Journal of Fiber Bioengineering and Informatics 14:2 (2021) 113–126

Cite as: Q. Huang et al.
doi:10.3993/jfbim00368

Influence of Fabric Properties on Clothing Thermal Comfort under Different Environmental Temperatures ⋆

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Abstract

Temperature greatly influences the choice of clothing type. It is difficult to study the effect of temperature on the performance of a garment and the used fabric, as changes in temperature varies significantly within a year, a season or even a day. This research paper studied the effect of fabric properties on human thermal comfort under different environmental temperatures. The main methodology entails using a CAD software to simulate clothing thermal comfort value of a garment made of 6 fabric types, then conducting analysis on the simulation results. The results indicate that fabrics perform better within a range of temperature. The further they stray from the range, the smaller the impact of the fabrics on human comfort. The results from the methodology also demonstrates that activity types and temperature greatly affect the comfort value.

Keywords: Textile CAD technology; Mathematical modeling; Mathematical analysis; Big data model

1 Introduction

Clothes have played an indispensable role in people's daily life, they not only protect the human body from injuries, they also help people adapt to stress in varying and extreme temperatures (i.e., the cold or the heat).There is a demand for a software tool that can predict which garment is suitable for a person to wear in relation to the local weather and climate. Clothing companies are also interested in a software tool that can help them predict the thermal comfort demand of customers.

A key factor that influences the decision-making process of the consumer when choosing clothes is the comfort experience. Thermal comfort value plays a key role in a person's comfort experience and is susceptible to the environmental thermal condition (i.e., temperature, wind velocity,

⋆Project supported by EU Horizon 2020 and University of Manchester through the project entitled "Fashion Big Data Business Model" (project No. 761122).

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humidity). To acquire information on the best physiological fit of a garment for a particular consumer group, the software is designed to predict the comfort value of a clothing given a set of environmental thermal condition.

The environmental thermal condition is prone to change, in many cases a significant change can take place within a day. Take the environmental temperature as an example, In the example shown in Figure 1, the temperature ranges from 21 °C to 9 °C within 17 hours. indicating that the data which the software needs to deal with are tremendous. With a generic temperature setting based on climate, it will be difficult for people to clearly assess the comfort temperature range. Hence, this dissertation simplifies and quantifies the changeable temperature condition for evaluating clothing comfort.

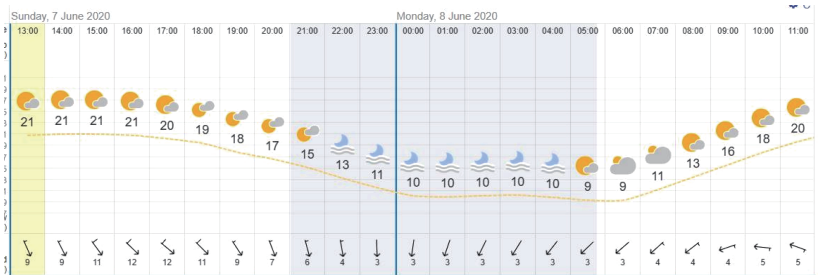

Fig. 1: A hour-by-hour forecast in London[1]

2 Methodology

This experiment uses the "e-thermal CAD" website and "s-smart" software to simulate the thermal environment of the human body[2]. The clothing thermal CAD system is based on a multi-disciplinary math model and previous clothing thermal CAD systems[3-6]. The *Introduction for E-thermal Simulation* manual is available on the e-thermal website[7].

The s-smart software has an algorithm that takes into consideration the wind speed, relative humidity, and temperature to simulate the environmental condition. Wind speed is the velocity of air relative to a fixed point on earth, and relative humidity is the ratio of the vapor partial pressure in the air to the saturation vapour pressure of water under the same temperature condition[8]. Relative humidity impacts whether people feel dry or wet physiologically.

In this study, there are 6 fabric types and 3 temperature condition, each type of fabric will be simulated in each temperature condition once, with a total of 18 times of simulations. Figure 2 shows the simulation result of Fabric ID 007. A single simulation has a set of 6 graphs as follows: comfort value, dampness sensation, thermal sensation, skin relative humidity, core temperature and skin temperature. Each simulation has one set of graphs for each temperature condition, so there in total are 18 sets of graphs, as shown in Figure 4 to 21.

Besides the environmental condition, the software also requires input of other data.

2.1 The settings of fabric

Table 1 is a list of all the fabric types and their respective properties. Figure 2 are images of the 6 fabric types. These 6 fabric types are all suitable for making the same clothing style, and the

data of the fabric content are collected from a company.

