conditions are provided by human experimental conditions and human thermal response model. The wall temperature, air temperature and wind speed of climate chamber are the same as those of human experimental conditions. The surface temperature of the corresponding parts of the dressed human model is calculated by human thermal response model. After setting the model and boundary conditions and determining the under-relaxation factor, initialize and start iterative calculation until convergence to obtain the sensible heat exchange between human body and environment.

Physical model selection

Fluid and heat transfer models need to be selected for CFD calculation. Because the research goal of this paper is different temperature and humidity of underwear due to the change of movement characteristics and clothing characteristics, k-ε model is selected.

The re-normalisation group (RNG) k-ε model is the simplest complete turbulence model, and it is also the most commonly used CFD model. It has high stability and calculation accuracy, is widely used, and has good prediction ability. Moreover, RNG k-ε model is an easily convergent model under various flow conditions. Because the experimental clothing is tight underwear, the accuracy of the near-wall surface is required to be high. If the grid is of high quality, the RNG k-ε model can be used, and better calculation results are expected.

Calculation and post-processing

Because the fluid flow is dominated by the laws of physical conservation, and the governing equation is the mathematical description of the laws of conservation, the CFD simulation model is established according to the laws of mass conservation, momentum conservation and energy conservation.

Mass conservation equation

Any flow problem must satisfy the law of mass conservation. It refers to the increase of mass in fluid microelements in unit time and the net mass flows into the micro-elements in this time interval. According to this law, the mass conservation equation can be obtained as flow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho \vec{u})}{\partial x} + \frac{\partial(\rho \vec{v})}{\partial y} + \frac{\partial(\rho \vec{\omega})}{\partial z} = 0 \tag{2}$$

where ρ [kgm^{-3}] is the air density, $\vec{u}$, $\vec{v}$, and $\vec{\omega}$ [ms^{-1}] – the velocity vectors of fluid in x-, y- and z-directions, respectively, and t [s] – the time.

Momentum conservation equation

Any flow system must satisfy the momentum conservation equation. It means that the rate of change of momentum flowing in a micro-element with respect to time is equal to the sum of various external forces acting on the micro-element. According to this law, scalar forms of momentum conservation equations in x-, y- and z-directions can be derived:

$$\frac{\partial(\rho u)}{\partial \mathrm{t}}+\mathrm{div}(\rho u U)=\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+F_x \tag{3}$$

$$\frac{\partial(\rho \upsilon)}{\partial \mathrm{t}}+\mathrm{div}(\rho \upsilon U)=\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial y}+F_y \tag{4}$$

$$\frac{\partial(\rho \omega)}{\partial \mathrm{t}}+\mathrm{div}(\rho \omega U)=\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial z}+\frac{\partial \tau_{yz}}{\partial z}+\frac{\partial \tau_{zz}}{\partial z}+F_z \tag{5}$$

where P [Pa] is the pressure on the fluid microelement, U [ms^{-1}] – the closing speed, τ_{xx}, τ_{xy}, and τ_{xz} [Pa] – are components of viscous stress, τ, acting on the micro-element due to molecular viscosity action, and F_x, F_y, and F_z – the physical force on the microelement, if the physical force is only gravity and the z-axis is vertical upward, $F_x = 0$, $F_y = 0$, and $F_z = -\rho$g.

Energy conservation equation

Energy conservation is the basic law that the flow system of heat exchange must satisfy. It refers to the increase rate of energy in the micro-element body is equal to the net heat flow into the micro-element body plus the work done to the micro-element body by physical force and surface force. This law is actually the first law of thermodynamics:

$$\frac{\partial(\rho T)}{\partial t}+\mathrm{div}(\rho U T)=\mathrm{div}\left(\frac{k}{c_p}\mathrm{grad}T\right)+S_T \tag{6}$$

where C_p [Jkg^{-1}K^{-1}] is the specific heat capacity, S_T [J] – the internal heat source of fluid and the part where fluid mechanical energy is converted into heat energy due to viscous action, sometimes referred to as viscous dissipative phase for short, T [K] – the temperature, and k [Wm^{-1}K^{-1}] – the heat transfer coefficient of the fluid.

