DOCTORAL DISSERTATION

Experimental Study on Responses of Physiological and Thermal Sensation during Exercise in Indoor Thermal Environment

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Acknowledgement

“Life is not lack of beauty, but a lack of discovery.”

Romain Rolland

The "Acknowledgements" of my doctoral dissertation have finally arrived, which means the end of this dissertation. The moment has finally come for me to graduate from my doctoral program, which means the end of an important phase of my life. At this moment, I had mixed emotions. Imagine my excitement as I tapped this familiar keyboard for the last time to bring this doctoral thesis to a close! Dickens compared *David Copperfield*, his autobiographical novel, to his most beloved child. At this moment, I am also deeply aware that no one has ever loved this child as much as I have, for a work of scholarship that took three years and a great deal of effort and dedication to complete! I cherish him so much, not because of his academic value, but because of the joy and pain, I feel, like a mother's pregnancy. He accompanied me through the pleasures and hardships of my doctoral career.

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Abstract

With the development of technology, indoor temperature regulators such as air conditioners and electric heaters have become essential appliances in homes and provide year-round temperature adjustment to a comfortable range. However, the thermal sensation and the comfort of the human body often change significantly because of changes in environmental conditions or the different activities in the building. From the viewpoint of heat transfer, the various factors that affect human thermal comfort and thermal sensation are influenced by the heat transfer methods such as evaporation, convection, and radiation between the body and the surrounding thermal environment, affecting human thermal comfort and thermal sensation. There are two common directions in which human thermal sensation and thermal comfort are often assessed and discussed: one is to study thermal sensation by exposing the body to specific thermal environments (e.g., different temperatures, humidity, thermal radiation, and air velocities). The other is to establish an intrinsic relationship with thermal sensation from the viewpoint of human physiological parameters. This work falls into the second category.

Few studies currently involve thermal sensation and thermal comfort at moderate-high exercise intensity. Such research is necessary for places such as construction sites, gyms, and urban fitness trails. Even in recent years, there have been many cases where the thermal environment has significantly impacted athletes' sports competitions. However, previous research has mainly focused on changes in the human body's physiological parameters in exercise in a thermal environment and less on changes in thermal sensation. This study began with the idea of building comfortable thermal environments in exercise scenarios. Various physiological indicators in an exercise state are significantly different compared to the static state. In particular, the changes in the physiological parameters are more involved around the dynamic-static step. This research focuses on three core questions. How can physiological parameters and psychological factors adjust and change after exercise state change affects exercise thermal sensation? Second, whether it is possible to use physiological parameters closely related to metabolic rate and be easily measured, and relate these parameters to thermal sensation to predict thermal sensation. Third, Are psychological factors significant in the research of exercise thermal sensation?

This research provides a comprehensive and systematic review of the concepts, evaluation methods, and the evolution of classical models of exercise thermal sensation. Two exercise intensities were selected in a steady-state environment using a physiological indicator recorder and a thermal sensation questionnaire in a climate chamber. The experimental data were analyzed and processed using Origin 2018, IBM SPSS Statistics 25, and Gephi, including linear correlation analysis, stepwise regression analysis, etc. The specific physiological parameters and thermal comfort changes during the experiment were explained and discussed in more detail. The influence of psychological factors on the exercise thermal sensation was considered.

The methodology and significant findings point to important factors and complexities that influence exercise thermal sensation. This study's results provide an important reference for designing experimental protocols to study exercise thermal sensation. Besides, the study is highly practical as it attempts to use physiological indicators that are easily measurable and can effectively predict thermal sensation. It also provides basic research for the further development of smart bracelets and the rational design of urban fitness trails.

Keywords: *Exercise thermal sensation; Dynamic-static steps; Physiological parameter; Regression model; Thermal alliesthesia*

CONTENTS

ACKNOWLEDGEMENT

ABSTRACT

CONTENTS………………………………………………………………………………….....I

LIST OF FIGURES……………………..…………………………………………….………VI

LIST OF TABLES………………..…………………………………………...……….....IX

NOMENCLATURE...…………………………………………………………………...XI

Chapter 1: Introduction and purpose of research

1.1 Background *1-1*

1.2 Research Statement *1-3*

1.2.1. Physiological indicators and thermal sensation at a static state *1-4*

1.2.2. Physiological parameters and thermal sensation in exercise *1-5*

1.2.2.1. Metabolic rate and exercise thermal sensation *1-5*

1.2.2.2. Other physiological parameters and exercise thermal sensation *1-5*

1.2.3. About the model of the exercise thermal sensation *1-6*

1.3 Research Questions *1-7*

1.4 Research Objectives *1-8*

1.5 Scope of Research *1-8*

1.6 Research Outlines *1-9*

References: *1-12*

Chapter 2: Building thermal environment and human thermal sensation (static state)

