EFFECTS OF CLOTHING ON RUNNING PHYSIOLOGY AND PERFORMANCE IN A HOT CONDITION

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TO MY FAMILY AND TEACHERS

For their constant love, support and encouragement

ABSTRACT

Distance running, more than any other sport, is etched with the tragedy of heat-related deaths. Clothing as a uniform required in formal competitions satisfies a variety of purposes for athletes during exercise, as it serves as a barrier between skin surface and ambient environment. Clothing plays a vital role in addressing the health and performance of distance runners. In a hot and humid environment, appropriate clothing with improved pattern design and fabric materials can increase the capability of heat dissipation (CHD) from the body to the outer environment. It also helps the body to improve subjective sensations and physiological responses to heat stress, and subsequently affect overall wearing comfort and exercise performance. The aim of this study was to develop a method in designing running clothes to improve the athletes' running performance and wearing comfort in a hot condition, and establish an evaluation system that can be used to quantify the functional performance of developed clothing and to assess the influence of the clothing on athletes' whole-body/local thermal responses, running performance and wearing comfort during running.

In this thesis, a theoretical framework was established for developing functional running clothes by studying and identifying the thermal requirements of different body parts. Thermal zones of the human body were specified according to the summary of regional skin temperature and sweat evaporative distribution. Each thermal zone was marked with the specific demands on pattern design and the selection of fabric materials to fulfill the thermal physiological requirements. This helped in developing a new design methodology for summer running clothes, which aimed at increasing the heat dissipation efficiency of clothing and improving the running performance of the athletes. Two types of running clothes with a thermal mapping-designed concept were manufactured based on the newly developed methodology.

An evaluating system was developed that can be used to quantify the functional performance of thermal mapping-designed clothing. This system includes three aspects: basic tests on fabric physical properties, assessment of whole clothing properties, and determination of physiological/psychological effects on the human body. The basic tests of fabric physical properties were conducted following existing measurement standards. For the mapping-designed aspect, the clothing properties were calculated according to the physical properties of the fabric and each of its covered area portion. Furthermore, three new indices related to human body's thermal and moisture dissipation via clothing were defined to simulate the overall CHD when the clothing is worn. The overall CHD of clothing is composed of the Capability of Dry Heat Loss (CDHL) and Capability of Latent Heat Loss (CLHL), which were evaluated by a manikin test and calculating methods respectively. The physical properties of the mapping-designed running clothes were evaluated using this system. Evaluation results show that the overall CHD of mapping-designed clothing (CloA) increased by 11%, while that of CloB was at 7% as compared to existing commercial clothing. This proves that clothing designed with mapped patterns and specified functional properties of materials according to the thermal requirements in each body part has positive influence on the overall CHD. The evaluation methods for wear trials, including the experimental design, methodology, and measuring instruments, were discussed for investigation on human body.

A parallel-blinded wear trial with a 45 min steady-state running protocol followed by a 1.5 km time trial was conducted. The trial aimed to investigate and verify the effects of mapping-designed running clothes on whole-body thermal responses and running performance on human subjects in a hot condition, and examine the relationships among clothing overall performances, whole-body thermal responses and the time of running performance. The experiments were conducted in a completely controlled heat-conditioned chamber. Subjects were eight endurance male athletes tasked to complete the three tests at random, which was carried out in separated week. The subjects wore one kind of clothing in each test. Findings showed that the clothing designed with an increased CHD by altering design pattern and fabric materials resulted in decreased skin temperature (T_s), less heat storage (S) and delayed increasing of core temperature (T_c) during the rest and steady-state running periods in a hot condition, which were related to the time of performance running (PR) of 1.5km-sprint ($P < 0.05$). The changes of thermal responses and PR were correlated with the physical properties of clothing ($P < 0.05$). Specifically, $\mathrm{WVP_t}$ and $\mathrm{OMMC_t}$ of clothing, which affect the CLHL, have negative relationships with S, ΔT_c, and PR. The $\mathrm{clo_t}$ and $\mathrm{AR_t}$ relating to the CDHL has a positive effect on S at 30 min rest and during running performance. Besides, T_c and T_s at the time point of Running End can be predicted by the overall capability of dissipate heat (CHD), as well as the d and the $\mathrm{W_t}$ of the clothing. The PR can be directly predicted by the CLHL through the clothing.

The effects of mapping-designed running clothes on local thermal responses of athletes were investigated in a wear trial, and the relationships with whole-body thermal responses and running performance were studied. Findings showed that the defined body thermal zone of human body had different thermal responses during the tests, with some responses correlated to the whole-body thermal responses at different exercise statuses and running performance ($P < 0.05$). Subsequently, the potential mechanism on how the mapping-designed clothing affected the thermal responses and running performance were explored. To sum up, the higher capacity of heat dissipation of the fabric and/or the whole clothing, the less the heat stored in the body and slower increases of T_c, hence inducing less adverse impact of clothing on the running performance while running in a hot condition.

The effects of mapping-designed running clothes on subjective sensations and athletes' wearing comfort were examined, and the relationships between clothing properties and each

sensory factor at different time points were explored. Findings revealed that the specially designed running clothes increased overall wearing comfort and satisfied the related subjective sensations such as coolness, smoothness, and lightness at different exercise statuses ($P < 0.05$). Five sets of a predictable model were constructed to predict the overall comfort by the four sensory factors at each time point. The agreements between the real comfort sensation obtained from the questionnaire and the predicted comfort by the models were observed respectively with the R^2 from 0.47 to 0.57 at each time point, except that at Recovery 30 min. Besides, a factor analysis was conducted to identify the main sensory factors of wearing comfort, some of which were tended to correlate to PR. The finding indicated that these sensation factors could not only predict the overall clothing comfort, but might also have some effects on running performance in a hot condition.

In summary, a functional design model and a related evaluating system for thermal mapping-designed running clothes were developed scientifically and systematically in this study. The effect of clothing designed on human responses while running in a hot condition and their mechanisms were examined based on evaluating system. These findings would contribute to the sportswear industry and the field of sports by developing a scientific understanding on the management of heat stress and the improvement of exercise performance with clothing. The results can also enhance the application of sports science in textile industry and provide practical scientific guidelines, technical suggestions, and evaluation systems for product optimization and promotion of sports clothing.

RESEARCH OUTPUTS

Publications and Conference Presentation:

1. **Jiao J**, Yao L, Chen YJ, Wong SHS, Guo YP, Ng FSF, Li Y. Effects of sportswear design on thermal stress and endurance running performance in hot condition. *Medicine and Science in Sports and Exercise.* 2012;44:480.
2. **Jiao J**, Yao L, Li Y, Wong SHS, Ng FSF, Teng Y, Guo YP. Thermal physiology and local responses of human body during exercise in hot conditions. *Journal of Fiber Bioengineering and Informatics.* 2012;5(2):115-124.
3. **Jiao J**, Yao L, Chen YJ, Guo YP, Wong SHS, Ng FSF, Li Y. Effects of clothing on heat stress and running performance in a hot condition. *Research in Sports Medicine*. 2014. (in submission)
4. **Jiao J**, Li Y, Hu JY, Wong SHS, Ng FSF. Evaluation System for Performance Running Clothing in Hot Conditions. *Journal of Fiber Bioengineering and Informatics.* (in submission)
5. Yao L, **Jiao J**, Lau KW, Tse YM, Gohel MDI, Guo YP, Li Y, So R. Effects of thermal mapping running wear on running capability in the heat. *Journal of Strength and Conditioning Research.* 2013. (submitted)
6. Teng Y, Li Y, Li J, **Jiao J**, Wang RM, Luo XN, Ameersing L. Multi-dimensional space mathematical model for clothing thermal function deign. *Textile Research Journal.* 2013. (in submission)
7. Teng Y, Wang R, Li Y, Luo XN, Li J, **Jiao J**. M-Smart–an improved multi-style engineering design CAD system or clothing thermal functions. *Journal of Fiber Bioengineering and Informatics.* 2011; 4(1):71-82.
8. **Jiao J**, Li Y, Yao L, Hu JY, Guo YP, Sun S. Application of specific thermal responses on running clothes design. Textile Bioengineering and Informatics Symposium Proceedings, Vols 1, 2013: 386-390; Xi' an (P. R. China)
9. **Jiao J**, Li Y, Yao L, Zhou DX, Li QH. Effects of exercise and clothing on skin temperature and electrical skin resistance at the finger and toe tips. Textile Bioengineering and Informatics Symposium Proceedings, Vols 1 and 2, 2012: 825-830; Unda (Japan).
10. **Jiao J**, Yao L, Chen YJ, Guo YP, Wong SHS, Ng FSF, Li Y. Effects of water ingestion on core temperature measurement by gastrointestinal pill during wear trial in hot conditions. Textile Bioengineering and Informatics Symposium, Vols 1-3, 2010: 1421-1424; Shanghai

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11. **Jiao J**, Yao L, Lau KW, Li Y. Effects of clothing wicking and moisture management characteristics on perception of breathable-airtight. Textile Bioengineering and Informatics Symposium Proceedings, Vols 1 and 2, 2009: 640-644; Hong Kong (P. R. China).
12. Guo YP, Li Y, Luo J, Yao L, Cao ML, **Jiao J**. Reduction in skin temperature and increase in stratum corneum water content and transepidermal water loss during cycling. Textile Bioengineering and Informatics Symposium Proceedings, Vols 1 and 2, 2012: 831-838; Unda (Japan).

Patents:

1. Li Y, Yao L, Sun S, Zhou JY, Hu JY, Wang YJ, **Jiao J**, Lau KW. Manufacture of sportswear for running and sportswear manufactured according to it. US patent 201010507140.X, RIP-25A, Oct 14, 2010.
2. Li Y, Hu J, Yao L, Luo J, Cao XY, Chao H, Guo YP, Zhou JY, Sun S, Wang YJ, **Jiao J**, Lau KW. Manufacture of sportswear for cycling and sportswear manufactured according to it. US patent 201010255317.1, RIP-31A, Aug 17, 2010.

Exhibitions:

1. Li Y, Yao L, Sun S, Zhou JY, Hu JY, Wang YJ, Cao XY, **Jiao J,** Lau KW. “C_Power” – The Brilliance of Olympic and Sportswear Innovation, Hong Kong, Jul., 2012
2. Li Y, Yao L, Sun S, Zhou JY, Hu JY, Wang YJ, Cao XY, **Jiao J,** Lau KW. “M_Power” – The Brilliance of Olympic and Sportswear Innovation, Hong Kong, Jul., 2012
3. Li Y, Yao L, Sun S, Zhou JY, Hu JY, Wang YJ, Cao XY, **Jiao J,** Lau KW. “P_Power” – The Brilliance of Olympic and Sportswear Innovation, Hong Kong, Jul., 2012

Honors and Awards:

1. Li Y, Yao L, Sun S, Zhou JY, Hu JY, Wang YJ, Cao XY, **Jiao J**, Lau KW. “ExperiDesign-Running Wear”, **Successful Design Award** in China’s Most Successful Design Awards Competition, Shanghai, China, Nov, 2011

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LIST OF DEFINED ABBREVIATION

A	Whole body surface area (m^2)
$A_{clothing}$	Body surface area covered with clothing (m^2)
A_{skin}	Body surface area covered without clothing (m^2)
AM	Allow movement-Does not allow movement sensation
AR	Air resistance of fabric (KPa.s·m^{-1})
AR_t	Air resistance of whole clothing (KPa.s·m^{-1})
ATP	Adenosine triphosphate
BW	Body weight (kg)
C	Rate of convective heat transfer
CBF	Cerebral blood flow
CDHL	Capability of dry heat loss through clothing (kJ·h^{-1})
CHD	Capability of heat dissipation through clothing (kJ·h^{-1})
CHO	Carbohydrate
CLHL	Capability of latent heat loss through clothing (kJ·h^{-1})
clo_t	clo value of whole clothing
CS	Cotton shirt
d	Thickness of fabric (mm)
DD	Damp-Dry sensation
E	Rate of evaporative heat transfer
E_n	Energy (J)
EE	Energy expenditure (J)
EML	Evaporative mass loss (g)
$EML_{clothing}$	Liquid and moisture evaporation from skin with clothing
EML_{skin}	Liquid and moisture evaporation from skin without clothing
GI	Gastrointestinal
H	Height of human body (m)
HL	Heavy-Light sensation
HR	Heat rate (beat·min^{-1})
IS	Itchy-Smooth sensation
K	Rate of conductive heat transfer
LS	Loose fit-Snug fit sensation
M	Metabolic heat production
MAR_b	Maximum moisture absorption rate (%·s^{-1})
MMT	Moisture management tester
NS	No shirt
OMMC	Overall moisture management capacity
$OMMC_t$	Overall moisture management capacity of whole clothing
OWTC	One-way transport capacity
P	Power input (W·m^{-2})
PI	Proportional Integral
PP	Polypropylene
PR	Time of 1.5 km performance running (s)
PS_m	Prickly-Smooth sensation
RER	Respiratory exchange ratio
R_a	Rate of radiant heat transfer
R	Thermal resistance tested by manikin (m^2·W^{-1}·°C)
RH	Relative humidity (%)

RH_{back}	Relative microclimate humidity of the back (%)
RH_{calf}	Relative microclimate humidity of the calf (%)
RH_{chest}	Relative microclimate humidity of the chest (%)
RPE	Rating of perceived exertion
RPT	Rating of perceived thirsty
S	Heat storage ($W \cdot m^{-2}$)
SS	Synthetic shirt
SS_b	Average speeds of the moisture spread on the bottom surfaces to reach the maximum wetted radius ($mm \cdot s^{-1}$)
SS_m	Sticky-Smooth sensation
SS_t	Soft-Stiff sensation
SV	Stroke volume
SW	Sweat rate ($g \cdot min^{-1} \cdot m^{-2}$)
t	Time (s)
T_a	Ambient environment temperature (°C)
T_{arm}	Skin temperature of arm (°C)
T_b	Body temperature (°C)
T_c	Core temperature (°C)
T_{calf}	Skin temperature of calf (°C)
T_{chest}	Skin temperature of chest (°C)
TI	Thermal insulation (clo)
TPC	Thermal performance capacity (°C)
T_r	Radiant temperature (°C)
T_{thigh}	Skin temperature of thigh (°C)
T_s	Mean skin temperature (°C)
UV	Ultraviolet
VO_2	Oxygen consumption
VO_{2max}	Maximal oxygen consumption
W	Rate of work
W_t	Unit weight of fabric ($g \cdot m^{-2}$)
WVP	Water vapor permeability of fabric ($g \cdot m^{-2} \cdot day^{-1}$)
WVP_{air}	Water vapor evaporation from standard cups without fabric covering ($g \cdot m^{-2} \cdot day^{-1}$)
WVP_t	Water vapor permeability of whole clothing ($g \cdot m^{-2} \cdot day^{-1}$)
α_n	Area proportion ratio of a single fabric (n=1, 2, 3…)
α_{skin}	Area proportion ratio without clothing
λ	Latent heat of vaporization for liquid

CHAPTER 1 INTRODUCTIOIN

1.1 Research Background

Running, the primary sport in the early sports culture, is also currently one of the most popular sports that can be practiced by almost everybody. The ultimate goal during competitions is to run faster than the other runners over a certain distance [66]. However, being a successful runner is not a universal gift. The history of distance running, more than any other sports, is etched with heat-related deaths [64]. As early as 490 BC, a young Greek collapsed and died after running 26.2 miles from Marathon to Athens. This incident may be the first record involving the sudden death of an athlete [47]. Despite heat-related deaths being preventable, more than 100 athletes have died from excessive heat stress because of exertional heat stroke during competitions in the recent 20 years [127]. At the Standard Chartered Hong Kong Marathon 2013, 55 runners were reported to have fallen unconscious, been rendered comatose, and suffered from collapse because of heatstroke [116, 119]. Thus, certain measures must be taken to prevent similar occurrences during endurance running under hot conditions.

Heat-related disorders are mainly induced by heat stress in extreme environment, preventing the dissipation of excess body heat and elevating the internal body temperature to critical level [187]. The core temperature (T_c) of the human body at rest is normally regulated at approximately 37 °C [127]. During running, active tissues produce additional metabolic heat, which must be intricately offset by heat loss to the environment [187]. Human thermoregulation mechanism tends to maintain the T_c of the body within certain boundaries. When the T_c increases, it activates several physiological reactions automatically to speed up body heat dissipation including sweating by stimulating the sweat gland and automatically adjusting the cardiovascular system [127]. During cardiovascular adjustment, the blood is redistributed from the core organs to the skin to facilitate heat dissipation, and the active muscles require blood supply to deliver oxygen for maintenance of activity [39]. Meanwhile, the heart rate (*HR*) increases to sustain cardiac output and blood supply to the working muscles and the skin [39, 185]. Thus, when heat stress is superimposed on athletes during prolonged running, the burden on the cardiovascular system accumulates [187]. The increased burden raises the risk of overheating, causing early fatigue and drastically impaired performance [45, 51].

To reduce the risk of overheating and improve running performance, athletes must lower their effort to reduce metabolic heat production or undertake effective measures to increase heat dissipation. Under hot conditions, athletes can conduct exercise sessions in a less stressful environment [187]. However, athletes participating in competitions have limited control over prevailing weather conditions. Nonetheless, clothing as a uniform required in most formal competitions is a major consideration [187]. Pascoe (1994) indicated that clothing was an interactive barrier between the ambient environment and the skin surface, which could alter the condition of the macroclimatic environment and exert thermoregulation effects on the body [147]. In a hot and humid environment, appropriate clothing using different fabric materials can affect heat dissipation from the body to the outer environment and related thermoregulation [30]. Various clothing designs can improve athletes' subjective sensation and physiological responses to heat stress, affecting overall comfort and physical performance of exercise [163, 194]. With the thermal requirement of each body part considered, clothing specifically designed for running under hot conditions is important in sports and the clothing industry [97].

A review of the literature suggests a lack of study which systematically investigates the development and evaluation of functional running clothes under hot conditions according body thermal mapping design. Moreover, the effects of the well-developed functional running clothes on human thermal responses, running performance, and wearing comfort are still unknown. Therefore, it is necessary to conduct a systematically research on the development and evaluation system for functional running clothes, and on how the fabric material properties and clothing design affect athletes' thermal-physiological responses, running performance and wearing comfort.

1.2 Research Aim and Objectives

The aim of this study was to develop a method in designing running clothes to improve the athletes' running performance and wearing comforter in a hot condition, and establish an evaluation system that can be used to quantify the functional performance of developed clothes and to assess the influence of the clothing on athletes' whole-body/local thermal responses, running performance and wearing comfort during running.

To fill these knowledge gaps (described in detail in Section 2.7 of Chapter 2) and achieve the research aim, the following six objectives have been presented:

1. To establish a theoretical framework for developing and evaluating functional running clothes for hot conditions;
2. To investigate the thermal requirements in each body part and apply them into a new design methodology of summer running clothes;
3. To develop evaluation system that can be used to quantify the functional performance of thermal mapping-designed clothing;
4. To investigate and verify the effects of mapping-designed running clothes on whole-body thermal responses and running performance on human subjects in a hot condition, and examine the relationships among clothing overall performances, whole-body thermal responses and the time of running performance;
5. To investigate the effects of mapping-designed running clothes on local thermal responses

of different body parts, and explore the relationships with whole-body thermal responses and running performance;

6. To investigate the effects of mapping-designed running clothes on different subjective sensations and wearing comfort of athletes in a hot condition, and explore the relationship of clothing properties and each sensory factor at different time points.

1.3 Research Methodology

To achieve the aforementioned objectives, the following methodologies were employed:

1. Establishment of a theoretical framework to develop and evaluate functional running clothes (Chapter 2):

   - A comprehensive literature review was conducted on heat balance, human body thermoregulation, heat stress, and running performance, as well as the possible relationships between clothing and running performance;
   - A scientific framework was developed to determine the properties of clothing, design, and effect of contraction on running performance as determined by thermal response, as well as wearing comfort;
   - A framework was presented, addressing the knowledge and procedures involved in human thermal physiology, clothing technology, and their relationships; and
   - Primary knowledge, developed methodology, and the procedures for the proposed framework were identified

2. Investigation of the thermal requirements in each body part which was applied into a new design methodology of summer running clothes (Chapter 3):

   - A theoretical knowledge was established by reviewing the comprehensive literature, including updated fabric technology and functional clothing design, as well as the thermal response of athletes during running;

- A thermal function zone was created, and the thermal requirement for each body part was determined by evaluating and summarizing the natural race, distribution of sweat evaporation, and local skin temperature obtained in previous studies;
- A thermal functional design of running clothes was developed using a mapping-designed concept and the fabric requirements for running clothes was demonstrated;

3. Establishment of a system to evaluate quantitatively the functional performance of thermal mapping-designed clothing, i.e. overall capability of heat dissipation (CHD), and to investigate the testing methods in the wear trials of human body (Chapter 4):

- The fabric properties were determined to meet the fabric requirement of the clothing design;
- Methods were explored and new indices were defined to evaluate the physical properties of the whole clothing, including estimating the traditional thermal and moisture properties of the whole clothing and calculating the Capability of Latent Heat Loss (CLHL), Capability of Dry Heat Loss (CDHL), and overall CHD; and
- The evaluative methodology was developed and identified. Specifically, the testing measures and instruments of thermal responses, running performance and psychological responses of human subjects in wear trials were discussed. .

4. Conduction of wear trials on human body to investigate the effects of mapping-designed running clothes on whole-body thermal responses and running performance, and examine the relationships among clothing overall performances, whole-body thermal responses and the time of running performance (Chapter 5):

- Human subjects were selected and wear trials were conducted in a well-controlled climate chamber; and
- Data obtained from the wear trials was analyzed by Repeated-ANOVA, Pearson correlation, linear regression analyses using SPSS software.

5. Conduction of wear trials on human body to investigate the effects of mapping-designed running clothes on local thermal responses of different body parts, and explore the relationships with whole-body thermal responses and running performance (Chapter 6):

   - Human subjects were selected and wear trials were conducted in a well-controlled climate chamber; and
   - Data obtained from the wear trials was analyzed by Repeated-ANOVA, Pearson correlation, linear regression analyses using SPSS software.
   - The mechanism that determines the influence of mapping-designed clothing on thermal responses and running performance was discussed based on the results of statistical analysis.

6. Conduction of wear trials on human body to investigate the effects of mapping-designed running clothes on different subjective sensations and wearing comfort of athletes in a hot condition, and to explore the relationship of clothing properties and each sensory factor at different time points (Chapter 7):

   - Human subjects were selected and wear trials were conducted in a well-controlled climate chamber; and
   - Data obtained from the wear trials was analyzed by Repeated-ANOVA, Pearson correlation, linear regression analyses, cluster analysis and factor analysis using SPSS software.

1.4 Research Significance and Value

This study presents a new design methodology for functional running clothes via increasing the efficiency of clothing heat dissipation to improve the running performance of a wearer. Running clothes were fashioned with mapping-designed concepts based on defined thermal zones and specific thermal requirements for each body part. This concept provides another consideration in clothing design, leading to functional performance clothing development with thermal physiology and performance considered.

This study also establishes an evaluation system to assess the characterization of clothing with mapping-designed and multi-fabric materials. The evaluation begins with basic tests of the physical properties of the fabric that can determine thermal characteristics such as water permeability and thermal insulation. The results obtained from these tests can help in fabric selection for covering specific body parts of a wearer, thereby providing reference for clothing design and manufacture. The estimation of overall physical properties such as Water Vapor Permeability of the whole clothing (WVP_t) and new defined indices such as CHD provide references for athletes and coaches to combat the adverse effect of environmental stress when selecting clothing for training and/or competition. The estimated results can also be used to conduct physiological wear trials to investigate the effects of clothing on human subjects. The test methodology and process described can be applied not only to clothing developed for active sports but also to civilian clothing, protective clothing, and military uniforms, among others.

The findings obtained from the wear trials can be used as references for the systematic understanding of the effect of clothing on the thermal responses, performance, and wearing comfort of the athlete running under hot conditions. Athletes and coaches can practically benefit from optimized designs, which can also improve running endurance and effectively help prevent heat stroke. The data obtained from the wear trials can be used for predictive modeling and furthering studies on clothing and exercise physiology. The results can also enhance the application of sports science in textile industry and provide practical scientific guidelines, technical suggestions, and evaluation systems for product optimization and promotion of sports clothing.

1.5 Thesis Outline

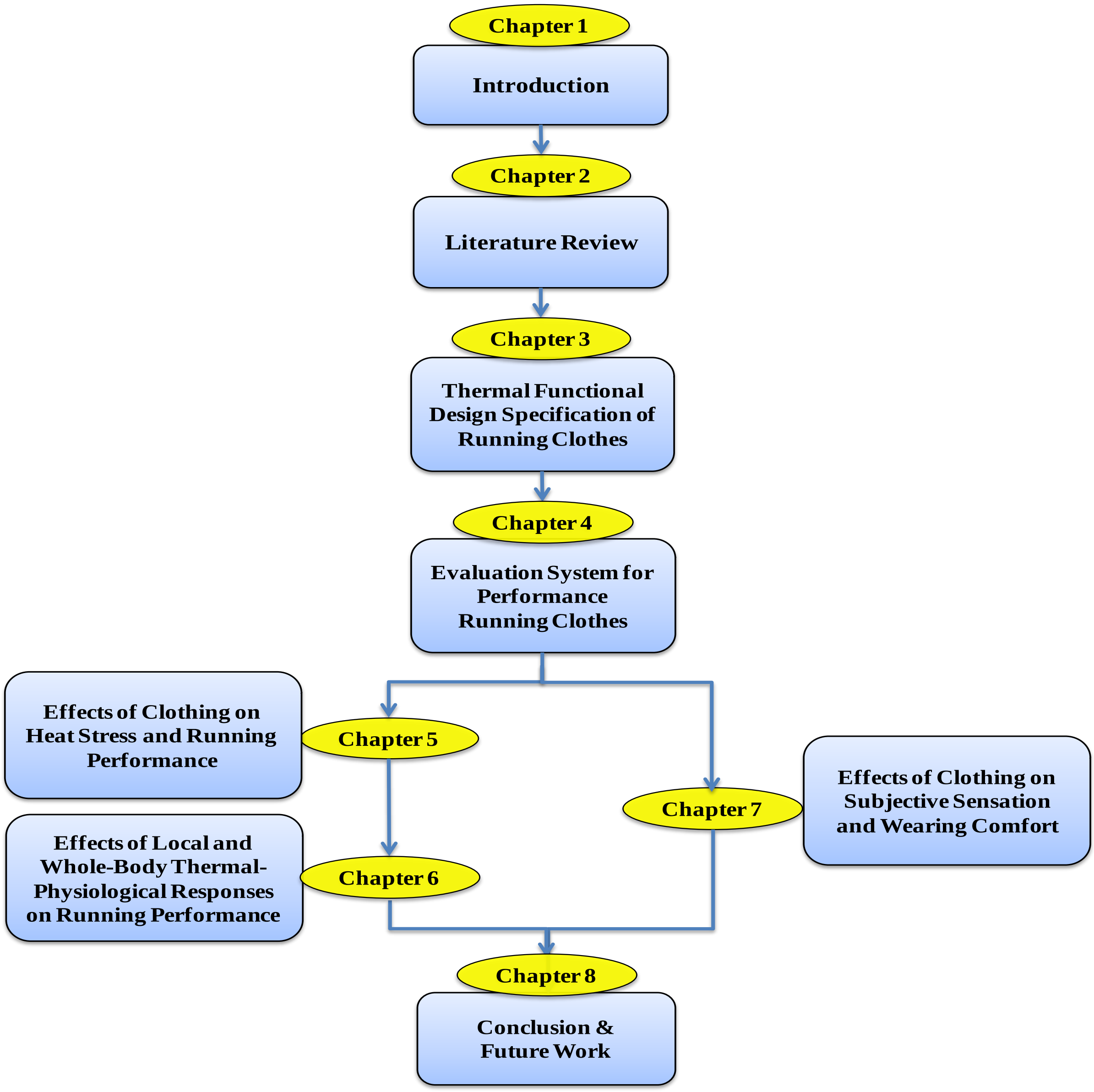


Figure 1.1 The structure of thesis

This thesis consists of eight chapters, the structure of which is shown in Figure 1.1.

Chapter 1 provided an overview of the research background, objectives, and methodology.

Chapter 2 reviewed the related literature to provide background knowledge and identify knowledge gaps to ensure the originality of this study.

Chapter 3 established a theoretical framework for developing functional running clothes by studying and identifying the thermal requirements of each body part. A new design methodology for performance running clothes was developed according to the regional skin temperature and sweat evaporative distribution, which aimed at increasing the heat dissipation efficiency of clothing and improving the running performance of the athletes. Fabric selection was also illustrated in this chapter to meet the thermal requirements.

Chapter 4 developed an evaluation system assessing the characterization of clothing properties to quantify the thermal functional performance of the clothing. The system includes three aspects: basic tests on fabric physical properties, objective characterization of the whole mapping-designed clothing, and determination of evaluation protocol used in the wear trials of human subjects. Furthermore, three new indices related to human body’s thermal and moisture dissipation via clothing were defined to simulate the overall CHD when the clothing is worn.

Chapter 5 investigated and verified the effects of mapping-designed running clothes on whole-body thermal responses and running performance by conducting wear trials on human subjects in a hot condition, and explored the relationships among clothing properties, thermal responses, and running performance. This chapter also confirmed the feasibility of the experiment protocol, including a submaximal steady-state running followed by a 1.5 km time trial, to simulate the effects of clothing on athletes in a real running competition.

Chapter 6 investigated the effects of mapping-designed running clothes on local thermal responses of athletes in a wear trial, and explored the relationships with whole-body thermal responses and running performance, with the aim of interpreting the potential mechanisms on how the mapping-designed clothing affect their thermal responses and running performance.

Chapter 7 examined the effects of mapping-designed running clothes on subjective sensations and overall wearing comfort of athletes in a wear trial under hot conditions. This chapter also explored the relationship of clothing properties and each sensory factor at different time points.

Chapter 8 summarized the primary findings and provided direction for future studies.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Relevant literature on a Body-Clothing-Environment system is reviewed in this chapter. In this system, human body as an independent individual has basic process of heat exchange and thermoregulation under hot conditions, and its exercise performance would be affected by some factors such as diet, energy production, strength/skill, neuropsychology, and environment [8, 124]. Among these factors, clothing which establishes a microclimate environment around body would have direct effects on the thermoregulation and exercise performance [188]. Thus, this chapter aimed at acquiring a general understanding of the aforementioned topics.

The following aspects are included: 1) Body–Clothing–Environment system, 2) heat balance and thermoregulation of human body, 3) mechanisms of heat exchange during running process and influence on running performance and 4) possible application of clothing to improve/adjust human physiological responses, running performance, subjective sensation and wearing comfort.

2.2 Body–Clothing–Environment system

Nowadays, clothing as an integral part of human life is not only used to cover the body but is also considered a symbol of status, protection, and modesty [80]. Luxurious, fashionable, and well-fitted clothes can reflect the wearer's status and enhance self-confidence as well as comfort. Clothing serves as a second skin of human being to protect the human body against the external environment and aids in adjusting the thermal and moisture exchange between the body and its surroundings [80, 148]. The thermal and moisture exchange has been widely recognized as an important factor that influences the thermal status [74], comfort perception [114, 134], even the survival under extreme conditions of the wearer [147, 148]. In the Body–Clothing–

Environment system, the heat balance of the human body is maintained by the processes of heat production and heat loss via radiation, conduction, convection, and evaporation [90, 148], and these processes would have effects on the physiological responses and exercise performance of human body, especially under hot conditions. The interactions of each part in the system are illustrated in Figure 2.1.

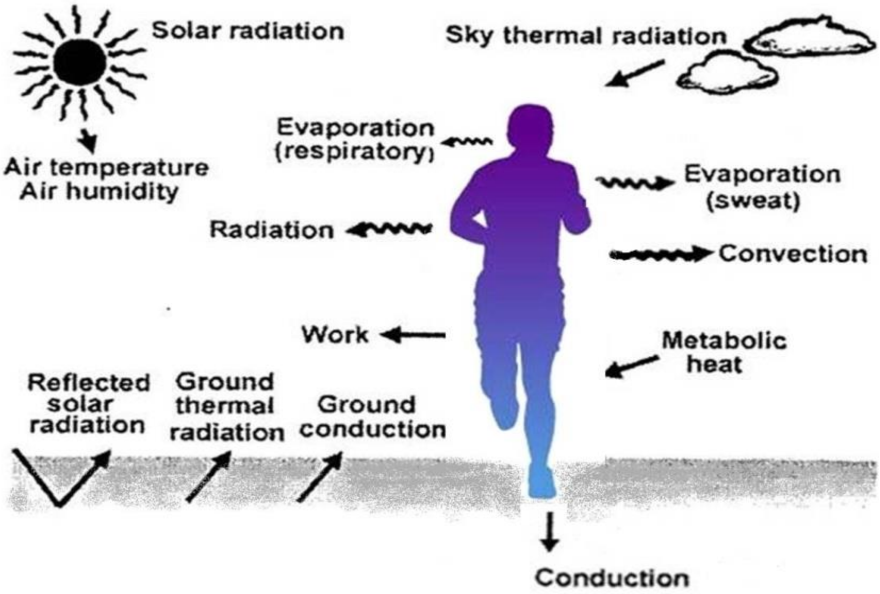


Figure 2.1 Heat exchange of human body

In order to understand the relationships between clothing, heat exchange, thermal responses, and exercise performance in this system, the basic mechanisms of heat exchange and thermoregulation of human body were firstly reviewed.

2.3 Heat Balance and Thermoregulation

The normal core temperature (T_c) of healthy adult humans is about 37 °C [62, 63]. This temperature is lower during the morning after an entire night’s rest and is higher at night because of muscular activity and food intake. In general, women have slightly higher T_c than men. T_c should be maintained at a relatively stable value, and can various in a very narrow range of

35 °C to 40 °C. This temperature range is critical to human beings because metabolic pathways and cellular structures are affected by temperature. A decrease in body temperature below 34 °C may cause abnormal cardiac function and slow down metabolism, whereas an increase in body temperature above 45 °C may destroy the protein structure of enzymes, thereby inducing death. Therefore, maintenance of the heat balance of the human body to sustain the T_c within a certain range is critical [74].

2.3.1 Heat balance

The maintenance of actual body temperature is determined by the balance of two processes, namely, heat production and heat loss (shown in Figure 2.1). Thus, the heat storage (S) of a resting subject can be represented by the overall heat exchange equation (Equation 2-1) [90, 148].

$$S = M - (\pm W) - (\pm E) - (\pm C) - (\pm K) - (\pm R_a) \tag{2-1}$$

where S is the rate of heat storage (in $W \cdot m^{-2}$) (positive = increase in body heat content, negative= decrease in body heat content); M is the rate of metabolic heat production (always positive in a living animal, during rest, M = metabolic heat production); W is the rate of work (positive = external work accomplished, negative = mechanical work absorbed by the body); E is the rate of evaporative heat transfer (positive = evaporative heat loss, negative = evaporative heat gain); C is the rate of convective heat transfer (positive = transfer to the environment, negative = transfer into the body); K is the rate of conductive heat transfer (positive = transfer to the environment, negative = transfer into the body); R_a is the rate of radiant heat transfer (positive = transfer to the environment, negative = transfer into the body)

Metabolic heat production (*M*)

Metabolic heat production (M) is the rate of transformation of chemical energy into heat by the breakdown of complex materials, such as carbohydrates, fats, and proteins. Humans extract oxygen from the air in the lungs and acquire energy sources by ingesting food, which is a combination of carbohydrates, fats, and proteins. Carbohydrates are converted into glucose in the gut and liver, and become pyruvic acid in glycolysis. Fats are converted into fatty acids, while proteins are converted into amino acids and then into acetoacetic acid. After the first process of conversion, a small amount of energy is released. All the chemicals are transported into the mitochondria, also referred to as "the power factory of the cell." Here, the chemicals combined with oxygen are acted upon by a series of enzymes to produce adenosine triphosphate (ATP), carbon dioxide, and water (Krebs cycle). Approximately 95% of total body energy is produced in the mitochondria [150]. In addition to the oxidation of carbohydrates, fats, and proteins, the human body stores extra energy that can be used anaerobically for a short period. The above process is widely accepted as the method for providing energy for all bodily functions; however, energy cannot be used efficiently because most of it is released as heat that is distributed throughout the body. The integration of the energy produced is referred to as the total metabolic heat production of the body. Thus, M includes basal metabolic rate (M_b), which evaluates the heat production of a person at rest, as well as metabolic rates due to posture (M_p), type of work (M_w), and whole body movement (M_m). The formula is given in Equation 2-2.

$$M = M_b + M_p + M_w + M_m \tag{2-2}$$

The unit of $W \cdot m^{-2}$ or $kcal \cdot min^{-1} \cdot kg^{-1}$ is used due to the value that estimates M for a specific activity is usually related to the surface area of a body or related to body weight (BW). Generally, values of 1.6 m^2 and 60 kg are respectively assumed for the surface area and BW of a female model; for a male model, the values of 1.8 m^2 and 70 kg are respectively assumed [62,

[63]. The heat produced by an average body at rest is 1.25 kcal to 1.5 kcal per minute. During exercise, the heat produced can exceed 15 kcal per minute. Except the energy consumption of work, the heat produced should be dissipated by the body though thermoregulation to maintain the body temperature within a narrow range.

The amount of heat energy that can raise body temperature depends upon the specific heat and size of the individual (i.e., BW). The specific heat, which is a characteristic of body tissue, refers to the amount of heat energy required to raise 1 kilogram of body tissue by 1 °C. In the human body, the specific heat is about 0.83 kcal per kilogram of BW [150]. Therefore, the amount of heat required to increase T_c by 1 °C is computed as Equation 2-3.

$$H_{\mathrm{e}}=\lambda * BW \tag{2-3}$$

where H_{e} is Heat required increasing body temperature by 1°C, λ is specific heat, BW is body weight.

During heavy exercise, the body indeed generates a large heat load when temperature increases. Such condition serves as a serious test of the ability of the body to maintain body temperature, particularly in hot/humid environments.

Several methods for estimating metabolic heat production are available despite the complexity of energy production. For instance, metabolic heat production can be measured directly by using a whole-body calorimeter or by observing the total heat loss from the body in thermal homeostasis. It may also be estimated by measuring the oxygen consumption, carbon dioxide production, and energy released from food, which is evaluated by the metabolic rate (M) and by the calculation of the external work performed (W) [62].

Effective external work (W)

Energy is expended when people perform daily tasks. Two important factors, namely, intensity and duration, indicate the effects of the strenuousness of a particular physical task. When the body is at rest, heat production indicates the amount of heat produced for the body's basic functions, such as respiration and blood circulation, which provide nutrients and oxygen to body cells. In this case, W can be regarded as 0. However, for well-defined tasks, such as cycling and running, the need for nutrients and oxygen provided to active muscles increases because the muscles burn these nutrients during the activities. In this process, most of the energy is released in the body as heat, and only a small part of it is released outside the body for external work. However, the percentage of energy stored as heat or for external work depends on how efficient the body performs the work. Efficiency refers to how well energy is conserved in the accomplishment of a task. It is usually defined as work output divided by energy input. Generally, the efficiency of the body ranges from 20% to 30%, with 70% to 80% of the energy expended released as heat during exercise [59].

Radiation (R_a)

Radiation (R_a) is heat transfer by infrared rays from one surface of an object to that of another, with no physical contact between the two surfaces. In a comfortable environment with a temperature of 21 °C, the human body loses 60% of heat via radiation. This rate of heat loss is possibly the result of thermal gradient, wherein the temperature of the skin (T_s) is greater than that of the surrounding objects (floor, air, walls, etc.). However, if the surface temperatures are greater than T_s on a sunny and hot day, the body can gain heat via radiation [136]. Therefore, heat transfer by radiation can result in either heat gain or heat loss depending on the environmental conditions. Heat exchange by radiation is expressed in Equation 2-4 [58, 148].

$$R_a = \sigma\varepsilon\,(A_r/A_d) * (T_s^4 - T_r^4) \qquad (2\text{-}4)$$

Radiation (R_a in $W\cdot m^{-2}$) is dependent upon the Stephan–Boltzman constant σ ($5.67 \times 10^{-8}\ W\cdot m^{-2}\cdot K^{-4}$). In the given equation, ε is the emittance from the body surface (usually 0.99), A_r/A_d is the ratio of skin involved in the radiative heat transfer (usually 0.725 for standing posture, 0.696 for sedentary), and T_s and T_r are the mean skin temperature and mean radiant temperature of the environment (in Kelvin), respectively.

The human skin is heterogeneous and has variable thickness to incident radiation. The smoothness and color of the skin surface can also influence the emissivity and absorption of radiant heat. For example, white and black skin can absorb about 97% of infrared heat from the sun and respectively reflect around 40% and 18% of the sun's radiation. Not all body surfaces are exposed to the environment for radiant heat loss to occur. Generally, about 70% to 85% of the skin surface is open for effective radiation, which is determined by the body position. For a clothed person in a standing position, the percentage of skin surface exposed to radiation is roughly 72% [21, 148].

The general principle of radioactive heat transfer described in Figure 2.1 can also be used to express the process of heat transfer through clothing materials. Clothing may provide functional protection from thermal radiation but may interfere with evaporation in hot/humid climates. The intensity of radioactive heat transfer is related to the thickness of the clothing materials as well as to the ratio of the radiation penetration depth and the temperature gradient of the medium [42]. Farnworth pointed out that under circumstances wherein the radiation depth is comparable to fabric thickness, the amount of radiation and the conduction heat flow are considered the same, and that radioactive heat flow should not be ignored [42]. The color and smoothness of the fabric can also affect radiation.

Conduction (*K*)

Conduction (K) refers to the transfer of heat from the body into the molecules of cooler objects that come into contact with the body surface. In general, only small amounts of heat is lost from the body to the environment via this process, unless the person is working in water, special gas mixtures, and supine positions or is handling cold products [59]. Conduction can be represented by Fourier's law of heat flow in Equation 2-5 [25, 148].

$$K = k/d * (T_1 - T_2) * a \tag{2-5}$$

Conductive heat loss is dependent upon the specific heat of the substances (K in $W \cdot m^{-2}$), the thermal resistance between the contacted surface of two bodies and their relative mass (k), conductor thickness (d), the temperature gradient between two objects (T_1-T_2), and the area of contacting surface (a).

The conduction equation can be used to express the heat flow between the core and peripheral skin surface, skin surface and environment, skin and clothing, and between clothing and environment by replacing the appropriate values. In cold environments, vasodilatation or vasoconstriction of the skin can eliminate cutaneous blood flow, thereby reducing heat convective, conductive, and radiant losses. In this situation, the subcutaneous fat and musculature provides an insulative layer. By contrast, a significant amount of peripheral tissue can be involved in increasing blood flow to help achieve conductive and convective heat loss [148] in hot environments, wherein environmental temperatures normally range from 23 °C to 30 °C [17, 77, 171].

Convection (*C*)

Convection (*C*) is another important form of heat loss and refers to the physical exchange of heat between the body and an adjacent moving medium (e.g., air or water). To express the overall effect of convection, Newton's law of cooling in Equation 2-6 can be used:

$$C = a * K_c * (T_s - T_a) \qquad (2\text{-}6)$$

Where C (in $W \cdot m^{-2}$) is convection heat exchange, a (in m^{-2}) is the surface area exposed to conductive exchange, K_c is the convection heat transfer coefficient (environmental characteristics) (in $W \cdot m^{-2} \cdot °C^{-1} \cdot$). Convection heat transfer coefficient is the quantity of heat that passes in unit time through unit area of a plate of particular thickness when it's opposite faces differ in temperature by one Kelvin. Besides, it is inversed of thermal insulation (TI). (T_s-T_a) is the temperature differences between T_s and medium (ambient environment temperature (T_a)).

Evaporation (*E*)

Evaporation is the process whereby heat is transferred from the body as sweat on the skin surface and converted into water vapor, taking the heat away from the body. During exercise in most environmental conditions, evaporation is the most important process of heat loss even though it accounts for only about 25% of heat loss when the body is at rest. Evaporation of water requires the absorption of 580 kcal (2430 kJ) of heat per liter and depends upon vapor pressure gradients (skin, air, clothing, and environment) [148]. The equation for evaporation is written in Equation 2-7.

$$E = H_m * i_m * a\ (P_{s,sk} - P_w) \qquad (2\text{-}7)$$

The evaporative heat exchange (E in W·m^{-2}) depends on the heat transfer coefficient of mass (H_m), clothing permeability (i_m), surface area (a), and gradient between the saturated vapor pressure of skin ($P_{s,sk}$) and the ambient vapor pressure (P_w).

2.3.2 Thermoregulation

The human body has the mechanism to maintain T_c within certain boundaries despite variations in surrounding temperatures. The regulated temperature is that of the body core, which is physiologically defended by both autonomic and behavioral responses [161]. Even small fluctuations in the T_c can stimulate the human body's neural autonomic outflow controlled by the chemical coordination of the hypothalamus, cardiovascular responses, and a cascade of vasomotor reflexes. This section discusses some principles of thermoregulation in terms of the adjustment of the hypothalamus, thermal responses in hot conditions, and some heat disorders resulting from failure to maintain thermoregulation.