The CFD simulation results

Taking the thermal comfort test experiment of wearing S1,P1 as an example, the human thermal response model provides skin temperature as the boundary condition for CFD simulation, and the sensible heat calculated by CFD is used as the input value of the human thermal response model. Figure 15 shows the CFD system calculating the changes of human body temperature in different motion states.

Error analysis

The temperature of human chest, back, hip, and thighs in different motion states is calculated by CFD model, and the error of the two data is obtained by comparing the simulated value with the experimental value, as shown in fig. 16.

It can be seen from the fig. 16 that the simulated temperature error of the chest is the largest, the mean absolute deviation value is 0.41 and the maximum absolute error value is 0.53. Followed by the back, the mean absolute deviation is 0.30, and the maximum absolute error value is 0.43. The main reason for this is that the chest and parts are the main concentrated areas of human sweat glands. In real-life experiments, the human body will sweat at the same time during heat production, which causes the human body temperature to change for a certain period of time, but CFD cannot realize this process, which is also the limitation of CFD simulation. The simulation effect of hip is the best, and the maximum absolute error is 0.05.

Generally speaking, the error between CFD simulation value and experimental measurement value is small, which can truly reflect the skin temperature of human body in different sports states. Traditional subjective evaluation and laboratory test methods of human

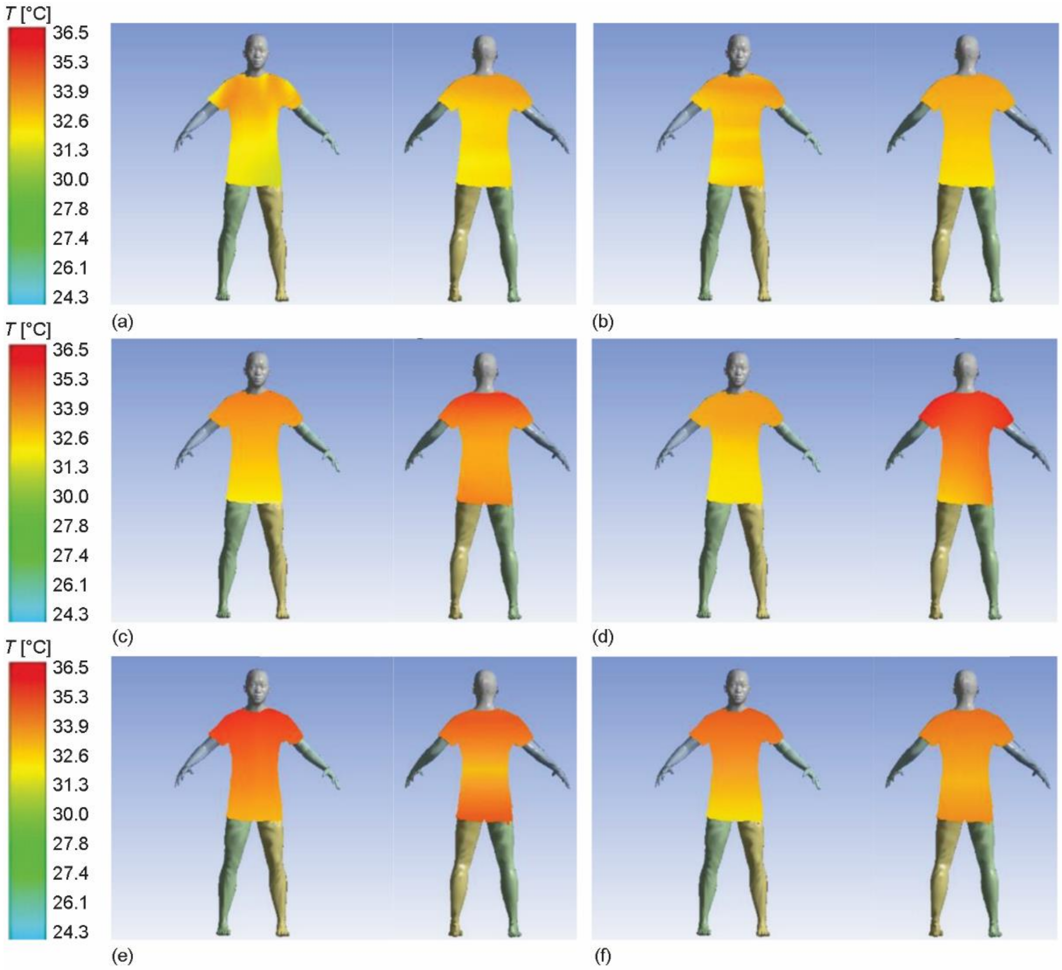

Figure 15. Temperature simulation; (a) sitting, (b) standing, (c) squat, (d) leg lift, (e) jogging, and (f) rest

body have the disadvantages of high cost and long measurement period. However, CFD simulation method has the advantages of low cost, easy change of test parameters and high repeatability of test. CFD simulation method greatly reduces the experimental cost, avoids uncontrollable factors in the experimental process and improves the experimental efficiency.

Conclusions

In this paper, underwear with different fabrics is selected as experimental clothing. Through fabric test, human wearing experiment and subjective feeling investigation, body surface temperature and humidity are selected as measurement indexes, and subjective evaluation is taken as a supplement to objective temperature and humidity test. The thermal and wet comfort of wearing underwear with different fabrics for different limb movements is systematically studied. The quantitative research provides guidance for the development of underwear products and provides reference for consumers when choosing such products. The application prospect of CFD technology in the field of clothing comfort research is prospected. The main conclusions of this topic are as follows.