2.1. Relevant concept *2-1*

2.1.1 Thermal environment *2-1*

2.1.2. Heat stress *2-1*

2.1.3 Thermal adaptation *2-2*

2.1.4 Thermal sensation and thermal comfort *2-3*

2.1.5 Relationship between thermal environment, heat stress, thermal adaptation, and thermal sensation *2-4*

2.1.6 Human thermal balance *2-4*

2.2. Factors influencing thermal sensation *2-7*

2.2.1. Air temperature *2-7*
2.2.2 Humidity *2-8*
2.2.3 Air velocity *2-9*
2.2.4 Mean radiation temperature *2-9*
2.2.5 Metabolic rate *2-11*
2.2.6 The clothing factor *2-12*
2.2.7 Other factors *2-15*
2.3 Overview of human thermal sensation models *2-17*
2.3.1 The Fanger model *2-17*
2.3.2 The Gagge model *2-19*
2.3.3 The COMFA model *2-21*
2.3.4 Multi-layered multi-node model *2-23*
2.3.5 The Rayman model *2-26*
2.3.6 Wet-bulb globe temperature *2-27*
2.4 Evaluating human thermal sensation *2-27*
2.4.1 Thermal sensation scale *2-28*
2.4.2 Skin temperature *2-29*
2.4.3 Human core temperature *2-30*
2.4.4 Heart rate variability *2-31*
2.4.5 Metabolic rate *2-31*
2.4.6 Electroencephalogram(EEG) *2-31*
2.4.7 Electromyogram(EMG) *2-32*
2.4.8 Sweating rate *2-32*
2.5 Summary *2-34*
References *2-36*

Chapter 3: Research and domain applications related to exercise thermal sensation

3.1 Physiological mechanisms of thermal sensation during exercise *3-1*
3.2 Thermophysiological responses of the human body during exercise *3-3*
3.3 Physiological indicators related to thermal sensation during exercise *3-4*
3.3.1 Correlation between skin temperature and thermal sensation during exercise *3-4*
3.3.2 Correlation between core temperature and thermal sensation during exercise *3-5*
3.3.3 Correlation between sweating rate and thermal sensation during exercise *3-7*
3.4 Influence of psychological factors on human thermal sensation during exercise *3-8*
3.5 Several models for predicting thermal sensation during exercise *3-9*

3.5.1 COMFA model predicts thermal sensation during exercise *3-10*
3.5.2 Fanger model predicts thermal sensation during exercise *3-11*
3.5.3 Kenny's model of human thermal sensation during exercise *3-12*
3.5.4 Reviews of other models of thermal sensation during exercise *3-12*
3.6 Reviews of exercise thermal sensation studies in different research domains *3-14*
3.6.1 Case study of exercise thermal sensation in indoor thermal environment *3-14*
3.6.2 Research in the domain of sports science and medical science *3-19*
3.7 Summary *3-22*
References *3-24*

Chapter 4: Experimental investigation into the responses of physiological parameters and thermal sensation in the whole exercise process of different intensities

4.1 Experimental method *4-2*
4.1.1 Subjects *4-2*
4.1.2 Experimental conditions and measurements *4-3*
4.1.2.1. Experimental environment *4-3*
4.1.2.2 Measurement of physiological parameters *4-3*
4.1.2.3 Subjective voting *4-8*
4.1.3 Experimental procedure *4-9*
4.1.4 Data processing and analysis methods *4-10*
4.2 Results and analysis *4-11*
4.2.1 The impact of dynamic-static step changes on physiological parameters in exercise. ...*4-11*
4.2.1.1 Skin temperature *4-11*
4.2.1.2 Oral temperature *4-12*
4.2.1.3 HR and HRV *4-13*
4.2.1.4 Electrodermal activity *4-15*
4.2.2 The impact of dynamic-static step changes on subjective sensation in exercise. *4-18*
4.2.2.1 Thermal sensation *4-18*
4.2.2.2 Thermal comfort *4-19*
4.2.2.3 SFI *4-20*
4.2.2.4 Fatigue index *4-21*
4.2.3 Differences in the impact of gender and BMI on TSV and TC *4-23*
4.3 Summary *4-25*