2.3.2.1 Thermostate-hypothalamus

The T_c is maintained by the control center of the brain called the hypothalamus, which is composed of the anterior and posterior hypothalamus. The anterior hypothalamus is responsible for acting upon increases in T_c, whereas the posterior hypothalamus reacts primarily when T_c falls. In general, the hypothalamus is much like a thermostat that sets the T_c around a set point of approximately 37 °C [150].

Information for temperature regulation is collected from receptors in both the core and the skin. Stimulations from T_a are primarily detected by thermal receptors located in the skin and transmitted as nerve impulses to the hypothalamus, which then initiates the appropriate response in an effort to maintain the temperature around the set point. Temperature-sensitive neurons located in the hypothalamus and the spinal cord also detect changes in the T_c.

Once cold receptors are stimulated in the hypothalamus or in the skin, the thermoregulatory control center initiates actions to limit heat loss and to increase heat production. First, the vasomotor control center directs the response to stimulate the vasoconstriction of peripheral blood vessels. Blood is diverted from skin capillaries and withdrawn to deeper tissues to minimize radiant heat loss from the skin surface [95, 128]. Second, the hypothalamus limits the action of sweat glands to reduce heat loss from evaporation. If the T_c drops sharply, skeletal muscles activate, and involuntary shivering occurs. The pilomotor center is also stimulated to promote piloerection. This reaction is an effective method to increase the insulation space over the skin in fur-bearing animals. However, this method is not effective for humans in preventing heat loss; clothing is used instead. Additional responses include the release of norepinephrine to increase the non-shivering thermogenesis, which is achieved by cellular metabolism. Finally, the posterior hypothalamus indirectly arouses the production and release of thyroxin, which results in an increase in cellular heat production.

When heat receptors sense an increase in the T_c above the set point, the thermoregulatory control center initiates a series of physiological actions to hasten the process of heat loss. First, the anterior hypothalamus initiates sweating by stimulating the sweat glands to increase evaporative heat loss. Second, the vasomotor center dilates the blood vessels of the skin and increases blood flow to boost radioactive heat loss from the skin [95, 128]. Physiological temperatures should be maintained to enable the body to respond almost precisely to the heat load arising from the hot environment and exercise.

When the body returns to homeostasis with normal T_c, all stimulation and responses associated with thermoregulation are removed. The entire process of how the hypothalamus responds to cold/heat stress is summarized in Figure 2.2

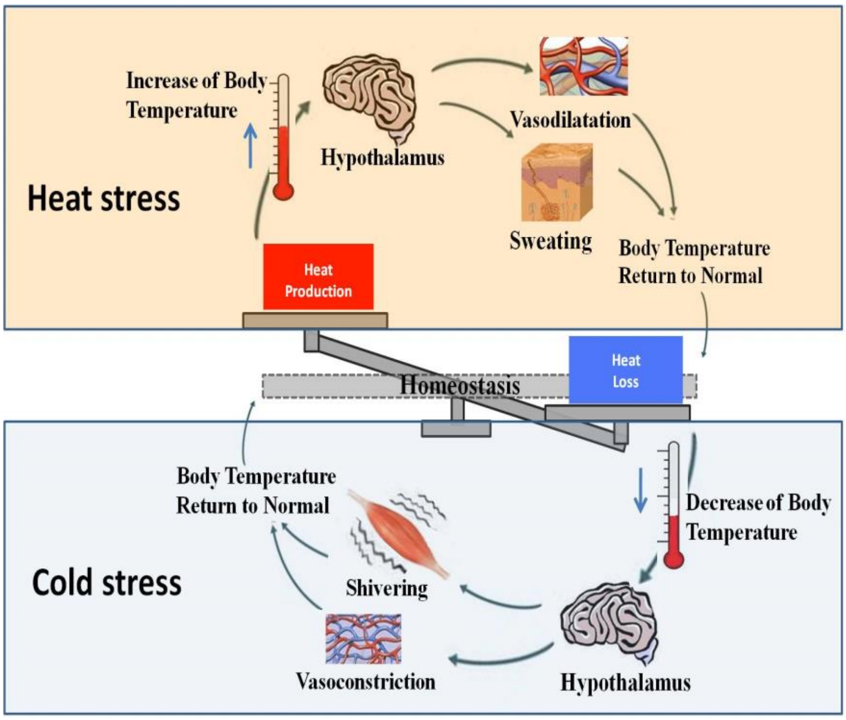


Figure 2.2 Thermoregulation of human body under heat stress and cold stress

In summary, the physical mechanisms of heat transfer between the human body and the environment involve heat transfer via radiation, convection, conduction, and evaporation. The maintenance of actual T_c is necessary for two processes, namely, heat production in the body and heat transfer to the environment, which is achieved by the physiological adjustment of thermal regulation [90, 148]. The process of thermoregulation contributes to the central adjustment of the hypothalamus and coordinates blood redistribution and sweating of the skin for heat dissipation. Skin evaporation is regarded as the primary mechanism that affects thermoregulation in hot conditions and thus should be reviewed. Some thermal responses, such as T_c, T_s, heart rate (HR), and sweat rate (SW), which reflect the status of heat stress, should also be introduced.

2.3.2.2 Thermal responses under hot conditions

Core temperature (T_c)

The T_c is maintained at a stable range of 35 °C to 40 °C, and the normal T_c of healthy adult humans is 37 °C [43]. The T_c increases as heat is stored in the body. In moderate environments, the T_c increases for about 20 min after the initiation of sweating and then plateaus, indicating that sweat evaporation has achieved thermal balance [1, 140]. The increase in T_c is not dependent solely on metabolic rate, as is also determined by the intensity of the exercise. Some studies have demonstrated that compared with the T_s, the T_c is controlled by the amount of exertion during exercise and is independent of a wide range of ambient environments [45, 118, 139]. In addition, a prescriptive environmental zone may not affect T_c. The prescriptive zone is defined as the optimum temperature for an athlete to perform in and varies with metabolic heat production [118]. However, as the effect of ambient environment is so great that heat dissipation from the skin to the environment is inefficient, the T_c can be affected because of gradual increases in S. When exercising in hot conditions, the clothing establishes a microclimate environment covering the skin. This condition is presumed to either facilitate or impair heat dissipation in terms of its influence to T_c.

Skin temperature (T_s)

The T_s is regarded as the average temperature of the body surface and plays an important role in the heat exchange between the skin surface and the ambient environment by the evaporation of sweat and the adjustment of circulation responses [1]. T_s is influenced by heat exchange via conduction, convection, radiation, and evaporation at the skin surface of the human body. It is also affected by the temperature of the arterial blood reaching a particular part of the body and by the variations in skin blood flow [87]. In light clothing, T_s is largely independent of metabolic rate but widely varies with ambient temperature [1] and air velocity [35]. Theoretically, the dry heat exchange with the environment by radiation and convection is determined by the temperature gradient between the environment and the T_s as well as by the thermal transmittance of clothing worn with its air layers. T_s has a narrow range compared with the changes of ambient environment. Thus, T_s can be altered by adjusting the thermal resistance of clothing (clo) or by exercising. T_s is usually lower in a free moving exercise than when the body is at rest because T_s changes while heat dissipates from the skin to the environment by sweat evaporation. At rest, T_s is only affected by the thermal resistance of clothing and air flowing through the skin. As skin initiates sweat during exercise, heat dissipation through clothing increases rapidly and involves a more complex mechanism [49, 148].

Heart rate (*HR*)

The *HR* reflects the increased metabolic rate induced by exercise and cardiac strain due to thermal stress [143]. The increase of *HR* (ΔHR) in human subjects is very strongly related to the increase in T_c. The ΔHR for an increase of 1 °C in T_c is defined as thermal cardiac reactivity (in $\text{beat}\cdot\text{min}^{-1}\cdot{}^{\circ}\text{C}^{-1}$), which is a very important parameter in determining thermal strain [87]. The ΔHR is usually around 33 $\text{beat}\cdot\text{min}^{-1}$ per degree increase of T_c. However, thermal cardiac reactivity varies greatly among different individuals. Even for the same subject, thermal cardiac reactivity varies according to whether thermal stress is due to metabolism (endogenic) or due to climate (exogenic). This parameter also depends on the involved muscular group because of the different types of exercise [87]. Thus, in situations where thermal stress could be very high, an upper limit for ΔHR must be set, and the T_c must be measured.

Sweat rate (*SW*)

Sweat evaporation is the primary mechanism of heat dissipation in hot conditions and is also independent of metabolic rate. It is the process in which water molecules are transferred from the core to the skin and converted into water vapor, taking the heat away from the body. Every gram of water evaporation would absorb 580 kcal (2430 kJ) of heat [148]. At rest, water evaporation accounts for approximately 25% of daily heat dissipation; during exercise, it accounts for about 80% of the total heat loss [48, 187]. The amount of sweat evaporated from the skin is dependent upon the area of wetted skin for heat exchange, vapor pressure gradient, and natural convective currents [150]. The maximal *SW* of humans ranges from 10 $g \cdot min^{-1} \cdot m^{-2}$ to 15 $g \cdot min^{-1} \cdot m^{-2}$. The *SW* is found to vary widely among different individuals [68, 166], sex [84], ages [82, 83], and nationalities [180, 186]. The factor that limits heat loss during exercise is not only temperature gradient but also the humidity of the microclimate environment of the clothing and the human body. When clothing is dry, the sweating and evaporative cooling times are shorter as determined by the properties of the clothing. If sweat does not evaporate immediately from the skin–clothing surface, the humidity of the environment increases, thereby disturbing the thermo-regulatory mechanism [196]. Hence, clothing of different design styles and fabric with varying moisture properties has diverse thermal effects on the human body.

Distribution of sweat production and skin temperature

The increases in sweat production is brought about by the increased participation of sweat glands [4]. The skin surface has non-uniform *SW* in each part of the body because of the differences in sweat gland density and sensitivity in the body [4, 94]. As early as 1946, Randall plotted the sweat gland distribution in different body areas (as shown in Table 2.1) and suggested that the average density of active glands depending on the individual is around 125 $glands \cdot cm^{-2}$ to 200 $glands \cdot cm^{-2}$ [152].

Table 2.1 Distribution of sweat gland

Segment	Sweat glands (functional pores·cm^{-2})
Forearm, extensor surface	213
Upper arm, over biceps	177
Dorsum of hand	377
Trunk – anterior chest	151
Trunk – scapular region of back	30
Leg (over gastrocnemius)	99
Thenar eminence	284
Face – forehead	167
Face – zygomatic arch (temple)	21
Face – buccal (cheek, jaw)	16

Source: Randall WC. Quantitation and regional distribution of sweat glands in man. *Journal of Clinical Investigation*. 1946;25:761-767.[152]

Sweat production in various body parts is relevant to the analysis of the heat exchange of the human body because of the various clothing types used to cover different body parts and because of the regional heat transfer coefficient differences due to air and body movement. The summary of sweat distribution has potential benefits in the functional design of clothing and prevention of heat disorder [148, 164]. The distribution of eccrine sweat production over the entire body has been explored in several studies, such as in the summary by Kuno shown in Table 2.2 [101]. The entire body also has various orders of sweating for each body part. When sweating is initiated, the first area that undergoes sweating is the forehead, followed by the upper arms, hands, thighs, feet, and back and abdomen [78]. Several studies have found different orders of sweating [94]. Thus, further investigation and a systematical summary of sweat distribution are necessary.

Table 2.2 Distribution of eccrine sweat production

	Body parts
Greatest	Forehead, neck, back of hand and forearm, back and front of trunk
Middle	Cheeks, arms and legs, lateral surface of trunk
Least	Inside of thighs, soles, palms, armpits

Source: Kuno Y. *Human perspiration*. U.S.: Springfield, I11; 1956.[101]

The distribution of skin temperature is not constant because of the variations in anatomical structure and tissue thickness as well as in blood flow under the skin, which is also affected by the variation of sweat evaporation in different body parts [94]. A number of studies have focused on the distribution of skin temperature [145, 164, 193]. However, this topic has not been quantitatively summarized because of the different research protocols, measurement methods, and ambient environments. Thus, the various skin temperatures of each body part cannot be applied properly in sports studies and the clothing industry [94].

2.3.2.3 Heat disorders

Heat becomes a problem when hot/humid environment and radiant heat combine with strenuous exercise (heat production) to raise the T_c beyond safety limits. Heat disorders are a threat to human health (Table 2.3). A generally known heat disorder is hyperthermia. Hyperthermia is defined as an increase in the T_c above the set range specified for the normal active state of humans (37 °C at rest and 38 °C during moderate intensity exercise) when heat dissipation mechanisms are impaired or overwhelmed by internal (metabolic heat production) and external (environmental or induced) heat [39, 55].

Table 2.3 Classification of temperature and related heat disorders

	Core temperature
Hypothermia	< 35.0°C (95.0 °F)
Normal	36.5-37.5°C (98 - 100 °F)
Fever	>37.5 - 38.3°C (100 - 101 °F)
Hyperthermia	>38.4 - 39.9°C (101 - 104 °F)
Hyperpyrexia	>40.0 - 41.5°C (104 – 107 °F)
Heat stroke	>41.5°C (107 °F)

Note: The difference between fever and hyperthermia is the mechanism: a fever is caused by a shift of T_c set-point.

Generally, heat stroke occurs when the T_c exceeds about 41.5 °C, which may lead to collapse [35, 141]. Heat stroke is the most serious and complex heat disorder that requires immediate medical attention. All heat strokes occur concomitant with signs of heat stress such as thirst, tiredness, grogginess, and visual disturbances, resulting in the failure of cardiovascular compensation.

Thermoregulation failure and adverse environments have etched the tragedy of heat-related deaths in the history of distance running [65]. As early as 490 BC, Phidippides, a young Greek, collapsed and died after running 26.2 miles from Marathon to Athens. This death of Phidippides is probably the first recorded incidence of the sudden death of an athlete [47]. During the 1912 Olympics Games in Stockholm, a Portuguese athlete, Francisco Lazaro, died following his collapse from heat stroke after running 19 miles. In the 1954 Empire Games marathon, Jime Peters, the first marathon runner to break the barrier of 2 h and 20 min, collapsed before reaching the finish line despite arriving in the stadium 15 min ahead of his nearest rival [65]. Although heat-related deaths are regarded as preventable cases, 21 deaths of relatively anonymous athletes were recorded between 1995 and 2001. In the last 20 years, over 100 athletes have died from excessive heat stress due to exertional heat stroke during competitions [127]. In 2010, another marathon runner, Remus Fuentes, was reported to have died from multiple organ failure due to heat stroke secondary to severe dehydration two days after his 21K race in the 34th Milo Marathon [41]. During the Hong Kong Standard Chartered Marathon in 2013, 55 runners fell unconscious, lapsed into a coma, and collapsed from heat stroke because of the hot and humid environment [116, 119]. All these cases draw our attention to the impairment of heat stress during distance running and to the need to optimize strategies of heat dissipation during running in hot conditions.

2.4 Running Performance

2.4.1 Factors affecting running performance

Running is currently one of the most popular exercises that can be practiced by almost everybody. Table 2.4 shows three kinds of running, namely, springing, middle distance, and long-distance running. Given key physiological features, the heat disorders mentioned in the previous section mainly occur in distance running covering 800 m to 10000 m or even longer.

Running induces sweat for heat dissipation and muscle fatigue. Distance running induces thermal stress and/or serious thermal stress because of extreme metabolic heat production during the athletes' best running performance [65]. Being able to run faster than the other athletes over a certain distance has been regarded as the highest praise to be achieved in running since the birth of competitive sports. The need to improve running performance has therefore increased [66].

Table 2.4 Physiology behaviors for different running

	Definition	Key physiological feature
Sprinting	Up to and including 400m	Light sweating Muscle fatigue
Middle distance	Distance from 800 to 5000m	Sweating Muscle fatigue Thermal stress
Long distance	10000m or longer	Heavy sweating Serious thermal stress Muscle fatigue

Running performance is characterized and diversified by the indices of work efficiency, which is determined by velocity, duration, and power [33]. Several factors affect running performance. Examples include diet, energy production, strength/skill, neuropsychology, and environment [8, 124] (Figure 2.3). Specifically, every performance requires a certain amount of "strength," the "skill" to apply that strength, "diet" to provide "energy" sources, and psychological commitment to "go for the gold." Aside from these factors, "environment" may also play an important role in endurance performance [8, 124]. Clothing which establishes a microclimate environment around body would tend to have effect on performance. (This factor would be separately discussed on a dressed body in Section 2.5). Previous studies have suggested that the serious consequences of heat stress induced by hot environment are an independent cause of fatigue that further impairs exercise performance [51]. Experts have recognized the serious threat of hyperthermia to an athlete's health [133]. Thus, the next section discusses the influence of heat stress on fatigue and running performance based on three aspects, namely, cardiovascular adjustment, muscle metabolism, and central nervous responses.

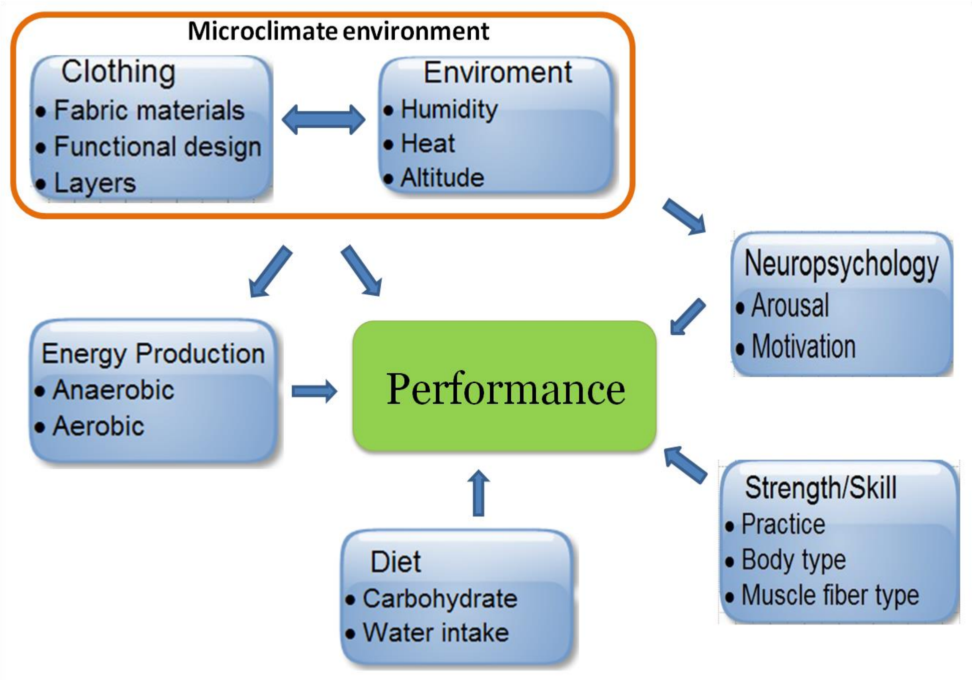


Figure 2.3 Factors affect performance

Sources: McArdle WD, Katch FI, Katch VL. *Exercise Physiology: energy, nutrition, & human performance*. 6th ed. Philadelphia: Lippincott Williams & Wilkins; 2007 [8, 127].

2.4.2 Influence of heat stress on running performance

Studies have suggested that setting the end point of the T_c is critical, as it serves as a definitive safety brake against tragic heat-induced injury or death. Generally, exhaustion in untrained subjects exercising in hot conditions would be induced at the T_c between 38 °C and 39 °C, which relates to the complex combination of exercise intensity and duration, large external heat stress, exercise motivation, and training status [129]. Trained athletes who participated in such studies started repeated trials with varied T_c, but they eventually became exhausted at a similar T_c of 40 °C with dissimilar heat storage capacities and different exercise durations [39, 124, 137]. Although athletes become exhausted or unwilling to continue running as the T_c exceeds 40 °C, they would continuous running until the end of competition. An increase in T_c to a range of 40 °C to 41°C are prevalent in trained athletes during endurance running [35, 141], but they may unaware that they were at high risk of heat stroke, and what will happen afterwards. In this situation, the ability to dissipate excess heat during whole process would be essential. The detailed reasons for fatigue under thermal stress are explained through the following three aspects which will be discussed in the next sections (Figure 2.4).

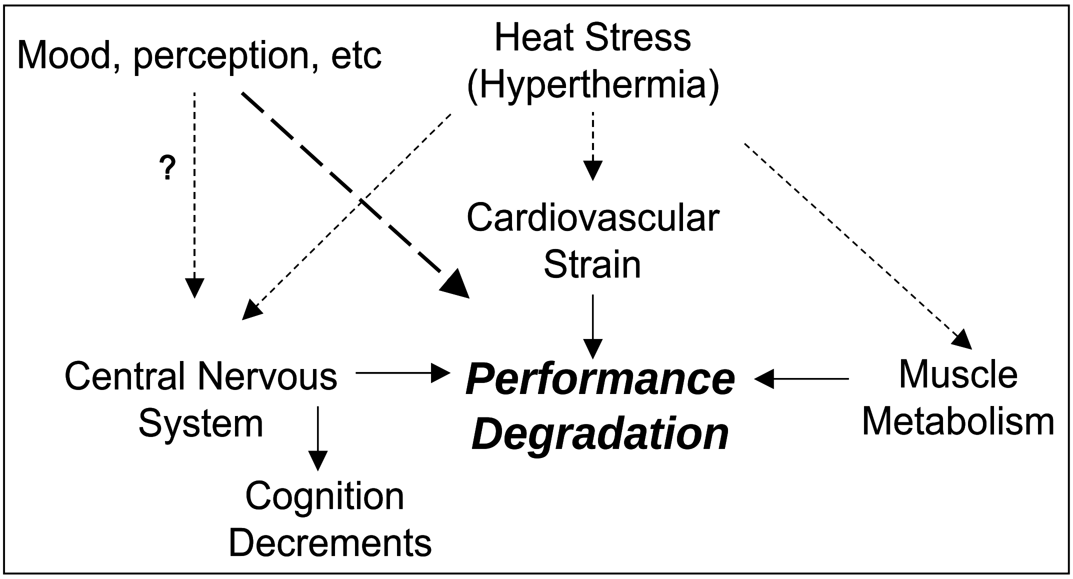


Figure 2.4 Model of heat stress and performance

Source: Drust B, Rasmussen P, Mohr M, Nielsen B, Nybo L. Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiologica Scandinavica.* 2005;183(2):181-190. [39]

2.4.2.1 Circulatory adjustment

The primary requirement for a successful performance of a middle distance runner is to maintain a high power output for short periods. However, the challenge in long distance events is sustaining the submaximal effort for prolonged periods of time [65]. Compared with spring runners, distance runners must compensate to some degree for a relatively lower oxygen consumption (VO_2) and higher capacity to maintain a high portion of aerobic power for prolonged periods [65]. However, various factors may limit VO_2. Endurance-trained runners have a high capacity for oxidative metabolism in their muscles and a highly developed cardiovascular system. During exercise, oxygen is used by a large amount of muscles, wherein oxygen utilization is limited by the rate of oxygen delivery to the active muscle rather than by the capacity of the oxygen utilized by the muscle [45]. Thus, oxygen delivery by the cardiovascular system appears to be an important factor that may limit performance.

Previous studies have suggested that certain limitations to oxygen uptake are imposed by the lungs [65, 168, 169]. During exercise with submaximal intensity, the oxygen saturation in the blood may fall because of the mismatch between local diffusion capacity and perfusion of the vascular bed. When cardiac output increases due to the increases of exercise intensity, completing equilibration becomes difficult because of time limitations for oxygen to transfer to the pulmonary capillary. Some studies have reported differences in pulmonary diffusion capacity and maximum ventilator function between elite distance athletes and sedentary individuals, even though the former has a cardiac output that is two to three times larger than that of the latter. However, studies have also suggested that specific training could improve functional lung capacity. Moreover, additional equipment and adverse conditions may overburden the cardiovascular system [65, 168, 169]. The maximum cardiac output that can be achieved is another factor closely related to the VO_{2max} and hence to distance running performance [65, 168, 169]. As elite athletes have a narrow range of maximal *HR*, stroke volume (*SV*) has been found to be a major factor in determining VO_{2max} and performance.

Cardiac output, central blood volume, and *SV* during exercise with moderate intensity in hot conditions have been compared with those in neutral conditions. The results suggest that heat stress reduces cardiac output because of the large decline in *SV* and the increase in *HR* during moderately intense exercise [51, 157]. Gonzales et al. (1997) suggested that an increase of 1 °C in body temperature would reduce *SV* by 11±3 ml and increase *HR* by 9±1 beats·min^{-1} when skin blood flow is constant [52].

Changes in *HR* are probably caused by the lower central blood volume and the increases in skin blood flow and volume [51, 157]. When exercising in hot conditions, the body is initially thermoneutral. A few minutes later, the heat produced by active muscles starts to accumulate in the body. The accumulated heat must be transferred from the core to the skin for heat dissipation, which depends on the variation between T_c and T_s as well as on the perfusion of the blood to the skin [39, 185]. Skin blood volume and flow must therefore increase while the perfusion of the internal organs decreases. The redistribution of cardiac output initiates the increase in *HR* to meet the increased need for perfusion of the skin [3]. If the intensity of the exercise is low or even moderate under hot conditions, the compensatory increase in *HR* can adequately achieve the required blood redistribution and perfusion. However, during submaximal exercise in adverse conditions, the magnitude of heat production is so great that increased blood flow in the skin cannot completely initiate heat dissipation. As the T_c elevates and hyperthermia develops, the maintenance of cardiac output is impaired because of the decline in *SV*.

As blood is redistributed, the decrease in *SV* may be influenced by diastolic filling time and shortened cardiac cycle, which are both results of the increased *HR* [44]. The decline in *SV* with hyperthermia is also affected by the cardiac filling pressure because of increased peripheral blood flow and reduced central blood volume [44, 51, 157]. The extent to which the decline in SV influences cardiac output appears to be related to body position, exercise intensity, and level of heat stress [51, 138]. If heat stress is prevented, and exercise intensity is low, then the increased *HR* will compensate to limit the reduction of cardiac output within 1 l·min^{-1} [39, 51]. Although an increase in the perfusion of the skin and active muscle is required, the compensatory increase in *HR* may sufficiently maintain the arterial blood and oxygen supply derived from the splanchnic and renal flow. However, when the intensity of the exercise is increased to 60% of VO_{2max} or above, cardiac output may decrease by 2 $l \cdot min^{-1}$ or less if hyperthermia develops, particularly if the body is dehydrated, and fluid intake could not compensate for sweat losses. Under this condition, the decreases in cardiac output induce a decline in muscle blood flow, accompanied by a slightly increase in the release of lactate due to increased glycogen utilization instead of fat metabolism. Fatigue would be provoked when stored muscle glycogen, muscle ATP, and Creatine phosphate are depleted as well as when muscle lactate and H^+ accumulate at the point of exhaustion [39, 51].

2.4.2.2 Metabolism responses

Runners who aspire to establish better records during championship races require a high rate of energy production to maintain a consistently high average speed throughout a race. The energy supplied to the muscles comes from the catabolism of ATP, and only when the ATP is sustained can the muscular work be maintained. As the ATP is hydrolyzed, the amount of ATP resynthesized must be equal. The energy provided for ATP resynthesis is from a combination of anaerobic and aerobic sources during all running distance races. In short-distance running, for example, a 100 or 200 m race, the contribution of anaerobic energy metabolism is enormous because anaerobic metabolism provides a high rate of power output to fuel maximal effort within a short time. In middle-distance running, the top performance requires not only a high rate of anaerobic metabolism but also a great amount of oxidative metabolism. Studies have suggested that the relative contribution of aerobic and anaerobic energy metabolism to the total energy demand is about 80% and 20% in a 1500 m running race with maximum effort for a duration of 4 min [65]. At longer races, the energy source provided by anaerobic metabolism declines, and the requirement for high aerobic capacity is obviously increased. A report has suggested that the percentage of anaerobic energy demand decreases to less than 1% of the total energy demand in a 42.2 km running exercise lasting for 2 h [65]. Thus, an effective aerobic energy production is essential for a successful performance in long-distance running.

Athletes are still more dependent on anaerobic metabolism during progresses in submaximal exercise under hot conditions than under cooler conditions [26]. Hyperthermia advances the encroachment on glycogen reserves, accumulation of lactate, and premature fatigue during prolonged moderate exercise. The increased accumulation of lactate is due to two factors, which are decreased muscle catabolism of circulation lactated because heat dissipation drives blood redistribution from the core to the periphery, and reduced lactate uptake by the liver because of decreased hepatic blood flow [51, 127, 138].

2.4.2.3 Central nervous system

Athletes experience confusion when their body temperature increases to 40 °C, which may be explained by the brain temperature [153]. The balance of heat produced by the cerebral energy turnover and the lost heat has been considered as the brain temperature. The heat convection between the cerebral tissue and capillaries is very high. Thus, the temperature of the cerebral tissue is likely equal to that of the cerebral venous blood. The thermoregulation of the brain can be evaluated by measuring the difference between the internal jugular venous and arterial blood temperatures. The cause of hyperthermia-induced fatigue during a prolonged exercise in a hot environment is mainly located in the central nervous system [153]. Nybo and Nielsen (2002) found that the development of hyperthermia during a prolonged exercise is associated with a decrease in global cerebral blood flow by 18% and coincident with an increase in the arteriovenous differences for oxygen and glucose and in the cerebral metabolic rate [39]. If a cooling system for the head is manufactured using fast-cooling materials that can help decrease brain temperature, then the heat-induced fatigue of the central nervous system can be delayed, and exercise performance can be prolonged [39].

2.4.3 Summary

In conclusion, heat production during distance running can rapidly increase the T_c and S in the human body. Combined with the heat stress induced by a hot environment, such heat production would not only threaten the health of runners but also induce thermal fatigue and impair running performance with regard to cardiovascular responses, muscle metabolism, and central nervous system. Therefore, improving heat dissipation, reducing the cardiovascular strain, and further decreasing the impairment of heat stress are important to exercise performance under hot conditions.

2.5 Clothing System and Running Performance

Athletes must decrease their effort to reduce metabolic heat production during distance running or take several effective measures to increase heat dissipation in hot environments to reduce the risk of overheating and to improve running performance. In hot conditions, athletes can move exercise sessions to a less-stressful environment to prevent overexposure to the sun [187]. However, athletes can do little about prevailing weather conditions during actual competitions.

Clothing as a uniform required in formal competitions can be an important consideration [187]. It serves as an interactive barrier between the ambient environment and the skin surface, which can alter the condition of the macroclimatic environment. It also protects the body against the external environment and affects the thermal responses of the body, which may further influence running performance [147].

Conducting a comprehensive review regarding the following aspects is necessary because of the possible effects of clothing on thermal responses and running performance in the Body-Clothing-Environment system: 1) the development of functional clothing; 2) evaluation methods for the physical properties of clothing, especially in the moisture and thermal aspects; 3) evaluation methods for human physiological responses; 4) the possible effects of clothing on thermal responses and running performance; and 5) the possible effects of clothing on wearing comfort and related subjective sensations.

2.5.1 Development of functional clothing

A designer is normally required to consider aesthetics along with the use of the basic skills and knowledge in fashion, textiles, and graphics. Recent attention on the application of "smart" textiles and optimized technology to clothing has made fashion designers realize that the functional design of performance clothing is becoming a trend in sportswear [163]. Customer needs that related to active sports include protection, performance, and comfort [163]. For active wear and endurance sports, the clothing should be capable of protecting athletes from environmental elements such as Ultraviolet (UV) rays, rain, and wind. It should also be able to maintain the heat balance between the excess heat production of wearers due to increased metabolic rate and to help dissipate body heat [163].

Existing design concepts are based on ergonomical and biomechanical analyses which related to sports morphology, anatomy, and mechanics. Functional textiles and improved technology are incorporated in the product development process of sports clothing and devices (e.g., aerodynamic properties for swimming, breathable waterproofing for outdoor pursuits, and thermal properties for cold-weather sports [163]). US patent 2007101478 specifically claimed a design for warming gloves that can provide a thermodynamically efficient garment for cooling and/or heating the body [100]. Thermodynamic efficiency is provided in part by targeting the heat exchange capabilities of the garment to specific areas and/or structure of the body. Patents WO 2001/048278, JP 2008127695 [144], CN 2625405 Y, and CN 101120824 presented other aspects in providing thermodynamic efficiency using different functional fibers or using specially designed fabric structures. These patented fabrics can provide excellent stretch ability or additional benefits such as blocking of UV rays and antibacterial qualities, among others. EP 1002470(A2) presented a way to add a venting arrangement for sportswear. KR 20040081546, ZL 200410043157.9, and ZL 200620136950.8 claimed to control microclimate temperature using a phase change material. Another group of patents, including US 2007006360(A1), JP 2008150732 (A), and WO 2008020347, claimed a method to improve wearing comfort using different accessories. GB 2373728 A and US 2008083055 also disclosed a way to design sportswear by adjusting the pressure distribution on the body. Apart from the patents, Luo (2012) has considered the thermal requirements during submaximal cycling exercise when designed cycling clothes [122]. However, the fundamental scientific mechanisms of clothing functional design in relation to the human thermal physiology has not been systematical investigated. To sum up, the previous studies have developed new technologies to enhance the clothing design process considering the thermal demands of clothing. As documented in Section 2.3.2.2, different distributions of skin temperature, *SW*, and sweat evaporation are noted at different body parts during exercise, which may have various impacts on the thermal status of athletes. Although the physical responses of skin surface in some body parts have been investigated and applied in the development of running clothes in Wang's study [183], its work has focused attention on the methodology of dynamic clothing pattern making for biomechanical functional performance during sports activity. However, the study did not consider the clothing thermal body mapping design in relation to the thermal physiology, thermal comfort and running performance [183]. Therefore, to our best knowledge, few studies have systematically investigated the distribution of skin temperature and sweat evaporation during different exercise statues, and considered the application of different thermal requirements in each body part during the development of summer running clothes.

2.5.2 Evaluation of clothing physical properties

Fabrics used for clothing may result in distinct thermal responses of human body by influencing the heat and moisture transfer at specified body parts. The different types of clothing worn by human subjects directly influence the heat exchange between the body and the environment [11, 12, 86]. Basic fabric tests alone do not consider other factors, such as the integration of various fabrics, distribution of fabric layers over the body, and the cover ratio of the component clothing, during the design process [11, 12]. Measures should be conducted to assess whether the developed clothing would pose less thermal strain compared with existing products in the market [105, 143]. Results of these measures can be used to determine the thermal stress, running performance, and thermal comfort in the environment. Lothens and Havenith [60, 121] explained that several methods were available to test heat insulation and water vapor resistance with varying degrees of accuracy and effort. These methods can be classified into the following five categories:

1) Guarded hot plate

The guarded hot plate test can measure the dry and evaporative heat transfer on single- or multiple-layered textile materials to determine the permeability and insulation values [85, 143]. Measurements include the test plate heater wattage and temperature measurements of the guard ring, the test plate, and the bottom plate. The test specimen is placed on the instrument, and the system is allowed to equilibrate. The procedure is designed to simulate heat transfer between the human skin surface and the surrounding ambient environment through the tested fabric materials [13, 14, 85]. The advantage of this method is that it can rank numerous similar materials, and the testing procedure is quick and simple. However, a limitation of the guarded hot place testing is that the vapor permeability and thermal resistance values measured for a flat, two-dimensional sample may not be the same when the material is constructed into an ensemble [105, 143].

2) Direct measurement while human subjects are dressed

Direct measurement is one method used when the clothing is worn by human subjects in the actual or simulated environment. This method is laborious and requires sophisticated equipment to obtain realistic data [121] as well as a sufficient number of subjects and numerous estimations of the human body to obtain satisfactory results [60, 121]. Furthermore, the calculations involved contain much estimation, such as estimated clothing insulation and metabolic rate, which substantially increases measurement uncertainty [60, 121].

3) Thermal and sweating manikin

A life-sized thermal copper manikin in a controlled environmental chamber can be used to determine vapor permeability and TI [11, 12, 73]. The manikin is automatically controlled by a computer to maintain constant T_s when the test clothing is worn. Standard reference clothing should be used as a control. The advantage of this method is that heat transfer characteristics are evaluated on the entire clothing, accounting not only for the specific fabric materials but also for factors such as clothing pattern and design, body coverage, size, and fitting [75, 105, 143]. This method has better reproducibility, but it cannot be widely used in the clothing industry because of restrictions in the mobility of the manikin, the unavailability of driving machines, usage condition, and expensive cost, among other factors. The thermal manikin is encapsulated by a fitting cotton "skin," which can only represent the non-sweating condition or the surface area that is 100% wetted through a complete saturation with distilled water [105, 143]. Estimating the primitive sweat process may be difficult when sweat is elicited as liquid water accumulated on the skin surface and as transferred liquid via the clothing.

4) Regression methods

A regression equation is developed to determine insulation based on the means of previous data obtained from manikin measurements. Results can also be obtained with regression on the physical characteristics of clothing (such as thickness) and on the covered skin area. The method predicts reasonably well in several properties, but vapor resistance data are rarely available for clothing with special functions [121].

5) Thermograph

Thermograph is a method of detecting the infrared radiation emitted by objects to evaluate the temperature distribution at the clothing surface via thermal images. However, results are normally shown in a visual image style and need further image treatment to obtain the physical meaning behind the images. Thus, this method is not a direct and accurate measure for the evaluation of TI [135].

In summary, different kinds of testing standards are available for the measurement of the physical properties of basic fabric. However, only a few evaluation systems are available to quantitatively evaluate the clothing designed with multi-fabrics and its effects on the human body. Parameters and methods for estimating the overall ability of heat dissipation when wearing certain kinds of clothing in hot conditions are also limited.

2.5.3 Evaluation of human physiological responses

After evaluating the fabric/clothing properties, the physiological evaluation of clothing to determine the responses of wearers can be conducted in three kinds of trials: manikin test [75, [105, 128, 190], computer simulation [54], and wear trials. The manikin test can be applied not only to evaluate the overall properties of clothing systems but also to simulate the thermal responses of wearers, such as T_s, SW, and thermal comfort [69], as well as to further predict heat strain in hot conditions. These measurements extensively rely on knowledge and experience derived from human experiments and should be regarded as complementary to, rather than a replacement for, practical testing [75]. In computer simulations, the computer can automatically simulate the thermal responses of the human body in different environments when information on the physical properties of clothing is provided [54]. However, these two methods have several limitations. Specifically, only several manikin tests can simulate the thermal responses and wearing comfort of human subjects during running, which lack international standards [72, 173]. For a multi-layered clothing ensemble, the thermal performance of clothing cannot be accurately tested by a computer simulation [54]. Thus, wear trial is still used by most researchers because it can accurately reflect the various responses of the human body at rest and during exercise under different kinds of environments.

The wear trial normally includes the following parts: experimental design, volunteer testing, familiarization, preliminary measurements, clothing testing, experimental protocol, and physiological measurements. Participants in the volunteer testing should be healthy and physically fit and must meet the test-specific criteria, such as limits on medications, alcohol, regular training, and dietary supplements. The requirements are meant to ensure their safety, to complete the testing, and to coinstantaneously assure the accuracy of the study [143]. Statistical determination of the sample size of the subjects is required. The sample size is based on the expected difference in a criterion measurement and the standard deviation in the measurements [3, 175]. A familiarization session and preliminary measurements are required to introduce the subjects to the procedure, the potential sensations, and the risks involved in the trials, as well as to record the anthropometric and fitness data of the subjects. The familiarization session is also an opportunity to fit the clothing to each subject. Conditions of the study may be limited by scientific or ethical reasons associated with the exposure of human volunteers to stressful environments [143].

Any evaluation that uses human subjects must be detailed in a protocol, which undergoes both scientific and human use review by institutional review boards [143]. Several kinds of protocols are used. The performance and thermoregulation protocols are examined when wearing compression garments in hot conditions. Here, subjects are required to perform sets of exercise consisting of repeated cycles of intermittent, varied-intensity shuttle running to simulate a team sport activity in hot conditions [79]. Drust et al. used intermittent cycling sprints and resting on a cycle ergometer to assess the effects of hyperthermia on intermittent exercise and repeated sprint performance [39]. Performance can also be assessed by match analysis during football games and by a repeated sprint test [130]. In another study, performance capability was assessed using a stepwise speed-incremented treadmill test to voluntary maximum termination when wearing two kinds of clothing [192]. This test is one of the most common cardiac stress tests that determine exercise tolerance under stress. The time trial protocol is another widely used method [7, 123, 167]. Using this protocol to assess running performance has been proven to be more reliable than that used at a given work rate until exhaustion [27]. The time trial protocol requires subjects to perform long, steady-state running followed by an all-out performance at a given work rate or distance in the fastest possible time. This protocol is perhaps a more appropriate method to simulate actual competitive endurance running events [28, 37]. With regard to the intensity of constant running, previous studies on how nutritional intake affects endurance running performance used the intensity of 70% VO_{2max}, as this intensity is believed to represent the aerobic capacity in prolonged exercise. Furthermore, the processes lower the measurement of endogenous substrate stores, such as muscle glycogen, of endurance runners before performance running, which is essential for distinguishing the effects of different nutritional intakes [28, 37]. However, few studies have used a similar protocol to compare the improvement of different kinds of running clothes.

Four main physiological parameters—T_c, T_s, HR, and ΔBW—are considered in measuring, interpreting, and assessing the thermal stress and strain of humans when wearing different clothing types in hot environments [87]. The measurement methods are discussed as follows.

Measurement of core temperature (T_c)

The measurement of T_c is an essential factor in monitoring the heat strain of athletes during exercise [5, 117]. A high T_c is commensurate with exercise intensity in high environmental temperature and humidity [117]. In hot conditions, even a moderate intensity exercise can increase the T_c and induce heat strain. Hence, accurately monitoring the T_c of the subject during a high intensity exercise in hot conditions is critical. Four kinds of measurements will be introduced.

Ear canal, rectal, and gastrointestinal (GI) temperatures are commonly used for T_c measurement. Ear canal measurement is simple and convenient because it only requires the placement of a probe into the ear canal. However, the ambient environmental condition affects the accuracy of the T_c measurement [156]. Rectal measurement is a method wherein a thermistor rectal probe is inserted past the external anal sphincter into the rectum. The temperature reading for rectal measurement is relatively stable. However, this invasive T_c measurement causes discomfort for the subject. GI temperature is measured through the ingestion of a telemetric sensor that wirelessly transmits the temperature of the GI environment to an external logger. This method has key advantages because it measures the temperature continuously and with minimal discomfort for the user [117, 131]. However, standardizing the location of sensors is difficult because it may influence the T_c measurement. Among the three kinds of methods, the GI temperature measurement is found to be the best, as it achieves the best balance of comfort, practicability, and scientific validity [117]. Thus, GI temperature measurement is often selected to measure the T_c in physiological studies.

Measurement of mean skin temperature (T_s)

The T_s varies widely over the surface of the body, especially in a relatively cold ambient environment. Hence, the local skin temperature is commonly measured at a specific point of the body surface and is used to estimate the T_s by weighting an ensemble of local skin temperature based on the area they characterize [87]. However, local skin temperature may not be directly used to evaluate thermal strain, as it constitutes an important criterion to estimate thermal comfort. For a nude subject, T_s is measured using non-contact infrared radiation probes at a given point of the body surface whenever technically possible. However, for clothed subjects, thermistor probes are preferred by placing them on the skin surface. The probes can be attached to the skin with an adhesive tape to avoid the influence of local microenvironment and thermal isolation. However, the size of the tape should be strictly limited, and covering the probes with tape should be avoided because of the heat exchange interference that the tape may cause [22]. Applying adequate corrections on the measures is also suggested [87].

Three weighting schemes of 4, 8, or 14 measuring points of the local skin are proposed to distinguish the T_s from the local skin temperature at different body parts. T_s is calculated by the weighting coefficient that matches the specified surface of the body area with each local temperature [87]. In hot or warm conditions, the weight scheme with 4 points can be chosen, while in cold or neutral condition, 8 or 14 points, including the addition of extra points, is recommended [87].

Measurement of heart rate (*HR*)

The *HR* is traditionally measured using bipolar electrodes, but these electrodes rarely remain on the body during exercise because of the high *SW* under hot conditions. A highly reliable method is the use of an electrode band worn around the chest, with the signal transmitted to a wristband receiver [143]. The selected system should continuously monitor *HR* in real time during exercise.

Measurement of body weight loss (ΔBW)

The ΔBW of the subject during wear trials is the difference between the *BW* measured at the beginning and at the end of the trial. The ΔBW includes sweat loss, mass loss due to evaporation, and the mass variation of the body due to water intake, excretion (urine) [87] and respiration. Hence, water intake during the whole trial should be recorded. Furthermore, ΔBW can be used with the relevant values of metabolic rate to assess the degrees of comfort of the condition [87].