Table 1: The data of fabrics

Fabric ID	Fiber Content	Thickness (cm)	Fabric Porosity	Fabric gas tortuosity	Liquid water contact angle (deg)	Fabric thermal conductivity (cal/s*cm *deg)	Membrane			
							Thickness (cm)	Composite	Water vapor Permeability (g/cm^2*day)	Thermal resistance (deg*cm^2* s/cal)
007	CO 56% PA 44%	0.031	0.55	1.82	146	1.16E-04	0.001	Coating 20% PU	0.048	263.2
008	PA 36.0 % PL 50.6 % EA 13.4%	0.079	0.7	1.44	0	1.41E-04	0.001	PU 11%	0.05	555.2
010	PA 78% EA 22%	0.096	0.74	1.35	138.02	1.32E-04	0.001	Unknown Membrane	0.091	718.2
013	PA 81.1% EA 18.9%	0.06	0.67	1.5	0	1.24E-04	0.001	PU 5%	0.046	483.9
017	PC 34% PL 23% WO 15% CO 4% PA 24%	0.116	0.75	1.33	140.66	1.39E-04	0.001	PU 5%	0.064	836.4
018	PL 67% VI 33%	0.046	0.65	1.54	118.12	1.25E-04	0.001	Coating 14%PU	0.1	368.8

Although the "s-smart" software database includes fiber types commonly used worldwide, such as wool, cotton and polyester, there are some new and unique manmade fiber types that are not included. In this study, they are substituted with Nylon and adjustments were made in the density. The density of the EA is 1.005 g/cm^3, the density of the PC is 1.17 g/cm^3, and the density of the VI is 1.48 g/cm^3. Similarly, all membranes will be substituted by PU through changing property settings.

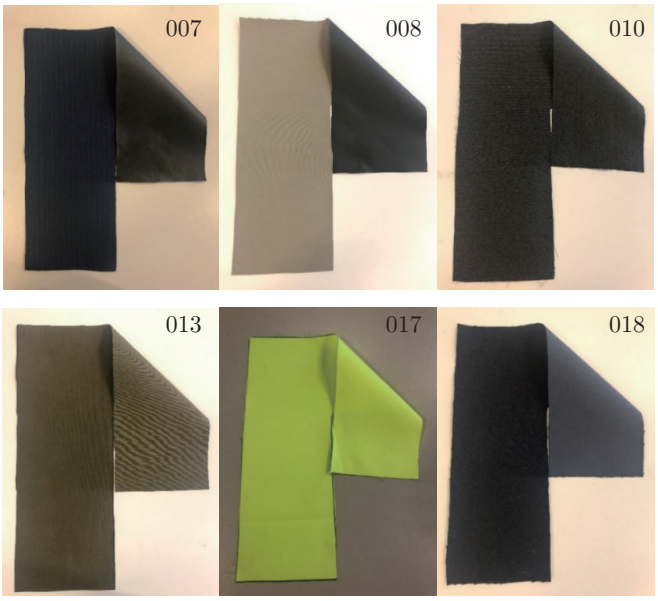

Fig. 2: The appearances of 6 kinds of fabric used in the research

2.2 The setting of other factors

Table 2 shows the settings of office activity, environment, human body and garment.

Table 2: The data of other factors

Office Activity	Environment	Human Body	Garment
Moving activity: 20 min Harder activity: 20 min Standing activity: 20 min (all outdoor)	High Temp: 24 °C Mean Temp: 9 °C Low Temp: −3 °C Humidity: 77% Wind: 3.58 m/s	Female 165.99 cm 65.67 kg	Garment style (80% coverage) loose fit fibre content

The setting of the human body is based on the mean body data of the adult population in the Czech Republic[9].

The setting of the garment is a clothing type widely used in the company who provided the fabric data, as shown in Figure 3.

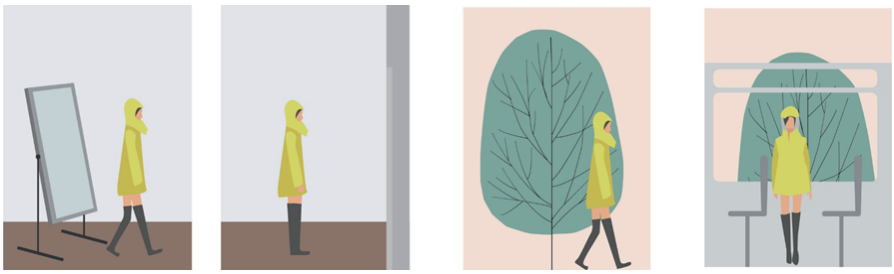

Fig. 3: The garment style used in the simulation

3 Result

3.1 Comfort value

Figure 4 lists examples of simulation results of comfort values for fabric ID007 and 017, and table 3 is the comparison of comfort value. UN means uncomfortable, AC means acceptable.

When the temperature is −3 °C, there is a distinct effect of fabric types on comfort value. All 6 types of fabrics maintains a steady comfort value regardless of the person's activities. The differences in comfort value among 6 types of fabrics are also distinct.