References *4-26*

Chapter 5: Mathematical relationships between subjective perception and physiological parameters in the whole process of exercise (static-dynamic-static)

5.1 A comparison of the dynamic thermal sensation between the modified Stolwijk model and the Fiala thermal physiology *5-1*
  5.1.1 Stolwijk model *5-2*
    5.1.1.1 Passive part *5-2*
    5.1.1.2 Active part *5-3*
    5.1.1.3 Modifications Stolwijk model *5-3*
  5.1.2 Dynamic thermal sensation (DTS) *5-4*
  5.1.3 Fiala model *5-5*
  5.1.4 Variant calculations *5-5*
  5.1.5 The rates of change in mean skin temperature ($T_{sk,m}$) (Fiala, 1998) *5-6*
5.2 Mathematical models *5-9*
  5.2.1 Stepwise regression analysis between physiological indicators and TSV *5-9*
  5.2.2 Stepwise regression analysis between physiological indicators and TC *5-11*
  5.2.3 Average change and rate of change of physiological parameters *5-12*
  5.2.4 Stepwise regression analysis of TSV using average change and rate of change of physiological parameters *5-15*
5.3 Correlation analysis *5-19*
  5.3.1 The correlation coefficients between T_{sk}, T_{or}, HR, and HRV parameters (between objective physiological parameters) *5-19*
  5.3.2 Correlation analysis between objective physiological parameters and subjective perception *5-20*
  5.3.3 Correlation between subjective perceptions *5-22*
5.4 Summary *5-23*
References *5-24*

Chapter 6: Discussion of the influencing factors on the exercise thermal sensation in the experiments

6.1 HRV indicators and exercise thermal sensation (comfort) *6-1*

6.2 Oral temperature during exercise *6-3*
6.3 Thermal alliesthesia *6-7*
6.4. The relationship between TSV, TC, EDA and SFI. *6-8*
  6.4.1 TSV and TC *6-8*
  6.4.2 TSV and EDA *6-9*
  6.4.3 TSV and SFI *6-10*
  6.4.4 EDA and SFI *6-10*
6.5 LF/HF and thermal sensation and comfort *6-11*
6.6 Thermal environment and exercise thermal sensation *6-12*
6.7 Summary *6-15*
References *6-17*

Chapter 7: Conclusion

7.1. Conclusion of Research *7-1*
7.2 Further Research *7-4*

Appendix I .... **XII**
Appendix II .... **XV**
Appendix III .... **XX**

LIST OF FIGURES

Fig.1. 1 Common fitness trails in China *1-1*
Fig.1. 2 Research Outline *1-11*

Fig.2. 1 Relationship between thermal environment, heat stress, thermal adaptation, and thermal sensation *2-4*
Fig.2. 2 Heat transfer of human body (CLIMATEMEDADMIN, 2020) *2-5*
Fig.2. 3 Factors influencing thermal comfort (sensation) (Godbole, 2018).................................... *2-7*
Fig.2. 4 Simplified schematic diagram of the multi-layered multi-node model (STOLWIJK, 1966) ……………………………………………………………………………………......*2-23*
Fig.2. 5 Schematic diagram of the Berkeley thermal sensation model... .... *2-24*
Fig.2. 6 Schematic diagram of the Fiala thermal sensation model (Fiala and Psikuta et al., 2012)……………………………………………………………………………………………. *2-25*