In summary, numerous evaluation methods and protocols on the physiological area have been developed. T_c, T_s, *HR*, and ΔBW can be used as indices to describe the thermal status of the human body and can be employed in wear trials for the evaluation of running performance.

2.5.4 Effects of clothing on thermal responses and performance

Studies on clothing have been undertaken for more than one century [155]. Relevant literature is often based on varied investigations related to fibers (e.g., polypropylene and wool) [71]; fabrics such as cotton and acrylic [110, 112], polyester and wool [15, 56], and wool and cotton [102]; fabric structures (e.g., fishnet and rib) [15]; fabric finishing treatments (e.g., phase-change materials) [154, 181]; moisture management materials [93, 158, 182]; sericin-processed materials [132]; nanosilver coating [34, 120]; and wrinkle-free treatment [103].

In 1955, two kinds of clothing with water vapor impermeable and permeable materials were used in wear trials of human subjects to observe the thermal responses of wearers. The rectal temperature and T_s were found to be significantly different between the two kinds of clothing. The T_s was also found to be a sensitive measure for environmental change. This study may be the first to suggest rectal and T_s differences when wearing different clothing types during wear trials of human subjects [38, 191]. In the last two decades, several studies that investigated the thermal effects of clothing on wearers have been published.

In 1988, Li et al. investigated the effects of eight kinds of clothing with different types of fiber on thermal and psychological responses during exercises in hot and cold environments [112]. They found significant differences in *HR*, *SW*, T_c, energy expenditure (EE), and thermal sensation between hot and cold environments. However, few significant effects were observed on the thermal parameters across all clothing types. The authors suggested that T_s, T_c, and *HR* are highly correlated with the thermal-wet sensation, and that tactile sensations are correlated only with T_s in hot conditions. In cold conditions, the thermal-wet sensation is mainly correlated with *HR*.

Pascoe et al. reviewed the influence of clothing and exercise on the thermoregulatory responses of humans [147]. They also concluded that the clothing function varies based on prevailing environmental conditions, gender and age differences, fabric thermal properties, garment design, and intended use. However, the relationships of new fabric, improved garment designs, technology, and physiological responses for thermal stress during varied exercises still need to be evaluated.

In 1995, Jeong et al. investigated the effects of wearing two different clothing ensembles (half vs. long) on an endurance performance of a handgrip exercise in a climatic chamber. They found a significant difference in the rectal temperature, T_s, *RH*, *HR*, and *SW* between the two clothing ensembles. An important result is the endurance performance of the handgrip exercise being significantly greater in the half ensemble than in the long ensemble, which was explained by the higher maintenance of T_c and T_s in the long ensemble than in the half ensemble during the 1 hr preliminary exercise [89]. However, they have not explored the relationship between exercise exhaustion and clothing ensembles for handgrip exercise as well as the physiological mechanisms.

Gavin et al. [46] investigated the effects of clothing with different fabrics on thermoregulation in an exercise environment with a T_a of 30 °C and RH of 35%. They found that neither the fabric characteristics of clothing nor the addition of a modest amount of clothing alters physiological, thermoregulatory, or sensation responses before, during, or after exercise in a moderately warm environmental condition [46].

In the last decade, studies have been conducted to explore the mechanism of clothing and T_s/T_c as well as that of sweat evaporation. The moisture management of clothing that indicates the absorption of sweat and the transport of water vapor is proven to affect T_c, T_s, sweat evaporation, and the subjective perception of clothing comfort [16, 19].

The sericin-processed clothing was also found to have lower thermal strain, given the low values of T_c, HR, and SW as well as the exercise fatigue due to the increased moisture and water performance and sweat evaporation [132]. The study also suggested that clothing humidity is an important factor that reflects the thermal response of T_c, HR, and SW from the results of the correlation analysis.

One previous study investigated cardiovascular and thermoregulatory responses to treadmill running [188]. In the study of Wingo, nine active males were recruited for wear trials to test a synthetic shirt (SS) purported by the manufacturer to be advantageous in dissipating heat and in permitting more effective heat dissipation than a cotton shirt (CS) and having no shirt (NS) during a 45 min running session with an intensity of 65% VO_{2max} in a temperate environment. The researchers found that the SS provides a limited thermoregulatory benefit compared with a CS, as no difference was observed in the rating of perceived exertion (RPE), VO_2, ΔT_c, and *HR* between the two clothing types. However, thermal sensation was lower in SS and NS than in CS, and T_c water loss was lower in NS than in the other two [188].

Brazaitis et al. [19] also investigated the thermal responses of male subjects on two sets of clothing with different materials (100% polyester and 100% cotton, respectively) during a 20 min run at 8 $km \cdot h^{-1}$ in T_a of 25 °C and 60% *RH*. They reported that polyester had greater air permeability and water-transfer rate, and that the material induced less sweat accumulation and fast sweat evaporation during the exercise but with T_c and *HR* similar to that of the cotton ensemble [19].

A recent study on fabric properties investigated the influence of three polyester jerseys with different knit sizes on heat dissipation via convection and on the psycho-physiological responses of cyclists in a hot and humid environment [50]. Compared with jerseys with small knits, those with large knits induced lower T_s and increased thermal comfort during cycling on a stationary roller [50].

In summary, several relationships between the thermal responses of the human body and fabric properties (TI, air permeability, WVP, and moisture absorption) were identified in this section. Results of the studies generally indicate that high thermal stress with increased T_c, T_s, *HR*, and *SW* is related to inefficient heat dissipation, as determined by different kinds of clothing properties, treatments, and design with low air permeability and moisture management as well as high clo value. However, few studies have investigated the effect of clothing made up of multiple fabrics on the local thermal response, thermal status, and running performance. Most existing studies only provide limited information on the physical properties of clothing, such as the overall heat transfer throughout the whole clothing. Hence, the results cannot be easily applied for further usage.

2.5.5 Effects of clothing on subjective wearing comfort

As the second skin of the human body, the clothing system is constantly in a state of dynamic interaction with the former and its surrounding environment, which stimulates thermal, mechanical, and visual sensations. These sensations contribute to the wearing comfort of clothing, which is related to complex interactive processes involving the physical properties of clothing, physiological-psychological responses, and neurophysiological processes of the human body [114]. The wear comfort of clothing may include various sensory channels, such as visual, taste, smell, and touch, but it is mainly associated with sensory systems of the skin. Numerous comfort sensations can only be generated under certain wear situations and can be induced by relevant physical stimuli, such as heat, moisture, and mechanical stimulation from fabrics. Thus, a well-designed clothing system for running may not only affect the thermal responses of wearers, as discussed in the previous section, but also stimulate various wearing comfort by adjusting micro-environmental conditions (e.g., humidity and temperature) and the physiological states of the body (e.g., sweat) [80]. To date, several researchers have focused on the effects of clothing on wearing comfort.

As early as 1979, Hollies et al. conducted wear trial experiments to investigate the clothing sensory comfort of wearers. The testing process involved the following five aspects: 1) generation of main sensory descriptors, 2) selection of appropriate conditions to stimulate sensations, 3) design of rating scales to obtain sensory responses from subjects, 4) implementation of wear trials in a controlled environmental chamber for data collection, and 5) analysis of data obtained from wear trials and interpretation of the results. During the test, several sensory descriptors were listed for the subjects to evaluate. These descriptors included snug, loose, heavy, light, cold, damp, clammy, picky, rough, clingy, stiff, scratchy, and non-absorbent. The subjects were found to have a variety of sensations on different clothing, and strong sensations were experienced when heavy sweating occurred and during the chilling process of sweat [70]. The sensory descriptors generated in the trial were repeatedly used for many years.

In 1998, Li investigated the psychological sensory responses to clothing of subjects from different countries. A survey, which included 26 subjective sensory descriptors, was conducted in China, the US, and the UK. The results summarized four main aspects of sensory responses related to consumer lifestyle: tactile, moisture, pressure, and thermal sensory factors [107].

With regard to the relationship between the physical properties and sensation of clothing, Kawabata reported a method to objectively evaluate the thermal perception and fabric handle [98]. In 1991, Li et al. investigated the subjective preference for clothing derived from a range of fabric materials and objective physical factors by redundancy analysis and canonical correlation. The objective physical factors of fabrics were found to greatly predict the subjective preference, with the cumulative redundancy as high as 0.983 [113].

The same research group also conducted a series of psycho-physiological wear trials to investigate the subjective sensation of human subjects on T-shirts made from eight kinds of fiber under two environmental conditions [106]. The nine sensory descriptors that were tested could be classified into three groups of sensory factors through cluster and factor analysis. The three factors were called thermal-wet, tactile, and pressure sensory factors (Figure 2.5) [106, 109]. These results illustrate the main pattern and relationships among each sensory response and provide reference for further investigation of clothing comfort.

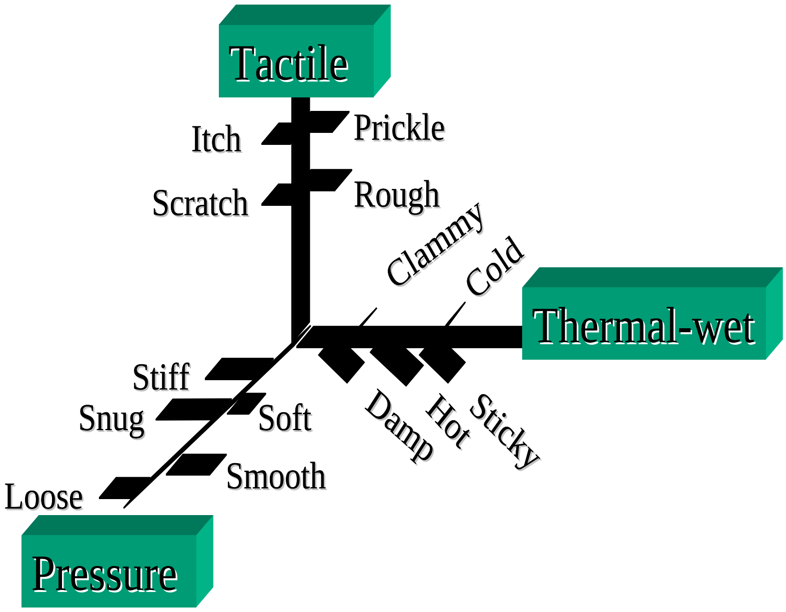


Figure 2.5 Three dimensions of wearing comfort sensations under hot conditions

Wong and Li [189] investigated the effects of different clothing types on the physiological responses and subjective perceptions of subjects in tight-fitting aerobic wear. The subjective perception of clothing comfort can be predicted based on human physiological and psychological responses related to temperature (thermal) and humidity (moisture). Results also indicate that the overall comfort of clothing varies with time slots and body locations [189].

Another study conducted by Li [108] investigated the psychophysical mechanisms of the perception of temperature and moisture sensations as well as the comfort in clothing during environmental transients. The perception of warmth was found to have positive relationships with skin and fabric temperatures. Perception of dampness appeared to have a negative relationship with T_s and was positively and nonlinearly related with *RH* in clothing microclimate. Perception of comfort was found to be positively related to the perception of warmth, negatively related to the perception of dampness, positively related to T_s, and nonlinearly and negatively related to *RH* in clothing microclimate.

Jiao et al. [93] conducted a study to investigate the influence of the wicking and moisture management properties of clothing with hydrophilic treatments on human sensory responses in neutral and hot conditions. The wicking and moisture management properties of clothing, which were significantly affected by hydrophilic treatments, seemed to play an important role in the subjective perceptions toward fabrics being breathable-airtight in different environmental conditions.

In a recent study by Jeon et al. [88], subjective perceptions of moisture and comfort were determined for four developed shirt fabrics at two different sweating levels. Cotton was found to provide effective moisture comfort because of the large threshold of sweat absorption behavior in low sweat situations; the high-performance polyester, which had the highest wicking rate of absorption capacity, provided effective moisture comfort in heavy sweat situations. The researchers also suggested the possibility of using the psycho-physical method as a tool to predict the end use-specific performance of functional textiles.

A recent study by Tiest et al. [176] described a psycho-physical experiment investigating the sensation of wetness of textiles treated with phase change materials. The study found that in 75% of the cases, the subjects observed that the treated fabric felt wetter than the untreated one, which may be uncomfortable. They recommended investigating a change in cooling properties to minimize the feeling of discomfort.

To sum up, previous studies on wearing comfort mainly focused on sensations generated by different clothing fabrics and treatments as well as their relation to the physical properties of clothing when the subject is at rest. Results suggest that material properties have significant effects on wear sensations and comfort. However, few studies have explored the comfort sensation of component clothing made of multiple fabrics and the trend of sensation during different exercise statuses, especially that under a hot environment using a protocol that stimulates real endurance running competitions. Additionally, the manner by which these sensations can be used to identify sensory factors and to predict overall comfort during such a protocol is still unknown.

2.6 Summary of Literature Review

The extensive literature review covered the areas of human physiological heat balance and thermoregulation within the Body–Clothing–Environment system, the influence of environment-induced heat stress and running performance, as well as the clothing and human responses and performance from previous studies. The following conclusions can be drawn.

In the Body–Clothing–Environment system, clothing has several functions as an interactive barrier between the ambient environment and the skin surface. Clothing not only serves as the covering of the body but also functions to protect the human body against the external environment and to maintain the heat exchange between the body and its surroundings.

In this system, the heat balance of the body is maintained by the processes of heat production, such as metabolic heat production and external work, and heat loss via radiation, conduction, convection, and evaporation. The T_c is maintained within certain boundaries determined by an automatic adjustment called thermoregulation and is combined with the function of clothing. However, thermoregulation may not be effective in maintaining heat balance because of the rapid increase in heat production during strenuous exercises under hot conditions and because of the impaired heat dissipation to the environment. Heat-related problems such as hyperthermia and heat stroke may occur with the continuous increase of T_c, which is a known threat to the health of human beings and coincidently impairs exercise performance. Numerous heat-related deaths have been reported in the history of distance running exercises. With regard to the influence of heat stress induced by hot environments on distance running, the running performance of humans is mainly investigated from three aspects, namely, circulatory adjustments, metabolism effects, and central fatigue. Thus, taking several effective measures is necessary in reducing the risks of overheating and in decreasing the impairment of heat stress on running performance.

Athletes can do little about the prevailing weather conditions during running competitions. However, clothing, as a uniform required in most formal competitions, can be an important consideration. Several new technologies have been added to the clothing design process to improve the functionality of clothing, with previous studies considering the thermal demands of the human body on clothing. As for the evaluation of physical properties of clothing, several methods and techniques, such as sweat/thermal manikin, guarded hot plate, direct measurement from human body, and calculation method based on regression analysis and previous data, have been used. The three main methods used to evaluate physiological responses and wearing comfort are the manikin tests, computer simulation, and wear trials. Measurements are widely used in the evaluation of clothing, but several limitations still exist. In the studies related to the effects of clothing on thermal responses, running performance, and wearing comfort, investigations were mainly based on clothing with different fibers, fabrics, treatments, and coating. These studies explored such effects on thermal responses, such as T_c, T_s, HR, SW, RPE, micro-climate RH, subjective sensation, and wearing comfort. Clothing with inefficient heat dissipation, which is determined by different kinds of clothing properties, treatments, and design, would result in high thermal stress and low comfort sensations. These responses are mainly related to the increased T_c, T_s, HR, and SW. The subjective sensation and wearing comfort are mainly related to the thermal and moisture properties of the material as well as to the thermal responses, such as T_s and the micro-climate RH of clothing.

2.7 Research Gaps

Running performance in a hot condition mainly be affected by the thermal responses of athletes to heat stress, which may be influenced by clothing design and materials. Although numerous individual areas related to the topic have been explored, several knowledge gaps still exist, especially in the application of running clothes in a hot condition. The related knowledge gaps have been identified as follows:

(1) The theoretical framework in the development and evaluation of clothing for running in a hot condition is not available.

(2) The application of local thermal requirements and sweat distribution in a thermal functional design method/system of running clothes has not been systematically investigated.

(3) Lack of scientific evaluation systems to quantify the functional performance of thermal mapping-designed clothing and to assess the influence of the mapping-designed clothing on a human body.

(4) The effects of body thermal mapping design on whole-body thermal responses and running performance under hot conditions has not been fully investigated.

(5) The effects of body thermal mapping design on local thermal response and the relationships with whole-body thermal responses and running performance need further investigation.

(6) The effects of body thermal mapping design on wearing comfort during running under hot conditions remain poorly understood.

On the basis of these knowledge gaps identified, six objectives have been developed and presented in Section 1.2 of Chapter 1.

CHAPTER 3 THERMAL FUNCTIONAL DESIGN SPECIFICATION OF RUNNING CLOTHES

3.1 Introduction

As the primary sport in early sports culture, running continues to be one of the most popular sports today. People can do running exercises without any special running devices during the daily work outs. However, in most professional competitions, running clothes as a uniform is required and may help the runner to improve his performance. Clothing specifically designed for running can protect skin from external radiation and/or heat injuries that arise from solar exposure in hot environments [191], may support muscles to prevent injury [162], and affect blood circulation to influence energy expenditure during exercise [20]. Clothing acts as second skin to the human body and represents a layer of insulation for heat and moisture transfer from skin surface to outer environment. The capacity of heat and moisture dissipation can influence the thermal responses and running performance of athletes. Limited heat and moisture dissipation can threaten their health and life under hot conditions. Heat-related deaths have plagued endurance running competitions recently [66]. Hence, specially designed clothing for running under hot conditions with improved functions is crucial in the field of sports clothing industry.

The traditional design of running clothes is based on fashion more than function. Extensive researches on emerging themes are not just for fashion, which uses improved technology to serve a specific function like UV protection, providing compression or cooling effects to the body. As documented in the literature discussed in Section 2.5.1 of Chapter 2, different skin temperature and sweat evaporation were observed at each body part during exercise, which may have various impacts on the thermal status of athletes. Although a recent study [183] has considered the physical responses of skin surface on different body parts, it was mainly focused on the methodology investigation of dynamic clothing pattern making based on the body mechanical characteristics during activity and material property requirements for Tight-fit sportswear. Few studies have considered the concept of body thermal mapping design in relation to the different thermal physiological responses on different body parts, and applied this design concept on the development of performance running clothes.

To fulfill the first and second objectives of this study, this chapter aims to establish a theoretical framework for developing functional running clothes, investigate the thermal requirements in each body part and propose its application in a new design methodology for performance running clothes in a hot condition. To identify the thermal requirements, the human body was classified into several specific thermal zones according to the T_s and sweat evaporative distribution, which was applied in the pattern design and selection of fabric physical properties.

3.2 Applicable Environment Conditions

Running clothes for daily professional training and competition of middle-distance athletes were designed in this study. Middle-distance running competitions range from 800 m to 5000 m and may induce heavy sweating, muscle fatigue, and heat stress especially under hot conditions. While running, a continual thermal interaction takes place within the system of the runner, his clothing, and the environment. The process includes the runner's thermoregulation and thermal exchange with the clothing-environment via radiation, conduction, convection, and evaporation (Figure 3.1). The athletes' sweat evaporation and T_s determine the capability of heat and sweat dissipation and significantly affects the runner's performance.

Hence, when designing running clothes that can improve the capability of heat and sweat dissipation from skin surface to outer environment, we considered thermal responses such as sweat evaporation and T_s, physical structure and material properties including TI and WVP. The following sections will discuss these three aspects.

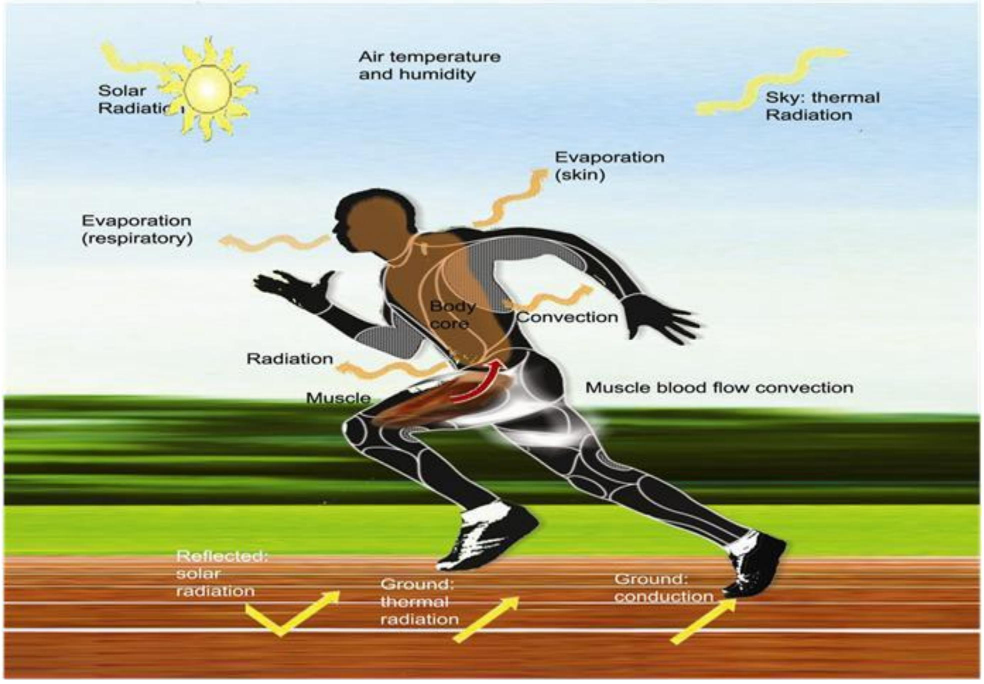


Figure 3.1 Environmental condition of the human running system

3.3 Thermal Physiological Requirements

Skin surface has non-uniform sweat evaporation on each body part because of the differences between sweat gland density and body sensitivity. Meanwhile, T_s distribution is not constant because of the variation of anatomic structures and tissue thickness as well as the distribution of blood flow. The distribution of sweat evaporation and regional T_s were investigated based on abundant literature and were used to create the thermal zone of the human body [94], finally applied on clothing design. The framework of this process is illustrated in Figure 3.2.

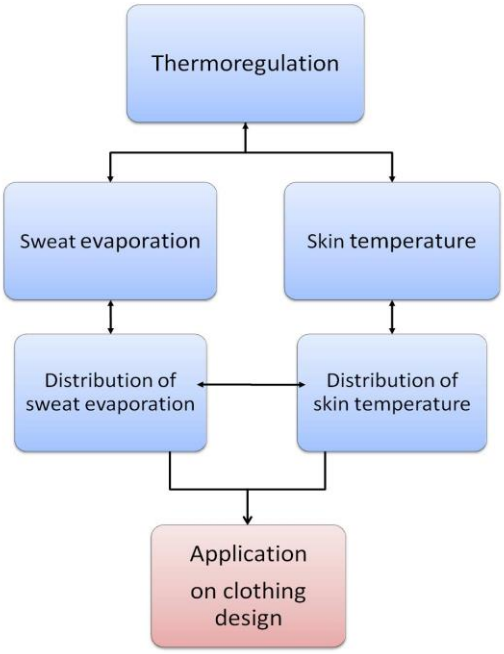


Figure 3.2 Relationships between thermal responses and clothing design

3.3.1 Distribution of skin temperature

Based on the results of the experiments conducted by Guo [53] and those from other literature mentioned in Chapter 2, the data of T_s on each body part are summarized in Table 3.1 [94].

Table 3.1 Summary of T_s (ºC) in each body part

	(Kilic, 2008)[99]	(Machado-Moreira, 2008)[125]	(Guo, 2011)[53]			(Wijayanto, 2010)[186]	
			Resting	Walking	Running	Resting	Running
Head	33.9		33.9±0.7	33.6±1	33.6±1.3	35.1±0.2	35.3±0.2
Chest	35.4	36.6	32.9±1.1	32.5±1.2	31±2.1		
Abdomen	35	35.5	32.8±1.1	32.3±1.3	30.6±1.9		
Under arm		37	33.7±1.1	33.3±1.1	32.3±1.7		
Upper arm	36.7		32.5±1.1	32.1±1.1	31.6±1.7		
Forearm			32.5±0.9	33.1±1.1	31.1±1.6		
Hand	33.2		33.3±1.1	33.1±1.1	32.3±1.4	34.7±0.1	34.7±0.1
Upper back	35.9	36.6	32.8±1	32.3±1.3	31.6±1.6		
Lower back		36.8	32.2±1.1	31.6±1.3	30.7±1.8		
Front thigh	34.6		33.4±1	32.1±1.1	31.8±1.4		
Back thigh			32.4±1.1	32.1±1.1	31.6±1.7		
Fossa			32.4±0.9	32.3±1	32.1±1.4		
Front calf	32		31.9±0.9	32±1.1	31.6±1.6		
Back calf			31.5±0.9	32±1	31.7±1.3		
Foot	31.1		32.2±1.2	33.2±1.2	34.1±1		

Figure 3.3 illustrates the regional skin temperature distribution. The head has the highest skin temperature. The upper/lower back, under arm, chest, and abdomen, all of which approach the trunk, are at the second-highest level. The thigh and the arm are at the third level, followed by the hand, forearm, and calf at the fourth level. The feet have significantly lower temperature than all the other body parts. The mapping pattern of skin temperature can be explained as the distance between body core and the other body parts, the balance of local heat production and heat loss, as well as the local blood flow [53, 54]. The highest skin temperature appears on or near the trunk part because the trunk is the core of the body in which the organs are proven to have higher temperature. The body parts located at a farther distance from the body core have lower skin temperature than the trunk. The exception is the hands, which may be due to the abundant capillary vessels and blood flow here compared to those in the forearm, calf, and feet [95, 128]. Usually, the summer running clothing does not cover the head, arm, hand, fossa, calf and foot. Therefore, only these data from the four areas, back, chest, abdomen and thigh, are useful for the designing of summer running clothing.

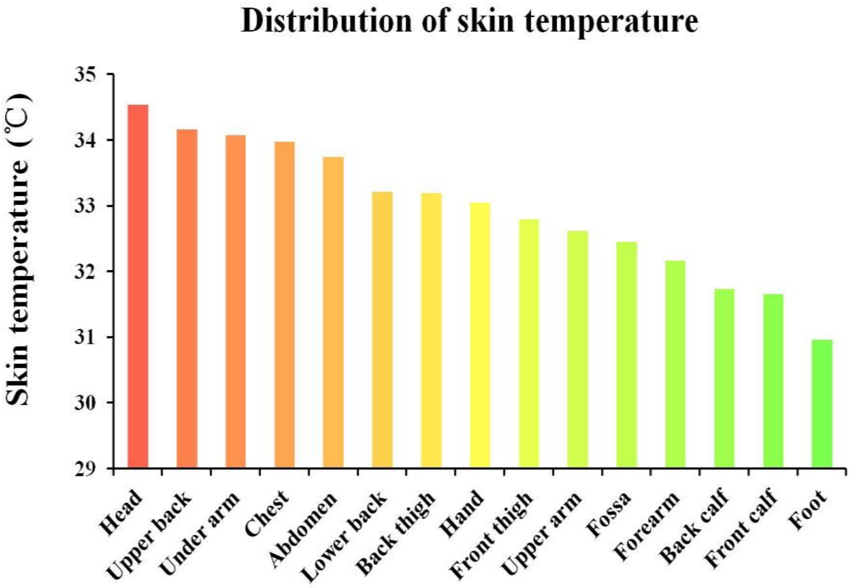


Figure 3.3 Summary of T_s in each body part

3.3.2 Distribution of sweat rate and evaporation

The summary of sweat distribution also has potential benefits in the functional design of clothing [2, 149]. Table 3.2 shows the summary of sweat evaporation in each body part based on previous studies[94].

Table 3.2 Summary of sweat rate ($g{\cdot}m^{-2}{\cdot}h^{-1}$) in each body part

	(Cotter, 1995) [32]	(Havenith, 2008) [61]	(Machado-Moreira, 2008)[125]	(Smith, 2011)[164]	
				I1	I2
Head	1434±744			894±708	2057±900
Chest	570±324	564±178	1050±186	324±148	606±262
Abdomen	390±162	715±248	846±144	383±170	658±267
Under arm	312±150	245±112	1122±168	145±81	258±90
Upper arm	570±276	540±187	1152±204	322±109	620±202
Forearm	450±240			238±140	359±80
Hand	546±456			98±58	126±53
Upper back		845±326		710±246	1062±360
Lower back	510±246	1024±287		797±250	1139±364
Front thigh	396±174			280±103	390±128
Back thigh				209±56	274±79
Fossa					
Front calf	456±162			355±210	441±218
Back calf				256±105	338±133
Foot	336±138			202±95	225±84

Notes: I1: exercise intensity of 55% VO_{2max}, I2: exercise intensity of 55% VO_{2max}

All the data from Table 3.2 were standardized and then treated by Fractional ranking [172]. Figure 3.4 summarizes the sweat evaporation in each part after ranking. The value of sweat evaporation in each part can be divided into three levels. The highest level is at the head and the lower and upper back, which are consistently found in some other studies as well [164]. The second level is at the fossa, chest, under/upper arm, foot, and abdomen, which are mainly located in the upper body, with the exception of the feet [54]. Finally, the third level is at the front/back thigh, hand, and front/back calf, major parts that are located in the lower body [32, 148].

With the same logic as skin temperature, only these four areas (e.g.: back, chest, abdomen and thigh) were considered for the mapping-designed clothing.

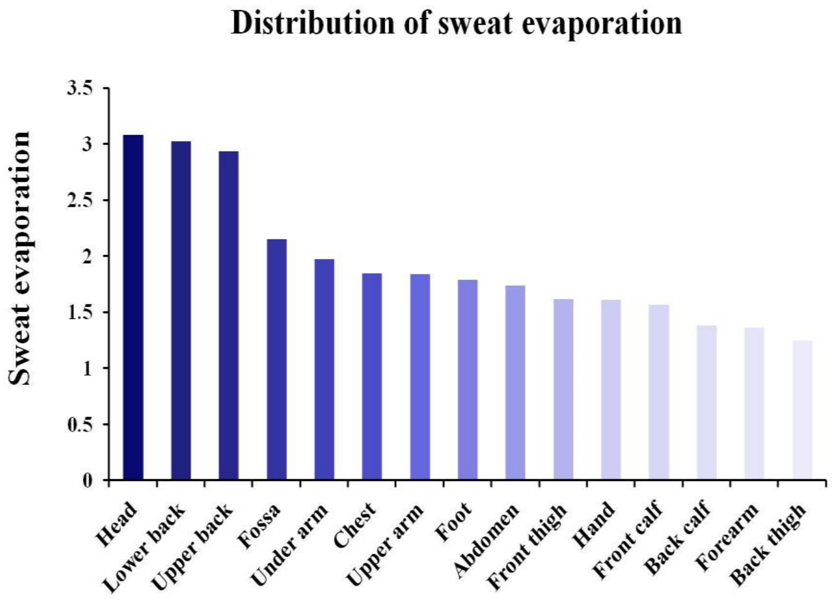


Figure 3.4 Summary of sweat evaporation in each body part

3.3.3 Data mapping visualization

To observe the thermal responses of the human body and associate them with the specific change in different exercise statuses, the body of the human model was painted like a map to determine the values of the summarized data. The painted visualized images in Figure 3.5 show the summary of T_s distribution during rest and while walking and running [24, 53]. The color bars from blue to red attached to the figure demonstrate the specific data value assigned as follows: Blue: 25°C to 30°C, Green: 30°C to 31°C, Yellow: 31°C to 32°C, Orange: 32°C to 34°C, and Red: 34°C to 40°C. As illustrated in the visualized images, the head with the darkest red color indicates the highest T_s of any other body part, and this part is not affected by the exercise status. The color of the chest, abdomen, and back changed from red (rest) to green (while running), indicating that these body parts have high T_s which decreases while the exercise intensity increases. The calf and arm show lower T_s and smaller changes than the trunk. The different changes may be due to the various sweat evaporations in each body part during different exercise statuses. Thus, to identify the thermal requirements of clothing, the designer must consider the distribution of sweat evaporation on each body part as well.

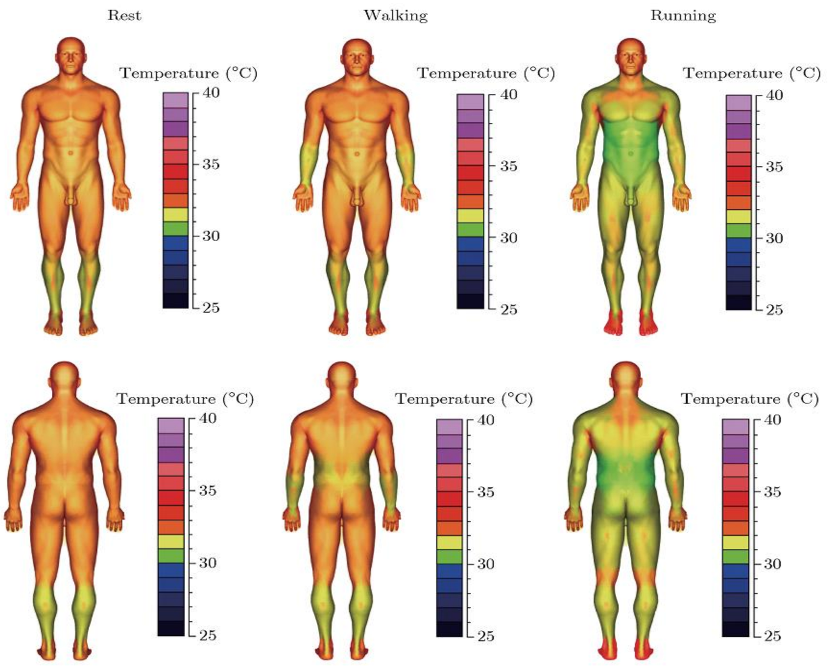


Figure 3.5 Color mapping of T_s during rest and while walking and running

The painted visual images in Figure 3.6 show the distribution summary of sweat evaporation in the human model during rest and while walking and running [24, 53]. The color bar adopted green and brown in different degrees to map the specific data values of sweat evaporation, which are assigned as follows: brown: 6 $g{\cdot}h^{-1}{\cdot}m^{-2}$ to 18 $g{\cdot}h^{-1}{\cdot}m^{-2}$, medium-low values with light green: 18 $g{\cdot}m^{-2}{\cdot}h^{-1}$ to 30 $g{\cdot}m^{-2}{\cdot}h^{-1}$, green: 42 $g{\cdot}m^{-2}{\cdot}h^{-1}$ to 45 $g{\cdot}m^{-2}{\cdot}h^{-1}$, and high values with dark green: 54 $g{\cdot}m^{-2}{\cdot}h^{-1}$ to 66 $g{\cdot}m^{-2}{\cdot}h^{-1}$. Similar to the principle of T_s, the changes from brown to dark green in the chest, abdomen, and lower back showed the biggest change in sweat evaporation. Smaller changes were found on the limbs like the upper arm.

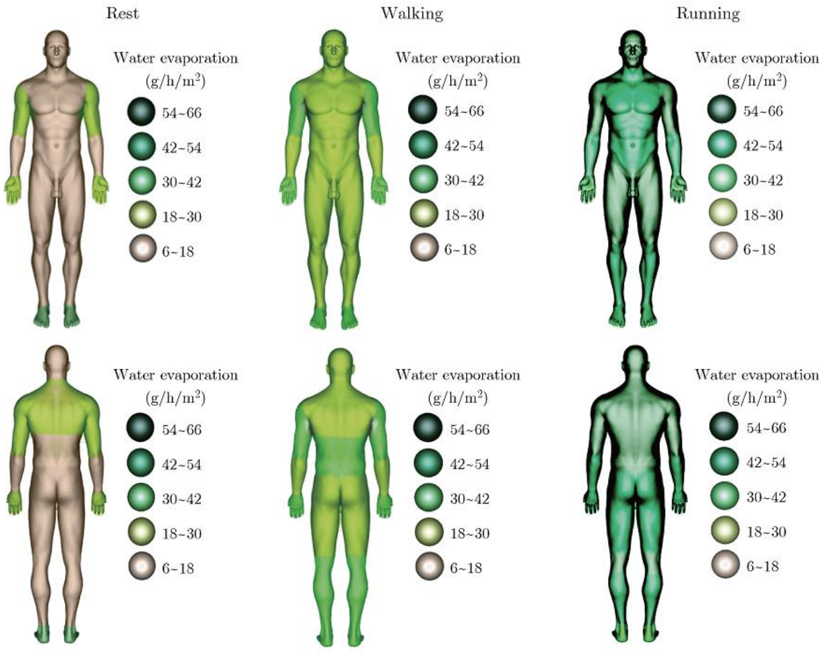


Figure 3.6 Color mapping of sweat evaporation during rest and while walking and running

By recognizing the different colors in each body part, the designer will easily distinguish the thermal requirements of running clothes and incorporate the visual information into the clothing design. For instance, red in the back part showing the highest skin temperature (Figure 3.5) indicates that the clothing fabric used in this area must have the highest efficient of heat dissipation. Meanwhile, dark green in the upper back showed the highest sweat evaporation while running. Thus, the clothing that covers this area should have an excellent capability of sweat dissipation. Considering the two aspects of thermal requirement, the fabric selected in this area may have low air resistance (AR) and TI, as well as high WVP and overall moisture management capacity (OMMC).

3.4 Function Zone Creation for Mapping-designed Clothing

As discussed in previous sections, different body parts have clearly distinguished thermal responses. Considering the distribution of thermal responses and the specific changes of these segments during different exercise statuses, the whole body was classified into 12 special segmentation zones [115, 183]. Through these zones, the design can easily define the functional characteristics and select the appropriate fabrics to fulfill the requirements of each zone. The clothing designed with this concept of body thermal mapping is defined as mapping-designed clothing. This kind of clothing has specific thermal requirements in each segmentation zone and has appointed functions for design [115, 183].

For instance, the function zone of the clothing design was created according to the analysis of thermal responses and similar functions of each body part (Figure 3.7). The 12 segmentation zones are summarized as chest (No. 1), abdomen (No. 2), armpits (No. 3), arms and calves (No. 4), thighs (No. 5), upper back (No. 6), lower back (No. 7), hypogastrium (No. 7-1), knees (No. 8), fossae (No. 9), sides (No. 9-1), other (No. 10) [115, 183]. The detailed characteristics of the thermal zones and the related functional requirements are discussed below.

The upper back (No. 6) on the trunk has the highest skin temperature, followed by the chest (No. 1), also on the trunk. Thus, it is critical to release heat and accumulated sweat from the back and the chest. The fabric covering these parts is considered to have excellent capability of heat and moisture transfer and quick drying properties to speed up heat dissipation moisture evaporation. It can be as thin as possible. Compared to the other body parts, the back requires the strongest UV protection. However, the fabric used for the chest, which is slightly different from that for the back, may be thin but not transparent to protect the privacy of that part.

The abdomen (No. 2) and the lower back (No. 7) have lower skin temperature than No. 1 and No. 6, but have similar sweat evaporation. These two parts also require fabrics with excellent capability of heat and sweat dissipation.

The armpits (No. 3) is a small area but has high skin temperature and strong sweat. Considering the difficulty of sweat evaporation, the fabric may be required to have high capability of sweat transfer and to allow movement. This may not be necessary if the clothing is designed as a vest with additional ventilation openings at the armpits [165].

The arms and calves (No. 4) and thighs (No. 5), as extremities and main muscle power, have similar skin temperature and sweat evaporation. These parts have low cover ratio for heat and sweat dissipation, and thus less fabric cover is recommended when running under hot conditions. If these parts have to be covered to respect religion or to observe safety in some regions, the fabric for these parts should have high capability of heat and sweat transfer and good support for muscle constriction.

The hypogastrium (No. 7-1) at the lower parts of No. 2 and No. 7 have similar skin temperature and sweat evaporation, and thus have similar requirements for the fabric properties on heat and sweat transfer capability as those for No. 2 and No. 7. However, special consideration is needed to protect the privacy of the body part being covered. The fabric should be opaque and have good support for the apparatus it covers.

The knees (No. 8), fossae (No. 9), and sides (No. 9-1) have less sweat accumulation and evaporation than those of other body parts, and thus do not need the capability of heat and sweat transfer. However, these are essential joints that play an active part in running, so a stretchable fabric is required to provide excellent support for the joints and muscles.

Group No. 10 contains the most active muscle groups in the thighs for running and for holding the trousers (with long pants). These parts were created considering the function of compression for the muscle groups to reduce muscle fatigue and energy expenditure, as well as the frapping function of the pants. For running clothes for hot conditions, short pants are highly recommended. Aside from the good capability requirement of heat and sweat transfer, high-grade compression is also needed for the power muscles of the thigh.

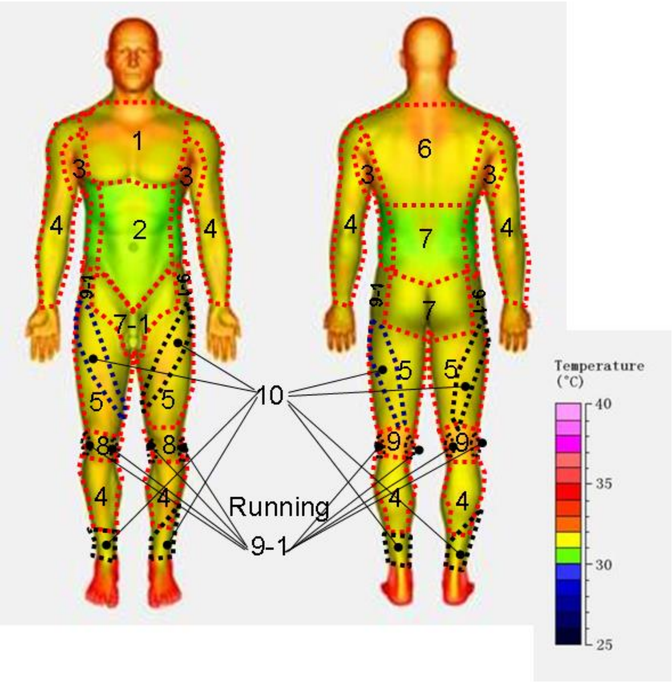


Figure 3.7 Function zone creation for mapping-designed clothing

3.5 Fabric Requirements in Each Zone

Based on the demands of the mapping thermal zones and the required functions for running, the fabric requirements are summarized in detail [115, 183]. The specified fabric properties were distinguished for the different purposes of each body part. For example, chest (No. 1) and upper back (No. 6) have the highest T_s and sweat evaporation; therefore, the fabric should be thin, breathable, and quick dry to enhance evaporative cooling [127]. Suggestions include selecting a net fabric with extreme light Weight (W_t), low Thickness (d), low AR, low TI, high WVP, and high OMMC on some areas in the back.

In general, running clothes for hot conditions should have the following properties: light W_t, low d, low AR, low TI, high WVP, and high OMMC for most body parts. For some body parts, the clothing should have additional functions such as strong UV protection for the back, elastic fabrics for knee joints to allow free movement, and compression fabric for power muscles.

Some body parts require fabric with a good hold and medium thickness to avoid privacy problems.

3.6 Specification for the Whole Clothing

After discussing the requirements for each body part in detail, other considerations such as style, appearance, and fitting are then added for the whole clothing.

For style, the cover ratio may be a main factor for running clothes because it is related to the conduction and convection heat transfer under hot conditions. Due to the smaller cover ratio, there are fewer barriers between the heat dissipation of the skin and of the ambient environment. Hence, the designer decided to design Clothing A (CloA) based on Clothing C (CloC), the popular style commonly used by marathon team runners (Figure 3.8) [115]. CloA consists of a simple vest and a pair of knee-length short pants, aimed to decrease the cover ratio for running athletes. As requested by marathon team runners, another clothing (CloB) was designed as a one-piece clothing. The design is different from traditional running clothes, and the concept is similar to that of the clothing of triathletes [92, 192]. Moreover, CloB has an added distribution of thermal requirements on each body part. The designed patterns of CloB and CloA are very similar, but still vary in style [115].

Final fitting is another element of clothing appearance considered during the design process. The fitting status includes loose-fit, just-fit, and tight-fit. Technically, loose-fit is defined as ample space between skin surface and clothing [183]. Just-fit, as the name suggests, means that the clothing is just fit to the body surface; the pressure of clothing on the skin is less than 9 mmHg [183]. Tight-fit refers to the frapping kind of clothing with a pressure of 10 mmHg on the skin. Fitting status does not only relate to aesthetics, but also to the function of the clothing. Specifically, loose-fit clothing has efficient pumping effect of wind and heat transfer via convection, but also increases the resistance of the runner, thus wasting more energy during the running competition. Tight-fit clothing with little heat convection may induce heat, stickiness, and a discomforting sensation. In addition, it may restrict the movement of joints due to the high pressure on the skin. Thus, the preferred fitting design for running clothes under hot conditions is just-fit clothing. To achieve the fitting requirement for all runners, a Three-Dimensional (3D) cutting technology was conducted based on the data obtained from a 3D body scan of each runner.