When the temperature is 9 °C, the influence of fabric types is limited. When the person is engaging in a strenuous activity, the comfort sensation quickly and permanently reaches the the maximum limit regardless of clothing fabrics. (suggesting that clothing fabrics affect on the comfort value is negligible). This is particularly true for ID008, ID013. The results for this range of environmental temperature setting indicates that the comfort sensation is mainly dependent on the person's activities.

When the temperature is 24 °C, fabric type and activity have little effect on comfort perception. The person instantly stays and remains at the maximum limit (uncomfortable).

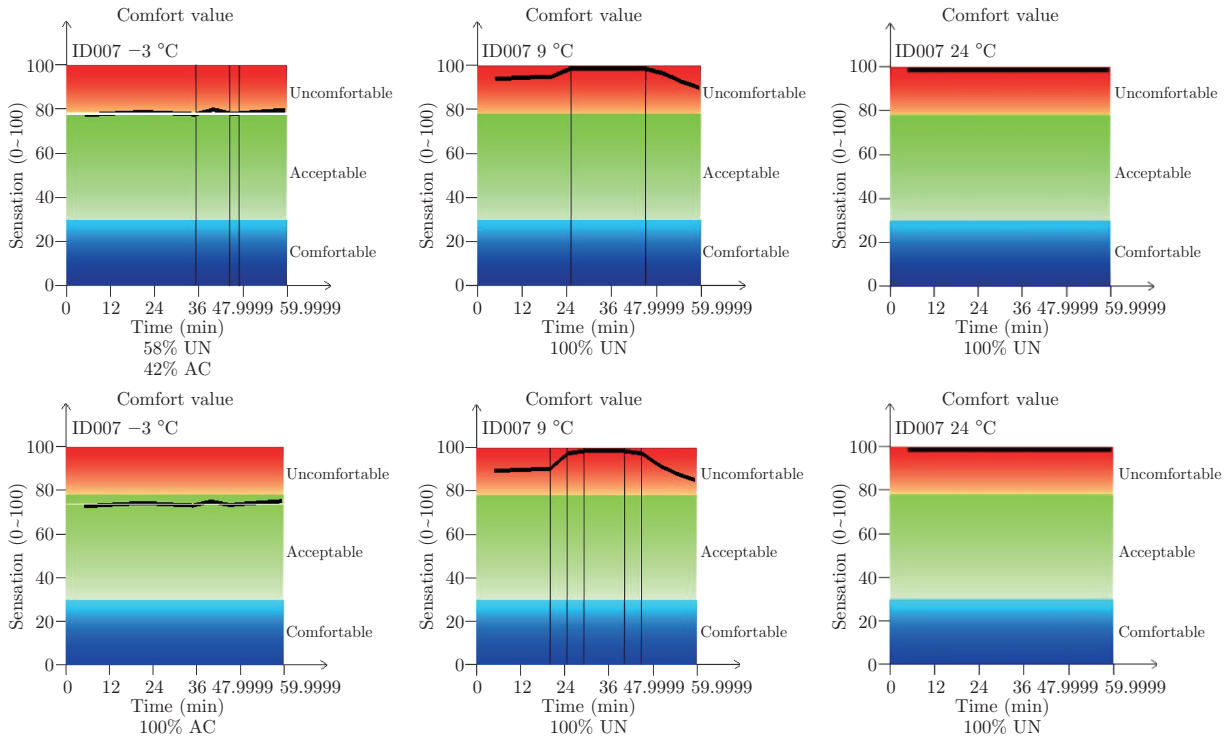

Fig. 4: Examples of simulation results of comfort values for fabric ID007 and 017

Table 3: The comparison of comfort value

Temperature (°C)	ID007	ID008	ID010	ID013	ID017	ID018
−3	58% UN 42% AC	100% UN (not too bad)	58% UN 42% AC	100% UN	100% AC	100% AC
9	100% UN	100% UN (very bad)	100% UN	100% UN (very bad)	100% UN	100% UN
24	100% UN (very bad)	100% UN (very bad)	100% UN (very bad)	100%UN (very bad)	100% UN (very bad)	100% UN (very bad)

3.2 Relative humidity of skin and Dampness sensation

Figure 5 lists the relative humidity of skin (up) and dampness sensation (down) results of fabric ID007.

Table 4 is a comparison of fabric type and the highest recorded degree of skin relative humidity. The effect of the fabric types is clear in all temperature settings. The higher the temperature, the more visible the effect.

Table 5 is a comparison of the dampness sensation. All fabric types regardless of temperature are in the range of VD (very damp).

When the temperature is −3 °C, the effect of fabric types is clear. The dampness sensation of fabrics ID017 and ID018 perform slightly better than the other fabrics, with a slightly lower dampness sensation.