Fig.3. 1 The physiological mechanism of thermal sensation during exercise in a thermal environment *3-1*
Fig.3. 2 Human thermoregulatory responses during exercise (Pryor JL et al., 2019)..................... *3-3*
Fig.3. 3 The thermophysiological response of the human to exercise in a thermal environment..... *3-3*
Fig.3. 4 Psychological factors influencing thermal sensation in the human body during exercise.. *3-9*
Fig.3. 5 Changes in physiological indicators at different ambient temperatures and metabolic levels (Li, 2016) *3-15*
Fig.3. 6 The comparison of TSV at different ambient temperatures and metabolic levels (Li, 2016) *3-16*
Fig.3. 7 The relation between metabolic rate and preferred temperature (Siru Gao et al., 2018) *3-17*
Fig.3. 8 Comparisons with PMV model (Siru Gao et al., 2018).. *3-18*
Fig.3. 9 The average changes of auditory canal temperature: (a) Compare with the initial value, (b) Compare with the last value. (Yuchun Zhang et al., 2020).. *3-18*
Fig.3. 10 The average changes of heart rate: (a) Compare with the initial value, (b) Compare with the last value (Yuchun Zhang et al., 2020) *3-18*
Fig.3. 11 Experiment procedure (Li, 2016) *3-20*
Fig.3. 12 Experimental procedure, (open circles indicate time to fill out the questionnaire or to measure physiological response, and the dot and arrow means continuous measurement) (Siru Gao et al., 2018) *3-20*

Fig.3. 13 Experiment procedure (Yuchun Zhang et al., 2020) 3-20

Fig.4. 1 Climatic chamber diagram.. 4-4
Fig.4. 2 Test points on the body... 4-6
Fig.4. 3 Tympanic (T_{ty}) and Sublingual (T_{or}) temperature at 20, 25, and 30°C 4-7
Fig.4. 4 Experimental procedure... 4-10
Fig.4. 5 Multiple line of mean skin temperature (95% CI) by time and phase.............................. 4-12
Fig.4. 6 Multiple line of mean skin temperature by time and phase.. 4-12
Fig.4. 7 Multiple line of mean oral temperature (95% CI) by time and phase............................... 4-13
Fig.4. 8 Multiple line of mean heart rate (95% CI) by time and phase... 4-14
Fig.4. 9 Multiple line of mean each indicator in the HRV (95% CI) by time and phase................ 4-15
Fig.4. 10 Multiple line of mean EDA (95% CI) by time and phase... 4-16
Fig.4. 11 Comparison of CR_1 and CR_2 between V_1 and V_2... 4-17
Fig.4. 12 Multiple line of mean TSV (95% CI) by time and phase.. 4-19
Fig.4. 13 Multiple line of mean TC (95% CI) by time and phase.. 4-19
Fig.4. 14 Multiple line of mean SFI (95% CI) by time and phase... 4-20
Fig.4. 15 Comparison of ΔSFI between V_1 and V_2... 4-21
Fig.4. 16 Comparison of the change value of Δ_1 and Δ_2 between V_1 and V_2................................ 4-22
Fig.4. 17 The biaxial plot of mean fatigue value and fatigue rate... 4-22
Fig.4. 18 Line chart of TSV and TC (95% CI) for different genders and BMI............................... 4-24

Fig.5. 1 Schematic representation of the passive part of the Stolwijk model (Stolwijk and Hardy, 1977)... 5-2
Fig.5. 2 Schematic representation of the active part of the Stolwijk model (Stolwijk and Hardy, 1977). 5-3
Fig.5. 3 Neutral: 29°C/RH = 40%, Cool:17.5°C/RH = 31%, Neutral: 29°C/RH41%...................... 5-6
Fig.5. 4 Discrepancy between the static comfort model and the dynamic response of subjects exposed to sudden changes in ambient temperature of Ta (28 - 18 - 28°C)............................ 5-6
Fig.5.5 Parameters of the bodily thermal state as predicted by the model for sudden changes from a thermally neutral environment to a cold climate of Ta 18°C and back to neutral. Predicted rectal temperature, mean skin temperature and the metabolic heat product........................... 5-7
Fig.5. 6 Discrepancy between the static comfort model and the dynamic response of subjects exposed.. 5-7
Fig.5. 7 Parameters of the bodily thermal state as predicted by the model for sudden changes from a

thermally neutral environment to a hot climate of T_a=48°C 5-8
Fig.5. 8 Normal Q-Q Plot and Scatterplot of the Regression Standardized Residual of TSV 5-10
Fig.5. 9 Normal Q-Q Plot and Scatterplot of Regression Standardized Residual of TC 5-12
Fig.5. 10 The average change of physiological parameters 5-13
Fig.5. 11 The rate of change of physiological parameters and TSV 5-14
Fig.5. 12 Thermal sensation as a function of the rate of change of physiological parameters 5-16
Fig.5. 13 Normal Q-Q Plot and Scatterplot of Regression Standardized Residual of DE 5-17
Fig.5. 14 Normal Q-Q Plot and Scatterplot of Regression Standardized Residual of PE 5-18
Fig.5. 15 Comparison of the model simulation results 5-19