3.7 Mapping-designed Clothing

As the functional requirements in each body zone and the basic style of commercial running clothes (CloC) have been identified, two sets of running clothes (CloA and CloB) were designed (Figure 3.8) [92, 115]. In marathon running at The Hong Kong Polytechnic University, CloC is a commonly used term. The design information of CloA, CloB and CloC are discussed in detail as follows (Figure 3.9):

1. CloA includes three main fabrics, A1, A2, and A3. Each fabric fulfills one kind of function. For instance, A1, as a primary fabric used for CloA, should be light, thin, have low AR and TI for heat dissipation, high WVP and OMMC for sweat dissipation, quick dry, and strong UV protection qualities to avoid heat injury. A2 covers the body parts with the highest sweat evaporation (back and abdomen), and should thus have extremely thin fabric with excellent capability of heat and sweat dissipation. In the current study, a big mesh fabric was selected to fulfill the thermal requirements. A3 is designed to provide relative pressure to power muscles and help hold the main organs.

2. CloB is knitted with Polypropylene (PP), the lightest fiber in density with super hydrophobic surface property, like PP-plain (B4), PP-lozenge (B1), PP-small mesh (B2),

and PP-large mesh (B3). B4 is a primary fabric for CloB with similar functions as A1 of CloA because B4 has a high capability of heat and sweat dissipation. B2 and B3 are similar to A2. They cover the body parts with the highest sweat evaporation and need excellent capability of heat and sweat dissipation. B1 has similar functions as A3 of CloA, and so B1 is selected to cover the same area as A3 covers.

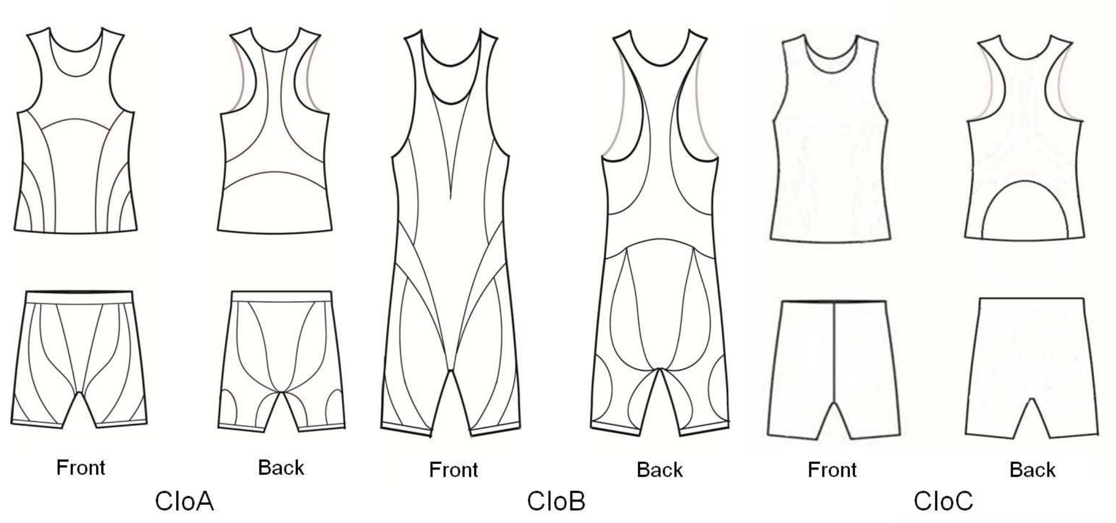


Figure 3.8 Design scheme of CloA, CloB and CloC

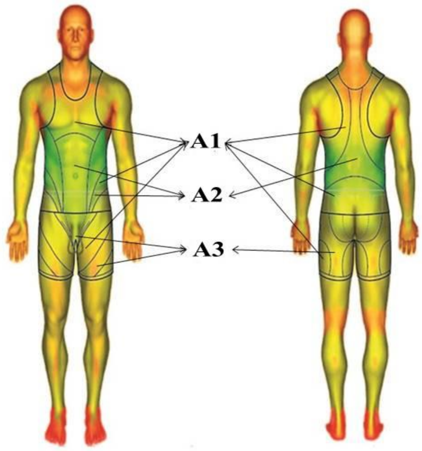


Figure 3.9 (a) The fabrics used in CloA

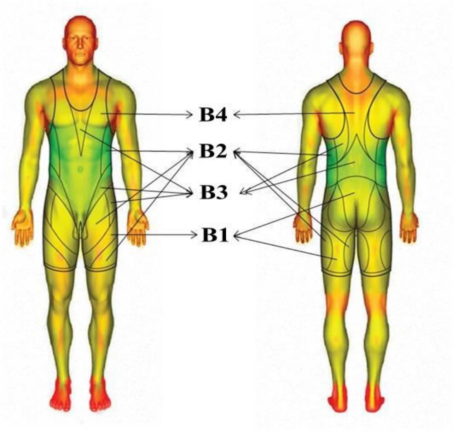


Figure 3.9 (b) The fabrics used in CloB

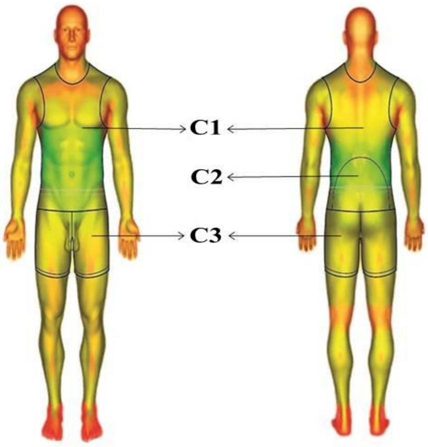


Figure 3.9 (c) The fabrics used in CloC

3.8 Conclusion

In this chapter, a new design concept of running clothes named body thermal mapping design was developed based on the thermal requirements in relation to distribution of skin temperature and sweat evaporation while running in hot conditions. In the new design concept, the applicable conditions of running clothes need to be confirmed firstly. The thermal biological characteristics in terms of distribution of skin temperature and sweat evaporation were investigated according to the data reported by previous literature. The summarized thermal characteristics were then used for mapping visualization and segmentation of function zone on the human body model. To fulfill the requirements of each function zone, specific fabric demands were discussed in detail. Based on these efforts, running clothes with mapping thermal requirements were developed.

The two sets of clothing designed and one set of commercial clothing will be evaluated (Chapter 4), and further investigation on their effects on athletes' local /whole-body thermal responses, running performance (Chapter 5 and Chapter 6), and wearing comfort (Chapter 7).

CHAPTER 4 EVALUATION SYSTEM FOR PERFORMANCE RUNNING CLOTHES IN HOT CONDITIONS

4.1 Introduction

In Chapter 3, two sets of clothing with body thermal mapping-designed concepts were developed based on the thermal requirement of each zone in human body parts. To fulfill the thermal function of each body zone, fabrics with specific physical properties were required and used for manufacturing. The physical properties of fabrics that contribute to various of heat and moisture transfer at specific body part covered by the fabric [85]. The developed clothing that made by different kinds of fabrics involve a complex combination of heat and moisture exchange among the Body-Clothing-Environment system, which may induce distinct thermal responses of human body and exercise performance. Therefore, measures should be conducted to assess and/or determine the overall thermal performance (such as ability for heat dissipation) of developed clothing and that of existing products in the market [105, 143].

The heat dissipation when wearing clothes includes dry heat loss and latent heat loss, which are related to the heat insulation and water vapor resistance of the fabrics, as well as the design of whole clothing. Determining the heat insulation and/or water vapor resistance of whole clothing has been accomplished in some previous studies [60, 121], with various efforts and accuracies involved. The existing methods are briefly characterized as follows: 1) Direct measurement when the clothing is worn by human subjects, which requires a sufficient number of subjects and numerous estimations of the human body during exercise (e.g., estimated metabolic rate) [60, 121]; 2) Measurement on a manikin at a well-controlled environmental chamber. The latter method has better reproducibility, but it cannot be widely used in the clothing industry due to the restrictions to the mobility of the manikin, usage condition, expensive cost and unavailability of driving machines. Besides, it is difficult to estimate the primitive sweat process when sweat is elicited as liquid water accumulated on the skin surface, as well as the liquid transferring process via clothing; and 3) Calculated method for the clothing made by individual fabric and/or pattern. To our best knowledge, the methods are limited to evaluate the overall performance on heat dissipation via the whole clothing which was made with mapping-designed concept. Additionally, it is difficult to quantitatively determine the amount of dry heat loss and latent heat loss of mapping-designed clothing without the manikin. Thus, it is essential to explore the evaluation system regarding the overall performance on heat dissipation of the whole clothing with mapping-designed concepts, and develop methods to simulate the capability of dry heat loss and latent heat loss via clothing.

To fulfill the third objectives of this study, this chapter systematically presents the evaluation system for the physical properties of mapping-designed clothing, which includes: 1) basic tests on fabric physical properties (Section 4.2); 2) physical evaluation of the whole clothing, including estimation of clothing physical properties (Section 4.3), definition and determination of the overall capability of heat dissipation (CHD), capability of dry heat loss (CDHL) and capability of latent heat loss CLHL (Section 4.4); and 3) exploration of clothing evaluative methods on the human body, including experimental design and measurements when investigating the physiological responses, running performance, and wearing comfort of athletes in the wear trials (which would be conducted in Chapter 5, 6 and 7) (Section 4.5). The theoretical framework is illustrated in Figure 4.1.

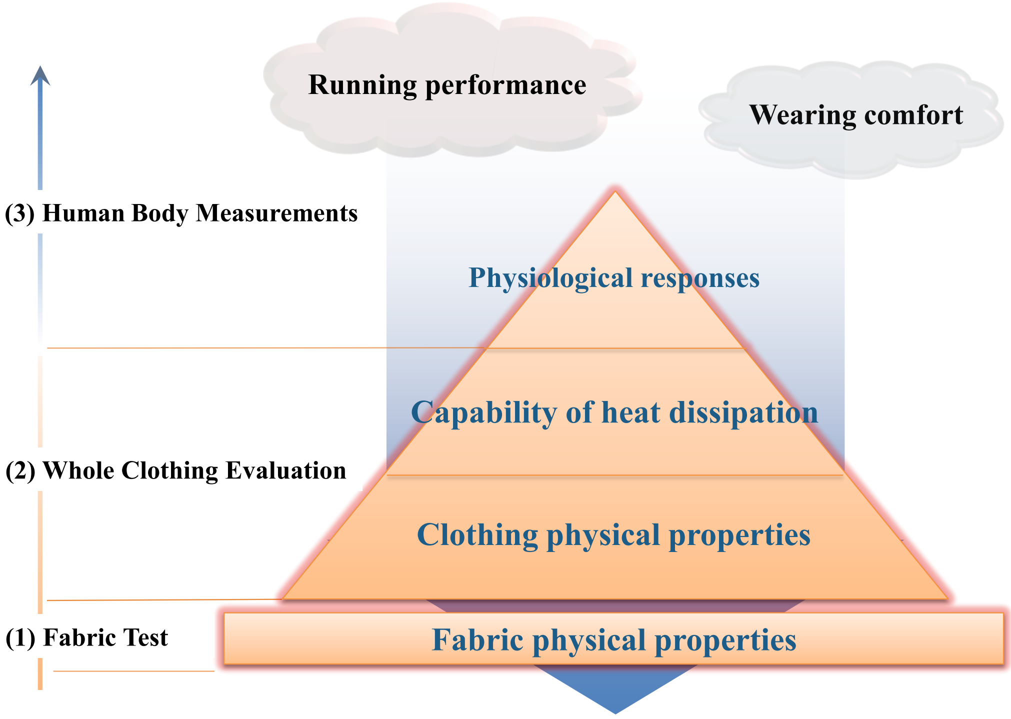


Figure 4.1 Theoretical framework of the evaluation system for mapping-designed clothing

4.2 Tests of Fabric Physical Properties

To fulfill the fabric requirement of functional clothing and to further evaluate the properties of the whole clothing, basic tests on the physical properties of fabric material was conducted. The tests included tests of unit weight (W_t), thickness (*d*), water vapor permeability (WVP), overall moisture management capacity (OMMC), air resistance (AR), and thermal insulation (TI, expressed in clo) (Table 4.1). At least five fabric samples were tested in each measurement of the physical properties. All fabric samples were placed in an environment at ambient temperature (T_a) of 20 °C and relative humidity (*RH*) of 60% for 24 h before testing. Figures 4.2 to 4.7 illustrate the instruments used to test the basic physical properties of the fabric according to standards.

Table 4.1 Summary of basic tests on the physical properties of fabric

Fabric physical properties	Instruments	Measurement standard
W_t	Balance (Figure 4.2)	ASTM D3376
d	Thickness meter (Figure 4.3)	ASTM D1777
WVP	Standard cups (Figure 4.4)	ASTM E96
OMMC	MMT (Figure 4.5)	MMT guideline
AR	Air permeability tester (Figure 4.6)	ASTM D737-96
TI	KES-F7 Thermo Labo II (Figure 4.7)	ISO 11092

MMT: Moisture Management Tester

4.2.1 Weight and thickness

Light and thin fabrics were preferred for mapping design. These were the two basic physical properties, weight (W_t) and thickness (d), tested and measured according ATSM D3376 and ATSM D1777 in this study. Figures 4.2 and 4.3 respectively show the balance and thickness meter used for fabric testing.

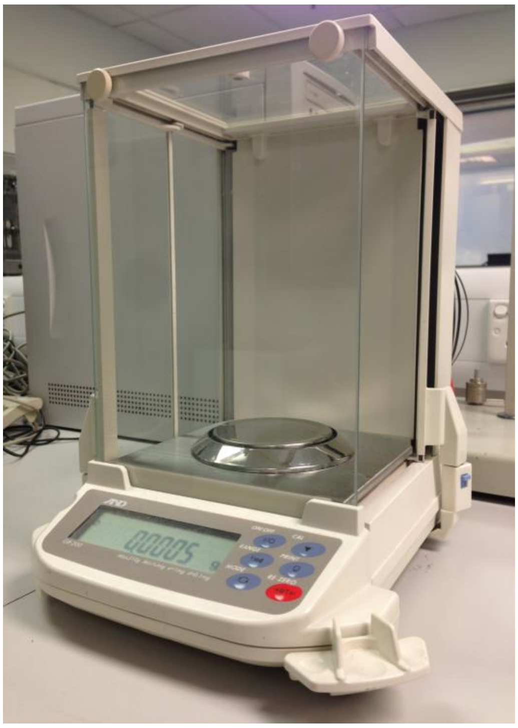


Figure 4.2 Balance tester

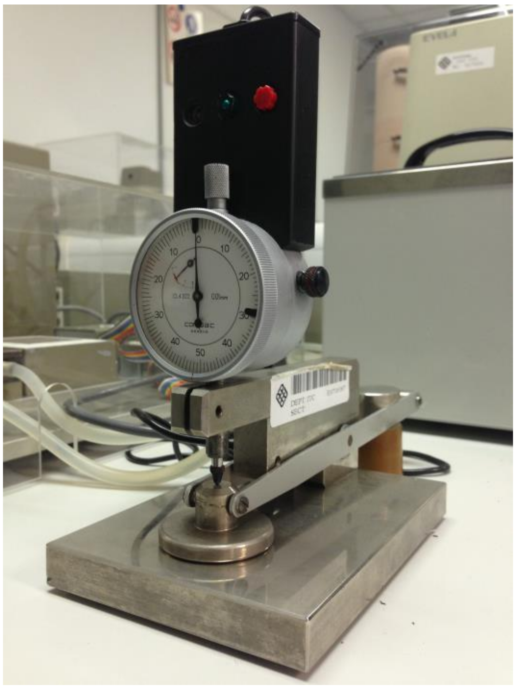


Figure 4.3 Thickness meter

4.2.2 Water vapor permeability

The water vapor permeability (WVP) of fabrics was measured by the standard ASTM E96 [10]. The cup method used in this study is very common for measuring the moisture transferability of fabrics. The measurement of WVP was used to obtain the reliable values of water vapor transfer through permeable fabric by means of a simple apparatus. As shown in Figure 4.4, the cups covered with one fabric sample contained distilled water and were placed in a controlled environment laboratory at T_a of 20 °C and RH of 60% for five days. To adjust the initial W_t of water, 80 g water was placed in the container. The initial weight of the cup and the daily weight were recorded every 24 h. The WVP (in $g{\cdot}m^{-2}{\cdot}day^{-1}$) were calculated using Equation 4-1:

$$\mathrm{WVP} = \Delta W_t / t * a \qquad (4\text{-}1)$$

where ΔW_t (in g) is the weight change of the cup with fabric sample, t is the time, and a (in m^2) is the testing area.

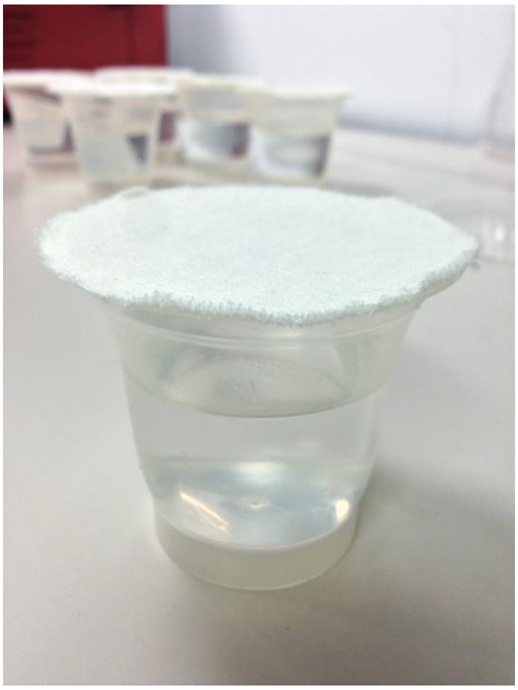


Figure 4.4 Testing of water vapor permeability

4.2.3 Moisture management capacity

Clothing absorbs sweat while running. In this study, overall moisture management capacity (OMMC) was used to measure the behavior of this dynamic transfer of liquid to the clothing fabric. It indicates the overall ability of fabric to manage the transport of liquid moisture, which includes three aspects of performance: moisture absorption rate of the bottom side, one-way liquid transport ability, and moisture drying speed of the bottom side represented by the maximum spreading speed[81]. Figure 4.5 shows the machine testing OMMC named moisture management tester (MMT). The OMMC was calculated as Equation 4-2:

$$\mathrm{OMMC} = C_1{*}\mathrm{MAR_b} + C_2{*}\mathrm{OWTC} + C_3{*}\mathrm{SS_b} \qquad (4\text{-}2)$$

where C_1, C_2, and C_3 are the weights of the indices of absorption rate ($\mathrm{MAR_b}$), One-Way Transport Capacity (OWTC), and spreading/drying rate ($\mathrm{SS_b}$), respectively .

Figure 4.5 Moisture management tester

4.2.4 Air permeability

An automatic air permeability tester (KES-F8-AP1) manufactured by KATO TECH CO. LTD is used to measure the fabric air resistance (AR) (Figure 4.6). The fabrics were tested according the Standard ASTM D737-96.

Figure 4.6 Air permeability tester

4.2.5 Thermal insulation

Fabric thermal insulation (TI) is measured by KES-F7 Thermo Labo II manufactured by KATO TECH CO LTD (Figure 4.7) according Standard of ISO 11092. The calculation of TI is shown in Equation 4-3:

$$TI = (w / \Delta T) * 100 \tag{4-3}$$

where TI is the thermal insulation, w is the reading of the machine, ΔT is the change of temperature (Machine temperature = 35 °C, T_a = 21 °C). The tested TI will then be computed to obtain the clo value.

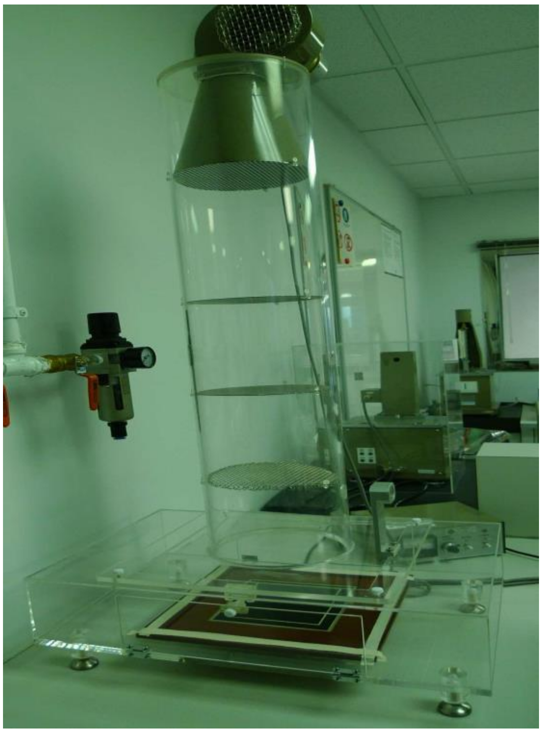


Figure 4.7 KES-F7 Thermo Labo II

Based on the test results and a wide selection of fabrics, three kinds of fabric were finally chosen for CloA (i.e., A_1, A_2, and A_3) and four for CloB (i.e., B_1, B_2, B_3, and B_4) (as shown in

Figure 3.8 of Chapter 3). Three fabrics were tested from CloC: C_1, C_2, and C_3. The specific physical properties of each fabric are summarized in Table 4.2.

Table 4.2 Summary of fabric physical properties of three sets of clothing

Fabric	Area (cm^2)	W_t ($g \cdot m^{-2}$)	*d* (mm)	AR ($KPa.s \cdot m^{-1}$)	TI (clo)	WVP ($g \cdot m^{-2} \cdot day^{-1}$)	OMMC
A1	4071	122.5±2.1	0.52±0.0	0.05±0.0	0.11±0.0	1248.7±57.5	0.74±0.0
A2	1559	66.4±0.1	0.26±0.0	0.01±0.0	0.14±0.0	1474.0±107.1	0.75±0.03
A3	2359	225.3±1.1	0.73±0.01	0.08±0.0	0.21±0.0	1134.2±81.5	0.60±0.15
B1	778.8	207.5±1.4	0.63±0.01	0.07±0.0	0.08±0.0	864.5±13.2	0.72±0.04
B2	564.2	172.9±2.3	0.71±0.01	0.07±0.0	0.10±0.0	694.5±11.4	0.64±0.05
B3	1244.0	183.4±0.8	0.83±0.01	0.08±0.0	0.08±0.0	712.1±8.2	0.54±0.06
B4	1090.8	225.5±1.5	0.75±0.01	0.09±0.03	0.14±0.0	785.0±7.0	0.84±0.06
C1	3918.6	172.1±8.8	0.41±0.0	0.17±0.01	0.37±0.0	767.3±3.9	0.52±0.04
C2	724.6	142.7±4.6	0.63±0.01	0.02±0.0	0.22±0.0	791.8±2.1	0.36±0.05
C3	3488.0	282.3±4.4	0.70±0.01	1.36±0.09	0.40±0.0	778.7±2.0	0.60±0.09

4.3 Estimation of Clothing Physical Properties

The heat transfer of fabric was determined by the physical properties of TI (clo) and AR., The water vapor and moisture transfer was affected by the WVP and OMMC of the fabric. However, mapping-designed clothing is designed with multiple fabrics and patterns with various physical properties of fabrics to affect the heat and vapor/moisture transfer. To estimate the physical properties of whole clothing and the subsequent CHD (includes CDHL and CLHL), the calculation method was explored.

First, a standard male human model was determined. He is 1.8 m in height (H) and 70 kg in *BW*. The body surface area (A in m^2) was calculated using Equation 4-4[40]:

$$A = (BW^{0.425} * H^{0.725}) * 0.007184 \quad (4\text{-}4)$$

where A (in m^2) is the body surface area of the model, *BW* (in kg) is the body weight, and H (in m) is the height. Therefore, the calculated body surface area was 1.735 m^2 for the standard male human model.

With the model clothed, A was divided into two parts: body surface area with clothing ($A_{clothing}$) and without clothing (A_{skin}). The Equation is shown as 4-5.

$$A = A_{clothing} + A_{skin} \tag{4-5}$$

$A_{clothing}$ (in m^2) is the sum area of each fabric when the clothing is manufactured by several kinds of fabrics that are mapping-covered on the skin in a single layer and have just fit to the body. It is calculated using Equation 4-6.

$$A_{clothing} = A_1+A_2+A_3+\ldots+A_n \tag{4-6}$$

where A_1, A_2, $A_{3\ldots}$and A_n stand for the area of each fabric.

To standardize the influence of each fabric on the area of a whole body, the area proportion ratio of a single fabric (α_n) on the A can be expressed as Equation 4-7, and the area proportion ratio of skin without clothing can be expressed as Equation 4-8.

$$\alpha_n = A_n/A \tag{4-7}$$

$$\alpha_{skin} = A_{skin}/A \tag{4-8}$$

The sum of the area proportion ratio of each fabric (α_1, $\alpha_{2\ldots\ldots}$and α_n) and α_{skin} without clothing is 1 and the Equation is shown as 4-9.

$$\alpha_1+\alpha_2+\alpha_3+\ldots\alpha_n+\alpha_{skin} = 1 \tag{4-9}$$

There were two methods for mass loss determined by the properties of the fabric: WVP and OMMC. WVP is the mass of moisture evaporation through the fabric unit surface [10], and OMMC is the 3D liquid transfer from the fabric inner surface to the outer surface [81]. The overall WVP_t of the whole human body with clothing (CloA, for instance) includes part of WVP for the three fabrics. The calculation of WVP_t is shown in Equation 4-10.

$$WVP_t = WVP_1*\alpha_1 + WVP_2*\alpha_2 + WVP_3*\alpha_3 \qquad (4\text{-}10)$$

where WVP_1, WVP_2, and WVP_3 are the WVP for the three fabrics of CloA, and α_1, α_2, and α_3 are the area proportion ratio of each fabric on the A.

The overall $OMMC_t$ is that part of OMMC covered by clothing because it is defined as the fabric's overall ability to manage the transport of liquid moisture. The larger the OMMC prediction, the higher the overall moisture management ability of the fabric [81]. The calculation of $OMMC_t$ is shown in Equation 4-11.

$$OMMC_t = OMMC_1*\alpha_1 + OMMC_2*\alpha_2 + OMMC_3*\alpha_3 \qquad (4\text{-}11)$$

where $OMMC_1$, $OMMC_2$, and $OMMC_3$ are the overall ability to manage the transport of liquid moisture for the three fabrics of CloA, and α_1, α_2, and α_3 are the area proportion ratio of each fabric on the A.

The overall AR_t is the part with clothing because it is also defined as an index for a fabric. The calculation of AR_t is shown in Equation 4-12.

$$AR_t = AR_1*\alpha_1 + AR_2*\alpha_2 + AR_3*\alpha_3 \qquad (4\text{-}12)$$

where AR_1, AR_2, and AR_3 are the AR of each fabric of CloA, and α_1, α_2, and α_3 are the area proportion ratio of each fabric on the A.

The overall TI (in clo_t), like AR_t, is the part with clothing because it is also defined as an index for a fabric. The calculation of clo_t is shown in Equation 4-13.

$$clo_t = clo_1*\alpha_1 + clo_2*\alpha_2 + clo_3*\alpha_3 \qquad (4\text{-}13)$$

where clo_1, clo_2, and clo_3 are the clo value of each fabric of CloA, and α_1, α_2, and α_3 are the area proportion ratio of each fabric on the A.

The calculated results are summarized in Table 4.3. As shown in the table, CloA has the highest WVP_t and $OMMC_t$, reflecting the highest ability of moisture and water transfer via clothing compared to CloB and CloC. CloA also has the lowest AR_t and clo_t, showing the highest air and thermal transfer through clothing than the other two. CloB has higher WVP_t and $OMMC_t$ than CloC, but lower AR_t and clo_t.

Table 4.3 Summary of clothing physical properties

Clothing	WVP_t ($g\cdot m^{-2}\cdot day^{-1}$)	$OMMC_t$	AR_t ($KPa.s\cdot m^{-1}$)	clo_t value
CloA	579.7	0.70	0.02	0.06
CloB	323.6	0.68	0.03	0.05
CloC	362.9	0.54	0.31	0.17

4.4 Determination of Capability of Heat Dissipation (CHD)

4.4.1 Overall CHD

The CHD (in $kJ\cdot h^{-1}$) is defined as the ability of a clothed human body to release heat by considering the CLHL and CDHL as shown in Equation 4-14.

$$CHD = CDHL + CLHL \tag{4-14}$$

CHD (in $kJ\cdot h^{-1}$) is the capability of heat dissipation. CLHL (in $kJ\cdot h^{-1}$) is defined as the ability of heat loss via liquid transfer from the skin to the outer surface of the fabric, and of moisture evaporation from skin and/or clothing during rest in a hot condition (T_a of 30 °C, RH of 50%). CDHL (in $kJ\cdot h^{-1}$) is defined as the ability of heat loss via convection, conduction, radiation with clothing during rest in a hot condition (T_a of 30 °C, RH of 50%). These three indices can be used as evaluation tools to estimate the effects of different clothing on heat loss of the whole human body.

4.4.2 Estimation of CLHL

The CLHL (in kJ·h^{-1}) may be measured in experiments with subjects or with a wetted or sweating thermal manikin [86]. If these are not possible, CLHL can be estimated from existing data, such as the value of potential evaporative mass loss (EML) affected by the physical properties of clothing and the latent heat of vaporization for liquid (λ), as shown in Equation 4-15.

$$CLHL = EML * \lambda \tag{4-15}$$

where EML includes the liquid and moisture evaporation from skin without clothing (EML_{skin}) and with clothing ($EML_{clothing}$), as shown in Equation 4-16:

$$EML = EML_{clothing} + EML_{skin} \tag{4-16}$$

EML_{skin} stands for the sweat loss directly evaporated from skin, as calculated in Equation 4-17:

$$EML_{skin} = WVP_{air} * \alpha_{skin} \tag{4-17}$$

where WVP_{air} stands for the water weight loss without fabric covering on the standard cups, but with the same testing condition and procedure as those for fabric testing. α_{skin} is the area proportion ratio of skin without clothing.

$EML_{clothing}$ at the area of the human body with clothing can be affected by the clothing's physical properties, namely, WVP_t and $OMMC_t$, which reflect the ability of liquid and moisture evaporation through the clothing (Equation 4-18):

$$EML_{clothing} = (WVP_t * (1-OMMC_t) + WVP_{air} * OMMC_t) * (1- \alpha_{skin}) \tag{4-18}$$

where WVP_t and $OMMC_t$ were evaluated using Equation 4.3. The $WVP_t * (1-OMMC_t)$ stands for the amount of sweat transfer through clothing when sweat evaporates as liquid or moisture. The value of $OMMC_t$ ranges from 0 to 1 [81]. When $OMMC_t$ equals 0, it means that the liquid condenses at the inner surface of the clothing and that sweat will only evaporate as moisture through clothing. The WVP_t determines the $EML_{clothing}$. When $OMMC_t$ equals 1, it means that all the sweat will transfer from the inner surface to the outer surface of the clothing as liquid and that the evaporation process will appear at the outer surface of the clothing. In this situation, $EML_{clothing}$ is determined by WVP_{air}. The $(1- \alpha_{skin})$ stands for the area proportion of the clothing covering the skin.

Overall, the calculation process (based on Equation 4-15, 4-16, 4-17 and 4-18) is summarized in Equation 4-19.

$$CLHL = (WVP_{air} * \alpha_{skin} + (WVP_t * (1-OMMC_t) + WVP_{air} * OMMC_t) * (1- \alpha_{skin}))*\lambda \tag{4-19}$$

4.4.3 Determination of CDHL

The assessment of CDHL provided by clothing can also be estimated by the calculated method of the physical properties of clothing. Another method exists which uses a thermal manikin to measure the resistance of dry heat loss and can be applied to estimate the CDHL of whole clothing.

The TI, which is also presented as the value in clo unit, was measured according to the manikin manual. The test specification referred to the standard test method of TI, ASTM F1291[11]. The heated manikin (P. T. Teknik, Delta Elektronika Limited) was dressed in three sets of clothing respectively in each trial.

Testing procedure

The manikin without clothing was initially hung in an environmental chamber by a hook in the head. The arms hung at the sides. The environmental conditions of the test were set at T_a of 20 °C and *RH* of 50%, similar to the conditions of a physical property test in the laboratory. T_a around the manikin was measured continuously with a thermal sensor.

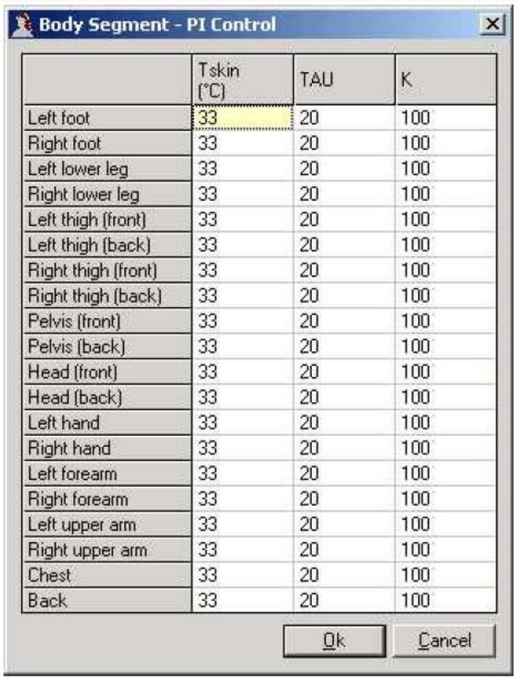
To obtain exact measurements, the calibration of manikin was conducted. The manikin was set in a no heat-mode as the hot wires of the manikin would not be activated during calibration. Three steps were taken from manikin manual:

1. A data record was logged while setting all parts of the manikin at a uniform temperature, such as 20 °C by selecting the calibrate temperature and the function body segment. The temperature of all body parts of the manikin should be the same.

2. The same procedure was repeated, but with the calibrate temperature B at another temperature, 35 °C.

3. The calibrated temperature constants were calculated automatically.

To conduct each trial, the skin surface temperature of the thermal manikin was set to 34 °C. Equilibrium was maintained for at least 2 h before testing and was indicated by a constant power reading that had variations within 2%. The nude manikin stayed in the chamber for 40 min, and the power input (P) (in $W \cdot m^{-2}$) was recorded every 30 s for a 30 min period[128]. Three different methods of controlling heat transfer to the manikin were available: Comfort Control, Proportional Integral (PI) Control, and Locked Power. We selected the PI control with a constant skin temperature at all parts of the manikin to predict the used power. Twenty body segments with specific skin temperature was shown at each segment (Figure 4.8).



	Tskin (°C)	TAU	K
Left foot	33	20	100
Right foot	33	20	100
Left lower leg	33	20	100
Right lower leg	33	20	100
Left thigh (front)	33	20	100
Left thigh (back)	33	20	100
Right thigh (front)	33	20	100
Right thigh (back)	33	20	100
Pelvis (front)	33	20	100
Pelvis (back)	33	20	100
Head (front)	33	20	100
Head (back)	33	20	100
Left hand	33	20	100
Right hand	33	20	100
Left forearm	33	20	100
Right forearm	33	20	100
Left upper arm	33	20	100
Right upper arm	33	20	100
Chest	33	20	100
Back	33	20	100

Figure 4.8 PI-setting used for thermal manikin test

The PI controller also performed integration. The power was calculated using skin temperature, K Constant (default 100), and TAU Constant (default 20). The calculation Equation is shown as follows (4-20):

$$P = K * (\Delta T + 1/t \int \Delta T dt) \qquad (4\text{-}20)$$

where $\Delta T = T_s - T_a$, and P is the power calculated ($P \geq 0$).

Three main methods were available to calculate the manikin clothing insulation (thermal resistance, R in $m^2 \cdot W^{-1} \cdot °C$), namely, global method [146], parallel method, and serial method, which was actually used and described in ISO 9920 [86]. In present test, we chose the global method, which is the general equation for defining the whole body resistance with clothing and performs an overall calculation of heat losses. The overall thermal resistance was calculated using Equation 4-21:

$$R = \Delta T / \sum(\alpha * P) \qquad (4\text{-}21)$$

where R is the overall thermal resistance (in $m^2 \cdot W^{-1} \cdot °C$), $\Delta T = T_s - T_a$, α is the area proportion ratio of each segment on the body surface area (A), and P is the power to maintain the T_s in each segment. When α=1, the P is related to the total heat flux for the whole body ($W \cdot m^2$). When α is equal to the area proportion ratio of segment, the R can be calculated for each segment.

The clo value of clothing was calculated by the power used to keep the manikin at a constant T_s of 34 °C (as shown in Equation 4-22).

$$1 \text{ clo} = 0.155 \text{ R} \tag{4-22}$$

According to the transfer equation of electric power (P in W), energy (E_n in J) and time (t in s) (as shown in Equation 4-23 [67]),

$$P = E_n * t^{-1} \tag{4-23}$$

where P is the power (in W), E_n is the energy (in J), and t is time (in s).

The CDHL ($kJ \cdot h^{-1}$), which reflects the total heat flux for whole body while wearing different sets of clothing, was converted from the power, as shown in Equation 4-24:

$$CDHL = P * 3.6^{-1} \tag{4-24}$$

where CDHL is the capability of dry heat loss (in $kJ \cdot h^{-1}$), P is the power used to maintain the T_s of manikin (in W).

$$CHD = (WVP_{air} * \alpha_{skin} + (WVP_t * (1\text{-}OMMC_t) + WVP_{air} * OMMC_t) * (1\text{-} \alpha_{skin}))*\lambda + P * 3.6^{-1} \tag{4-25}$$

Where WVP_{air} stands for the water weight loss without fabric covering on the standard cups; α_{skin} is the area proportion ratio of skin without clothing; WVP_t is the overall water vapor permeability of whole clothing; $OMMC_t$ is that part of OMMC covered by whole clothing; P is the power to maintain the T_s in each segment.

4.4.4 Application of evaluation methods

Table 4.4 summarizes the CLHL, CDHL and overall CHD based on the previously introduced calculated equations. Results show that CloA has the highest CLHL among the three sets of clothing, which increased by 13.5% in CLHL compared to that of CloC. CloA also has the highest CDHL, which increased by 6.8% compared to that of CloC and by 11.4% on CHD. CloB has the higher CLHL, CDHL, and CHD than CloC, which shows an increase of 7.6%, 6.8%, and 7.4%, respectively. The increasing CLHL, CDHL, and CHD of CloA and CloB are due to the mapping-designed concept and selected fabric with improved WVP and OMMC, as well as decreased AR and clo value when compared with CloC. The variation between CloA and CloB may be due to the different pattern designs (i.e., CloA vs. CloB, two-piece and one-piece), as well as the physical properties of fabrics used.

Table 4.4 Summary of calculated clothing properties

Clothing	CLHL ($kJ \cdot h^{-1}$)		CDHL ($kJ \cdot h^{-1}$)		CHD ($kJ \cdot h^{-1}$)	
	Absolute	Increased %	Absolute	Increased %	Absolute	Increased %
CloA	301.0	13.5	130.7	6.8	431.7	11.4
CloB	285.4	7.6	130.7	6.8	416.1	7.4
CloC	265.2	0	122.4	0	387.6	0

According to the thermal manikin test, the thermal properties of the fabric applied in each body segment were verified. The results are shown in Figure 4.9 and Table 4.5.

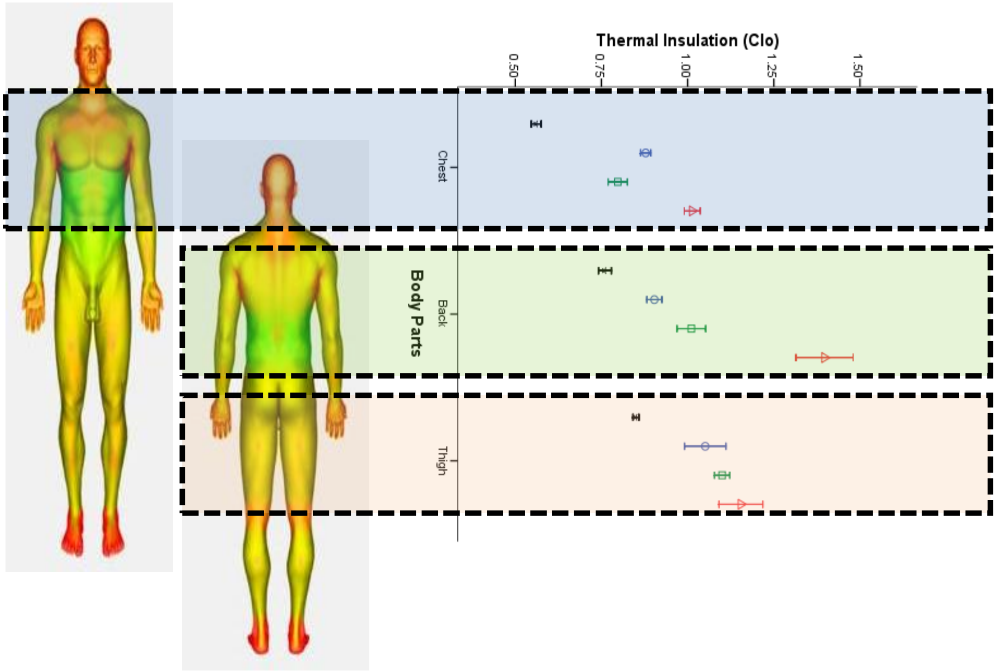


Figure 4.9 TI of each segment while wearing three sets of clothing

Table 4.5 Summary of the clo value of three sets of clothing

Clothing	Whole body	Chest	Back	Thigh
Nude	0.62 ± 0.00^{ab}	0.56 ± 0.01^{ab}	0.76 ± 0.01^{ab}	0.85 ± 0.00^{ab}
CloA	0.71 ± 0.01^{b}	0.88 ± 0.01^{ab}	0.90 ± 0.01^{b}	1.05±0.03
CloB	0.71 ± 0.02^{b}	0.80 ± 0.01^{b}	1.01 ± 0.02^{b}	1.10±0.01
CloC	0.76 ± 0.00^{a}	1.01 ± 0.01^{a}	1.40 ± 0.04^{a}	1.15±0.03

$^{a:}$ $p<0.05$ from CloB, $^{b:}$ $p<0.05$ from CloC

- Whole clothing: CloA has the lowest clo value, which was used to calculate for CDHL and was summarized in Table 4.5.

- Body part: CloB and CloA have lower clo values on the chest and back part of body than CloC. CloB has lower clo value than CloA on the chest.

4.5 Evaluation of Clothing on Human Body

With the standard human model wearing the mapping-designed clothing at a specified environmental condition, the physical properties and overall CHD was estimated. The two essential purposes for the design and manufacture of this kind of clothing are to increase the athletes' performance and wearing comfort. This is also the main target of this study.

To assess if the purposes are met, CloA and CloB were evaluated on the human body, the third level of the evaluation system. The next section will briefly introduce the method for evaluating the clothing on the human body.

4.5.1 Experimental design

Each subject visited the laboratory six times in this within-subject repeated-measure study. On their first visit, the subjects familiarized themselves with the experiment protocol, climatic chamber, and usage and safety precautions of the motorized experiment. On their second and third visits, they performed the maximal oxygen uptake (VO_{2max}) test and speed-oxygen uptake to determine their running speed at 70% VO_{2max}. On their fourth to sixth visits, which were conducted in a climatic chamber (T_a of 30 ± 0.2 °C, and RH of 50 ± 2%), the subjects randomly wore one of the three sets of clothing during each visit. The subjects performed the experiments once a week to avoid the effects of carry-over fatigue. Food intake of the subjects 24 h prior to each visit was recorded. To minimize variations in their dietary intake, the subjects were required to repeat the same dietary intake prior to each visit.

4.5.2 Experimental measurements and instruments

In order to conduct wear trials, the measurements and instruments would be selected and confirmed as part of preparation of experiments. The measures of the physiological and psychological responses of human body were also counted in the evaluation system of clothing in this study. These measures in details would be introduced as follow:

Body weight (*BW*, in kg)

Nude body weight of the subjects was measured by balance (EA150-feg, Startous, Germany) before and after the wear trial. Body weight loss (ΔBW) was applied to estimate evaporative heat loss by sweating and respiration.

Core temperature (T_c, in °C)

The measurement of T_c is an essential factor to monitor the heat stress of athletes during exercise [5, 117]. Thus, the telemetry sensor (CorTemp, HQ Inc, Palmetto, FL) was employed to record absolute gastrointestinal temperature, which was found to achieve the best balance of comfort, practicability, and scientific validity [117] (discussed in Section 2.5.3 of Chapter 2). A telemetry pill was swallowed by the subjects at 7:00am on the day of the experiment and the T_c was recorded 5 min before the experiment started. At 11:00am, the experiment started and the T_c was continuously recorded at 10 s intervals [23, 91].

Water is provided ad libitum before wear trial start in the hot condition to avoid dehydration from heat exhaustion and water loss through perspiration [129]. During the pre-trial when confirm the experimental protocol, water was found to impair T_c measurement using the telemetry sensor [23, 92]. Therefore, water was not allowed when experiment started.