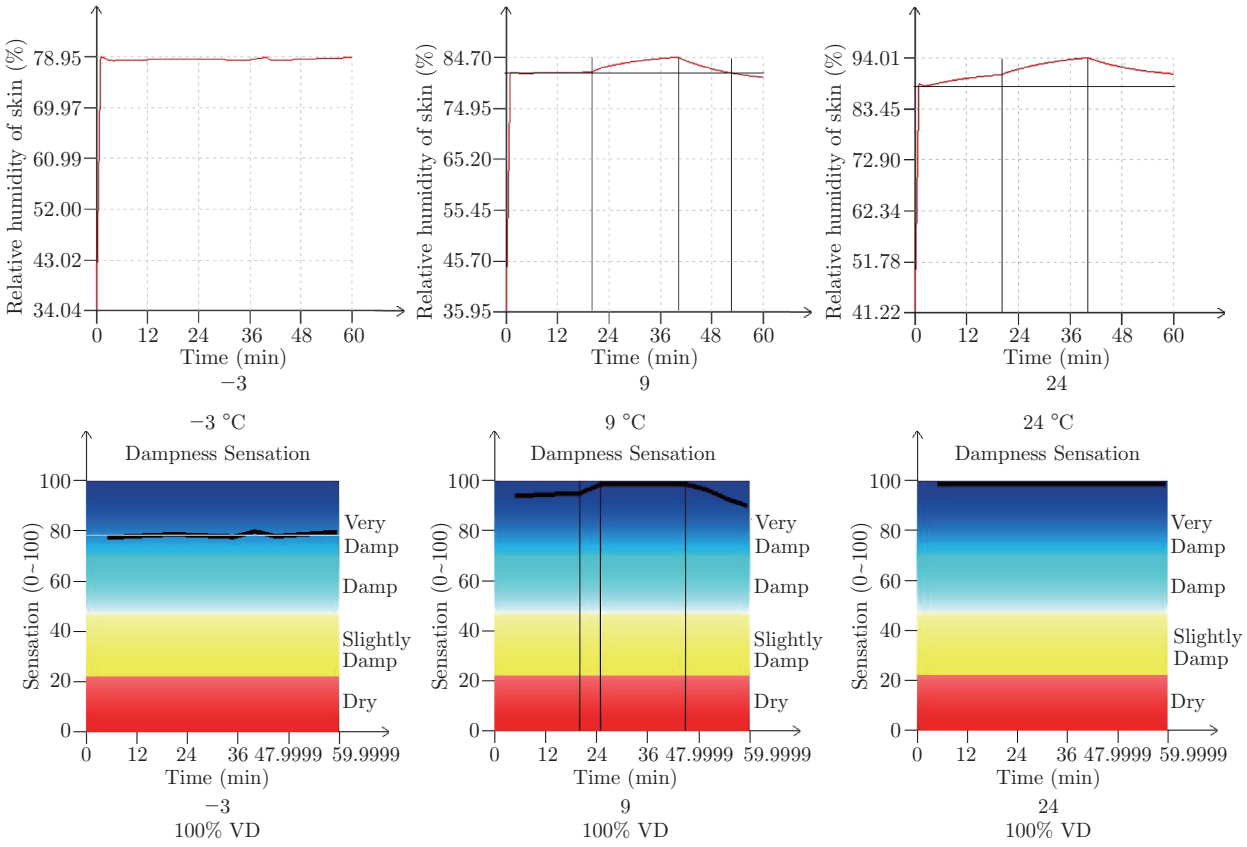

Fig. 5: The relative humidity of skin (up) and dampness sensation (down) results of fabric ID007

Table 4: The comparison of the highest relative humidity of skin (%)

Temperature (°C)	ID007	ID008	ID010	ID013	ID017	ID018	range	growing rate (%)
−3	78.95	79.31	80.17	80.76	79.31	78.13	2.63	3.37
9	84.70	85.90	84.40	86.95	83.89	83.85	3.10	3.70
24	94.01	96.29	94.16	96.73	93.47	93.24	3.49	3.74

Table 5: The comparison of the dampness sensation

Temperature (°C)	ID007	ID008	ID010	ID013	ID017	ID018
−3	100% VD	100% VD	100% VD	100% VD	100% VD (not too bad)	100% VD (not too bad)
9	100% VD	100% VD (very bad)	100% VD	100% VD (very bad)	100% VD	100% VD
24	100% VD (very bad)	100% VD (very bad)	100% VD (very bad)	100% VD (very bad)	100% VD (very bad)	100% VD (very bad)

When the temperature is 9 °C, the influence of fabric types is limited. Even when the person is moving slowly or standing, the person will always feel very damp regardless of the fabric type.

For ID008 and ID013, the sensations instantly stays and remains at the maximum limit of the VD range. The influence of activity types within this range is clear.

When the temperature is 24 °C, there is no apparent effect of fabrics types on dampness sensation. The sensations of all fabrics are always at the maximum VD limit regardless of the fabric type. Temperature within this range is the critical factor.