Fig.6. 1 The average changes of auditory canal temperature 6-4
Fig.6. 2 Measured means core temperature (n = 9) 6-4
Fig.6. 3 Tympanic (T_{ty}) and sublingual (T_{or}) temperatures at 20, 25, and 30°C 6-4
Fig.6. 4 Cutaneous vasomotor responses Cs and Dl, against the temperature error signal from the head core ΔT_{hy} (for three different skin temperatures) 6-5
Fig.6. 5 Parameters of the bodily thermal state as predicted by the model for sudden changes from a thermally neutral environment to a cold climate of T_a 18°C and back to neutral. 6-6
Fig.6. 6 Relationship between thermal sensation and thermal comfort during and after exercise... 6-9
Fig.6. 7 Relationship between thermal sensation and EDA during and after exercise..................... 6-9
Fig.6. 8 Relationship between thermal sensation and SFI during and after exercise 6-10
Fig.6. 9 Relationship between EDA and SFI during and after exercise 6-11
Fig.6. 10 Biaxial chart of the relationship between the LF/HF index, TSV, and TC 6-11
Fig.6. 11 HF, LF and LF/HF under different ambient temperatures (Ye Yao et al., 2007)............ 6-12
Fig.6. 12 The relation between metabolic rate and preferred temperature (Siru Gao et al., 2018) 6-13

LIST OF TABLES

Table 1. 1 Examples of Environment-based Comfort Metrics 1-3
Table 1. 2 Examples of Physiology-based Comfort Metrics 1-3

Table 2. 1 Categorization of PMV for different levels of thermal perception and physiological stress. 2-18
Table 2. 2 Categorization of SET for various levels of thermal perception and physiological stress 2-20
Table 2. 3 Categorization of PET for various levels of thermal perception and physiological stress.. 2-22
Table 2. 4 Thermal sensation and different groups of UTCI. 2-26
Table 2. 5 Necessary recommendations for outdoor activities according to WBGT values. 2-27
Table 2. 6 Comparing thermal perceptions in various bioclimatic indices (Blazejczyk et al., 2012) 2-28
Table 2. 7 Fanger 7-Point Scale 2-28
Table 2. 8 Spagnolo 5-Point Scale.. 2-28
Table 2. 9 TSENS 11-Point Scale 2-29
Table 2. 10 Comparison of physiological indicators for evaluating thermal sensation 2-33

Table 3. 1 Correspondence between actual thermal sensation and median of heat load (Kenny et al., 2009) 3-11

Table 4. 1Basic information on the subjects 4-3
Table 4. 2 Measurement instruments of this experiment.. 4-5
Table 4. 3Voting scale for the thermal sensation, thermal comfort, and sweat feeling indices 4-8
Table 4. 4Sakai Kazuhiro, items of Japanese subjective fatigue symptoms (2002 version). 4-9

Table 5. 1 Stepwise analysis of objective indicators and TSV 5-10
Table 5. 2 Stepwise analysis of objective indicators and TC 5-11
Table 5. 3 Stepwise analysis of objective indicators and TSV 5-17
Table 5.4 Stepwise analysis of objective indicators and TSV 5-17

Table 5. 5 The Pearson correlation coefficients between objective physiological indicators 5-20

Table 5. 6 Correlation coefficients between physiological parameters and TSV in different steps in V_I and V_2 5-21

Table 5. 7 Correlation coefficients between physiological parameters and subjective perception in V_1 and V_2 5-22