Change of core temperature (ΔT_c, in °C)

The change in T_c showing the change of heat stress is also an essential temperature index of performance. We defined ΔT_c to represent the changes in absolute T_c at each time point compared with T_c measured at 0 min of rest in Phase 1.

Thermal performance capacity (*TPC*, in °C)

The normal T_c of healthy human adults is about 37 °C [127]. When the T_c rises during endurance running, the performance is impaired because of the degrading function of the cardiovascular [39, 51], skeletal muscle [179], and central nervous systems [29, 64]. When the T_c rises above the critical level of 40 °C, which represents a safety brake for catastrophic heat injury, the athlete shows apparent symptoms of heat stress and exhaustion [18, 29, 142]. However, the index of thermal tolerance of an athlete has not been clearly defined yet at the T_c exhaustion rate of 40 °C, that is, the safety brake. The index should be another meaningful indication related to heat stress and performance as well. Thus, we define thermal tolerance as the thermal performance capability (*TPC*) at the exhaustion or critical T_c rate of 40 °C evoked by clothing. This parameter can also be explained as the buffer at which absolute T_c reaches the proposed safety brake as T_c reaches 40 °C [29, 124, 142].

Mean skin temperature (T_s, in °C)

At the start of the experiment at around 11:00am, T_s was continuously measured at 4 s intervals by four metal thermistor probes (LT8A, Gram Corporation, Saitama, Japan) attached to the chest, upper arm, thigh, and calf of the subject. The mean T_s was calculated as Equation 4-25 [151]:

$$T_s = 0.2(T_{\text{thigh}} + T_{\text{calf}}) + 0.3(T_{\text{chest}} + T_{\text{arm}}) \qquad (4\text{-}25)$$

where T_s is the mean skin temperature (in °C), T_{thigh} is the skin temperature of the thigh (in °C), T_{calf} is the skin temperature of the calf (in °C), T_{chest} is the skin temperature of the chest (in °C), and T_{arm} is the skin temperature of the arm (in °C).

Mean body temperature (T_b, in °C)

The temperature gradients from the core to the skin and from the skin to the environment are calculated as follows: core to skin = (T_c– T_s) and skin to environment = (T_c–T_a). Thus, T_b is calculated from T_c and T_s according to the Equation of Baum in 4-26 (1976) [7]:

$$T_b = 0.87T_c + 0.13T_s \quad (4\text{-}26)$$

where T_b is the mean body temperature (in °C), T_c is the core temperature (in °C), and T_s is the mean skin temperature (in °C).

Heat storage (S, in $W{\cdot}m^{-2}$)

The S is the instantaneous difference between metabolic heat production and net heat loss by combined dry heat exchange and evaporation [1, 57, 184]. S was estimated using the average specific heat, product of body mass, and change in T_b. S was calculated using Equation 4-27:

$$S = 0.97BW\,(\Delta T_b/\Delta t)/\mathrm{A} \quad (4\text{-}27)$$

where 0.97 is the specific heat of the body (in $W{\cdot}h{\cdot}kg^{-1}{\cdot}°C^{-1}$), BW is the body mass (in kg), $\Delta T_b/\Delta t$ is the change in T_b over time (in $°C{\cdot}h^{-1}$), and A is the body surface area (in m^2) [1, 57].

Microclimate relative humidity (RH, in %)

The RH reflects the status of sweat accumulated between the skin and the inner surface of the clothing. In the evaluation system of this study, microclimate RH was measured by humidity sensors (HIH-3610, HyCal Sensing Products, California, USA.) with a data acquisition system (PCL818H with two extended amplifiers and multiplexer boards PCLD 789D, from ADVANTECH®).

Heart rate (*HR*, in beat·min^{-1})

The HR was continuously evaluated using a Sunnoto monitor (Suunto T6, Finland) [23, 91].

Respiration measurement

The maximal oxygen uptake (VO_{2max}) test and Speed-oxygen uptake test (Speed-VO_2) of the subjects were conducted, and the respiration gas was collected and analyzed by a metabolic cart system (ParvoMedics TrueOne® 2400, USA) before the main trials. The testing procedure and protocol in detail will be introduced in the next chapter (Chapter 5) [127].

4.6 Conclusion

An evaluation system was developed to assess the performance of mapping-designed running clothes. The system includes three main parts: basic tests on fabric physical properties, estimation of physical properties of the whole clothing, and determination of the overall CHD, CLHL and CDHL. Specifically, the physical properties of the whole clothing were calculated by referring to each fabric physical property and the covered area portion of each fabric. According to the results of calculation, we found CloA has the highest WVP_t and $OMMC_t$, reflecting the highest ability of moisture and water transfer via clothing compared to CloB and CloC. CloA also has the lowest AR_t and clo_t, showing the highest air and thermal transfer through clothing than the other two. CloB has higher WVP_t and $OMMC_t$ than CloC, but lower AR_t and clo_t. In terms of estimation the overall CHD of the whole clothing findings revealed that the overall CHD of CloA increased by 11.4%, while that of CloB was at 7.4% as compared to existing commercial clothing. This proves that clothing designed with mapped patterns and specified functional properties of materials according to the thermal requirements in each body part has positive influence on the overall CHD.

The developed evaluation system was first established to determine the CHD, CDHL and CLHL by using calculation methods. These methods simplified the evaluation of the overall physical properties of the whole clothing, which consists of different kinds of fabric. The system also lays the foundation for further investigation on the effect of running wear on physiological/psychological responses of athletes, running performance, and overall wearing comfort sensation. Wear trials were conducted for clothing evaluation on the human body, and the related finding would be discussed in the next three chapters (Chapters 5, 6, and 7).

CHAPTER 5 EFFECTS OF CLOTHING ON HEAT STRESS AND RUNNING PERFORMANCE IN A HOT CONDITION

5.1 Introduction

In the past two decades, more than 100 athletes died from exertional heat stress during competitions in hot environments [127]. Heat stress threatens the health of athletes and restricts their running performance. If appropriate measures are not adopted, heat stress develops to a heat stroke, which is a life threatening illness characterized by hot, dry skin and central nervous system abnormalities [18]. When suffered from heat stroke, athletes show a marked reduction in their motivation to run [64], fail to maintain the force output of skeletal muscle [179], and opt to stop exercise volitionally when exhausted [29, 174].

Thermal responses of athletes, particularly the increase of core temperature (T_c), alone or combined with skin temperature (T_s), primarily explain the amount of heat stress in a hot environment [6, 45, 124, 174]. The normal T_c of a healthy human adult at rest is about 37 °C [127]. Maintaining a stable T_c depends upon the balance of heat production and heat dissipation. During exercise, increased muscular activity results in the production of heat. Some of the produced heat is dissipated into the environment through conduction, convection, radiation, and evaporation [127, 148]. Among these processes, sweat evaporation is considered to be the major one, accounting for up to 80% of the total heat dissipation during exercise in hot conditions [48, 187]. The rest of the heat is stored in the body, which results in a raised T_c. To delay the increase of T_c and heat storage (S) and subsequently reduce heat stress as well as its impact on running performance in a hot condition, it is essential to increase heat dissipation, particularly by evaporation during exercise.

Clothing, as an interactive barrier between the ambient environment and the skin surface, may alter the condition of the macroclimatic environment around the human body [147]. Clothing is not only required as a uniform in most sport, or in most occupation for that matter, but also serves as protection for the skin from external radiation and/or heat injuries caused by solar exposure in hot environments [187]. Optimized clothing design (including clothing pattern and fabric properties) and fitting can increase the athletes' heat dissipation, and thereby impact their exercise performance [147]. Therefore, clothing designed with increased capability of heat dissipation (CHD) and their effects on exercise performance under hot conditions has aroused the enthusiasm of researchers. With regard to fabric properties, a recent study investigated the influence of three polyester jerseys with different knit sizes on heat dissipation via convection and the effects on cyclists' psycho-physiological responses in a hot and humid environment[50]. Compared to small knits, jerseys with large knits induced lower T_s and increased thermal comfort during cycling on a stationary roller[50]. Brazaitis et al.[19] also investigated the thermal responses of male subjects on two sets of clothing with different materials (100% polyester and 100% cotton, respectively) during a 20 min run at 8 $km \cdot h^{-1}$ in an environment at T_a of 25 °C and RH of 60%. They reported that polyester had greater air permeability and water-transfer rate, which induced less sweat accumulation and fast sweat evaporation, but had similar T_c and heart rate (HR) than cotton ensembles during exercise. Gavin et al.[46] used an experiment protocol with a 30 min run at 70% VO_{2max} and a 14 min walk at 40% VO_{2max} to compare the effects of different clothing materials on thermal responses. Due to the short duration and sub-maximal intensity, it was difficult to observe different thermal responses induced by clothing materials during exercise. Besides, they did not investigate the clothing-induced differences in ΔT_c, S, and exercise performance. Wingo et al.[188], conducted a study to investigate the thermal responses induced by different clothing, including a 65% VO_{2max} run for 45 min in their protocol. They only found lower T_c of subjects at the end of the run. They suggested extending the exercise beyond a 45 min run in the future to further investigate the effects of clothing on thermal responses. Moreover, to our best knowledge, no study has investigated the effects of different clothing designs (pattern and fabric), by altering the CHD of clothing, on human thermal responses and running performance under hot conditions.

Therefore, to fulfill the fourth objectives of this study, this chapter aims to investigate and verify the effects of mapping-designed running clothes on whole-body thermal responses and running performance on human subjects in a hot condition using a protocol that includes sub-maximal steady-state running followed by an all-out sprint. The relationships among clothing overall performances, whole-body thermal responses and the time of running performance were examined. We hypothesized that clothing designed to increase the capacity of heat dissipation would lead to a larger decrease of T_s, delay the increase of T_c and S, and improve subsequent all-out running performance in a hot condition. We further hypothesized that the time of all-out running performance was correlated with these thermal responses.

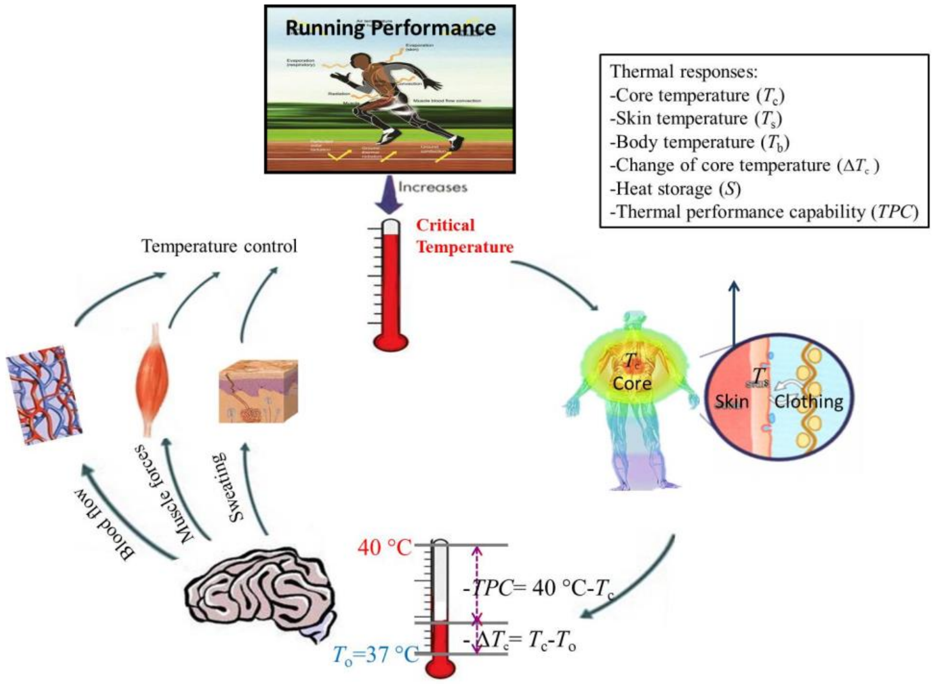
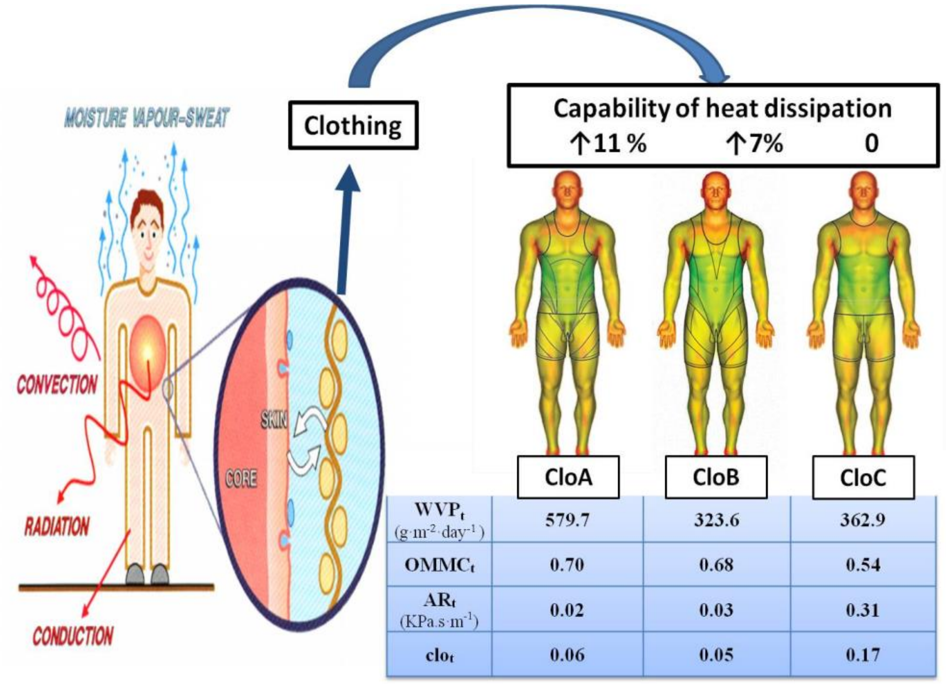


Figure 5.1 Theoretical framework on clothing and thermal responses during exercise

5.2 Methodology

5.2.1 Clothing

In this study, three sets of clothing, CloA, CloB, and CloC (control group), were used in each subject's visit. The patterns and physical evaluation of clothing properties were introduced in Chapter 3 and 4. To sum up, CloA and CloC included a vest and a pair of short pants. CloB comprise an one-piece clothing. CloA has the highest WVP and OMMC among the three sets of clothing. CloA and CloB have higher clo values than CloC. Overall, CloA and CloB respectively had 11% and 7% higher CHD compared to CloC, which is evaluated in Chapter 4 and summarized in Figure 5.2 [92, 111].



	CloA	CloB	CloC
WVP_t ($g \cdot m^{-2} \cdot day^{-1}$)	579.7	323.6	362.9
$OMMC_t$	0.70	0.68	0.54
AR_t ($KPa.s \cdot m^{-1}$)	0.02	0.03	0.31
clo_t	0.06	0.05	0.17

Figure 5.2 Three sets of clothing and overall capacity of heat dissipation

5.2.2 Subjects

Eight healthy male subjects who regularly trained in various sports volunteered to participate in this study. Their characteristics were as follows (mean ± SEM): age, 21.8 ± 0.5 years; height, 172.6 ± 2.2 cm; *BW*, 61.8 ± 2.8 kg; and VO_{2max}, 57.0 ± 2.4 $mL \cdot kg^{-1} \cdot min^{-1}$. The exercise protocol and possible risks of the experiment were presented. A written consent was gathered from each subject prior to participation. All subjects were required to complete a questionnaire to determine whether they experienced symptoms of respiratory infection and/or took medication within one month prior to the study. None of the subjects had cardiovascular, pulmonary, or metabolic diseases, venous insufficiency, and peripheral vascular disease, or were on medication. They were required to refrain from alcohol and any vigorous physical activity for 24 h and to fast 12 h before each visit. All experimental procedures were approved by the University Research Ethics Committee prior to the start of the study.

5.2.3 Experimental procedures

Preliminary tests

Familiarization (the first visit)

Subjects were introduced and familiarized with the laboratory environment. Control and safety cautions of the motorized treadmill, as well as the experiment protocols were thoroughly introduced. They were also introduced to the methods of expired air collection. This familiarization can help alleviate subjects' anxiety.

Maximal oxygen uptake (VO_{2max}) Test (the second visit)

Subjects' maximal oxygen uptake was determined by a continuous, incremental graded uphill treadmill running test to volitional exhaustion. After 5 min of warm up, subjects were told to run at an initial speed of 5 $mile \cdot hr^{-1}$ and the speed progressively increased by 1 $mile \cdot hr^{-1}$ at 1 min intervals up to 9 $mile \cdot hr^{-1}$. When the speed reached 9 $mile \cdot hr^{-1}$, it was kept constant and then increased by 1 $grade \cdot min^{-1}$. Subjects were urged to run as long as possible to achieve their maximum exertion. Strong verbal encouragement was given throughout the whole test until volitional exhaustion. *HR* was monitored continuously throughout the test and the Rating of Perceived Exertion (RPE) was recorded at the beginning of each stage. While running, ventilation and oxygen and carbon dioxide concentration of the inhaled and exhaled air were measured continuously by a metabolic analyzer (TrueOne 2400, Parvo Medics Utah, USA). The highest value of VO_2 with a Respiratory exchange ratio greater or equal to 1.1 and the *HR* within 5 $beats{\cdot}min^{-1}$ of predicted maximum age will be considered as subjects' VO_{2max}.

Speed-oxygen uptake test (VO_2 -Speed Test) (the third visit)

This test aimed to discover the relationship between running speed and VO_2 on a motorized treadmill. In the test, composed of four stages with different speeds, subjects had to run continuously for 4 min in each stage. The test started with an initial speed of 6 $mile{\cdot}hr^{-1}$ and progressively increased by 1 $mile{\cdot}hr^{-1}$ per stage up to 9 $mile{\cdot}hr^{-1}$. Expired gas samples were collected at the last minute of every stage and *HR* was monitored continuously throughout the test. The relationship between running speed and VO_2 was then determined by using linear regression to the four coordinates between speed and VO_2.

Main tests (the fourth to sixth visits)

The experiments started at 8:00am and ended at 1:00pm. The subjects were served standardized breakfast to control their dietary intake. The experiment was conducted in a climatic chamber through four phases (Figure 5.3): Phase 1) 30 min rest in a sitting position, Phase 2) 5 min warm up at 5 $km{\cdot}h^{-1}$ and 45 min preloaded running at a constant speed of 70% VO_{2max}, Phase 3) 1.5 km time trial performance running and Phase 4) an hour of passive recovery[91]. Phase 1 allowed the subjects to adapt to the hot environment and physiologically prepared them for the subsequent running performance [28, 37]. Phase 2 allowed them to achieve a "steady state" of physiological response at sub-maximal intensity [28, 37]. This protocol may be an advantage in distinguishing the effects of clothing on the physiological response of the subject before or during the PR in Phase 3 [28, 37]. It lowered the measurement of endogenous substrate stores, such as muscle glycogen, of the endurance runners before the performance running [28, 37] and was essential for assessing the effects of clothing on the running performance in Phase 3 in a hot condition. The 1.5 km performance running in Phase 3 simulated the final sprint in a real running competition. The time of 1.5 km performance running was defined as "PR" for further analysis. Subjects were allowed to drink water ad libitum before Phase 1.

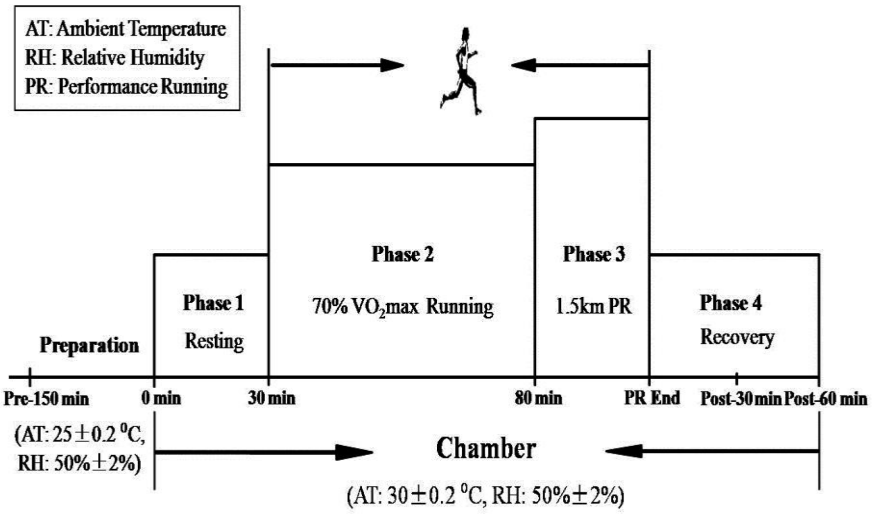


Figure 5.3 Schematic representation of the experimental protocol

5.2.4 Experimental measurements

The experiment aimed mainly to evaluate the thermal responses related to heat stress and PR while the subjects were wearing the three sets of clothing. Chapter 4 presents the detailed measurements, including PR and whole-body thermal responses: T_c, T_s, ΔT_c, T_b, TPC, S, HR, ΔBW. The T_c, T_s, ΔT_c, T_b, TPC, S, HR were continuously recorded during the whole trial, and obtained data at some critical time points for analysis (i.e. Resting 0min, 30min, Running 15min, 20min, 40min, 45min and Running End). The ΔBW was the balance between the BW measured at the beginning and at the end of the trial, after counting the water intake and urine during the whole trial [87].

5.2.5 Statistical analysis

Data are presented as mean ± SEM. Thermal responses and PR were examined by ANOVA with repeated measurements among the three sets of clothing. Upon detection of a significant difference in the ANOVA test, Tukey's post hoc test was performed to examine the pairwise comparison. The Pearson correlation coefficient was used to assess the relationship of PR with each physiological index measured at different time points (i.e. Resting 0min, Resting 30min, Running End), as well as the relationships among physical properties of whole clothing, and thermal response and PR. The magnitude of the correlations was determined using the following modified scale by Hopkins: $r < 0.1$, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; > 0.9, nearly perfect; and 1, perfect [76]. All statistical analyses were conducted using the SPSS package version 16.0 (SPSS, Inc., Chicago, IL, USA). The significance level was set at $P < 0.05$.

To examine the relationships among the time of running performance, whole-body thermal responses, and clothing overall performances, linear regression analyses were conducted based on the data obtained from the wear trials. As a result, the equations which established from statistical analyzing results may reflect the relationships among the indices in similar protocols as the present study under the hot conditions (T_a of 30 °C, *RH* of 50%). .

5.3 Results

5.3.1 Running performance

Clothing tends to have significant effects on PR (F=3.35, P=0.06). The PR while wearing CloA was shorter by 8.5% compared to that of CloC (323.1 ± 10.4 s vs. 353.6 ± 13.2 s, $P < 0.05$). There was no significant difference on the PR induced by CloB (338.1 ± 18.7 s) compared to the other two sets.

5.3.2 Thermal responses in the four phases

Phase 1: 30 min rest

The T_c slightly decreased at the beginning of the 30 min rest and then remained constant at approximately 25 min (Figure 5.4). T_s increased and stabilized at the end of the resting period (Figure 5.5). There was no significant difference among the T_c, T_s, and T_b between the three sets of clothing in this phase (Table 5.1).

The decrease of ΔT_c of CloA was bigger than the other two sets of clothing ($P < 0.05$, Table 5.1 and Figure 5.4). Among the three sets of clothing, only CloA had a negative S and the other two had positive S values in this phase. The S values of CloA and CloB were significantly lower than that of CloC ($P < 0.05$, Table 5.1).

Phase 2: 45 min run

The T_c continuously increased throughout the running exercise and remained relatively constant at around the 40 min run (including the 5 min warm up) (Figure 5.4). T_s decreased during the first 20 min and then remained constant (Figure 5.5). There was no significant difference between the T_c and T_b of the three sets of clothing, but a significant difference was found in T_s (Table 5.1). Specifically, T_s was lower when CloA was worn compared with when CloB was worn in this phase ($P < 0.05$, Table 5.1).

CloA resulted in a smaller increase in ΔT_c than the other two sets of clothing ($P < 0.05$, Table 5.1 and Figure 5.4). CloA also resulted in a lower S than that of CloC ($P < 0.05$, Table 5.1).

Phase 3: 1.5 km performance

The T_c increased and T_s fell sharply during this phase (Figure 5.4 and Figure 5.5 respectively). There was no difference between the T_c and T_b of the three sets of clothing, but lower T_s occurred when CloA was worn compared with that of CloC ($P < 0.05$, Table 5.1).

The increase of ΔT_c of CloA was smaller than the other two sets ($P < 0.05$, Table 5.1 and Figure 5.4). There was no significant difference among the S values of the three sets of clothing (Table 5.1).

Phase 4: 60 min of recovery

The T_c reached its maximum at 5^{th} min of recovery. At the time point of Recovery 30min, T_c decreased 2 min after the subjects drank water (Figure 5.4). T_s fluctuated during the first 25 min of recovery and then increased (Figure 5.5). There was no significant difference among the T_c, T_s, and T_b of the three sets of clothing (Table 5.1).

CloA exhibited a smaller increase in ΔT_c than the other two sets of clothing ($P < 0.05$, Table 5.1 and Figure 5.4). There was no significant difference among the S values of the three sets of clothing (Table 5.1).

Table 5.1 Thermal responses induced by CloA, CloB and CloC in the four phases

Phases	CloA	CloB	CloC
Phase 1: 30min resting			
- T_c	36.8±0.2	36.7±0.1	36.8±0.1
- T_s	33.9±0.1	33.9±0.1	33.9±0.1
- T_b	36.6±0.1	36.4±0.1	36.4±0.1
- ΔT_c	-0.22±0.01*†	-0.15±0.01†	-0.05±0.01
- S	-1.3±2.7†	2.2±1.7†	9.2±2.9
Phase 2: 45min running			
- T_c	38.3±0.1	38.2±0.2	38.3±0.1
- T_s	31.9±0.3*	32.6±0.3	32.5±0.2
- T_b	37.6±0.2	37.6±0.2	37.7±0.1
- ΔT_c	0.84±0.06*†	0.95±0.07†	1.01±0.07
- S	43.4±6.4†	52.7±8.1	62.1±9.9
Phase 3: 1.5km performance			
- T_c	38.5±0.1	38.6±0.1	38.5±0.1
- T_s	31.2±0.1†	31.7±0.2	31.8±0.3
- T_b	37.7±0.2	37.8±0.2	37.8±0.1
- ΔT_c	1.38±0.03*†	1.59±0.02†	1.60±0.03
- S	65.2±19.5	91.2±7.8	76.3±9.0
Phase 4: 60min recovery			
- T_c	37.5±0.0	37.3±0.1	37.5±0.1
- T_s	33.2±0.2	32.9±0.4	33.0±0.3
- T_b	37.0±0.2	36.8±0.1	36.9±0.1
- ΔT_c	0.46±0.10*†	0.56±0.11†	0.74±0.08
- S	38.3±14.8	57.4±7.1	45.0±11.4

Core temperature (T_c in °C), mean skin temperature (T_s in °C), body temperature (T_b in °C), Change of core temperature (ΔT_c in °C); heat storage (S in W·m^{-2}).

*: significantly different with CloB at $P < 0.05$; †: significantly different with CloC at $P < 0.05$.

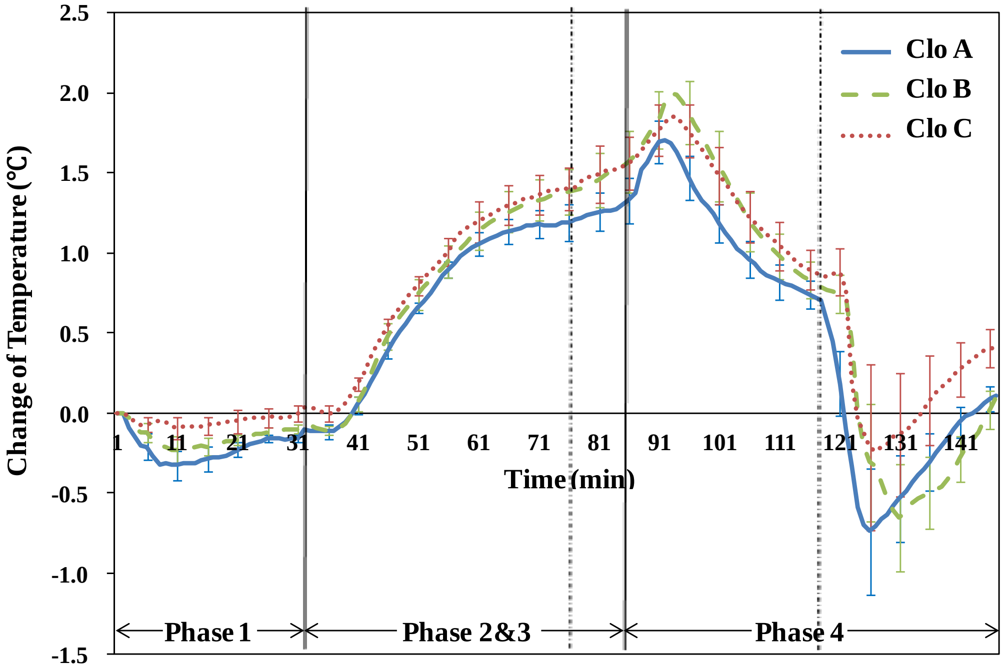


Figure 5.4 Change of core temperature of the three sets of clothing

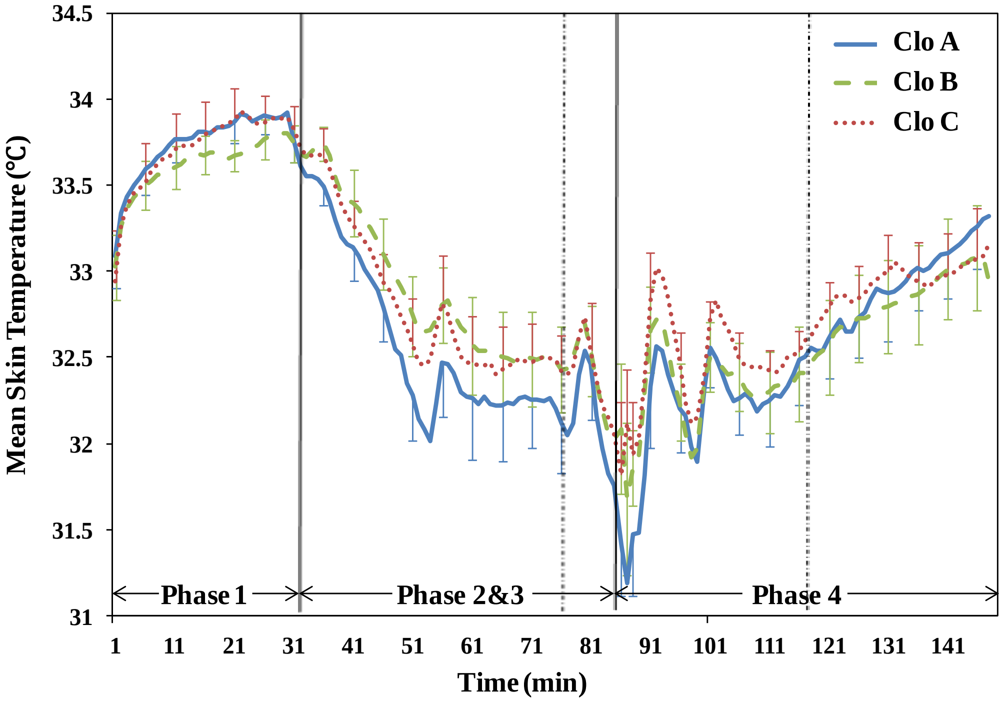


Figure 5.5 Mean skin temperature on the three sets of clothing

5.3.3 Other physiological responses

There was no significant difference in ΔBW when wear the three sets of clothing (CloA vs. CloB vs. CloC: 1071.75 g vs. 989.57 g vs. 1186.29 g), which indicated similar amount of sweat loss and respiratory evaporation under the three clothing conditions

5.3.4 Relationships between PR and thermal responses

The correlation of PR with T_c was moderate to large (0.44–0.52) (Figure 5.6a). In other words, when T_c increased from 36.5 °C to 37.5 °C at the beginning of Phases 1 and 2, 26.0% to 27.0% of the PR was explained by T_c. When T_c increased from 37.5 °C to 39.5 °C at the beginning of Phase 3, only 19.4% of the PR was explained by T_c.

The PR had moderate correlation with T_s (0.42–0.49) (Figure 5.6b). Specifically, 17.6% to 24.0% of the PR was explained by T_s. T_s at the beginning of Phases 1 and 2 had an especially positive correlation, but had a negative correlation with PR at the beginning of Phase 3.

The PR had moderate to large correlation with T_b (0.40–0.60) (Figure 5.6c). That is, up to 36.0% of the PR can be explained by T_b at the beginning of Phase 1, which exhibited the highest correlation with PR among all physiological responses at all the time points. At the beginning of Phases 2 and 3, T_b had a 32.5% and 16.0% positive correlation with the PR respectively.

The PR had moderate to large correlation with *TPC* (0.40–0.60) (Figure 5.6d). This means that when *TPC* ranged from 2.5 °C to 3.6 °C at the beginning of Phases 1 and 2, 31.4% and 28.1% of the PR negatively correlated with *TPC*. When *TPC* decreased to 2.5 °C or less, the percentage of *TPC* on the PR fell to 18.5% at the beginning of Phase 3.

The PR had small to trivial correlation with *S* at the beginning of Phases 1, 2, and 3 (0.006–0.27).

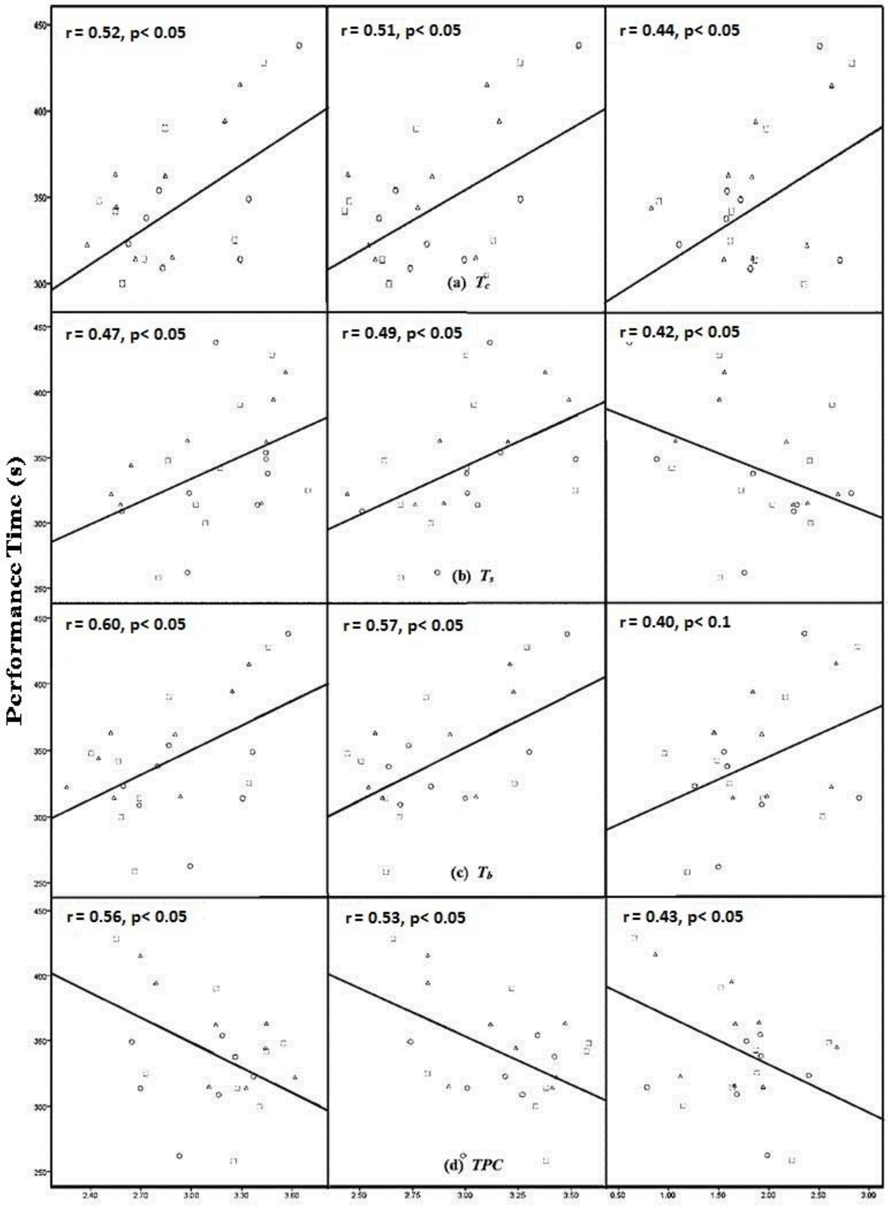


Figure 5.6 Relationships among the physiological responses in the different phases

The results of regression analysis indicated that the PR can be predicted by the whole-body thermal responses, T_c and T_s (collected at seven time points: Resting 0min, 30min, Running 15min, 20min, 40min, 45min and Running End), as shown in Equation 5-1 (R = 0.323, $P < 0.05$):

$$PR = 0.082T_c + 9.871T_s + 9.686 \quad (5\text{-}1)$$

where PR is the time required to complete 1.5 km in an all-out running performance after 45min steady-state running, T_c is the core temperature (in °C), and T_s is the mean skin temperature (in °C).

5.3.5 Relationships between clothing physical properties and thermal responses

The relationships of the physical properties of the clothing with whole-body thermal responses and PR are shown in Table 5.2. The physical properties WVP_t and OMMC_t exhibit negative correlations with S during the Resting 30 min and Running 45 min periods. The clo_t and AR_t exerted positive effects on S during the Resting 30 min period ($0.05 < P < 0.1$). These results indicate that higher clo_t and AR_t, which are associated with increased heat transfer ability from skin to the ambient environment through clothing, would result in higher S. If sweat was initiated during resting, higher WVP_t and OMMC_t would lead to less S because of higher heat dissipation and sweat evaporation, as determined by the aforementioned factors.

WVP_t tended to be negatively correlated with T_c at Running 45 min and Running End and with ΔT_c at Running 45 min. These results indicate that the continuous effects of clothing on moisture vapor evaporation are associated with whole-body thermal responses. OMMC_t tended to have negative effects on T_c at the Running 45 min time point, which differed from the effects observed in WVP_t. OMMC_t also tended to be correlated with T_s at the Running End. These observations could be attributed to the different sweat states at Running 45 min and Running End of PR, as well as the different effects of WVP_t and OMMC_t on moisture evaporation. At the Running 45 min time point, certain parts of the clothing remained dry with the capacity to absorb liquid and transfer the absorbed liquid to the outer surface of the clothing. At the Running End, the skin surface might be fully covered with sweat after 1.5 km of performance running. OMMC_t, which affects the capacity to manage fabric moisture, probably exhibited enhanced effects on the management of sweat liquid in the said states compared with $\mathrm{WVP_t}$. These effects were directly reflected on the observed correlation with T_s at Running End.

The physical properties of the clothing, $\mathrm{WVP_t}$ and $\mathrm{OMMC_t}$, exhibited negative correlations with PR, whereas $\mathrm{clo_t}$ and $\mathrm{AR_t}$ exhibited positive effects with PR ($P < 0.05$). $\mathrm{WVP_t}$ and $\mathrm{OMMC_t}$ determined the moisture transfer ability and evaporation through clothing, whereas $\mathrm{clo_t}$ and $\mathrm{AR_t}$ reflected heat dissipation from the skin through the clothing.

Table 5.2 Relationships between clothing physical properties, thermal responses and PR

		$\mathrm{WVP_t}$	$\mathrm{OMMC_t}$	$\mathrm{clo_t}$	$\mathrm{AR_t}$
Resting 30min	S (W)	$-0.34^{\dagger}$	-0.64^{**}	0.66^{**}	0.67^{**}
Running 45min	T_c (°C)	$-0.33^{\dagger}$	$-0.33^{\dagger}$		
	ΔT_c (°C)	$-0.33^{\dagger}$			
	S (W)	$-0.36^{\dagger}$	-0.54^{*}		
Running End	T_c (°C)	$-0.37^{\dagger}$			
	T_s (°C)		$-0.37^{\dagger}$		
PR (s)		$-0.37^{\dagger}$	-0.48^{*}	0.42^{*}	0.43^{*}

**: $P < 0.01$; *: $P < 0.05$; †: tend to be significant, $0.05 < P < 0.1$.
WVP: water vapor permeability ($\mathrm{g \cdot m^{-2} \cdot day^{-1}}$); OMMC: overall moisture management capacity [9, 81]; AR: air resistance ($\mathrm{KPa.s \cdot m^{-1}}$)

One of the most important thermal response indices, T_c at the time point of Running End can be predicted by the overall capability of dissipate heat (CHD), as well as the d and the $\mathrm{W_t}$ of the clothing, as shown in Equation 5-2 (R = 0.626, $P < 0.05$):

$$T_c = -0.216\mathrm{CHD} + 15.361d + 0.012\mathrm{W_t} + 30.360 \qquad (5\text{-}2)$$

where T_c is the core temperature at the time point of Running End (in °C), CHD is the overall capability of heat dissipation through the clothing (in $\mathrm{kJ \cdot h^{-1}}$), d is the mean clothing thickness (in mm), and $\mathrm{W_t}$ is the clothing weight (in g).

The T_s at the time point of Running End can also be predicted by some of the clothing properties, as shown in Equation 5-3 (R = 0.304, $P < 0.05$):

$$T_s = -0.092\text{CHD}-6.861d -0.006\text{W}_t +3.542 \qquad (5\text{-}3)$$

where T_s is the mean skin temperature (in °C),CHD is the overall capability of heat dissipation through the clothing (in $\text{kJ}\cdot\text{h}^{-1}$), d is the mean clothing thickness (in mm), and W_t is the clothing weight (in g).

Besides, the PR can be directly predicted by the CLHL through the clothing, as reported in Equation 5-4 ($R = 0.479$, $P < 0.05$) in Chapter 4:

$$\text{PR} = -0.848\text{CLHL}+225.472 \qquad (5\text{-}4)$$

where PR is the time of running performance (in s), and CLHL is the capability of latent heat loss (in $\text{kJ}\cdot\text{h}^{-1}$) through the clothing.

5.4 Discussion

5.4.1 Thermal responses

The major finding in this study was that the mapping-designed clothing with increased CHD resulted in lower T_s, smaller ΔT_c and S while running, and shorter time in all-out performance compared with CloC in a hot condition. Specifically, the PR of CloA is shorter by 8.5% than CloC, which may be due to the lower T_s combined with smaller ΔT_c and S at the beginning of PR. The three sets of clothing in Phase 1 showed similar T_s. CloA in Phase 2 induced a faster decrease of T_s during the first 15 min of the run and remained on a lower level compared with the other two sets of clothing. The difference in T_s responses can be explained by the differences in capacity of heat dissipation induced by the fabric properties among the three sets of clothing, such as clo_t, AR_t, WVP_t and OMMC_t. When the subjects started running, dissipation of dry heat occurred due to the increasing T_c and the temperature gradient between skin (34 °C) and T_a (30 °C). The CloA had lower clo_t value, which helped increase the dissipation of dry heat from the subject's skin to the environment before sweating. Upon sweating, the heat dissipation via sweat evaporation became the major process of heat loss [48, 187]. The higher WVP_t and $OMMC_t$ of CloA induced efficient water and moisture transfer from the subjects' skin to the outer surface of clothing, and resulted in increased heat dissipation via sweat evaporation. This finding is supported by Brazaitis et al. [19], who investigated the thermal responses of eight male subjects on two sets of clothing with different materials (100% polyester and 100% cotton) during a 20 min run at 8 $km \cdot h^{-1}$ in an environment at T_a of 25 °C and RH of 60%. They reported that polyester has greater air permeability and water-transfer rate, and therefore induces less sweat accumulation and fast sweat evaporation. Faster sweat evaporation can help dissipate heat and cool the body during exercise and recovery, which lead to lower T_s [19]. CloB is also designed to increase the CHD, but the differences in thermal responses between CloB and CloC were limited. This may be due to the different pattern designs of CloC (CloB vs. CloC: one-piece vs. two-piece), which overlay the positive effect of increased heat dissipation induced by fabric properties on athletes' thermal responses.

Furthermore, ΔT_c and S, which may be essential indicators to distinguish performance, were not used in previous studies [19, 46, 188]. In the current study, a delayed increase of T_c (smaller ΔT_c) and a smaller S induced by CloA at the end of Phase 2 were observed. In this regard, the smaller ΔT_c and S at the beginning of PR provided a larger capacity for S and could potentially perform better during the subsequent all-out run [6, 178]. This is similar to the mechanism of pre-cooling effect on performance shown in some previous studies. Lee and Hatmes [104] investigated the running performance in warm condition (24 °C) and found that running endurance increased after 30 min of pre-cooling (5 °C), which resulted in less S and heat stress. Arngrimsson et al. [7], who also found that a 5 km run in a hot condition (T_a of 32 °C and RH of 50%) was significantly shorter by 13 s when T_c was 0.2 °C lower at the beginning of the exercise. Their pre-cooling effects were conducted at rest or at the warm-up process with lower T_c and smaller

S before the exercise. However, in this study, the positive impact of smaller ΔT_c and S on PR appeared at the beginning of PR, when the T_c increased to a relatively high level after the 45 min exercise. It suggests that even if T_c appeared to be nearing the critical body temperature of exhaustion, the smaller ΔT_c and S affected by clothing may also have a positive effect on subsequent running performance.