3.3 Thermal sensation and temperature of skin

Figure 6 lists the temperature of skin (up) and thermal sensation (down) results of fabric ID007.

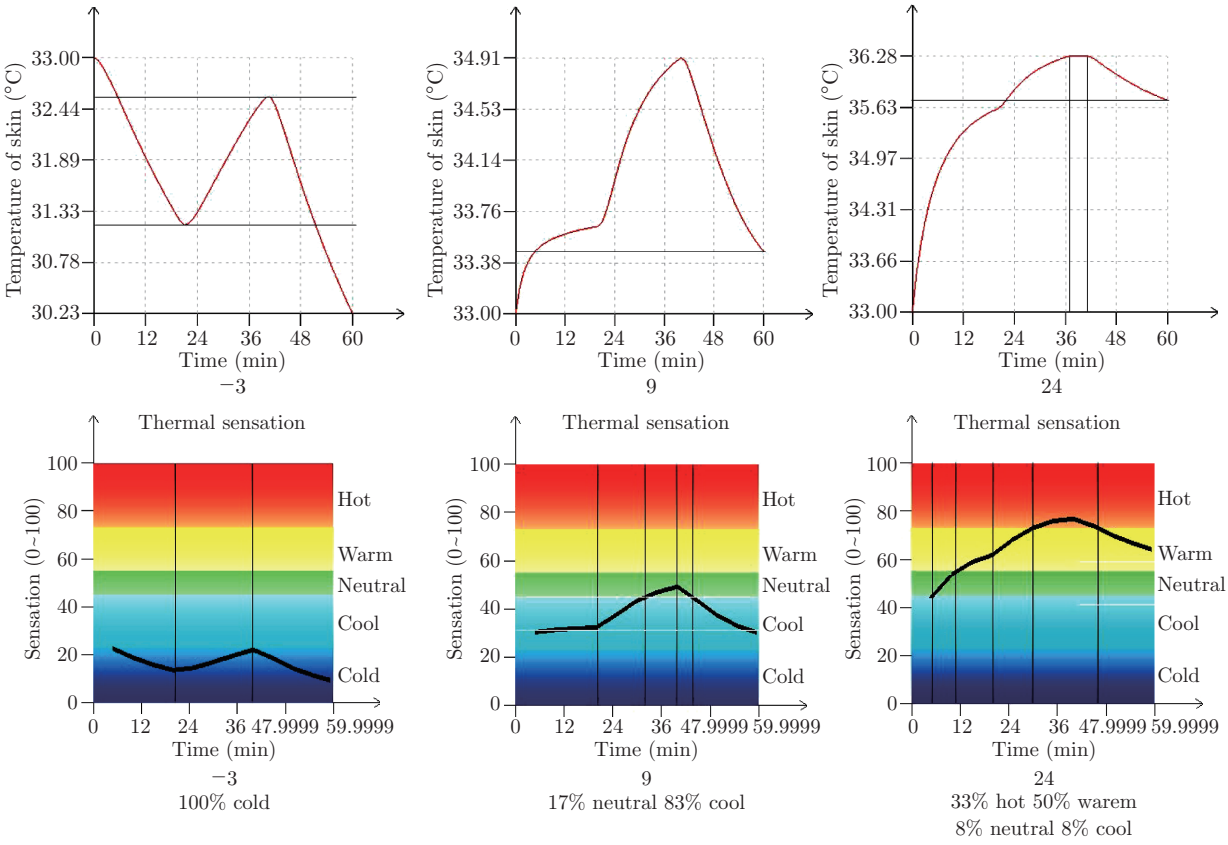

Fig. 6: The temperature of skin (up) and thermal sensation (down) results of fabric ID007

Table 6 is a comparison of the thermal sensation.

When the temperature is −3 °C and 9 °C, there is no effect of fabrics types, all changes in thermal sensations are similar. When the temperature is 24 °C, the effect of fabrics types is limited, there are only a few small changes between ID007-013 and ID017-018.

When temperature is −3 °C, the fluctuation of thermal sensation is small and negligible. When it is 9 °C, the range difference becomes apparent. When the temperature is 24 °C, the fluctuation is more obvious.

Under these three temperature conditions, there is a distinct effect of activity types.

Table 7 is a comparison of the fabric types and the highest recorded skin temperature. There is no effect of fabric types at −3 °C, and the effect of fabric types in 9 °C and 24 °C are negligible.