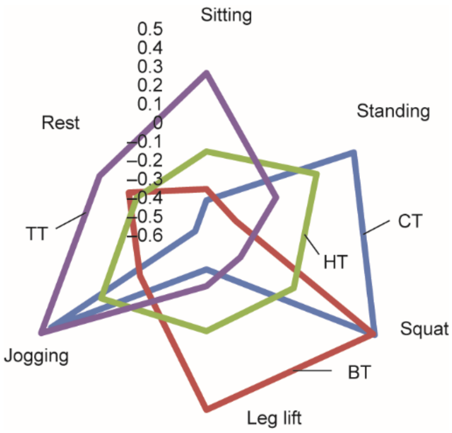

Figure 16. Temperature error

- The matching of upper and lower underwear with different fabrics has certain influence on thermal comfort. The thermal and wet comfort of pure cotton underwear is worse than that of blended or interwoven underwear, which is consistent with the previous research results (the thermal and wet comfort of multi-fiber fabrics is better than that of single fiber fabrics), and the relationship between human physiology and thermal and wet comfort of clothing is analyzed more comprehensively.
- The temperature and humidity of chest, back, hip, and thighs of human body change with the change of exercise state, and the results of thermal and humidity comfort of each part are different, and the thermal and humidity of chest and back change greatly, so when designing underwear, the design of thermal comfort of back can be emphasized. In addition, the subjective evaluation results of thermal and wet comfort are basically consistent with the objective evaluation results, which verifies the relevance between objective physical indicators of thermal and wet comfort of fabrics and subjective feelings of human body.
- The simulated values obtained by CFD simulation system are in good agreement with the experimental measured values, which can be effectively used to predict human skin temperature, and overcome the individual differences in human experiments and avoid danger from exposure to repeated high environmental temperature during experiment.
- Further work to be done. In the future research, more underwear samples of fabrics should be selected, and the influence of fabric composition ratio on thermal and wet comfort of underwear should be studied more systematically, so as to provide better guidance for developing underwear fabrics with superior thermal and wet comfort. According to different wearing environments, different experimental methods are designed to study the main factors that affect the thermal and wet comfort of wearing, so as to provide a more comprehensive theoretical basis for the development of such products.

Acknowledgment

The authors would like to acknowledge the financial support from the Fundamental Research Funds for the Central Universities (2232020G08) and national key research and development plan *Science and technology in Winter Olympic Games* (2019YFF0302100).

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Paper submitted: March 10, 2019
Paper revised: July 27, 2019
Paper accepted: August 13, 2019