Table 5. 8 Pearson correlation coefficient among subjective perceptions. 5-22

Table 6. 1 The force-guided graphs between HRV and TSV 6-3

Nomenclature

T_{sk}	mean skin temperature, °C
T_{or}	oral temperature, °C
HR	heart rate beats per minute (BPM)
BMI	body mass index
R-R	beat intervals, ms
SDNN	recommended parameters for time-domain measures, The standard deviation of normal sinus R-R interval (take the natural logarithm)
RMSSD	recommended parameters for time-domain tests, the square root of the mean of the sum of the squares of differences between adjacent beat intervals (take the natural logarithm)
LF	power (0.04–0.15 Hz) in normalized units; LF/(TP-VLF) × 100, n.u.
HF	power (0.15–0.4 Hz) in normalized units; HF/(TP-VLF) × 100, n.u.
LF/HF	ratio LF/HF,
EDA	electrodermal activity, μS
M	rate of metabolic heat production, W/m^2
W	rate of mechanical work accomplished, W/m^2
C	rate of convective heat, W/m^2
R	rate of radiant heat, W/m^2
E_{sk}	total evaporative heat loss from skin (including natural diffusion E_{dif} and regulative sweating E_{sw}), W/m^2
C_{res}	rate of convective heat loss from respiration, W/m^2
E_{res}	rate of evaporative heat loss from respiration, W/m^2
S	rate of heat storage in the body, W/m^2
MTSV	mean thermal sensation vote
TC	thermal comfort
SFI	the sweat feeling index
PMV	predicted mean vote

CHAPTER 1

INTRODUCTION AND PURPOSE OF RESEARCH

1.1 Background *1-1*

1.2 Research Statement *1-3*

  1.2.1. Physiological indicators and thermal sensation at a static state *1-4*

  1.2.2. Physiological parameters and thermal sensation in exercise *1-5*

    1.2.2.1. Metabolic rate and exercise thermal sensation *1-5*

    1.2.2.2. Other physiological parameters and exercise thermal sensation *1-5*

  1.2.3. About the model of the exercise thermal sensation *1-6*

1.3 Research Questions *1-7*

1.4 Research Objectives *1-8*

1.5 Scope of Research *1-8*

1.6 Research Outlines *1-9*

References: *1-12*

1.1 Background

The initial inspiration for the topic chosen for this thesis came from the observation and consideration of two things. The first was about a highly anticipated badminton match, which took place on the evening of August 11, 2013, at Tianhe Stadium in Guangzhou, China, between Lin Dan and Li Zongwei in the men's singles final of the World Badminton Championships. Li, unfortunately, choosing to withdraw from the match at the end of the game because he was unable to continue. After the match, the Malaysian head coach expressed his dissatisfaction with the organization and service of the tournament. He described the situation as follows: in the second game of the final, the air conditioning in the stadium was suddenly switched off, and Li was so hot during the match that his energy consumption increased, and he was unable to continue the game until the end of the third game. The news media widely reported the news. The second thing is my personal experience. The earliest design and construction of fitness trails in China appeared in Hong Kong and Taiwan in the 1980s and 1990s. At present, they have formed their unique trail systems. I often run in the fitness trails as well. However, a phenomenon caught my attention. In the middle of summer, there are hardly any runners between 10 am and 4 pm. When asked, I found that the lack of shade and greenery in the fitness trails caused the heat to increase and comfort to deteriorate quickly. This phenomenon occurs in many cities in China, where fitness trails are used. As shown in Figure 1.1. The analysis shows that due to the increased thermal sensation caused by exercise, the person sweats quickly, the fatigue comes earlier, and the exercise comfort becomes poor.

Fig.1. 1 Common fitness trails in China (Source: Google Image)

Even there is a significant increase in energy consumption caused by the thermal environment, which makes the exercise meaningless. These factors have led to the author's interest in the issue of " Exercise thermal sensation and comfort ".