Table 6: The comparison of the thermal sensation

Temperature (°C)	ID007	ID008	ID010	ID013	ID017	ID018
−3	100% cold	100% cold	100% cold	100% cold	100% cold	100% cold
9	17% neutral 83% cool	17% neutral 83% cool	17% neutral 83% cool	17% neutral 83% cool	17% neutral 83% cool	17% neutral 83% cool
24	33% hot 50% warm 8% neutral 8% cool	33% hot 50% warm 8% neutral 8% cool	33% hot 50% warm 8% neutral 8% cool	33% hot 50% warm 8% neutral 8% cool	25% hot 58% warm 8% neutral 8% cool	25% hot 58% warm 8% neutral 8% cool

Table 7: The change of the highest temperature of skin

Temperature (°C)	ID007	ID008	ID010	ID013	ID017	ID018	range	growing rate (%)
−3	33	33	33	33	33	33	0	0
9	34.91	34.94	34.91	34.96	34.9	34.89	0.07	0.20
24	36.28	36.3	36.29	36.30	36.28	36.28	0.02	0.06

3.4 The temperature of core (°C)

Figure 7 lists the temperature of core results of fabric ID007.

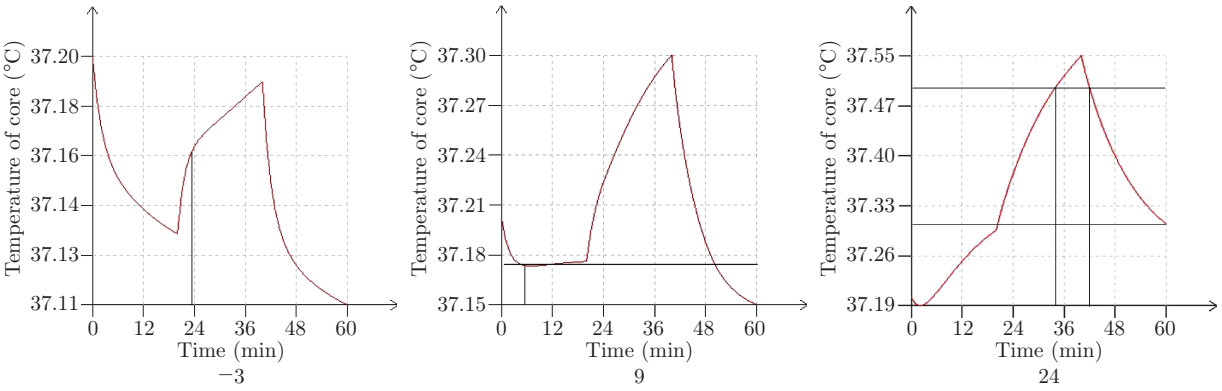

Fig. 7: The temperature of core results of fabric ID007

The normal human body core temperature performs optimally in the range of 37 ± 0.5 °C. The maximum limit to which the body can deviate from the core temperature is 2 °C (35–39 °C) before it becomes life-threatening[10].

Table 8 is the core temperature classification.

Table 9 is the comparison of the starting time when over or below the 37.50 °C core temperature when temperature is 24 °C.

Table 10 is the comparison of the highest core temperature.

The effect of fabrics types is negligible under these three temperature conditions. The core temperature is affected by the activity types.

Table 8: The temperature classification[11]

Indication	Temperature (°C)
hypothermia	< 35
normal	36.5–37.5
Fever	37.5–39
hyperthermia	> 39

Table 9: The comparison of the time when over or below the 37.50 °C core temperature when temperature is 24 °C

Fabric ID	The start time of being over 37.50 °C (min)	The start time of being below 37.50 °C (min)	The duration time of over 37.50 °C (min)	Duration time (min)
007	34	42	8	8
008	33	43	10	10
010	34	42	8	8
013	33	43	10	10
017	35	42	7	7
018	35	42	7	7

Table 10: The comparison of the highest temperature of core

Temperature (°C)	ID007	ID008	ID010	ID013	ID017	ID018	range
−3	37.20	37.20	37.20	37.20	37.20	37.20	0
9	37.30	37.30	37.30	37.30	37.30	37.30	0
24	37.55	37.55	37.55	37.55	37.54	37.54	0.01

At −3 °C, the changes in the core temperature of all fabrics are similar. The lowest and highest core temperature and the trends are all the same. The peaks of the changes in core temperature are all no higher than the initial value. At 9 °C, the differences are also not distinct. At 24 °C, as shown in Table 9, the differences of the duration at which the core temperature is higher than 37.50 °C of different fabrics are no longer than 4 minutes, and the difference of of core temperature peak is only 0.01 °C.

4 Discussion

4.1 Analysis on the effects of the activity types

In Table 11, “Yes” indicates that the effects of activity types are distinct; “Limited” indicates that the effects are small; “No” indicates that there is no effect of activity types or the effects are negligible.