To our best knowledge, this study is the first to use such kind of protocol including sub-maximal steady-state running followed by a time trial, to determine the effects of clothing on thermal responses and running performance in a hot environment. This protocol simulated the situation in most of the competitions, while most of the previous studies only used constant running or cycling at mild to moderate exercise intensities [19, 46, 188]. Although there was a difference in heat dissipation between the two clothing, there was little thermal advantage induced by clothing [19]. The short duration and relatively low intensity in these aforementioned studies may have hidden the true difference in thermal responses that is induced by clothing. This was supported by Wingo et al. [188] who found no differences in T_c during 45min running at 65% VO_{2max}, but showed lower T_c at the end of 45min running. They suggested that the differences in final T_c might reflect the real effects induced by different clothing, and these impacts might have been more pronounced as exercise continued [188]. In the present study, clothing-induced difference in thermal responses was observed during the 45min running at 70% VO_{2max}, and the difference was enlarged during the subsequent all-out running performance.

5.4.2 Relationships between PR and thermal responses

This study revealed that PR had moderate to large correlation with T_c at the beginning of Phases 1, 2, and 3. A few studies examined the relationship between PR and T_c at different time points in a preloaded time trial, and high T_c values during exercise are shown to impair the endurance performance due to the degraded function of the cardiovascular [39, 51], skeletal muscle [179], and central nervous systems [29, 64]. A smaller correlation between T_c and PR was found when T_c increased while running. Specifically, T_c ranged from 36.5 °C to 37.5 °C at the beginning of Phases 1 and 2. In this condition, T_c explained 26.0% to 27.0% of the PR, whereas only 19.4% of the PR was explained when T_c increased from 37.0 °C to 39.5 °C at the beginning of PR. In a hot condition, well-trained and moderately fit individuals are believed to terminate exercise when T_c is about 40 °C and 38.5 °C respectively, regardless of T_c at the beginning of exercise and S during the exercise [39, 51, 124]. This study suggests that while the performance is determined by T_c, the absolute value of T_c is regarded as an essential indicator of performance. However, the level of correlation varied during different time points depending on the variations in ΔT_c, T_s, and S.

The PR was also found to have a negative correlation with *TPC*. This suggests that a short PR is accompanied with a higher buffer of T_c to approach the critical level, 40 °C. The correlation between PR and *TPC* decreased during Phases 2 and 3 because of the increases in T_c and ΔT_c as well as the decrease in T_s, resulting in decreased heat loss and increased S while running.

This study also showed a large correlation between PR and T_s at three time points during the experiment. This finding is in agreement with the results of a previous study showing that T_s, or a combination with T_c ($T_c + T_s$), affects and adjusts the cardiovascular and oxygen uptake, which may have impaired performance [29]. In this study, PR is positively correlated with T_s at the beginning of Phases 1 and 2, but negatively correlated with T_s at the beginning of Phase 3. Positive correlation can be explained by the heat transfer from the core to the periphery resulting from the thermal differences between T_c and T_s. The skin surface was still dry at the beginning of Phases 1 and 2. If T_s was low at the beginning of Phase 1, then there was a large thermal difference between T_c and T_s. This difference caused an increased cutaneous blood flow [96, 148] which elevated heat transfer from the core to the skin and potential heat loss from the skin to the environment. The elevated capability of heat transfer and heat loss would then delay the increase in heat stress during the following run in Phases 2 and 3 [29, 148]. There was also sufficient time for heat to transfer from the core to the skin, and subsequently, to the environment before PR. However, when sweating was initiated as running started in Phase 2, sweat evaporation became the primary process of heat loss and was dependent on the temperature as well as vapor pressure gradient between the skin and the environment [127]. Hence, lower T_s at the beginning of Phase 3 meant that a lower gradient of the skin–environment temperature limited heat loss to the external environment via evaporation and increased heat stress during PR in Phase 3. It subsequently increased the PR of the subject. Although increased blood flow might have brought heat from the body core to the skin faster when T_s was low at the beginning of PR, there was insufficient time for skin to dissipate the heat produced during PR because the PR continued for only a few minutes. These phenomena may explain the distinct correlations between PR and T_s at the three different time points.

The T_b, calculated with 87% weight of T_c, had the same pattern as T_c in terms of the relationship with PR. However, T_b exhibited the largest correlation with PR among all the physiological indices related to temperature regulation because of the combined effects of T_c and T_s on performance. Hence, when T_c and T_s were both considered, dry heat transfer in the body from the core to the skin, as well as evaporative heat dissipation from the skin to the environment both explained the effect of temperature regulation on PR.

This study also found trivial to small correlations between PR and S at the beginning of Phases 1, 2 and 3. By definition, S is the instantaneous difference between metabolic heat production and net heat loss by combined dry heat exchange and evaporation [1, 57, 184]. S was estimated using average specific heat, product of body mass, and change in T_b. Considering that specific heat and body mass remained constant throughout the experiment, the rate of S was calculated by the minute-by-minute changes in T_b [1]. Therefore, the present finding on S and the PR indicated that running performance in a hot condition was not considerably associated with the instantaneous difference in heat production and heat loss prior to PR during this preloaded time trial.

Among these whole-body thermal responses, lower T_s, which is determined by lower local skin temperature and RH, is expected to obtain an increased gradient with T_c during heat transfer by blood flow conduction. Increased heat transfer from the core to skin surface, as well as improved heat dissipation through the clothing, lowers the increases in T_c and S. As suggested in previous studies (discussed in Chapters 2 and previous sections), these thermal responses determine the states of heat stress. Under heat stress, the elevated T_b in athletes caused by failed thermoregulation leads to hyperthermia. Hyperthermia during exercise under hot conditions is regarded as an independent cause of fatigue. No other single factor has been recognized to pose a greater threat to health and performance than does hyperthermia [133]. González-Alonso and his group (1999) found that the time to exhaustion on trained subjects at different T_c, ranging from 28 min to 63 min, was adversely related to the initial body temperature and the rate of heat storage [51]. Under heat stress, the circulatory system, in addition to nutrient transport and metabolism, is responsible in transferring metabolic heat from the active tissues to the skin surface for heat dissipation. Factors that tend to increase heat stress and overload the cardiovascular system drastically increase the risk of heat stroke and impair performance [31]. Efficient heat dissipation induced by clothing provides an enhanced capacity to reduce hyperthermia, increasing the potential to improve performance under hot conditions.

5.4.3 Relationships between clothing physical properties and thermal responses

From the correlation found in this study, the relationships between clothing physical properties, thermal responses and running performance can be presented in Figure 5.7. The physical properties of the whole clothing (i.e., WVP_t, $OMMC_t$, AR_t, and clo_t) have direct relationships with the thermal response at different time points. This finding was also found in some previous studies. They indicated that the physical properties of the fabric, such as AR_t and clo_t can cause changes in T_s [74, 148]. The WVP_t of the fabric and $OMMC_t$ can significantly influence the behavior of moisture transfer in a fabric, which can further impair heat transfer of a Body–Clothing–Environment system [81, 148]. But the previous studies did not investigate the relationship between the overall CHD of a whole clothing and the athletes'' thermal responses. To our best knowledge, this is the first study which reported the possible equations of T_c and T_s (at some time points) predicted by clothing physical properties, i.e. W_t, d, and CHD from the results of wear trials and statistical analysis (as shown in Equation 5-2 and 5-3). It indicated the possibility to adjust and simulate the thermal responses of human body by altering the overall performance of whole clothing. Besides, the PR which was related to the thermal responses (as shown in Equation 5-1) can also be predicted by the CLHL of whole clothing (as shown in Equation 5-4). However, due to the small sample sizes of clothing and experimental subjects used in the wear trials, the predicted equation can only explain the results of present study. Further investigation with larger samples sizes of clothing and human subjects are required.

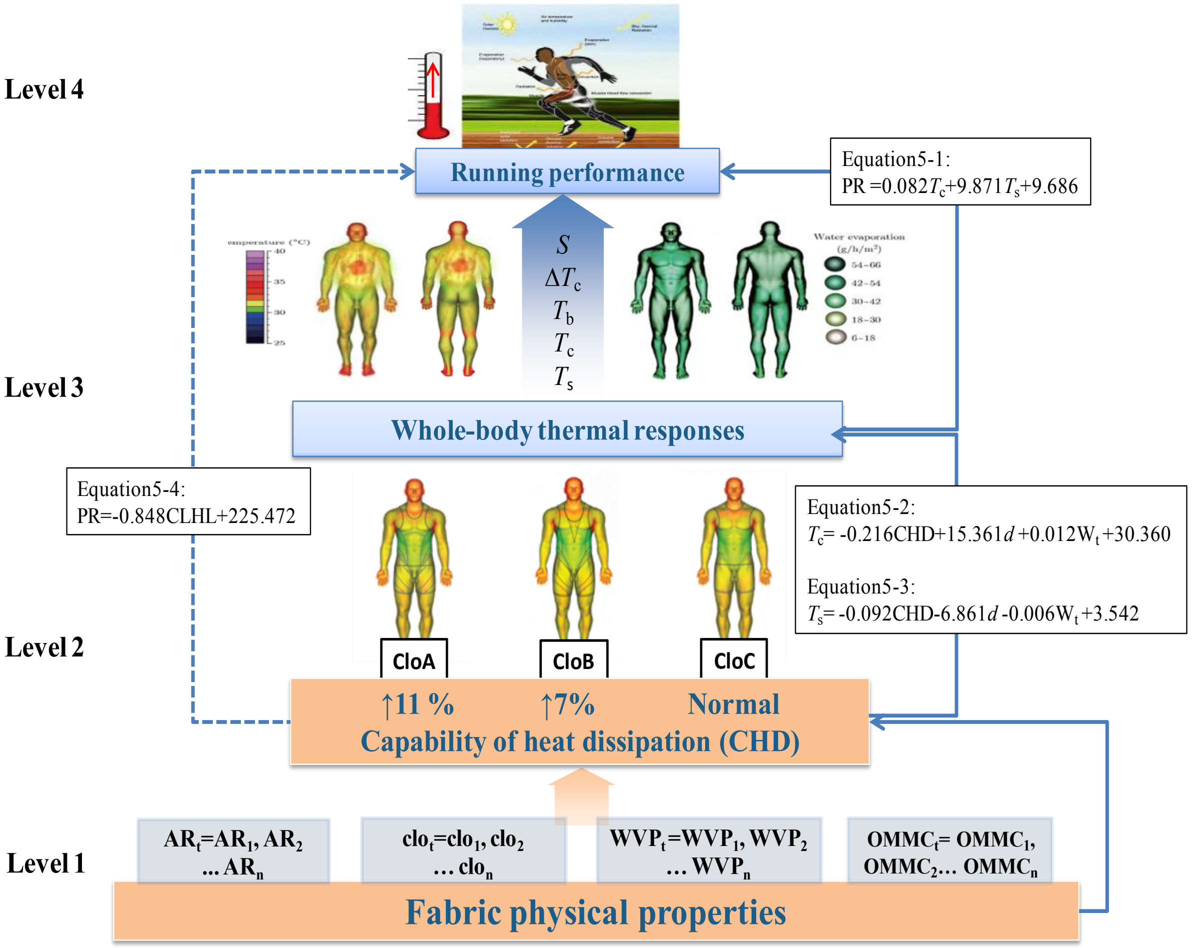


Figure 5.7 Mechanism of the clothing overall thermal functional performance on running performance under hot conditions

5.5 Conclusion

This study showed that clothing designed to increase heat dissipation induced a larger decrease of T_s, delayed the increase of T_c, T_b, and S, and subsequently increased the running performance in a hot condition. Large negative ΔT_c during rest in Phase 1 could provide a larger capacity for S and contribute to improved performance during the subsequent running performance in Phases 2 and 3.

The PR had moderate to large correlation with thermal responses (T_c, T_s, and T_b) at the beginning of Phases 1, 2, and 3. Thus, PR is affected by heat stress variations induced by different clothing properties in a hot condition.

The changes of thermal responses and PR were correlated with the physical properties of clothing ($P < 0.05$). Specifically, WVP_t and $OMMC_t$ of clothing, which affect the CLHL, have negative relationships with S, ΔT_c, and PR. The TI_t and AR_t relating to the CDHL has a positive effect on S at 30 min rest and during running performance. Besides, T_c and T_s at the time point of Running End can be predicted by the overall CHD, as well as the d and the W_t of the clothing. The PR can be directly predicted by the CLHL through the clothing.

Although the relationships between the clothing overall performances, whole-body thermal responses of athletes and running performance were investigated, the mechanism on how the mapping-designed concept with its pattern and specific fabrics affect the thermal responses and running performance need further investigation.

CHAPTER 6 EFFECTS OF LOCAL AND WHOLE-BODY THERMAL-PHYSIOLOGICAL RESPONSES ON RUNNING PERFORMANCE IN A HOT CONDITION

6.1 Introduction

As reported in Chapters 2 and 3, different skin temperature and sweating evaporation were observed during exercise, and these may have various influences on the thermal status of athletes. According to the different thermal requirements, mapping-designed clothing was developed to affect the local thermal responses, whole-body thermal responses, and running performance. In Chapter 5, the results of wear trial verified that the mapping-designed clothing affects the whole-body thermal responses and running performance in a hot condition. However, the mechanism on how the mapping-designed clothing affects the athletes' thermal responses and running performance has not been fully investigated.

In order to fulfill the fifth objectives of this study, this chapter investigated the effects of mapping-designed running clothes on local thermal responses of different body parts in a wear trial, and explored the relationships with whole-body thermal responses and running performance, with the aim of interpreting the potential mechanisms on how the mapping-designed clothing affect their local/whole-body thermal responses and running performance.

6.2 Methodology

6.2.1 Clothing

In this study, three sets of Clothing, CloA, CloB, and CloC (control group), were used in the experiments. The pattern and physical evaluation of clothing properties are presented in

Chapters 3 and Chapter 5. The fabric physical properties at each body part are presented in Table 4.2 of Chapter 4.

6.2.2 Subjects

Eight healthy male subjects who regularly trained in various sports volunteered to participate in this study. Their characteristics and the detailed requirement are presented in Chapter 5.

6.2.3 Experimental procedures and protocol

All the experimental procedures and protocol, as well as the environment conditions, are presented in Chapter 5. The experiment was conducted in the climatic chamber through four phases (Figure 5.3): Phase 1) 30 min rest in a sitting position, Phase 2) 5 min warm up at 5 $km \cdot h^{-1}$ and 45 min preloaded running at a constant speed of 70% VO_{2max}, Phase 3) 1.5 km time trial PR, and Phase 4) 60 min of passive recovery followed by a 5 min cool down [91].

6.2.4 Experimental measurements and data collection

This study mainly presents the local thermal responses of athletes while wearing the three sets of clothing respectively. The measurement items include skin temperature of the chest (T_{chest}), skin temperature of the arm (T_{arm}), skin temperature of the thigh (T_{thigh}), skin temperature of the calf (T_{calf}), relative microclimate humidity of the chest (RH_{chest}), relative microclimate humidity of the back (RH_{back}), and relative microclimate humidity of the thigh (RH_{calf}) individually. All above parameters were monitored and recorded during whole experiment. The data obtained at each key time points (i.e. Resting 0min, 30min, Running 15min, 20min, 40min, 45min and Running End) were used to be as indexes to describe the subjects' physiological states. The data collected were used to assess the relationship of physical properties and local thermal responses at each time point.

6.2.5 Statistical analysis

All statistical analyses were conducted using the SPSS package version 16.0 (SPSS, Inc., Chicago, IL, USA). The significance level was set at $P < 0.05$. The analyze method has been introduced in Chapter 5.

To explore the potential mechanism explaining the influence of the physical properties of fabric on local thermal responses and running performance, linear regression analyses were conducted based on the data of local thermal responses obtained from the wear trials at aforementioned seven time points. As a result, the equations which established from statistical analyzing results may reflect the relationships among the indices in similar protocols as the present study under the hot conditions (T_a of 30 °C, *RH* of 50%).

6.3 Results

6.3.1 Local skin temperature at chest, thigh, arm, and calf

Skin temperature at chest (T_{chest})

Figure 6.1 shows the T_{chest} while the three sets of clothing were worn during the four phases. The values were the same at the beginning of Phase 1 and then slightly increased thereafter. The slight increase at rest in Phase 1 might be explained by the heat adaptation of the human body from the natural environment during the preparation process (T_a of 25±0.2°C, *RH* of 50±2%) to a hot condition in Phase 1 (T_a of 30±0.2°C, *RH* of 50±2%). During the adaptation, CloB induced a smaller increase of T_{chest} than the other two, which indicated that the physical properties of CloB had a smaller effect on dry heat transfer at the chest. The assumption is reflected from the results of the manikin test in Table 4.4 of Chapter 4, in that the TI (in clo value) of CloB on the chest was significantly lower than that of CloA and CloC (CloA vs. CloB vs. CloC: 0.88±0.01 vs. 0.80±0.01 vs. 1.01±0.01, $P < 0.05$).

When the athletes started to run in Phase 2, the T_{chest} sharply decreased during the first 20 min and fluctuated at around 31.5 °C 20 min later in Phase 2. The three sets of clothing induced similar effects on the change of T_{chest} during the first 20 min and different influences on the fluctuation of T_{chest} 20 min later. These differences might be explained by the various abilities of clothing to evaporate sweat while running. Specifically, when the athletes began to sweat, the sweat was absorbed and evaporated via clothing. The physical properties of fabric at chest, such as WVP and OMMC, might have directly affected the efficiency of sweating evaporation and heat dissipation during evaporation, and subsequently affected the T_{chest}. The effect was essential and obvious when the RH_{chest} was near 100%.

During the 1.5 km PR in Phase 3, the T_{chest} decreased sharply, an effect which appeared to be similar among the three sets of clothing. The sharp decrease might be explained by the sudden increase of the running mode and the intensity in this phase. Due to the extreme intensity and the long duration of the run, the three sets of clothing were almost 100% wet, such that their effects on sweat evaporation and heat dissipation were similar.

When athletes stopped running, the T_{chest} increased immediately. Then when they began to walk for cool down in Phase 4, the T_{chest} decreased again. This might be explained by the blood returning from the active muscle and skin capillaries to the trunk when they stopped running and blood perfusion going toward the active muscle again while walking in the cool down period. The heat would be transferred from the limbs to the trunk with the redistribution of blood flow and thus induce the change of T_{chest}. When athletes rested for recovery in this phase, the stable increase of T_{chest} was due to sweat evaporation. Among the three sets of clothing, CloA had the fastest increase of T_{chest}. This might be explained by the slower sweat evaporation and lower heat dissipation determined by the physical properties of OMMC and WVP. The T_{chest} while wearing CloB and CloC was found to have a similar increase during the period.

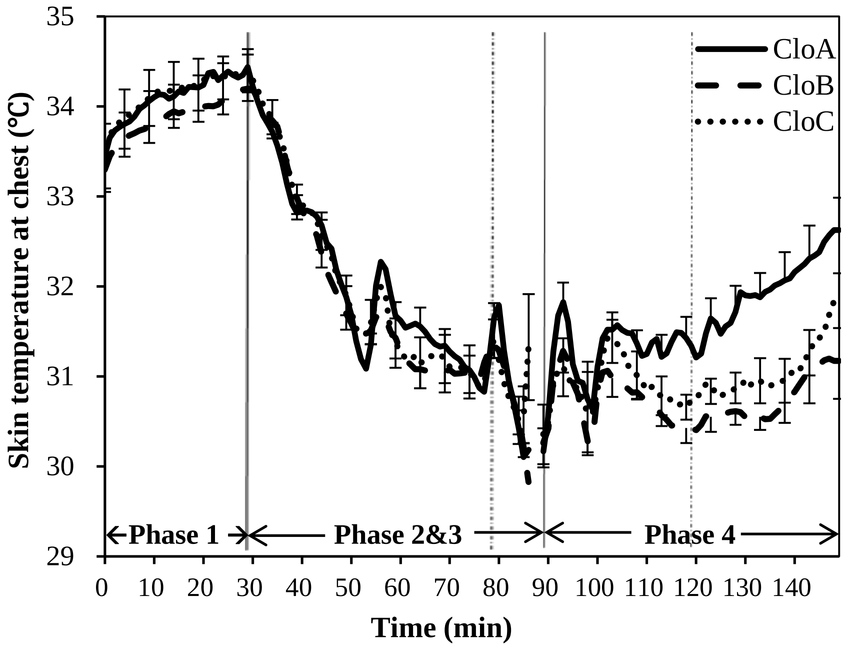


Figure 6.1 T_{chest} while wearing the three sets of clothing

Skin temperature at the thigh (T_{thigh})

Figure 6.2 shows the T_{thigh} while the three sets of clothing were worn during the four phases. The T_{thigh} of the three sets of clothing were the same at the beginning of Phase 1 and then slightly increases thereafter. As found at the chest, the slight increase at rest in Phase 1 might be explained by the heat adaptation of the human body from the natural environment during the preparation process to hot conditions. The T_{thigh} induced by the three sets of clothing was similar during the adaptation process, although there were differences in the fabrics covering the thigh. This finding indicated that the physical properties of clothing at the thigh had small effects on dry heat transfer while at rest.

When athletes started running in Phase 2, the T_{thigh} continually decreased during the first 25 min and remained stable at around 32.5 °C 20 min later in Phase 2. Among the three sets of clothing, CloA induced the largest decrease of T_{thigh} during the first 10 min, and after that CloA had a lower T_{thigh} compared to CloC. The first 10 min-decrease of T_{thigh} was due to the sweat of athletes, which heat dissipated with sweat evaporation via clothing. The lowest WVP of CloA might determine the largest decrease of T_{thigh} during the first 10 min. While the clothing absorbed the sweat and eventually evaporated, the lower OMMC of CloA and CloB might have caused the lower T_{thigh} compared to CloC. The RH_{thigh} of the three sets of clothing in Figure 6.7 could also be a reference to explain the sweat evaporation as moisture and/or liquid via clothing while running.

During the 1.5 km PR in Phase 3, there were similar decreases of T_{thigh} brought about by the three sets of clothing. The sharp decrease, which was also observed in T_{chest}, was due to the sudden increase of intensity after Phase 2. The various clo, AR, WVP, and/or OMMC of specific fabric did not result in different effects at the thigh during the extreme run.

When athletes stopped running in Phase 4, the T_{thigh} of the three sets of clothing fluctuated during the first 20 min. The responses might have the same reasons as observed in the T_{chest}. When running stopped, the blood was redistributed between active muscles, deep organs, and capillaries of the skin surface during the different levels of the run. Among the three sets of clothing, CloA induced the lowest T_{thigh} during the recovery process ($P < 0.05$). The reason might be explained by the RH_{thigh} in Figure 6.7.

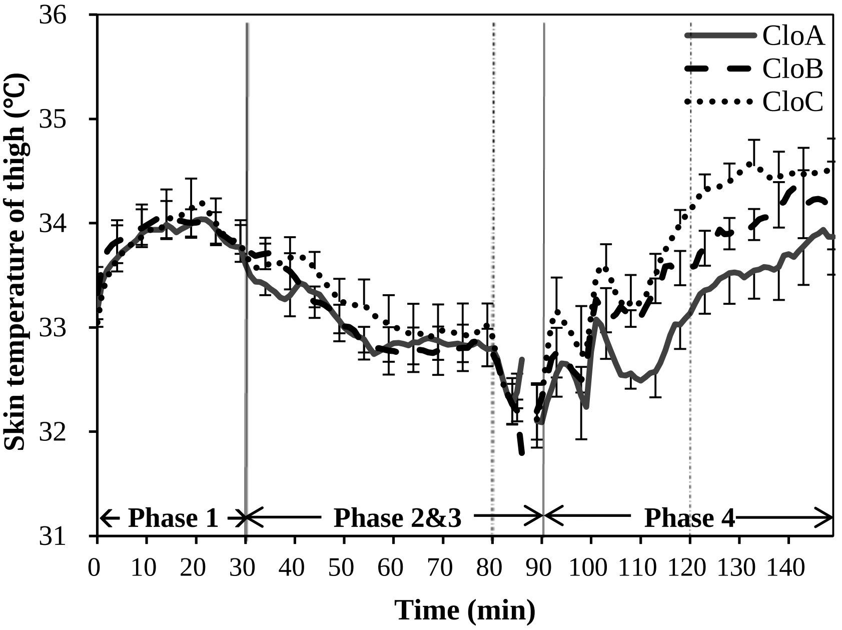


Figure 6.2 T_{thigh} while wearing the three sets of clothing

Skin temperature at the arm (T_{arm})

Figure 6.3 shows the T_{arm} while the three sets of clothing were worn during the four phases. The T_{arm} of the three sets of clothing were the same at the beginning of Phase 1 and then slightly increases to remain stable at around 20 min. This is the process of heat adaption observed by the human body for hot conditions. No significant difference was found among the three sets of clothing as there was no fabric covering the arm.

When the athletes started to run in Phase 2, the T_{arm} decreased sharply during the first 20 min and remained stable on the 25th minute in Phase 2. Among the three sets of clothing, CloA had the lowest T_{arm} and CloC showed the highest one. However, no significant difference was found among the three sets of clothing. During the 1.5 km PR in Phase 3, the three sets of clothing induced a sharp decrease of T_{arm}. However, the T_{arm} of CloA was the lowest among those induced by the other two. As one group of the most active muscles for running was at the arm, the different T_{arm} may affect the power used for running and may be related to the muscles' performance.

When athletes stopped running in Phase 4, the T_{arm} of the three sets of clothing fluctuated for about 20 min, which might be due to the blood redistribution of the active muscles. Among the three sets of clothing, no significant difference was found, although CloA seemed to have lower T_{arm} during the first 20 min of the recovery process.

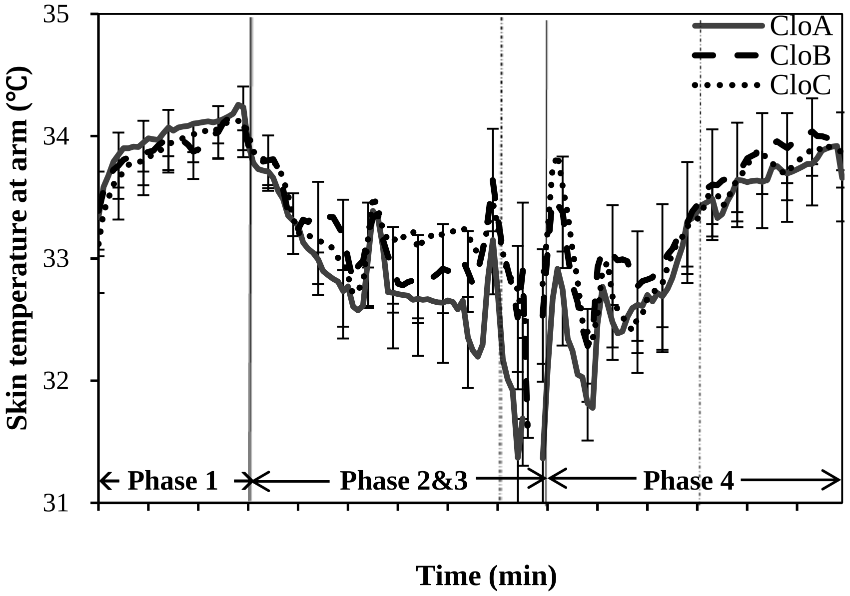


Figure 6.3 T_{arm} while wearing the three sets of clothing

Skin temperature at the calf (T_{calf})

Figure 6.4 shows the T_{calf} while the three sets of clothing were worn during the four phases. At the start of the experiment, T_{calf} slightly increased for 10 min and then remained stable on the 11th minute. The changes were similar to the local thermal responses of the other three body parts. Although there was no clothing covering the calf, the increase of T_{calf} at the beginning of experiments still existed. However, there was no difference of T_{calf} found among the three sets of clothing.

When athletes started to run, the T_{calf} increased sharply during the first 10 min and suddenly decreased during the second 10 min in Phase 2. After that, T_{calf} remained stable for 30 min while running until the 1.5 km running performance in Phase 3, where there was another sharp decrease observed for all the clothing. During the running period, no difference was found on T_{calf} induced by the three sets of clothing. No fabric covering was needed at the calf, which explains the similarity of sweat evaporation and heat dissipation while wearing different clothing. When the athletes stopped running in Phase 4, the T_{arm} increased from 32 °C to 34 °C within 5 min, which might be due to the heat transferring with the blood flow from the muscles to the capillaries of the skin surface. T_{arm} decreased to a stable status after the sharp increase because of the heat dissipation from skin surface to ambient environment. CloA showed lower T_{arm} than CloC during the last 50 min of recovery. The evident differences of T_{arm} among the sets of clothing may be explained by the blood flow from the adjacent body parts, such as chest and back, with distinguished blood temperatures due to heat conduction.

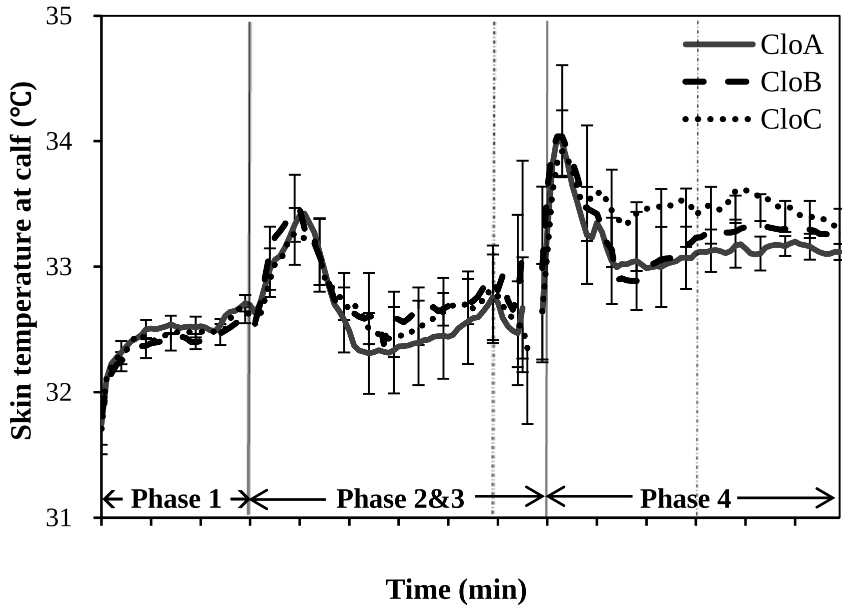


Figure 6.4 T_{calf} while wearing the three sets of clothing

6.3.2 Relative humidity at the chest, back, and thigh

Relative humidity at the chest (RH_{chest})

Figure 6.5 shows the RH_{chest} while the three sets of clothing were worn during the four phases. The RH_{chest} of the three sets of clothing were the same at the beginning of Phase 1 and remained stable at around 48%. The fluctuation of CloC during the last 10 min of rest might indicate the initial status of sweating while wearing CloC.

When athletes started to run in Phase 2, RH_{chest} increased sharply at the accumulation of sweat under the fabric. Among the three sets of clothing, RH_{chest} of CloC had the fastest increase rate and reached 100% at around 20 min of the run. Although the RH_{chest} of CloA had the lowest increase rate and did not reach 100% throughout the whole process, there was significant difference on the RH_{chest} between CloA and CloC ($P < 0.05$). The observed different RH_{chest} can be explained by the different sweat absorbing and/or transferring rates of clothing. Specifically, heat is produced by the active muscles of athletes during exercise, which increases the T_c and stimulates the sweating and blood distribution for heat dissipation. While the sweat is absorbed and/or transferred via clothing fabric for evaporation as moisture and/or liquid, heat would dissipate from the skin surface to the clothing microclimate environment and dissipated to the ambient environment of the clothing. During this process, CloA with increased WVP and OMMC would result in more sweat evaporation and heat dissipation compared with CloC. Meanwhile, the increase of RH_{chest} can explain the sharp decrease of T_{chest} during the first 20 min run in Figure 6.1.

During the recovery period in Phase 4, the RH_{chest} of CloC was maintained at 100%, but RH_{chest} of CloA decreased after the 10 min recovery. It was also due to the improved WVP and OMMC of CloA. Faster sweat evaporation of CloA from the skin surface and clothing surface to the ambient environment leads to a quicker decrease of RH_{chest} and an increase of T_{chest} compared to CloC. These clothing effects would be essential and can be used for a triathlon exercise because the faster return of RH_{chest} and T_{chest} might provide more potential to conduct thermoregulation while T_{c} increases, and more capacity for more exercises after running.

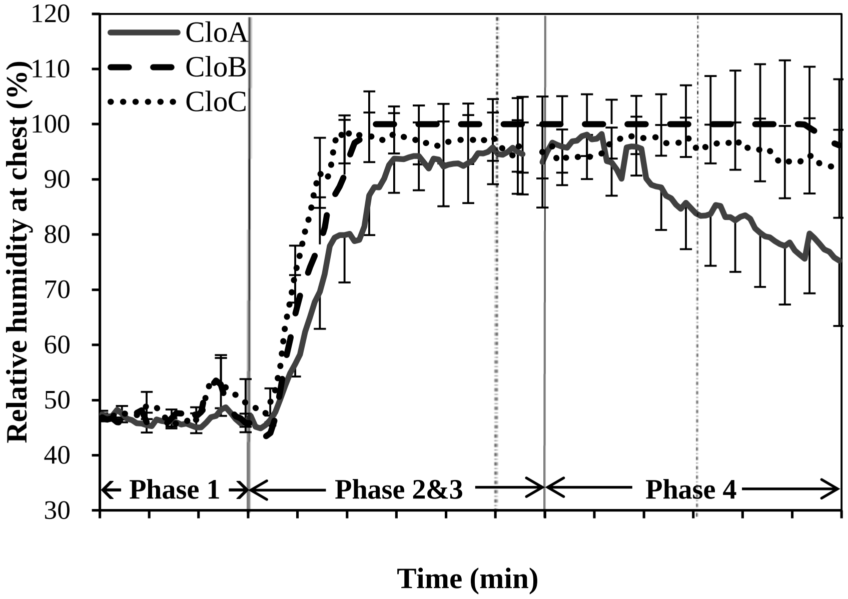


Figure 6.5 RH_{chest} while wearing the three sets of clothing

Relative humidity at the back (RH_{back})

Figure 6.6 shows the RH_{back} while the three sets of clothing were worn during the four phases. The RH_{back} of the three sets of clothing were the same at the beginning of Phase 1 and fluctuated during the 30 min rest. The large fluctuation of RH_{back} due to sweat accumulation confirmed the theory that the back is another body part with fast and high sweat rate. Regarding the effects of clothing on the RH_{back}, CloC had the tendency to initiate the higher RH_{back} ($P = 0.089$), which may be due to the relatively lower WVP than the other two.

When athletes began to run, RH_{back} increased and reached 100% at around the 15th minute of the running period in Phase 2. RH_{back} at 100% of the three sets of clothing maintained consistent until the end of the recovery period in Phase 3, except that of CloA, which began to decrease from the last 15 min of recovery. Among the three sets of clothing, CloT had the tendency to have lower *RH*back during the last 10 min of recovery in Phase 4 ($P = 0.068$). This was because CloA had the improved fabric physical properties of WVP and OMMC at the back, having faster sweat evaporation during recovery than the other two.

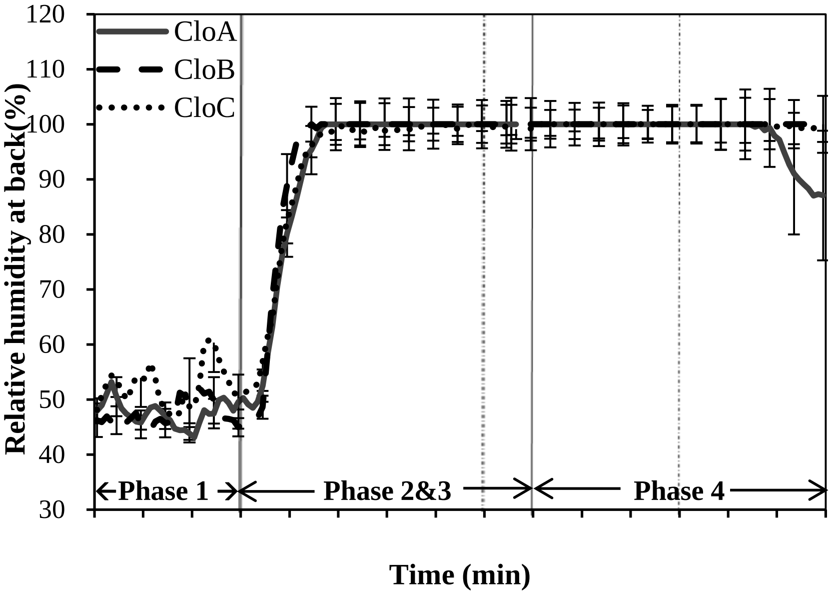


Figure 6.6 *RH*back while wearing the three sets of clothing

Relative humidity at the thigh (*RH*thigh)

Figure 6.7 shows the *RH*thigh while the three sets of clothing were worn during the four phases. The *RH*thigh of the three sets of clothing were the same at the beginning of Phase 1 and fluctuated between 45% and 50% during the 30 min rest. Among the three, CloC exhibit the largest fluctuation of *RH*thigh, which means less moisture was evaporated through CloC and there would be more sweat accumulated under the clothing during rest.

When the athletes started running in Phase 2, *RH*thigh increased sharply as the thigh began to sweat. Among the three sets of clothing, CloC induced the fastest *RH*thigh increase and reached 100% at around the 35th minute. CloA and CloB had slower *RH*thigh increase and reached a steady status at around the 30th minute, which were at 80% and 90% respectively. During the 1.5 km run in Phase 3, no significant difference on the RH_{thigh} was observed among the three sets of clothing. This might be due to the short duration of Phase 3, which lasted for only 3 to 5 min. Although the increasing intensity of the run induced sweat profusely, it was difficult to find changes in the RH_{thigh} during the short duration of the run.

During recovery, the RH_{thigh} of CloC remained at 100% until the last 20 min, but the RH_{thigh} of CloA decreased during recovery in Phase 4. At the end of the recovery, the RH_{thigh} of the three sets of clothing were at 86% for CloC, 78% for CloB, and 62% for CloA. The different responses of RH_{thigh} during running and recovery were due to the various physical properties of the fabric covering the thigh. Specifically, improved WVP and OMMC of CloA resulted in a quick transfer and evaporation of sweat to the ambient environment, and had less absorption of sweat at the inner surface of clothing. The low RH_{thigh} on CloA during the last 50 min of recovery may be due to the dissipation of heat produced from the active muscles via sweat evaporation. The effects of CloA give a faster return of RH_{thigh}. This is shown in Figure 6.7.

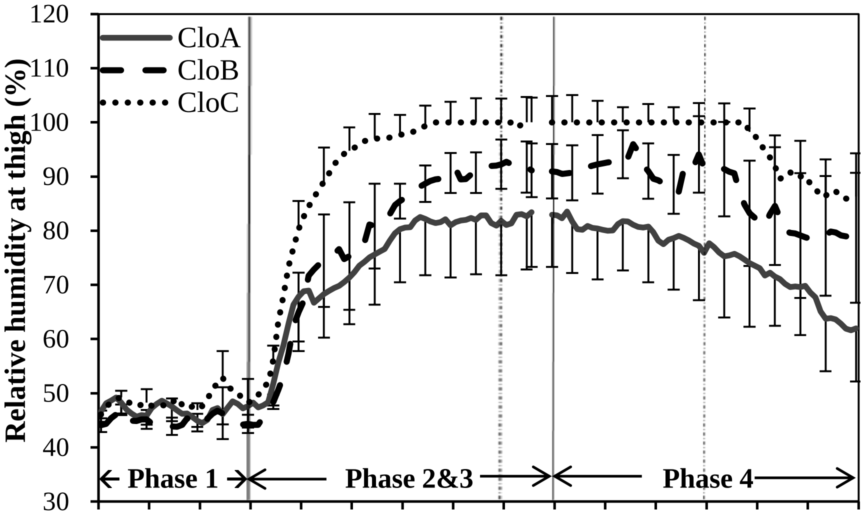


Figure 6.7 RH_{thigh} while wearing the three sets of clothing

6.3.3 Relationships between PR and local thermal responses

Table 6.1 shows the correlations and significance between PR and local thermal responses. The PR was found to be significantly correlated to the changes of RH_{chest} (ΔRH_{chest}) at 15 min running and 20 min resting 0 min ($P < 0.05$), and the changes of RH_{back} (ΔRH_{back}) at 15 min, 20 min, and 40 min running, and at 45 min resting ($P < 0.05$). It also showed that PR has the tendency to correlate with T_{arm} at 20 min running ($P = 0.06$) and with T_{chest} at 40 min running ($P = 0.07$). The results indicated that among the four body parts, T_{chest}, T_{arm}, ΔRH_{chest} and ΔRH_{back} respectively, at specified time points might have effects on the performance. Specifically, lower T_{chest} and T_{arm}, as well as smaller ΔRH_{chest} while running, were associated with shorter PR (better running performance).

In Chapter 5, we found that PR was positively correlated with T_{s} at the beginning of Phases 1 and 2, which agreed with previous studies that indicated T_{s} (alone or combined with T_{c}) is associated with increased skin blood flow and reduced cerebral blood flow. The redistribution of blood flow acts to reduce cardiac filling and elevate HR [170, 177], which may work at a greater percentage of maximal oxygen oxidation while performing an exercise at a given intensity [159] and then impair the following performance. The chest, which includes about 9.2% of the overall body skin surface [4], is the main area of sweat evaporation and contributes to a large percentage of overall T_{s}. Thus, the correlation of PR and T_{chest} found in Table 6.1 may be explained by a similar mechanism. When exercise intensity is constant, the T_{chest} at the 40 min run decreases to a steady status. The decreased T_{chest} builds the gradient between the T_{c} and the T_{chest}, providing a larger potential for the increase of skin blood flow while running and perhaps less impairment to the performance. Thus, the lower T_{chest} while running might be correlated to lower skin blood flow and higher capacity of performance.

The T_{arm}, having a similar pattern as T_{chest} while running, would induce similar effects on the skin blood flow. The muscles in the arm are part of the group of dynamic muscles in the body while running. Heat produced from the muscle would bring blood flow to the core and skin surface, a process associated with heat dissipation and performance. Specifically, the lower T_{arm} would have a larger gradient for heat transfer from the core and muscle to the skin surface, so that more heat would be dissipated. The larger heat dissipation and lower T_{arm} benefit the continuing performance of the arm muscles, and subsequently affect running performance.

The ΔRH_{chest} and ΔRH_{back} while running reflect the increase of sweat absorption from the skin surface to the inner surface of clothing. The amount of sweat produced, determined by exercise intensity and T_c, is relatively constant. Thus, the lower increase of RH_{chest} and RH_{back} (smaller ΔRH_{chest} and ΔRH_{back}) mean higher sweat evaporation from the chest and the back. Higher sweat evaporation would result in a higher heat dissipation and lower heat storage (S) while running, which all resulted in a shorter PR (higher running performance). This may be a result of the significant correlation between PR and ΔRH_{chest} and ΔRH_{back} while at a constant run in Phase 2 before the 1.5 km performance in Phase 3.

Table 6.1 Relationships between PR and local thermal responses

	Running 15min		Running 20min			Running 40min		Running 45min
R value	ΔRH_{chest}	ΔRH_{back}	T_{arm}	ΔRH_{chest}	ΔRH_{back}	T_{chest}	ΔRH_{back}	ΔRH_{back}
PR	0.52^*	0.47^*	$0.41^†$	0.53^*	0.46^*	$0.38^†$	$0.39^†$	$0.39^†$

*: $P < 0.05$; †: $0.05 < P < 0.1$, the different was tend to be significant

ΔRH_{chest} equals to the RH_{chest} at specific time point minus RH_{chest} at Resting 0 min.

ΔRH_{back} equals to the RH_{back} at specific time point minus RH_{back} at Resting 0 min.