In modern society, people engage in many activities indoors or outdoors outside of the rest of their lives. For example, work, work out, or running. To properly evaluate the thermal environment, a lot of research has been conducted worldwide, and well-known indicators and models for assessing the comfort of the thermal environment such as PMV (Predicted Mean Vote) have been developed. Still, the research results are mainly based on light office activities. However, the reality is that people are not always stationary indoors, nor are they limited to light activities such as sitting still, with some reaching moderate or even high-intensity levels of activity. Physical activity is an essential factor in thermal comfort, and the difference in thermal sensation is more significant at different activity levels within the same ambient parameters. Thermo-physiological regulation and heat dissipation patterns differ between humans at higher activity levels and those at lower activity levels. The thermal environment that is comfortable for the human body at higher activity levels will also be different from the typical thermal environment of an office building. Therefore the evaluation methods required will be other. Studies have shown that performing physical work in environments that deviate from comfort increases the probability of absenteeism and minor accidents, making workers less productive (Rou-xi, 2013). When the temperature is high, the efficiency of work, which requires the use of nerve operations and decision-making ability, decreases significantly. In contrast, low temperatures affect the skill of hand operations. Therefore, the creation of a suitable thermal environment is not only an essential function of the building itself but also has a necessary impact on social production and the economy by increasing efficiency and psychological satisfaction. At present, research on the human body in exercise in a thermal environment is mainly focused on heat stress and thermal adaptation. Heat stress research is primarily concerned with the changes in human physiological and biochemical indicators, the change of exercise ability (Bart and Romain, 2010; Racinais and Oksa, 2010; Jincheng and Aiping et al., 2012; Golbabaei and Zakerian et al., 2014), and how to reduce the heat stress in sports (Dugas and Jonathan, 2011; Siegel and Maté et al., 2011; Diqun, 2013; Xihe and Renwei et al., 2016; Zhaohuan and Fenghua et al., 2017) virtually. Thermal adaptation research pays more attention to the adaptive changes in physiological and biochemical indicators after a period of adaptive training in a specific thermal environment (Chalmers and Esterman et al., 2014; Dileo and Powell et al., 2016; Neal and Corbett et al., 2016), and less attention to the changes in psychological hands such as thermal sensation. It is because many factors influence the human thermal sensation and energy consumption during exercise, in which there are very complex physical processes, physiological responses, and psychological changes.

1.2 Research Statement

With the development of technology, indoor temperature regulators such as air conditioners and electric heaters have become essential appliances in homes and provide year-round temperature adjustment to a comfortable range(Chan L. S, 2005; Wan and Chao, 2002; Zhang et al., 2007). However, the thermal sensation and the comfort of the human body often change significantly because of changes in environmental conditions or the different activities in the building. For example, in a fitness center, if the indoor thermal environment is set to a comfortable or slightly warmer when people are in a static state, the thermal sensation caused by exercise is intensified, sweat sooner, fatigue earlier, and comfort is reduced. This unsuitable environment may cause extra body energy expenditure when performing high-intensity exercise. Therefore, it is important to study the exercise thermal sensation in-depth to control the thermal environment effectively.

Thermal comfort metrics can be categorized as either environment-based (Table 1.1), or physiology-based (Table1.2). Environment-based metrics typically require as inputs the air and surrounding temperatures, air velocity, clothing thermal resistances, humidity, as well as any other contributing factors to heat transfer to and from the body (e.g., solar loading).

Physiology-based comfort metrics require as inputs the thermo-physiological response to the environment, usually skin temperature, core temperature, evaporation rate as well as the rates of change of skin and core temperature.

Table 1. 1 Examples of Environment-based Comfort Metrics

Environment-based Metric	**Publication**
Predicted Mean Vote (PMV)	Fanger1970
Predicted Percent Dissatisfied (PPD)	Fanger1982
Equivalent Temperature (EHT)	Wyon et al., 1989

Table 1.2. Examples of Physiology-based Comfort Metrics

Physiology-based Metric	**Publication**
Wettedness as a comfort metric	Gagge, 1969
Dynamic Thermal Sensation (DTS)	Fiala et al., 2003
Berkeley Comfort Model	Zhang et al.， 2009

Accurate thermal comfort assessment requires comprehensive analysis of the environmental effects contributing to the heat transfer to and from the human body. A common comfort evaluation approach (e.g., PMV/PPD, Equivalent Temperature) is to find a direct correlation of comfort to environmental conditions (e.g., air temperature, relative humidity, clothing), thus implicitly accounting for the relationship between physiological response and thermal comfort. An alternate approach (e.g., Berkeley Comfort Model, Fiala's DTS) explicitly correlates comfort to basic physiological response (e.g., skin and core temperature), thereby separating the thermal analysis portion of the problem from the more subjective comfort analysis portion. It has been shown that comparable results can be obtained between environment-based comfort metrics and physiology-based comfort metrics; the latter should be employed for optimal prediction accuracy. This work falls into the latter category.