Table 11: The comparison of the effect of the activity types

Temperature (°C)	Comfort value	Dampness sensation	Thermal sensation	Temperature of core	Relative humidity of skin	The temperature of skin
−3	Limited	Limited	Limited	Yes	No	Yes
9	Yes	Yes	Yes	Yes	Limited	Yes
24	No	No	Yes	Yes	Limited	Yes

4.1.1 The conclusion of the effects of the activity types

When temperature is −3 °C, the effect of activity types is limited. When temperature is 9 °C, its influence is clear. When temperature is 24 °C, the influence of activity types decreases, and its effect on comfort value is negligible.

The comfort value is based on the dampness sensation and thermal sensation. At 24 °C, although the activity types influence the thermal sensation, their effects on comfort value are negligible. Hence, the influence of the activity types on thermal sensation is not significant enough to compensate for their little effect on dampness sensation.

4.1.2 The science behind activity type

Activity types affect the amount of generated metabolic heat and sweat excretion. The more intense the activity type, the greater the metabolic heat generated by the human body and the hotter the person will feel. Once a person starts sweating, he or she will feel damp.

Within a certain temperature condition, activity types will always affect the core temperature and the skin temperature, because the amount of generated metabolic heat and sweat excretion directly affect the core temperature and the skin temperature.

For dampness sensation, when in a cold environment, the human body will usually not sweat or sweat only a little even during intense activities, Activity types have therefore little impact on the dampness sensation little. When in room temperature, the variation in the different degrees of sweat rates in relation to activity type are distinct, indicating that activity type plays a key role. When in a hot environment, people sweat even doing normal activities, therefore, the influence of activity type on the comfort value is less significant.

For thermal sensation, when in a cold environment, the influence of activity type is not significant enough to alter the thermal sensation of the human body. When in room temperature or hot temperature, the differences of thermal feeling in relation to activity types are clear, hence the activity type has a more significant effect on the thermal sensation.

For comfort value, when in a cold environment, the effects of activity types on thermal and dampness sensation are both limited, therefore, the affect of activity types on the comfort value is limited. When in room temperature, activity types have a significant effect on the thermal and dampness sensation, therefore the effect of activity types on comfort value is also significant. When in a hot environment, the impact of the activity types on thermal sensation is not able to balance out the effect on dampness sensation.

4.2 The analysis of the effects of the fabric properties

To study the effects of the fabric properties, it is critical to study the effects of fabric composition and fabric types.

Table 12, 13 and 14 compare the effects of fabric types to the comfort value index. For comfort index, the skin relative humidity and the skin temperature can be omitted when the dampness sensation and the thermal sensation are taken into evaluation.

Table 12: The comparison of the effects of the fabric compositions when temperature is in −3 °C

Fabric ID/ Comfort index	Comfort sensation	Dampness sensation	Thermal sensation	Temperature of core
007	Acceptable	Bad	Bad	Good
008	Bad	Bad	Bad	Good
010	Acceptable	Bad	Bad	Good
013	Bad	Bad	Bad	Good
017	Acceptable	Bad	Bad	Good
018	Acceptable	Bad	Bad	Good

Table 13: The comparison of the effects of the fabric compositions when temperature is in 9 °C

Fabric ID/ Comfort index	Comfort sensation	Dampness sensation	Thermal sensation	Temperature of core
007	Bad	Bad	Good	Good
008	Very Bad	Very Bad	Good	Good
010	Bad	Bad	Good	Good
013	Very Bad	Very Bad	Good	Good
017	Bad	Bad	Good	Good
018	Bad	Bad	Good	Good

Table 14: The comparison of the effects of the fabric compositions when temperature is in 24

Fabric ID/ Comfort index	Comfort sensation	Dampness sensation	Thermal sensation	Temperature of core
007	Very Bad	Very Bad	Acceptable	Acceptable
008	Very Bad	Very Bad	Acceptable	Acceptable
010	Very Bad	Very Bad	Acceptable	Acceptable
013	Very Bad	Very Bad	Acceptable	Acceptable
017	Very Bad	Very Bad	Acceptable	Acceptable
018	Very Bad	Very Bad	Acceptable	Acceptable

4.2.1 Fabric composition analysis

As shown in Table 12 to 14 and the previous analysis, the properties of ID007 and 010, ID008 and 013, and ID017 and 018 are similar.

4.2.1.1 Conclusion: effect of fabric compositions

The content of ID007 is 56% cotton and 44% Nylon, and the content of ID010 is 22% EA and 78% Nylon.

The content of ID008 is 36% Nylon, 50.6% polyester and 13.4% EA, and the content of ID013 is 81.1% Nylon and 18.9% EA.

The content of ID017 is 34% PC, 23% polyester 15% wool, 4% cotton and 24% Nylon, and the content of ID018 is 67% polyester and 33% VI.

The composition types and the percentage of each composition in all 6 fabric types are all different regardless of the thermal performance. The composition of fabric is therefore not the critical factor in this research.