The relationships between the whole-body thermal responses (i.e. T_c and T_s) and the local thermal responses are expressed in Equation 6-1 (R = 0.799, $P < 0.05$) and Equation 4-23 (as shown in Section 4.5.2 of Chapter 4):

$$T_c = 0.022RH_{back} - 0.215T_{thigh} - 0.007RH_{thigh} + 0.145T_{calf} - 0.064T_{arm} + 40.805 \quad (6\text{-}1)$$

where T_c is the core temperature (in °C), RH_{back} is the relative microclimate humidity of the back (in %), T_{thigh} is the skin temperature of the thigh (in °C), RH_{thigh} is the relative microclimate humidity of the thigh (in %), T_{calf} is the skin temperature of the calf (in °C), and T_{arm} is the skin temperature of the arm (in °C).

$$T_s = 0.2(T_{thigh} + T_{calf}) + 0.3(T_{chest} + T_{arm}) \quad (4\text{-}23)$$

where T_s is the mean skin temperature (in °C), T_{thigh} is the skin temperature of the thigh (in °C), T_{calf} is the skin temperature of the calf (in °C), T_{chest} is the skin temperature of the chest (in °C), and T_{arm} is the skin temperature of the arm (in °C).

To sum up, the PR can be predicted by the local thermal responses based on Equation 5-1, 6-1 and 4-23, which were shown in Equation 6-2:

$$\text{PR}=2.9613T_{chest}+2.9561T_{arm}+1.9566T_{thigh}+1.9861T_{calf}+0.001804RH_{back}-0.000574RH_{thigh}+13.032 \quad (6\text{-}2)$$

where PR is the time of running performance (in s), T_{chest} is the skin temperature of the chest (in °C), T_{arm} is the skin temperature of the arm (in °C), T_{thigh} is the skin temperature of the thigh (in °C), T_{calf} is the skin temperature of the calf (in °C), and RH_{back} is the relative microclimate humidity of the back (in %), RH_{thigh} is the relative microclimate humidity of the thigh (in %).

6.3.4 Relationships between fabric physical properties and local thermal responses

The relationships between the physical properties of the fabric and the local thermal responses are shown in Table 6.2. The WVP of the fabric at the chest tended to exhibit negative correlation with RH_{chest} at Running 15 min and 20 min. During recovery, more correlations were observed between the fabric properties and the local thermal responses. As shown in Table 6.2, the WVP of the fabric at the chest show negative correlation with RH_{chest} at Recovery 30 min and 60 min ($P < 0.05$). This result indicates that the higher WVP of CloA at the chest can lead to a lower RH_{chest} when CloA is worn, compared with the other two clothing (as shown in Figure 6.5). The relationships can be explained by the definition of WVP, which is the ability for water vapor dissipation through fabrics. When athletes began to recover, the higher WVP of the fabric covering the chest resulted in larger amounts of sweat evaporation and decreased the amount of sweat accumulating between the skin surface and the inner surface of the clothing.

The WVP of the fabric at the chest also was also positively correlated with T_{chest} at Recovery 30 min and 60 min time points ($P < 0.05$). This result can be explained by the change in RH_{chest} during the recovery period. As shown in Figure 6.5, the reduced RH_{chest} during recovery indicates sweat evaporation from the skin surface to the ambient environment through the fabric. A faster decrease in RH_{chest} indicates faster drying of the skin surface, which is associated with an increase in T_{chest}. Thus, higher WVP correlates with lower RH_{chest} and higher T_{chest}.

The WVP at a specified body part is also negatively correlated with RH_{thigh} and RH_{back} at Recovery 30 min and 60 min, respectively. These results are similar to the mechanisms observed in the chest, wherein higher WVP induced faster sweat evaporation, leading to lower sweat accumulation on the skin surface of the thigh and the back.

The values of clo and AR tended to have positive correlations with RH_{chest} (%) and T_{thigh} at Running 15 min and 20 min. AR also tended to show positive correlation with T_{chest} at Recovery 30 min and 60 min as well as with RH_{back} at Recovery 60 min. The observed relationships may be explained by the effects of clo and AR on heat loss ability, which can influence skin temperature and *RH* in specific body parts.

Table 6.2 Relationships between fabric physical properties and local thermal responses

	R value	WVP	OMMC	clo	AR
Running 15min	RH_{chest} (%)	$-0.41^{\dagger}$		$0.39^{\dagger}$	$0.42^{\dagger}$
Running 20min	T_{thigh} (°C)			$0.38^{\dagger}$	$0.40^{\dagger}$
	RH_{chest} (%)	$-0.39^{\dagger}$			
Running End	RH_{chest} (%)		$0.39^{\dagger}$		
Recovery 30min	T_{chest} (°C)	0.55^{*}			$0.35^{\dagger}$
	RH_{chest} (%)	-0.56^{*}			
	RH_{thigh} (%)	$-0.44^{\dagger}$			
Recovery 60min	T_{chest} (°C)	0.67^{*}			$0.36^{\dagger}$
	RH_{chest} (%)	-0.51^{*}			
	RH_{back} (%)	-0.47^{*}			$0.41^{\dagger}$

*: $P < 0.05$; †: tend to be significant, $0.05 < P < 0.1$.
WVP: water vapor permeability ($\text{g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$); OMMC: overall moisture management capacity [9, 81]; AR: air resistance ($\text{KPa.s}\cdot\text{m}^{-1}$)

6.4 Discussion

6.4.1 Relationships between fabric physical properties and local thermal responses

Regarding the relationship between the local responses and the whole-body thermal responses, sweat loss from each body part can be calculated to determine whole-body sweat loss. Sweat evaporation depends on the surface area of the human body as well as the gradient between the saturated vapor pressure of the skin and the ambient vapor pressure [148]. Changes in skin temperature due to sweat loss from each body part affect T_s, because T_s is positively correlated to certain body parts [151]. T_s gradient, environmental temperature, and humidity determine heat loss and affect *HS* and T_c [160]. Alone or combined with T_c (T_s + T_c), T_s affects blood circulation [1] as well as the skeletal muscle and cardiovascular functions. Studies also suggested that cooling of specific body parts could vasoconstrict the underlying resistance vessels over the overall vascular conductance. The local effects of temperature are among the overall cutaneous vascular responses to environmental heating [97]. These thermal responses are essential factors that determine running performance. Thus, it is essential to consider the thermal demands of specified body part in different exercise statues, combined with overall thermal and moisture requirement of whole body.

Mapping-designed clothing was developed according to the thermal requirements for each function zone of the human body. To meet the requirements for a specific body part, fabrics with different physical properties were selected, affecting local thermal responses (discussed in Chapter 3). The relationships between the local thermal responses and the physical properties of fabrics covering a specific body part (presented in Table 6.1) were investigated. The results indicated that the mechanism of the effects of the physical properties of various fabrics vary according to the exercise status, that is, running and recovery.

During running, clo and AR of the fabric covering the chest and the thigh tended to correlate positively with the RH_{chest} and T_{thigh} (at $0.05 < P < 0.1$, as shown in Table 6.2). A large amount of heat is dissipated from the skin surface, especially the chest, transferring from the clothing to the environment. The clo and AR values of a specific body part mainly affect heat transfer from the skin–clothing microenvironment to the outer environment by convection and conduction, respectively. Thus, lower clo and AR in the fabric lead to increased heat dissipation and reduced heat accumulation in the micro-environment, as well as reduced increase rate in temperature on the skin surface. These findings induce decreases in skin temperature and RH.

The WVP of the fabrics covering the chest tended to be negatively correlated with RH_{chest} during running. The WVP mainly determines the moisture transfer ability from the inner to the outer surface of the fabric, which is related to sweat evaporation from the skin. The negative correlation between the WVP and RH_{chest} verified the effects of WVP on moisture evaporation during running. When sweating was initiated, the lower WVP of the fabric at the chest resulted in less sweat vapor transfer, and more sweat accumulated on the skin–clothing micro-environment, as indicated by a higher RH_{chest}.

After running, sweat accumulates on the skin surface, leading to very low skin temperature and *RH* around 100% in certain body parts. The athletes often felt wet and the clothing stuck on their bodies under these conditions and felt cold when the skin temperature remained low because of sweat accumulation and heat dissipation. To enhance the level of comfort among athletes, a quick-drying clothing is essential. The fabrics were required to cover specific body parts to induce quick sweat evaporation and efficient heat dissipation. The results of the present study confirmed the effects of the physical properties of the fabric on the local thermal responses of certain body parts, that is, T_{chest}, RH_{chest}, RH_{thigh}, and RH_{back}. Higher WVP indicated enhanced ability for moisture vapor transfer to the outer surface of the clothing and reduced sweat moisture in the skin–clothing environment. The effects led to a faster decrease in *RH* and resulted in a quick return of skin temperature to normal temperature before running. The mechanism can be used to explain the relationship between the WVP and the local thermal responses observed. With the same mechanism, the lower AR at the chest, which was related to higher ability for heat transfer through the fabrics, induced decreased heat accumulation on the skin surface and resulted in lower T_{chest}.

6.4.2 Potential mechanisms of the mapping-designed clothing on thermal responses and running performance

Figure 6.8 shows the theoretical framework of the mapping-designed clothing, as well as the relationships of the clothing with thermal responses and running performance. The theoretical mechanisms underlying them were discussed according to four levels listed below:

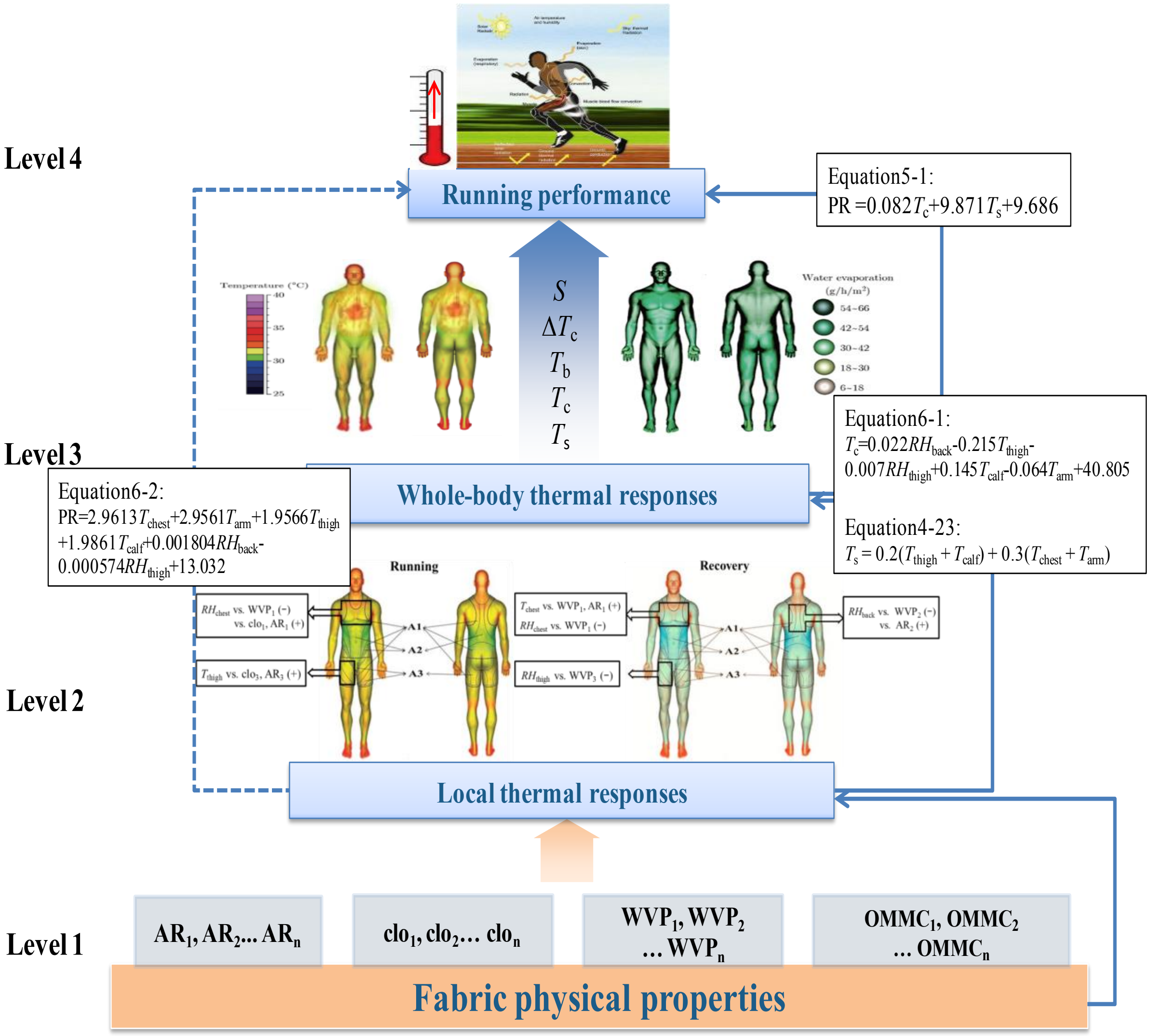


Figure 6.8 Theoretical framework of the mapping-designed clothing and running performance under hot conditions

1) Level 1 represents the physical properties of the fabric, including the thermal and moisture transport properties (i.e., AR, clo, WVP, and OMMC). Each fabric exhibits specific properties and can exert different efforts of whole clothing according to the covering area and proportion. Fabric 1 includes AR_1, clo_1, WVP_1, and $OMMC_1$ properties; fabric 2 includes AR_2, clo_2, WVP_2, and $OMMC_2$…; and fabric n includes AR_n, clo_n, WVP_n, and $OMMC_n$ (summarized in Chapter 4).

2) Level 2 is the mapping-designed clothing fashioned according to the thermal requirement for each body segment and manufactured using different fabrics that cover specific body

parts. As discussed in Chapter 3, the chest and back, which have the largest body or skin surface areas with high *SW* and changes in skin temperature, require enhanced sweat evaporation and heat dissipation during running. The fabrics covering these parts are expected to have higher WVP and OMMC as well as lower AR and clo, resulting in lower local skin temperature and relative humidity during running. Given that the clothing was manufactured with fabrics 1, 2,… and n, the physical properties of the entire clothing were estimated by each fabric and summarized as overall clothing performance (i.e., AR_t, clo_t, WVP_t, and $OMMC_t$). These physical properties can estimate capabilities for dry heat loss (CDHL), capabilities for latent heat loss (CLHL), and capabilities for heat dissipation (CHD) of the clothing when worn by a standard human body under a given condition (introduced in Chapter 3).

3) Level 3 illustrates the effects of heat dissipation process of the whole clothing on the thermal responses of the whole body by altering the local sweat status and blood flow during running. Such thermal responses influenced by clothing include core temperature (T_c in °C), mean skin temperature (T_s in °C), thermal performance capacity (*TPC* in °C), change of core temperature (ΔT_c in °C); heat storage (S in $W \cdot m^{-2}$) (presented in Chapters 5). The improved properties alter T_s and delay increase in T_c, which concurrently affects T_b and S. Besides, the local thermal responses which determined by clothing localized design can predicted some of the whole-body thermal responses (as shown in Equation 6-1 and 4-23). The aforementioned these thermal responses are considered critical determinants of running performance under hot conditions.

4) Level 4 demonstrates how running performance is associated with the whole-body thermal responses (connected to Level 3), which are affected by heat dissipation. The potential for continuous muscular activity increases with a relatively low body temperature. The capacity to improve running performance is enhanced because of efficient heat dissipation

and delayed increase in heat stress (presented in Chapters 5).

These mechanisms identified from the experimental findings may be further explained by the theoretical models on human thermoregulation such as Stolwijk's 25-node thermoregulatory model as shown in Figure 6.9 [126]. In the model, the whole human body was divided into six segments, including head, trunk, arms, hands, legs, and feet, while each segment consists of four layers, including core, skin, fat and muscle.

During various exercise, each body part has various levels of muscles activities, which could result in different levels of heat generation and sweating rate on the skin surface. For example, the legs and arms as the main dynamical parts would have high heat production and may induce high skin temperature, which raised blood transfer from muscles to skin surface for heat dissipation, and heat transfer to the other body parts via local blood flow. Some heat would be dissipated from skin surface by sweat evaporation, and the other proportion would be transferred to the body core by blood circulation and conduction. The larger amount of heat could be dissipated, the smaller heat would be stored in the body (S) and result in slower increases of T_c.

As the S and T_c increase, the skin temperature would increase, which would lead to higher sweat rate at these body parts for heat dissipation. The clothing covered on these body parts has critical influence on both the dry heat and latent heat dissipations on the skin surfaces of the specific local areas. The structural and thermal properties of the fabrics covering the local areas directly influence the heat and moisture transfer processes at the local boundaries, which has direct impact on the S and temperature of each segment. The amount of heat generated in local muscle activities and disseminated through clothing and air would subsequently be transferred to the brain and the whole body through the circulation of blood with the central core of the body (i.e. heart). Thus, the temperature at the brain, the perception of thermal comfort and thermal stress level would be affected accordingly as shown in Figure 5.1. As the results, the running performance would be affected due to the changes in the T_c and the thermal performance capacity of human body, as shown in the Equations 5-1, 6-1 and 4-23. These findings can be used for further investigation.

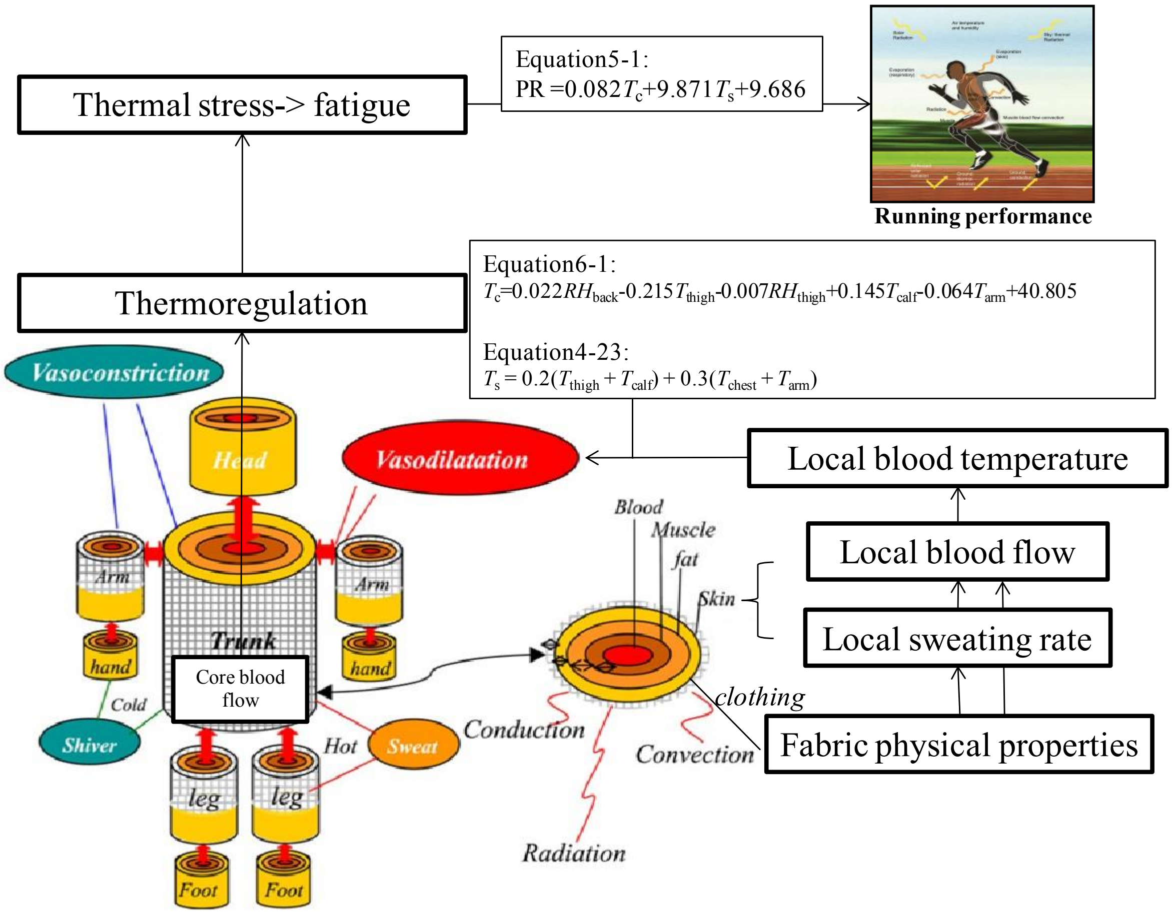


Figure 6.9 25-node model of human body

Revised base on the source: Mao AH, Li Y, Luo XN, Wang RM, Wang SX. A CAD system for multi-style thermal functional design of clothing. *Computer-Aided Design.* 2008;40(9):916-930.

6.5 Conclusion

This chapter investigated the effects of mapping-designed clothing on local thermal responses. Significant differences in skin temperature and *RH* were found at the chest, back, and thigh during the constant run in Phase 2, as well as during the 60 min recovery in Phase 4. No difference in local thermal responses was found during the 1.5 km run in Phase 3, which may be due to the extreme intensity and short duration of the run, providing a short time to determine the distinction of the thermal responses of the different clothing. However, some local thermal responses while running, T_{chest} for example, for 45 min, and ΔRH_{back} at 15 min, 20 min, 40 min, and 45 min of the run, were shown to have a relationship with the athletes' running performance. Besides, the local thermal responses which determined by clothing localized design can predicted some of the whole-body thermal responses. The findings could not only be used as reference for further design optimization of running clothes, but may be used for sports training strategies and competitions under hot conditions.

After verifying the local/whole-body thermal responses induced by mapping-designed clothing and its relationship with running performance in these two chapters (Chapter 5 and 6), what follows is a further investigation on the subjective sensations and wearing comfort of the clothing.

CHAPTER 7 EFFECTS OF CLOTHING ON SUBJECTIVE SENSATIONS AND WEARING COMFORT IN A HOT CONDITION

7.1 Introduction

The trend in designing clothes these days is comfort. Being “comfortable” in the clothes people wear ensures a state of sensory efficiency from their skin to their brain. This brings about a subjective perception of the clothing they wear [93, 195]. The physical properties of fabric such as surface structure, WVP, and AR strongly affect wearing comfort [93, 108]. Mapping-designed clothing aim to optimize the fabric physical properties to improve athletes’ performance and wearing comfort. In Chapters 5 and 6, wear trials were conducted to verify the effects of clothing designed on thermal-physiological responses and running performance. The wearing comfort of the clothing will be investigated in this chapter.

As summarized in Chapter 2, researchers have attempted to explain the relationship between wearing comfort and clothing. Previous studies on comfort focused mainly on the sensation at the static state of the subjects. Few studies explored the trend of comfort sensation during different statuses, especially the sensations in a hot condition using a protocol that includes sub-maximal steady-state running followed by an all-out sprint. Additionally, how these subjective sensations can be used to identify sensory factors and to predict overall wearing comfort during such a protocol is still unknown.

Therefore, in order to fulfill the sixth objective of this study, this chapter investigated the effects of mapping-designed running clothes on different subjective sensations and wearing comfort of athletes in a hot condition. The chapter also explored the relationship of clothing properties and each sensory factor at different time points.

7.2 Methodology

7.2.1 Wear trials

The environment, participants, experimental protocol, and measurements have been described in Chapter 2 (see Section 2.4). The three sets of clothing were the same used in Chapters 5 and 6. The subjective sensations at five different time points were examined through a questionnaire. The time points include: 1) Resting 0 min, 2) Resting 30 min, 3) Running End, 4) Recovery 30 min, and 5) Recovery 60 min. The subjective sensations include Clammy-Dry, Sticky-Smooth, Damp-Dry, Heavy-Light, Scratchy-Smooth, Prickly-Smooth, Rough-Smooth, Itchy-Smooth, Soft-Stiff, Cool-Hot, Breathable-Airtight, Loose-Snug fit, Allow movement-Don’t allow movement, and Overall Comfortable-Uncomfortable, all standardized ranging from 1 to 7.

7.2.2 Statistical analysis

a. To examine the differences on subjective sensations induced by the three sets of clothing, the raw data of the questionnaire were analyzed by ANOVA analysis with repeated measurement between the three sets of clothing. When a significant difference was observed, Tukey’s post hoc test was performed to examine the pairwise comparison. The significant level was set at $P < 0.05$ and data were presented in the format of mean ± SEM.
b. The linear regression analysis was used to explore the relationships between each sensation and Comfortable-Uncomfortable sensation, and to predict the Comfortable-Uncomfortable sensation at different time points.
c. Due to the similar mechanism of sensations, cluster analysis and factor analysis were used to classify the 14 sensations into a few factors to reduce the variables at each time point. The Varimax with Kaiser Normalization rotation method was applied to assess the

proportion of each sensation contributing to the overall wearing comfort.

d. Bivariate correlation analysis between clothing properties and each sensory factor obtained from factor analysis was applied to explore the relationship between them at different time points.

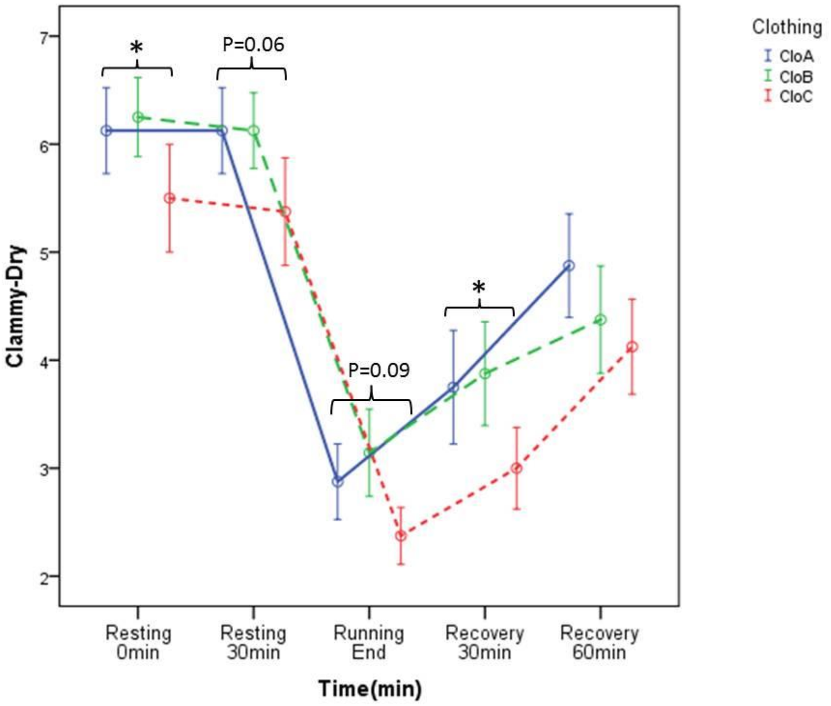
7.3 Results and Discussion

7.3.1 Subjective sensations of three sets of clothing at five time points

A total of 14 subjective sensations of three sets of clothing at each time point are summarized in Figure 7.1 to Figure 7.14 respectively.

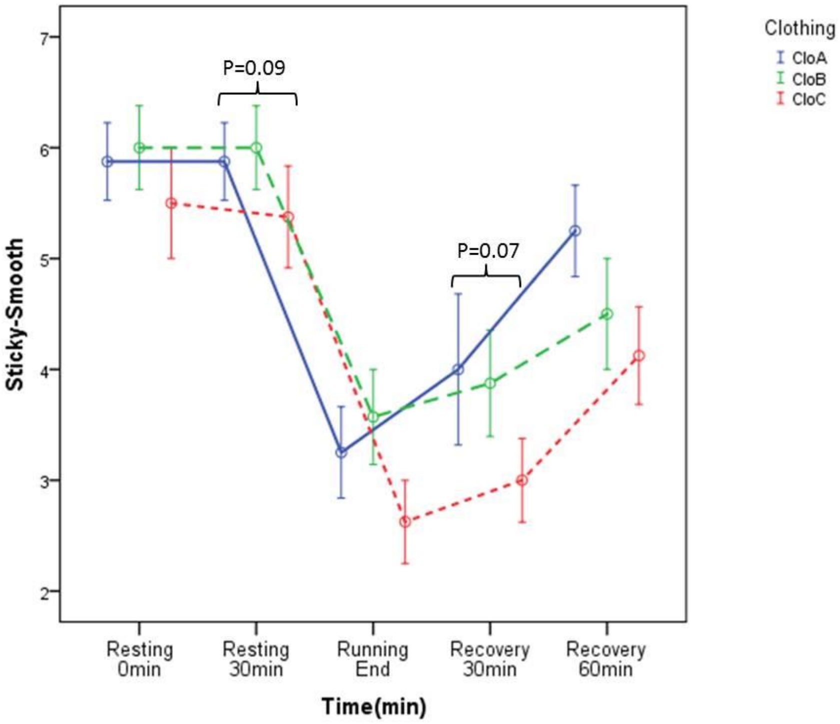
The Clammy-Dry sensation of the three sets of clothing is summarized in Figure 7.1. CloA and CloB had significantly higher value of Clammy-Dry sensation ($P < 0.05$) at Resting 0 min time point, and had the tendency to be higher at Resting 30 min time point ($P = 0.06$) compared with CloC. It indicated that participants were clammier wearing CloC compared with the other two sets of clothing while resting. The clammy sensation decreased sharply at the start of the participants' run and started to increase at the end. This may due to the sweat of the participants while running and the sweating evaporation after the run respectively. At the time points of Running End, Recovery 30 min, and Recovery 60 min, CloC showed the lowest clammy sensation of all sets of clothing. Participants were clammier while wearing CloC, not only while resting, but also while running and during the recovery period, which may be due to the fabric material of CloC.

The sensations of Sticky-Smooth, Damp-Dry, and Heavy-Light, as shown in Figures 7.2, 7.3, and 7.4, respectively, individually had similar patterns of changes as Clammy-Dry sensation during the whole experiment (Figure 7.1).



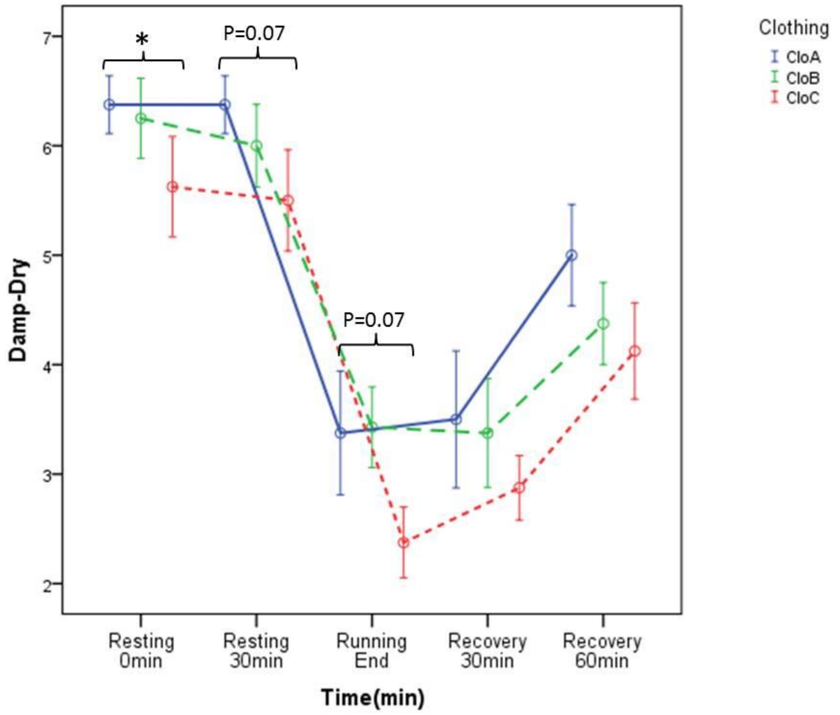
*: $P < 0.05$

Figure 7.1 Summary of Clammy-Dry sensation of the three sets of clothing



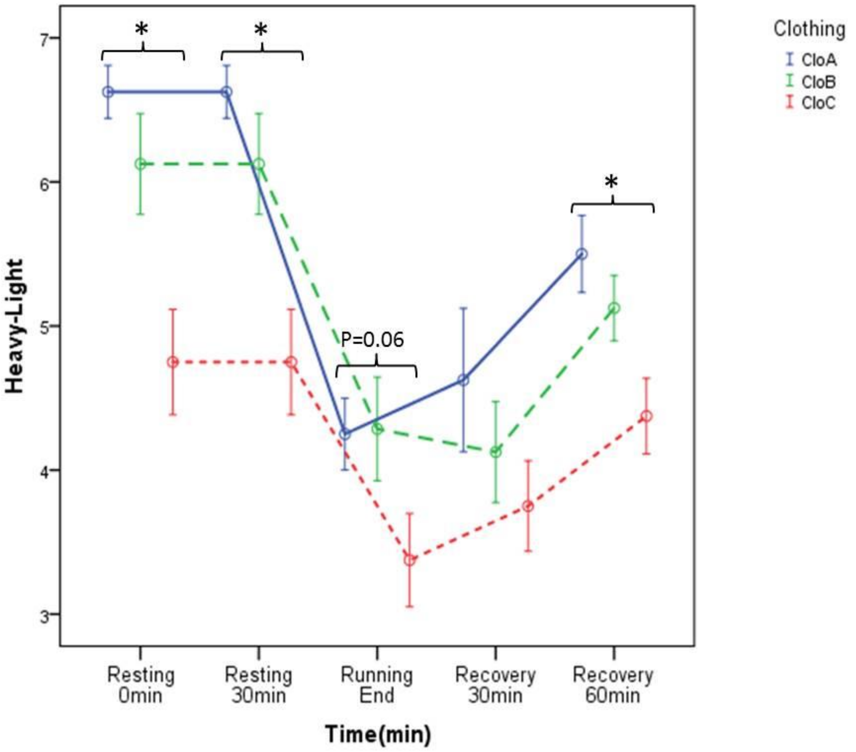
*: $P < 0.05$

Figure 7.2 Summary of Sticky-Smooth sensation of three clothing



*: $P < 0.05$

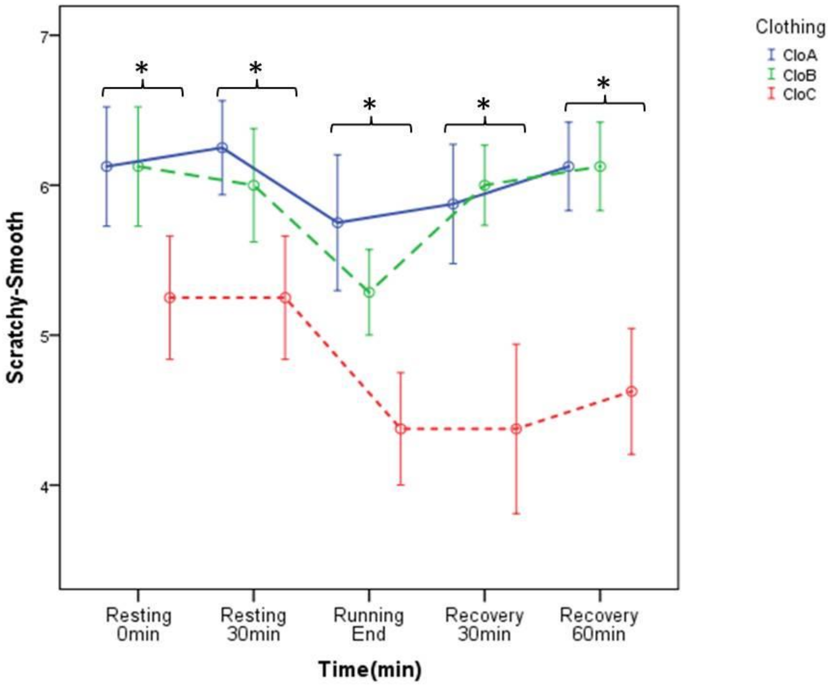
Figure 7.3 Summary of Damp-Dry sensation of three clothing



*: $P < 0.05$

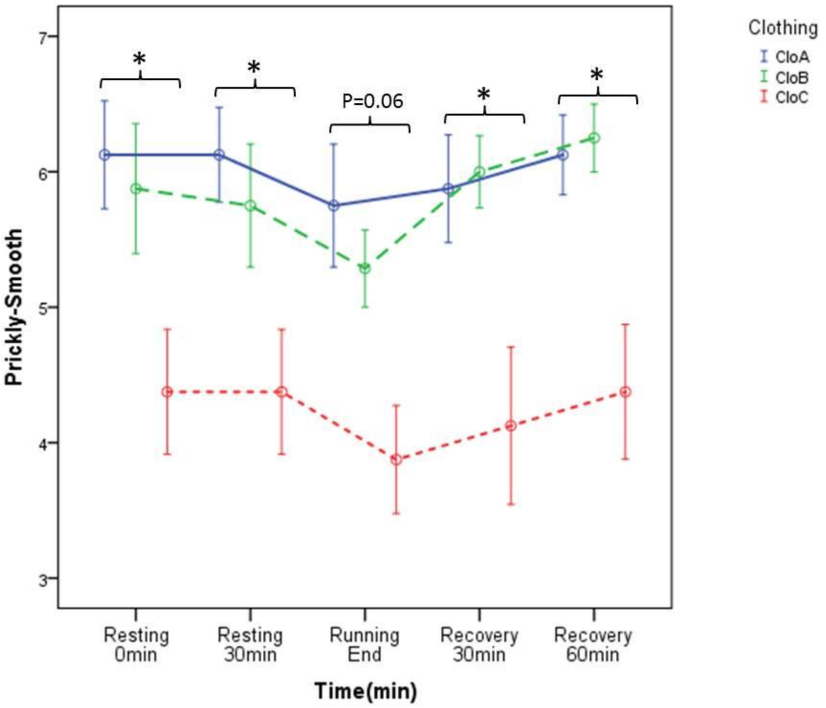
Figure 7.4 Summary of Heavy-Light sensation of three clothing

Figure 7.5 demonstrates the changes of the Scratchy-Smooth sensation during the whole experiment. The Scratchy-Smooth sensations of the three sets of clothing remained stable at the Resting 0 min and Resting 30 min time points, and decreased at Running End. During the recovery period, the Scratchy-Smooth sensation of CloA and CloC showed only a slight increase, which differed from the pattern of CloB. This might be due to the distinct sweat absorption and evaporative rates while wearing different kinds of clothing. When the participants began to run, the sweat made the clothing clammy and sticky to the skin, which may have increased the friction force between skin and clothes. The deposition of electrolyte on the skin and clothing after sweat evaporation will make the clothing rough, subsequently affecting the touch sensation, including Scratchy-Smooth, Tough-Smooth, Prickly-Smooth. Another possibility is that the sensibility of skin might be altered after running and sweating. Among the three sets of clothing, the CloC showed the lowest smooth sensation at each time point ($P < 0.05$).



*: $P < 0.05$

Figure 7.5 Summary of Scratchy-Smooth sensation of the three sets of clothing



*: $P < 0.05$

Figure 7.6 Summary of Prickly-Smooth sensation of three clothing

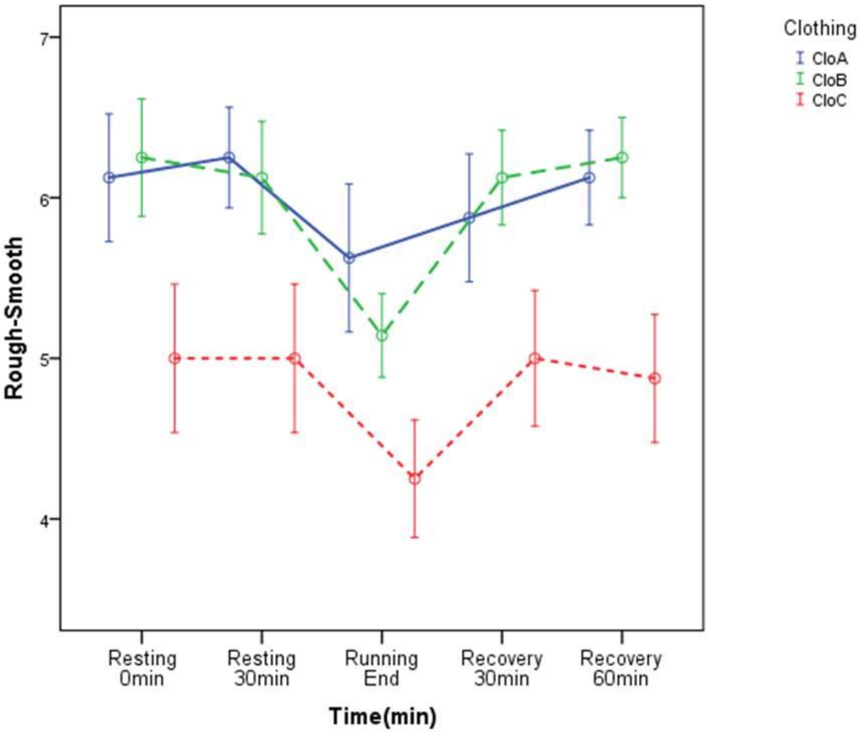


Figure 7.7 Summary of Rough-Smooth sensation of three clothing

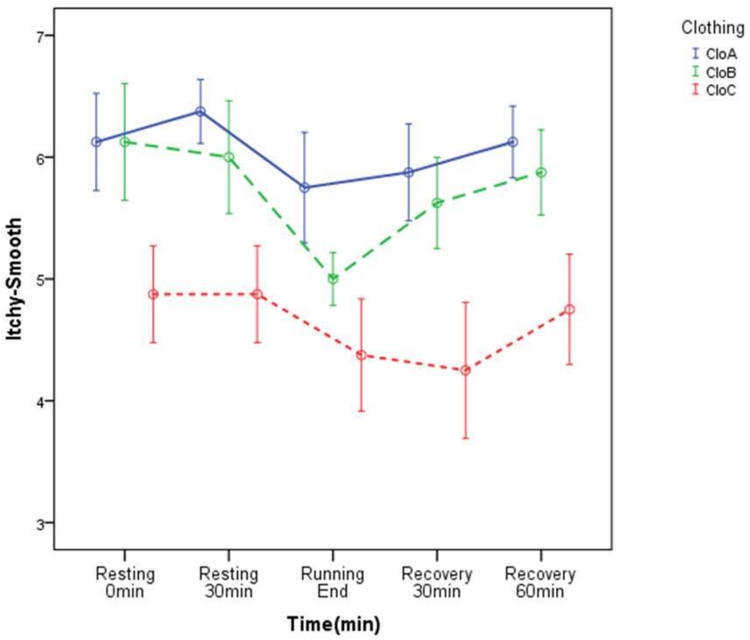
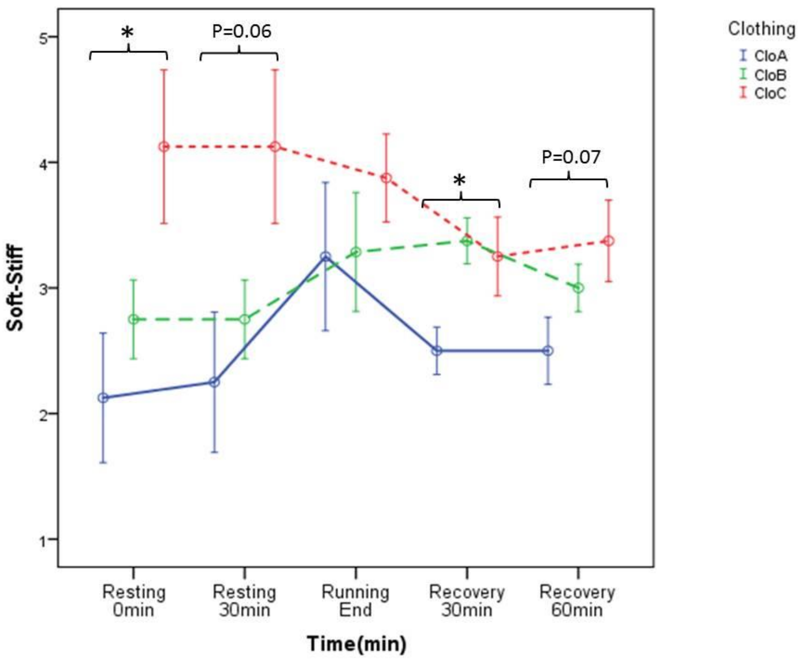


Figure 7.8 Summary of Itchy-Smooth sensation of three clothing

Similar patterns were also found on the Prickly-Smooth, Rough-Smooth and Itchy-Smooth sensations (Figure 7.6 to Figure 7.8 respectively).

The Soft-Stiff sensation of the three sets of clothing is summarized in Figure 7.9. At the Resting 0 min time point, CloC significantly showed the highest stiff sensation ($P < 0.05$) and had the tendency to be higher at the Resting 30 min time point ($P = 0.06$) compared with CloA and CloB. The stiff sensation of CloA and CloB increased at the start of the participants' run while the sensation of CloC decreased at the same time point. After running, the CloA and CloC had decreased stiff sensation and stayed stable during the recovery period. This indicated that the different clothing designs might have significant effects on the Soft-Stiff sensation at different statuses ($P < 0.05$).