4.2.1.2 Limitations in the influence of fabric composition

The composition types and the percentage of each composition in all 6 types of fabric are all different. It is therefore difficult to identify which type of material plays a more important role in a fabric, and when a material becomes an important factor. Moreover, as mentioned in 2.1, the compositions of the 6 fabric types are from a company, and they are all selected for the same style of clothing. If the database is not big enough, the influence of the fabric compositions can not be clearly defined.

4.2.2 Fabric types analysis

Table 15 is a conclusion on the effect of fabric types. "Yes" indicates that it has a significant influence; "Limited" indicates that the effects are small; "No" indicates that the fabric type has not affect or is negligible.

Table 15: The comparison of the effect of fabric types

Temperature (°C)	Comfort value	Dampness sensation	Highest relative humidity of skin	Thermal sensation	Highest temperature of skin	Temperature of core
−3	Yes	Yes (not enough)	Yes	No	No	No
9	Limited	Limited	Yes	No	No	No
24	No	No	Yes	Limited	No	No

4.2.2.1 Analysis on the effects of activity types

For the highest skin relative humidity, the effects of fabric types are clear regardless of temperature condition. For comfort value, dampness sensation and the highest skin temperature, the effects of fabric types are varied based on the temperautre. For thermal sensation, the effects are limited. For the core temperature, the effects are negligible.

Dampness sensation is based on the relative humidity of skin. Although the effect of fabric types to relative humidity of skin is distinct in all three temperature conditions, when it comes to dampness sensation, the effect is largely dependent on the temperature. This means that in

any temperature, the fabric type can affect the index of skin relative humidity, however, it is not significant enough to ignore or decrease the effect of temperature.

Thermal sensation is based on the skin temperature. The effect of fabric types in the highest skin temperature is negligible, so the effect of fabric types on thermal sensation is also small, which only appears slightly when the temperature is 24 °C.

The comfort value is based on the dampness sensation and thermal sensation. When the temperature is −3 °C, the effect of the fabric types on dampness sensation is apparent and the effect of the fabric types on the thermal sensation is negligible. It is also clear that fabric types have an effect on the comfort value, meaning that effect of the fabric types on the dampness sensation is very significant; When the temperature is 9 °C, the effect on dampness sensation is limited and the thermal sensation can be ignored, so the effect of the fabric types on comfort value is also limited; When the temperature is 24 °C, the effect of fabric types on dampness sensation is negligible, the effect of the fabric types on thermal sensation is limited, and the effect of the fabric types on comfort value is negligible, meaning that the limited effect of the fabric types on thermal sensation has little impact on comfort value.

4.2.2.2 How the fabric types work

Fabric types mainly affect heat and moisture exchange, liquid water absorption and transmission between the skin of the human body and the environment, hence their influence on core temperature is limited compared to activities types.

For dampness sensation, when the temperature is low, the amount of sweat excretion is small, so the dampness sensation mainly depends on breathability. The effect of fabric types is therefore significant. Nonetheless, in this temperature condition, the dampness sensations of all fabric types are still "very damp", this phenomenon reduces the differences in dampness sensation. When the temperature is normal, people sweat during intensive activities, both activities types and the fabric types have a significant impacts on the dampness sensation. The type of activity however plays a more critical role. When in a hot environment, people sweat even during normal activities. As the breathability and moisture management performance of all 6 fabrics are bad, the difference in performance between them are small.

For thermal sensation, the performances of the 6 fabrics are similar.

4.3 The conclusion of the effects of fabric types, temperature and activity types

Table 16 is a conclusion of the effect of fabric types, temperature, and activity types on the comfort value. "Yes" indicates that the effect of fabric type is significant; "Limited" indicates that the effect is small; "No" means that there is no effect of fabric types or the effect is negligible.

Table 16: The conclusion of the effects of fabric types, temperature and activities types to comfort value

Temperature (°C)	Fabric types	Temperature	Activity types
−3	Yes	No	Limited
9	Limited	Limited	Yes
24	No	Yes	Limited

As temperature increases, the effect of the fabric type on the comfort value decreases. while the effect of activity type increases. However, when the temperature is too high, both the activity and the fabric type have little influence on the comfort value.

5 Conclusion

This research paper uses e-thermal CAD software to simulate clothing thermal comfort value of 6 fabric types. The simulation results are then analysed to study how fabric properties affect human thermal comfort under different environmental temperatures while the wind speed and the relative humidity always remaine the same. In conclusion, comfort index performance is better in a low temperature environment, and worse in high temperature environment. Moreover, the influence of fabric composition is small for the effect of fabric type.

Most of the fabric types perform best within a certain range of temperature. Once they leave the range, the further they stray, the smaller their effects. Within the range of room temperature, activity type has the greatest influence on the comfort value. In more extreme temperature conditions, temperature play the critical role in the thermal comfort value.

Acknowledge

We would like to thank the support of the EU Horizon 2020 and University of Manchester through the project entitled “Fashion Big Data Business Model”, project No. 761122.

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