*: $P < 0.05$

Figure 7.9 Summary of Soft-Stiff sensation of the three sets of clothing

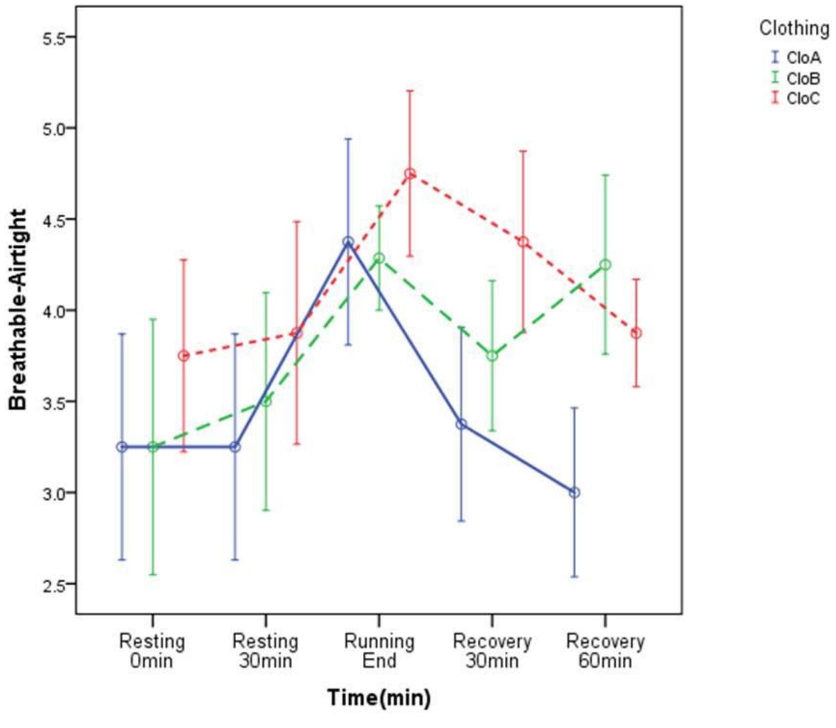


Figure 7.10 Summary of Breathable-Airtight sensation of the three sets of clothing

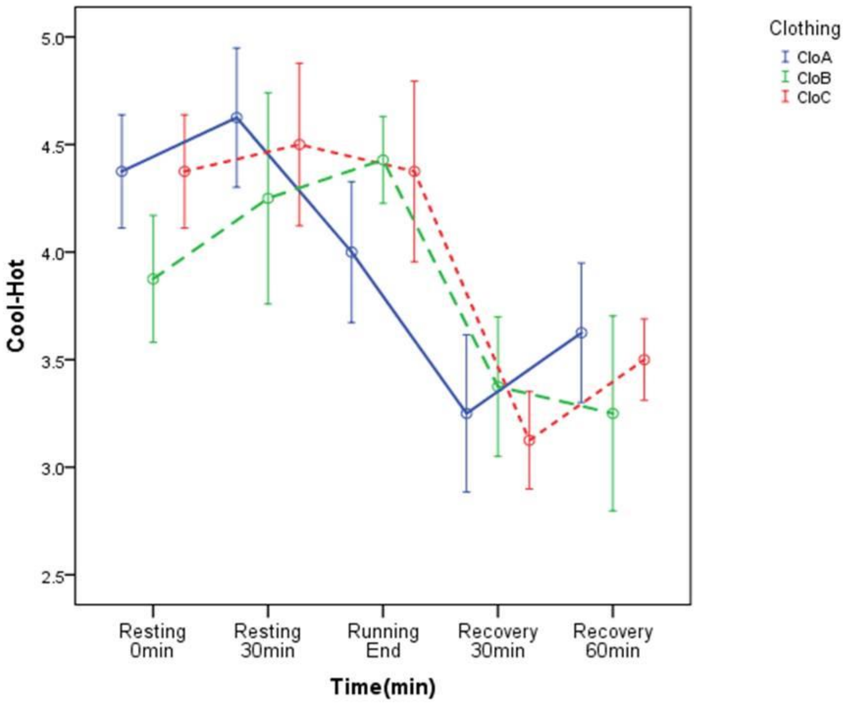
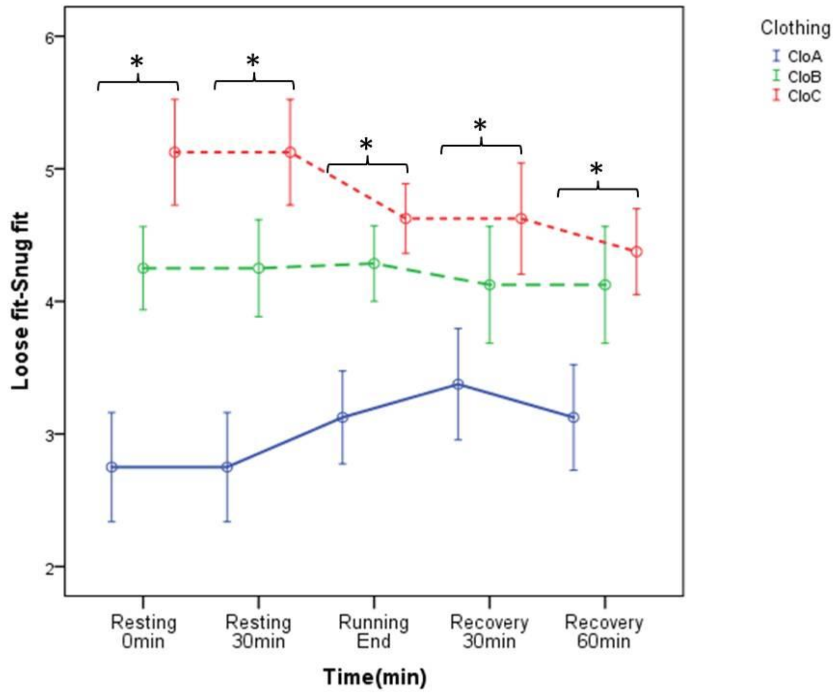


Figure 7.11 Summary of Cool-Hot sensation of three clothing

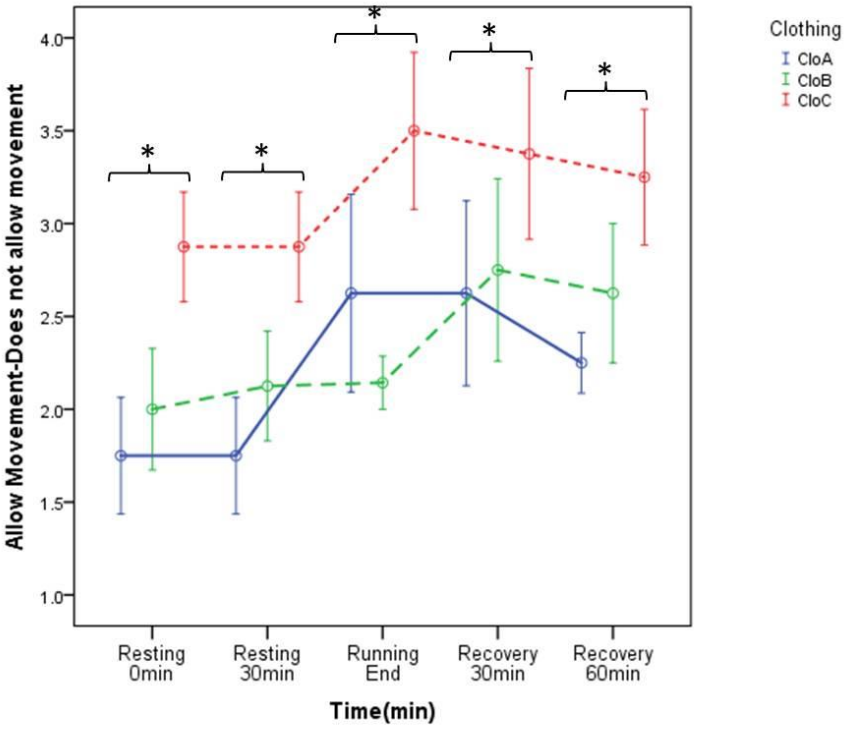
There were no significant differences on the two sensations of Breathable-Airtight and Cool-Hot induced by clothing at each time point, as shown in Figures 7.10 and 7.11 respectively.

The Loose fit-Snug fit sensation is summarized in Figure 7.12. The three sets of clothing had a stable sensation at the five time points. CloA had a greater Snug fit sensation after the run. Among the three sets of clothing, CloC had the highest snug fit sensation compared with CloA and CloB, and CloB had higher snug fit sensation than CloA at each time point.



*: $P < 0.05$

Figure 7.12 Summary of Loose fit-Snug fit sensation of the three sets of clothing

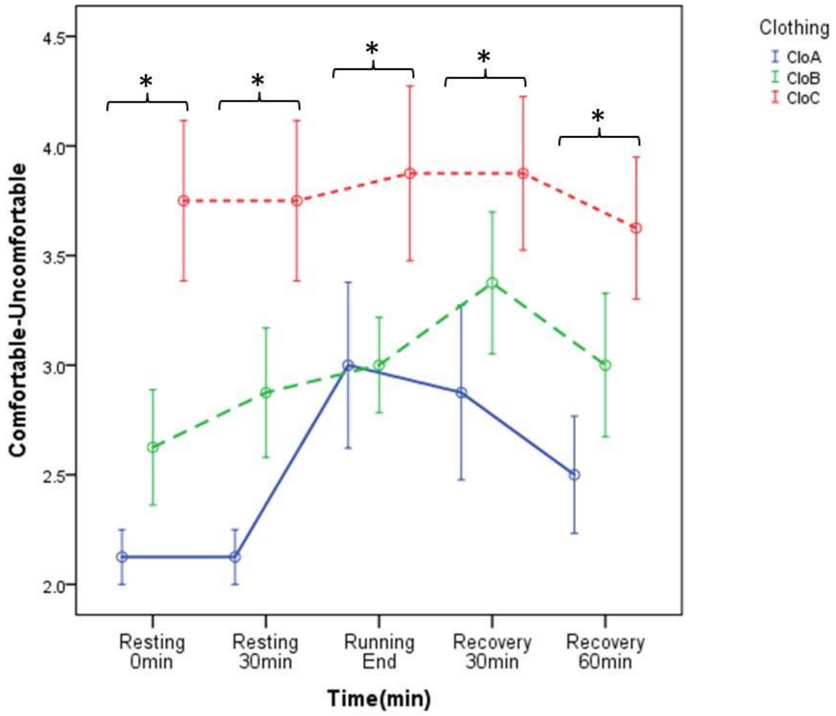


*: $P < 0.05$

Figure 7.13 Summary of Allow movement-Does not allow movement sensation of the three sets of clothing

Figure 7.13 illustrates the Allow movement-Does not allow movement sensation. Among the three sets of clothing, CloC had the highest value of does not allow movement sensation, but CloA and CloB had similar values of sensation at each time point.

The overall Comfortable-Uncomfortable sensation is summarized in Figure 7.14. Among the three sets of clothing, CloC had the highest value of uncomfortable sensation compared with CloA and CloB at each time point, and CloB had a higher uncomfortable sensation than CloA at the Resting 0 min, Running 30 min, and Recovery 60 min time points.



*: $P < 0.05$

Figure 7.14 Summary of Comfortable-Uncomfortable sensation of three sets of clothing

7.3.2 Relationships of overall comfort and each sensation

To explore the relationships between the sensation of overall comfort and individual sensation at the five time points, regression analysis was applied. The results are summarized in Table 7.1 accordingly.

Table 7.1 Regression models of overall comfort sensation and all other sensations

Time Point	Model	Model Summary		Standardized Coefficients	t	Sig.
		R	R^2	Beta		
Resting 0min	(Constant)	0.875	0.766		6.95	0.00
	Heavy-Light			-0.41	-2.96	0.01
	Damp-Dry			-0.39	-3.04	0.01
	Loose fit-Snug fit			0.32	2.64	0.02
Resting 30min	(Constant)	0.785	0.617		4.80	0.00
	Loose fit-Snug fit			0.36	2.40	0.03
	Itchy-Smooth			-0.57	-3.85	0.00
Running End	(Constant)	0.737	0.543		4.41	0.00
	Allow movement			0.74	5.00	0.00
Recovery 30min	(Constant)	0.918	0.843		3.88	0.00
	Allow movement			0.64	6.19	0.00
	Sticky-Smooth			-0.37	-3.65	0.00
	Soft-Stiff			0.19	2.10	0.05
Recovery 60min	(Constant)	0.838	0.703		12.57	0.00
	Sticky-Smooth	0.764	0.584	-0.43	-3.20	0.00
	Prickly-Smooth			-0.55	-4.11	0.00

To predict overall comfort sensation at different time points, five models were constructed and discussed as follows:

At the Resting 0 min time point, the combination of three sensations, e.g., Heavy-Light (HL), Damp-Dry (DD), and Loose fit-Snug fit (LS), account for 76.6% of the Comfortable-Uncomfortable sensation. The regression Equation can be expressed as 7-1:

$$\text{Comfort} = -0.41\text{HL}-0.39\text{DD}+0.32\text{LS} \tag{7-1}$$

Based on the equation, the HL and DD sensations had a negative effect on the Comfortable-Uncomfortable sensation, while the LS sensation was positively related to the Comfortable-Uncomfortable sensation, which indicates that more comfort sensation is correlated with lighter, drier and looser fit sensations. Therefore, a light, dry, and loose-fit clothing design increases the wearers' comfort at rest in a hot condition.

At the Resting 30 min time point, the combination of Loose fit-Snug fit (LS) and Itchy-Smooth (IS) sensations accounted for 61.7% of the Comfortable-Uncomfortable sensation. The regression equation can be expressed as 7-2:

$$\text{Comfort} = 0.36\text{LS}-0.57\text{IS} \tag{7-2}$$

The LS sensation had a positive effect on the Comfortable-Uncomfortable sensation while the LS sensation was negatively related to the Comfortable-Uncomfortable sensation, indicating that more comfort sensation is correlated with a smoother and more loosely-fit design. Therefore, a smoother and more loosely-fit design increases the wearer's comfort in a hot condition for at least 30 min. This may change when the comfort sensation changes and depending on how long the wearer stays in a hot condition.

At the Running End time point, the sensation of Allow movement-Does not allow movement (AM) can predict 73.7% of the Comfortable-Uncomfortable sensation. The regression equation can be expressed as 7-3:

$$\text{Comfort} = 0.74\text{AM} \tag{7-3}$$

The AM sensation had a positive effect on the Comfortable-Uncomfortable sensation, indicating that the comfort of clothing is mainly determined by the movement sensation while running. Thus, the clothing design should allow free movement while exercising in a hot condition.

At the Recovery 30 min time point, the combination of AM, Sticky-Smooth (SS_m), and Soft-Stiff (SS_t) sensations account for 84.3% of the Comfortable-Uncomfortable sensation. The regression equation can be expressed as 7-4:

$$\text{Comfort} = 0.64\text{AM}-0.37\text{SS}_m+0.19\text{SS}_t \tag{7-4}$$

The AM and SS_t sensations had a positive effect on the Comfortable-Uncomfortable sensation, while the SS_m sensation was negatively related with the Comfortable-Uncomfortable sensation. This indicates that a softer, smoother sensation plus more room for movement allow more comfort. Thus, the design of clothing for exercise and recovery should be softer, smoother and have more room for movement.

At the Recovery 60 min time point, the combination of SS_m and Prickly-Smooth (PS_m) sensation account for 58.4% of the comfortable-uncomfortable sensation. The regression equation can be expressed as 7-5:

$$\text{Comfort} = -0.43SS_m - 0.55PS_m \tag{7-5}$$

The SS_m and PS_m sensations are negatively related to the Comfortable-Uncomfortable sensation, indicating that smoother clothing gives more comfort.

To sum up, Comfortable-Uncomfortable sensation is predicted by the other sensations at different statuses. Therefore, a light, soft, smooth, loosely fit clothing design, plus more room for movement allow comfort. The ratio of these requirements changes while the wearer performs different exercise statuses.

7.3.3 Relationships of comfort sensation and clothing properties

Subjective comfort sensation at different time points could have been affected by the different physical properties of the clothing and vary according to the exercise states. The established models at different time points are listed as follows:

At Resting 0 min, a strong relationship was indicated between the overall CHD and the overall comfort sensation, where $R = 0.686$ and $P < 0.001$, as shown in Equation 7-6. The equation reveals that the CHD through the clothing negatively influences overall comfort sensation;

$$\text{Comfort} = -0.145\text{CHD}+3.712 \tag{7-6}$$

At Resting 30 min, wearing comfort can be predicted by the CLHL, expressed in Equation 7-7 ($R = 0.666$, $P < 0.001$);

$$\text{Comfort} = -0.045\text{CLHL}+15.774 \tag{7-7}$$

At Running End, wearing comfort can be predicted by the W_t of the clothing, expressed in Equation 7-8 ($R = 0.466$, $P < 0.05$);

$$\text{Comfort} = 0.005W_t+2.342 \tag{7-8}$$

At Recovery 30 min, wearing comfort can be predicted by the W_t of clothing, expressed in Equation 7-9 ($R = 0.408$, $P < 0.05$);

$$\text{Comfort} = 0.005W_t+2.494 \tag{7-9}$$

At Recovery 60 min, wearing comfort can be predicted by CLHL, expressed in Equation 7-10 ($R = 0.492$, $P < 0.05$);

$$\text{Comfort} = -0.031\text{CLHL}+11.956 \tag{7-10}$$

where wearing comfort refers to the comfort sensation of clothing, CHD is the capability of heat dissipation (in $kJ \cdot h^{-1}$), CLHL is the capability for latent heat loss (in $kJ \cdot h^{-1}$) and W_t refers to the weight of the clothing expressed (in g).

7.3.4 Cluster analysis of sensation

Figure 7.15 illustrates the relationship of the 14 sensations in the experiment. The scales range from 0 to 25, as indicated in the Squared Euclidean Distance of the sensations. The nearer the distance between two sensations, the closer the relationship between them.

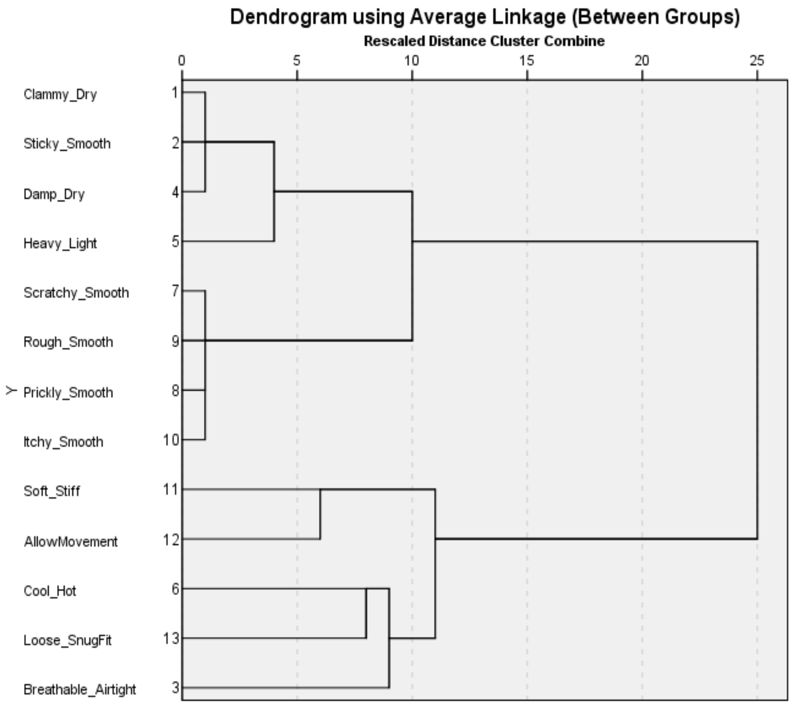


Figure 7.15 Relationship among sensations

Figure 7.15 proposes that the sensations could be generally considered for grouping according to their Squared Euclidean Distances between each other. Clammy-Dry, Sticky-Smooth, and Damp-Dry sensations, all related to moisture sensation, have close relationships because they showed similar distances with each other. They also have a close relationship with Heavy-Light sensation with the distance of 5. Scratchy-Smooth, Rough-Smooth, Prickly-Smooth, and Itchy-Smooth sensations, all related to touch sensation, are closely related to each other. Soft-Stiff is closely related to allow movement sensation, as well as Cool-Hot, Loose fit-Snug fit and Breathable-Airtight sensations. Although the cluster analysis generally showed the pattern of relationship among the sensations according to their distances, it cannot provide detailed information of their relationships and classify them into different groups to predict their contribution to overall comfort. Thus, further investigation by using factor analysis was conducted.

7.3.5 Factor analysis on subjective sensations

Factor analysis was employed to reduce the variable sensations and to ascertain the key influent factors of overall comfort. Based on the results, four independent sensory factors were extracted from the 14 sensations at the Resting 0 min, Resting 30 min, Running End, Recovery 30 min, and Recovery 60 min time points respectively. These sensations had different proportions of contribution to the overall comfort at different statuses of the participants.

Resting 0 min

The rotated component matrix of the sensory factors at the Resting 0 min time point is summarized in Table 7.2. Four factors can cumulatively explain 87.38% of the total variance. The first sensory factor (T1F1) mainly relates to the moisture sensations (Clammy-Dry, Damp-Dry, Sticky-Smooth, and Allow movement) and touch sensations (Itchy-Smooth, Rough-Smooth, Scratchy-Smooth, and Prickly-Smooth) of a clothing, which constitute the biggest factor group. This factor can explain the highest variance of comfort (44.55%) at the Resting 0 min time point. The second sensory factor (T1F2) includes sensations of Loose fit-Snug fit, Soft-Stiff, and Heavy-Light and can explain 20.29% of comfort. The third (T1F3) and fourth (T1F4) factors, both related to thermal sensations (Breathable-Airtight and Cool-Hot), can explain 13.72% and 8.82% of comfort respectively.

Table 7.2 Rotated factor matrix for 14 sensations at the Resting 0 min time point.

Sensations	Component			
	T1F1	T1F2	T1F3	T1F4
Clammy-Dry	0.94			
Damp-Dry	0.91			
Sticky-Smooth	0.90			
Itchy-Smooth	0.84			
Allow Movement-Does not allow movement	-0.82			
Rough-Smooth	0.75			
Scratchy-Smooth	0.68			
Prickly-Smooth	0.63			
Loose fit-Snug fit		-0.89		
Soft-Stiff		-0.67		
Heavy-Light		0.66		
Breathable-Airtight			-0.87	
Cool-Hot				0.95
% of variance	44.55	20.29	13.72	8.82
Cumulative %	44.55	64.84	78.56	87.38

The overall comfort at Resting 0 min time point (C-comfort1) can be predicted by the four factors, shown as 7-11 below:

$$\text{C-comfort1} = 0.445\text{T1F1}+0.202\text{T1F2}+0.137\text{T1F3}+0.882\text{T1F4} \qquad (7\text{-}11)$$

A linear relationship was found with $R^2 = 0.54$ between the C-comfort1 model (7-11) and the actual overall comfort obtained from the questionnaire at the Resting 0 min time point.

Resting 30 min

The rotated component matrix of the sensory factors at the Resting 30 min time point is summarized in Table 7.3. The analysis result of the four factors can cumulatively explain 87.78% of the total variance, which is similar to that at the Resting 0 min time point. The first sensory factor (T2F1) related to the moisture and touch sensations of the clothing, which still constitute the biggest factor group, is the same as that at the Resting 0 min time point. It can explain the highest variance of comfort (42.62%) at the Resting 30 min time point. The second sensory factor (T2F2) includes sensations of Loose fit-Snug fit, Soft-Stiff, and Heavy-Light and can explain 19.41% of comfort. The third (T2F3) and fourth factors (T2F4) can explain 13.37% and 12.37% of comfort respectively.

Table 7.3 Rotated factor matrix for 14 sensations at the Resting 30 min time point

Sensations	Component			
	T2F1	T2F2	T2F3	T2F4
Clammy-Dry	0.94			
Damp-Dry	0.93			
Sticky-Smooth	0.85			
Allow Movement-Does not allow movement	-0.83			
Itchy-Smooth	0.81			
Rough-Smooth	0.68			
Prickly-Smooth	0.65			
Scratchy-Smooth	0.60			
Loose fit-Snug fit		-0.89		
Heavy-Light		0.62		
Soft-Stiff		-0.55		
Breathable-Airtight			-0.92	
Cool-Hot				0.91
% of variance	42.62	19.41	13.37	12.37
Cumulative %	42.62	62.03	75.40	87.78

Overall comfort at the Resting 30 min time point (C-comfort2) can be predicted by the four factors, shown as 7-12 below:

$$\text{C-comfort2} = 0.426\text{T2F1}+0.194\text{T2F2}+0.133\text{T2F3}+0.123\text{T2F4} \qquad (7\text{-}12)$$

A linear relationship was found with $R^2 = 0.47$ between the C-comfort2 model (7-12) and the actual overall comfort obtained from the questionnaire at the Resting 30 min time point.

Running End

The rotated component matrix of the sensory factors at the Running End time point is summarized in Table 7.4. The analysis results of the four factors can cumulatively explain 78.61% of the total variance, which has a smaller proportion than at the Resting 0 min and 30 min time points. The first sensory factor (T3F1) includes only four touch sensations and can explain 28.46% of the clothing comfort. The increased proportion of touch sensation on the prediction of overall comfort may be related to the sweating process while running. When the participants began to sweat while running, the electrolytes accumulated on the skin and the inner surface of clothing with extended sweat evaporation. The increased accumulation of the electrolytes may affect the smoothness sensation on the clothing. The second sensory factor (T3F2) includes mixed sensations (Breathable-Airtight, Allow movement, Heavy-Light, etc.) and can explain 26.39% of the overall comfort. The third (T3F3) and fourth factors (T3F4) can explain 13.05% and 10.71% of comfort respectively. These findings indicate that the comfort sensation after running is mainly related to the touch sensation on the clothing, and the smoothness of the clothing may have an essential effect on overall comfort.

Table 7.4 Rotated factor matrix for 14 sensations at Running End

Sensations	Component			
	T3F1	T3F2	T3F3	T3F4
Rough-Smooth	0.96			
Prickly-Smooth	0.96			
Itchy-Smooth	0.88			
Scratchy-Smooth	0.85			
Breathable-Airtight		-0.90		
Allow Movement-Does not allow movement		-0.83		
Heavy-Light		0.80		
Damp-Dry		0.72		
Sticky-Smooth		0.58		
Cool-Hot			-0.78	
Loose fit-Snug fit			-0.64	
Clammy-Dry				0.70
Soft-Stiff				-0.66
% of variance	28.46	26.39	13.05	10.71
Cumulative %	28.46	54.85	67.90	78.61

Overall comfort at the Running End time point (C-comfort3) can be predicted by four factors, shown as 7-13 below:

$$\text{C-comfort3} = 0.285\text{T3F1}+0.264\text{T3F2}+0.131\text{T3F3}+0.107\text{T3F4} \qquad (7\text{-}13)$$

A linear relationship was found with $R^2 = 0.50$ between the C-comfort3 model (7-13) and the actual overall comfort obtained from the questionnaire at Running End.

Recovery 30 min

The rotated component matrix of the sensory factors at the Recovery 30 min time point is summarized in Table 7.5. The analysis results of the four factors can cumulatively explain 82.48% of the total variance. The first sensory factor (T4F1) includes four touch sensations and soft-stiff sensation and can explain 30.06% of the clothing comfort. The second sensory factor (T4F2) includes three moisture sensations (Clammy-Dry, Sticky-Smooth, and Damp-Dry) and can explain 22.44% of the overall comfort. This indicates that both touch and moisture sensations are obviously related to comfort when sweat evaporates or evaporated after running. The third (T4F3) and fourth factors (T4F4) can explain 21.85% and 8.13% of comfort respectively.

Table 7.5 Rotated factor matrix for 14 sensations at the Recovery 30 min time point

Sensations	Component			
	T4F1	T4F2	T4F3	T4F4
Prickly-Smooth	0.94			
Scratchy-Smooth	0.94			
Rough-Smooth	0.91			
Itchy-Smooth	0.91			
Soft-Stiff	-0.60			
Clammy-Dry		0.91		
Sticky-Smooth		0.89		
Damp-Dry		0.79		
Breathable-Airtight			0.80	
Heavy-Light			-0.75	
Allow Movement-Does not allow movement			0.74	
Loose fit-Snug fit			0.66	
Cool-Hot				0.96
% of variance	30.06	22.44	21.85	8.13
Cumulative %	30.06	52.50	74.35	82.48

The overall comfort at the Recovery 30 min time point (C-comfort4) can be predicted by four factors, shown as 7-14 below:

$$\text{C-comfort4} = 0.301\text{T4F1}+0.224\text{T4F2}+0.219\text{T4F3}+0.081\text{T4F4} \qquad (7\text{-}14)$$

Recovery 60 min

The rotated component matrix of the sensory factors at the Recovery 60 min time point is summarized in Table 7.6. The analysis results of the four factors can cumulatively explain 81.89% of the total variance. The first sensory factor (T5F1) includes four touch, Soft-Stiff, and Allow movement sensations, which can explain 33.23% of the clothing comfort. The second sensory factor (T5F2) includes three moisture sensations (Clammy-Dry, Sticky-Smooth, and Damp-Dry) and a Heavy-Light sensation, which can explain 25.67% of overall comfort. The third (T5F3) and fourth factors (T5F4) can explain 14.43% and 8.56% of comfort respectively. After the 60 min Recovery time point, the proportion of sensations on comfort had similar patterns at rest, but the moisture sensation was less obvious than touch sensation at the Recovery 60 min time point. The electrolytes accumulated on the clothing after sweat evaporation may explain the phenomenon.

Table 7.6 Rotated factor matrix for 14 sensations at the Recovery 60 min time point

Sensations	Component			
	T5F1	T5F2	T5F3	T5F4
Scratchy-Smooth	0.92			
Prickly-Smooth	0.91			
Rough-Smooth	0.89			
Itchy-Smooth	0.83			
Soft-Stiff	-0.69			
Allow Movement-Does not allow movement	-0.66			
Clammy-Dry		0.93		
Damp-Dry		0.93		
Sticky-Smooth		0.89		
Heavy-Light		0.59		
Loose fit-Snug fit			0.89	
Breathable-Airtight			0.88	
Cool-Hot				0.95
% of variance	33.23	25.67	14.43	8.56
Cumulative %	33.23	58.90	73.33	81.89

Overall comfort at the Recovery 60 min time point (C-comfort5) can be predicted by four factors, shown as 7-15 below:

$$\text{C-comfort5} = 0.332\text{T5F1}+0.257\text{T5F2}+0.144\text{T5F3}+0.086\text{T5F4} \qquad (7\text{-}15)$$

A linear relationship was found with $R^2 = 0.57$ between the C-comfort5 model (7-15) and the actual overall comfort obtained from the questionnaire at the Recovery 60 min time point.

7.3.6 Relationships between clothing properties and sensory factors

To explore the influence of clothing properties on each sensory factor at different time points, a correlation analysis was employed and the results are summarized in Table 7.7. At rest, sensory factors of comfort (T1F2 at Resting 0 min and T2F2 at Resting 30 min), including Loose fit-Snug fit, Soft-Stiff, and Heavy-Light sensations, were highly correlated with the clothing properties WVP, OMMC, AR, and clo. Sensory factors of comfort at Running End (T3F1), including four touch sensations, were correlated with WVP, OMMC, AR, and clo properties, and sensory factors (T3F3) consisting of Cool-Hot and Loose fit-Snug fit sensations were only correlated with WVP and OMMC. During recovery, sensory factors of comfort relating to touch sensations (T4F1 and T5F3) were highly correlated with the clothing properties, e.g., OMMC, AR, and clo, and the sensory factors (T4F3 and T5F3) were correlated with WVP and OMMC.

Besides, the results showed that some sensory factors tend to have a correlation with the PR, for example, T1F3 at Resting 0 min, T2F3 at Resting 30 min, and T3F3 at Running End, indicating that these sensation factors could not only predict overall clothing comfort, but might also have some effect on the running performance in a hot condition. For instance, the fabric properties, like OMMC, can increase the ability of heat and moisture release from specified body parts to outer environment (i.e., chest). Before sweating, the release of dry heat is the main process of heat dissipation on that body part, and when sweating starts, the heat will dissipate as sweat evaporation during exercise. The higher the capacity of heat dissipation of the fabric and the whole clothing, the less the heat stored in the body, hence inducing less impact of heat stress, running performance and wearing comfort while running in a hot condition.

Table 7.7 Relationships between clothing properties and sensory factors at each time point

		WVP	OMMC	AR	clo	PR
C-comfort1	T1F1					
	T1F2	0.59**	0.74**	-0.66**	-0.64**	
	T1F3					0.35†
	T1F4					
C-comfort2	T2F1					
	T2F2	0.56**	0.72**	-0.64**	-0.63**	
	T2F3					0.35†
	T2F4					
C-comfort3	T3F1	0.43*	0.58**	-0.53*	-0.53*	
	T3F2					
	T3F3	0.46*	0.41*			-0.36†
	T3F4					
C-comfort4	T4F1		0.46*	-0.49*	-0.49*	
	T4F2					
	T4F3	-0.42*	-0.35†			
	T4F4					
C-comfort5	T5F1		0.55*	-0.60**	-0.60**	
	T5F2					
	T5F3	-0.48*	-0.37†			
	T5F4					

WVP: water vapor permeability, OMMC: overall moisture management capacity, AR: air resistance; **: correlation is significant at the 0.01 level; *: correlation is significant at the 0.05 level; †: correlation is significant at the 0.1 level.

7.4 Conclusion

In this chapter, findings showed that subjective sensations such as Clammy-Dry, Scratchy-Smooth, Soft-Stiff, Loose-Snug fit, allow movement, and Comfortable are significantly affected by clothing and different statuses such as resting, running exercise, and recovery. Similar patterns among several sensations were also found at five time points from the plotted graphs. Overall comfort sensation can, therefore, be directly predicted by some of the subjective sensations at each time point. Based on the results of the cluster analysis and factor analysis, four independent sensory factors were extracted from the 14 sensations to predict the overall comfort at each time points individually. The four factors are mainly related to moisture sensation, touch sensation, body-fit sensation and thermal sensation, respectively. The sensation had different proportions to contribute to the overall comfort at different statuses of the subjects. At rest, the clothing comfort was mainly predicted by the moisture sensations (Clammy-Dry, Damp-Dry, Sticky-Smooth, and Allow movement) and touch sensations (Itchy-Smooth, Rough-Smooth, Scratchy-Smooth, and Prickly-Smooth) of the clothing. However, the touch sensation became the obvious sensation contributing to the overall comfort after running (time points of Running End, Recovery 30 min, and Recovery 60 min) due to the alteration of skin sensitivity after running and sweating, as well as the deposition of electrolytes on the skin and inner surface of clothing after sweat evaporation.

Five sets of a predictable model (C-comfort1 to C-comfort5) were constructed to predict the overall comfort by the four sensory factors at each time point. The agreements between the real comfort sensation obtained from the questionnaire and the predicted C-comfort by the models were observed respectively with the R^2 from 0.47 to 0.57 at each time point, except that at Recovery 30 min.

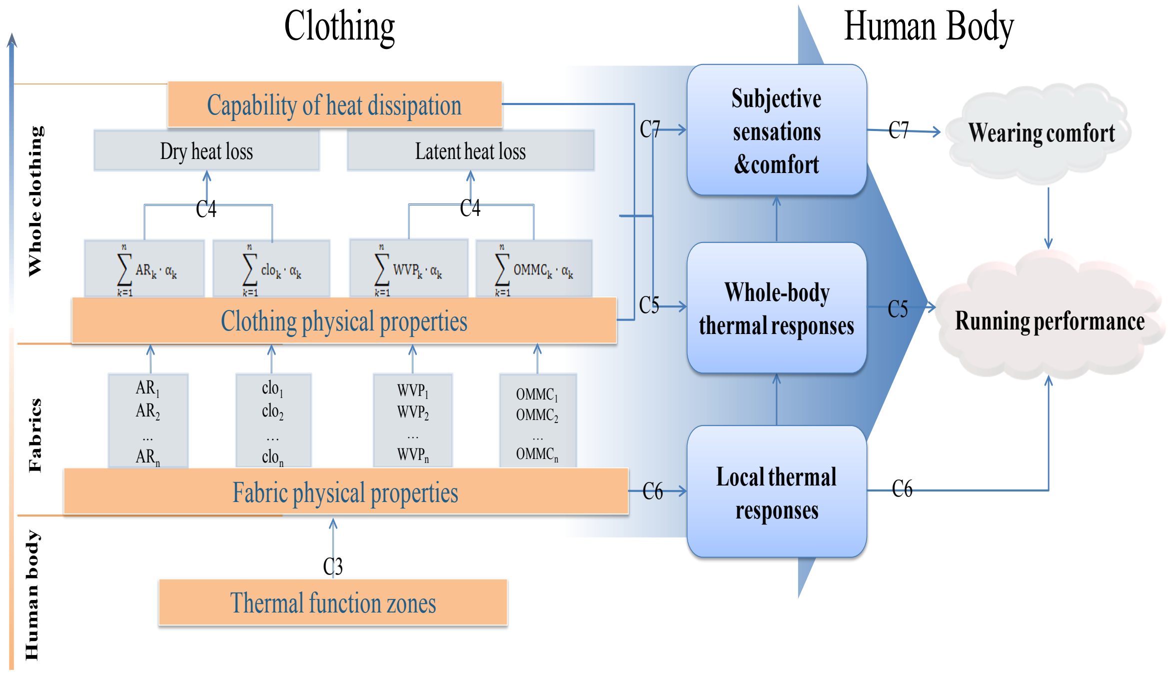
From the correlation analysis results between clothing properties and sensation factors, the clothing properties (WVP, OMMC, and clo) mainly affected the body-fit sensations (Loose fit-Snug fit, Soft-Stiff, and Heavy-Light) at rest. The clothing properties would be affected by the touch sensation at both Running End and Recovery period. Several sensory factors also tended to have a correlation with PR, e.g., T1F3 at Resting 0 min, T2F3 at Resting 30 min, and T3F3 at Running End, indicating that these sensation factors could not only predict the overall clothing comfort, but might also have some effects on running performance in a hot condition.

CHAPTER 8 CONCLUSION AND FUTURE WORK

8.1 Conclusion

This study aims to establish a design and evaluation system for performance running clothes in hot conditions to improve the running performance and wearing comfort of athletes, and further investigate the effects of the thermal mapping-designed running clothes on whole-body/local thermal responses of the athletes, running performance, subjective sensations and wearing comfort by an objective evaluation of clothing and wear trials in human subjects.

As reported in previous chapters, the main objectives of this study have been achieved. The detailed findings and results are summarized in Figure 8.1:



Notes: C3: Chapter 3, C4: Chapter 4, C5: Chapter 5, C6: Chapter 6, C7: Chapter 7.

Figure 8.1 Summary of the thesis

In order to establishment of a theoretical framework to develop and evaluate functional running clothes (in Chapter 1&2). A systematic literature review was conducted, providing background knowledge on a) heat balance and thermoregulation in the human body, b) an understanding of factors that can affect running performance and c) the possible relationships between clothing and running performance. A framework based on the literature was established (in Chapter 2 and Chapter 3) to address knowledge gaps and study the procedures involved in functional clothing design methodology, evaluation system, and physiological evaluation of human subjects.

Chapter 3 developed a new method in designing clothes for running under hot conditions by identifying the thermal requirements of athletes for different body parts, in which the applicable condition of clothing and thermal requirements for each athlete body part were analyzed, and 12 thermal zones on the human body were specified according to regional skin temperature and the distribution of sweat evaporation. Besides, different thermal zones were marked with specific demands in pattern design and selection of fabric materials to fulfill the physiological thermal requirements. At last, two types of running clothes with a mapping-designed concept were manufactured based on the newly developed methodology.

Chapter 4 established an evaluation system that can be used to quantify the functional performance of thermal mapping-designed clothing and to assess the influence of the mapping-designed clothing on thermal responses and running performance of human body in next chapters. Physical evaluation of the mapping-designed clothing is included: a) Basic tests of fabric physical properties were conducted, following existing measurement standards, b) for the mapping-designed aspect, clothing properties were calculated according to the physical properties of the fabric, as well as the specific body part covered by the fabric. Moreover, three new indices related to clothing science were defined to simulate the CHD when the clothing is worn. The overall CHD comprises the CDHL and CLHL, which were evaluated using a manikin test and computational methods. c) The investigation of evaluation methods for wear trials, including the experimental design, methodology, and measuring instruments, were discussed and confirmed for further investigation. By using the described system, the physical properties of the developed running clothes were evaluated using. The evaluation results show that the overall CHD of mapping-designed clothing (CloA and CloB) increased by 11% and 7% respectively as compared to existing commercial clothing.

Chapter 5 investigated and verified the effects of mapping-designed running clothes on whole-body thermal responses and running performance by conducting wear trials on human subjects (in Chapter 5). In this chapter, a parallel-blinded wear trial with a 45 min steady-state running protocol followed by an all-out sprint was conducted to test the different physiological effects of the developed clothing on the human subjects. The results showed that the clothing designed with increased CHD by altering the patterns and fabric materials resulted in decreased skin temperature, increased core temperature, and less heat storage during rest and steady-state running periods. Consequently, the performance of the athletes running in a hot condition significantly improved ($P < 0.05$). The moisture properties, such as $\mathrm{OMMC_t}$ and $\mathrm{WVP_t}$, exhibited negative correlations with T_c and S at certain time points. $\mathrm{WVP_t}$ was also correlated with T_s at the Running End time point. The thermal properties such as $\mathrm{clo_t}$ and $\mathrm{AR_t}$ exerted positive effects on S during the Resting 30 min period. $\mathrm{WVP_t}$ and $\mathrm{OMMC_t}$ also exhibited negative correlations with PR, whereas $\mathrm{clo_t}$ and $\mathrm{AR_t}$ showed positive correlations with PR. Besides, T_c and T_s at the time point of Running End can be predicted by the overall capability of dissipate heat (CHD), as well as the d and the $\mathrm{W_t}$ of the clothing. The PR can be directly predicted by the CLHL through the clothing.

Chapter 6 investigated the effects of mapping-designed running clothes on local thermal responses of athletes in a wear trial, and explored the relationships with whole-body thermal responses and running performance. The findings revealed that the defined body thermal zones had different thermal responses during the tests because of the varying physical properties of the fabric at the specified zones. In particular, WVP at a specified body part showed positive correlations with T_{chest} and negative correlations with RH_{thigh} and RH_{back} during recovery ($P < 0.05$). The clo and AR of the fabric showed a tendency for positive correlation with RH_{chest} (%) and T_{thigh} at the time points of Running 15 min and 20 min ($0.05 < P < 0.1$). The correlation results also indicated that T_{chest}, T_{arm}, ΔRH_{chest}, and ΔRH_{back} at specified time points affected the running performance ($0.05 < P < 0.1$). Subsequently, the potential mechanisms on how the mapping-designed clothing affected the thermal responses and running performance were explored. For instance, the fabric properties, like OMMC, can increase the ability of heat and moisture release from specified body parts to outer environment (i.e., chest). Before sweating, the release of dry heat is the main process of heat dissipation on that body part, and when sweating starts, the heat would dissipate as sweat evaporation during exercise. The higher the capacity of heat dissipation of the fabric and the whole clothing, the less the heat stored in the body and slower increases of T_{c}, hence inducing less impact of clothing on the running performance while running in a hot condition.

Chapter 7 examined the effects of mapping-designed running clothes on different subjective sensations and athletes' wearing comfort in a hot condition. Findings revealed that the specially designed running clothes increased overall wearing comfort and satisfied the related subjective sensations such as coolness, smoothness, and lightness at different exercise statuses ($P < 0.05$). Five sets of a predictable model were constructed to predict the overall comfort by the four sensory factors at each time point. The agreements between the real comfort sensation obtained from the questionnaire and the predicted comfort by the models were observed respectively with the R^2 from 0.47 to 0.57 at each time point, except that at Recovery 30 min. Besides, a factor analysis was conducted to identify the main sensory factors of wearing comfort, some of which were tended to correlate to PR. The findings indicated that these sensation factors could not only predict the overall clothing comfort, but might also have some effects on running performance in a hot condition. Further investigation is needed.

8.2 Future work

The major objectives of this study have been achieved, establishing an appropriate foundation for further studies on the subject.

The developed prediction models need to be improved using a larger population and sample sizes. In the present study, small sample sizes of clothing and experimental subjects were used to assess the evaluation system and conduct wear trials because of specific constraints to experiment conditions, resources, and time. The equations which established from statistical analyzing results may only reflect the relationships among the indices in similar protocols as the present study under the hot conditions (T_a of 30 °C, RH of 50%). Further investigation is needed.

The primary parameters related to heat stress have been investigated in this study. However, the mechanisms involved in heat stress and running performance are complex such that certain parameters have not been tested. These parameters include the following: change in blood flow, responses of energy metabolism, and status of skeletal muscles. The possible effects of clothing on the aforementioned factors were reported in previous studies [6, 36]. Thus, the correlation of clothing-related factors with running performance needs further investigation.

This study mainly focused on the thermal and moisture transfer properties of the fabric, as well as the influence of these properties on wearing comfort and related subjective sensations. However, the mechanical properties of clothing material, which may affect comfort and running performance, require further study.

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