1.2.1. Physiological indicators and thermal sensation at a static state

There are two common directions in which human thermal sensation and thermal comfort are often assessed and discussed: one is to study thermal sensation by exposing the body to specific thermal environments (e.g., different temperatures, humidity, thermal radiation, and air velocities). The other is to establish an intrinsic relationship with thermal sensation from the viewpoint of human physiological parameters. This work falls into the second category. Based on the human heat balance equation, Fanger(Fanger, 1967) established the prediction model of thermal sensation, proposed the PMV (Predicted Mean Vote), and found the regression equation between thermal sensation and heat load, metabolic rate, and body surface area. An increasing number of studies explore the relationship between changes in physiological mechanisms and the thermal sensation(Bai-Zhan et al., 2006; Huizenga et al., 2001). In addition to studying the subjective feelings of the human body, physiological parameters, and subjective feelings are also combined(Du et al., 2014; Zhu et al., 2012; Zhu et al., 2016). Choi et al.(Choi and Loftness, 2012) investigated the possibility of using human skin temperature to assess thermal sensation. Xiong et al.(Xiong et al., 2016) studied the physiological and biochemical responses of humans to temperature steps and showed that oral temperature, skin temperature, heart rate, and heart rate variability are sensitive to temperature step changes. Luo et al. (Luo et al., 2016)described the modified equation of metabolic rate change, which can provide a useful reference for thermal comfort research. Most of the studies above were conducted based on individuals with a low activity level (sitting). However, people are not always static indoors, and different levels of activity affect the human thermal sensation and thermal comfort in indoor thermal environments.

1.2.2. Physiological parameters and thermal sensation in exercise

1.2.2.1. Metabolic rate and exercise thermal sensation

From the viewpoint of heat transfer, the various factors that affect human thermal comfort and thermal sensation are influenced by the heat transfer methods such as evaporation, convection, and radiation between the body and the surrounding thermal environment, affecting human thermal comfort and thermal sensation. Among these influencing factors, air temperature, relative humidity, air velocity, mean radiation temperature, metabolic rate, and garment thermal resistance are the indicators that researchers are most concerned about. The metabolic rate is the most frequently occurring parameter in the study of thermal sensation in exercise.

McNall et al.(McNall and Jaax et al., 1967) found a modulating effect of metabolic rate, i.e., at lower metabolic rates, relative humidity on the thermal comfort and thermal sensation is less affected. However, as the metabolic rate increases, the effect of relative humidity on the body becomes more magnificent. These findings apply to a comfortable temperature range. Goto et al. (Goto et al., 2006) investigated the changes in physiological parameters and subjective responses caused by changes in metabolic rate. Thermal sensations began to increase or decrease immediately (within 1 min) after a change in metabolic rate, suggesting that a transient change in metabolic rate affects thermal sensations. After about 15-20 min of exercise, the subjective thermal response was very similar to that at steady state, and thermal sensation and skin temperature could be stabilized. The body's metabolic rate can reach stability after 5 min of sustaining the same activity level. They also proposed a model to estimate the transient thermal sensation after metabolic changes. Hasan et al. (Hasan et al., 2016)showed the application of the human-in-the-loop sensor data of wearable devices to provide continuous feedback for the averaged metabolism value of building occupants. However, the metabolic rate changes over time with exercise. In the current study, the metabolic rate determination was relatively complicated and not very accurate. The use of the metabolic rate to predict thermal sensation in daily exercise is difficult and inconvenient.

1.2.2.2. Other physiological parameters and exercise thermal sensation

Li et al.(Li et al., 2018) considered that the temperature of the skin on the wrist and its jet lag and heart rate could be used to estimate the human thermal sensation with high accuracy for different activities. Research by Zhang et al. (Zhang et al., 2020)revealed a specific relationship between thermal sensation votes and physiological indexes. The human body typically takes 3–5 min to reach a new metabolic level after walking and 4–5 min to return to a normal sedentary state after exercise.

Choi et al. (Choi et al., 2012)believe that the heart rate is significantly related to the human metabolic rate and maybe a potential parameter that directly (or indirectly) affects the cause of thermal comfort. The purpose of the research by Wang et al. (Wang and Hu, 2016)is to understand better the real thermal sensation of individuals performing moderate activities. They found that the thermal sensation of the subjects was related to sweat activity. As the activity intensified, the subjects expected higher air velocity. Thermal stress has been involved in previous studies(Golbabaei et al., 2014; Meeusen and Roelands, 2010; Racinais and Oksa, 2010). Nielsen et al. (Nielsen B, 1979) noted that the human preferred comfortable skin temperature decreases with increasing activity (heat production), while preferred skin moistness increases linearly with activity. The main concerns are the changes in the physiological and biochemical indexes of the human body in exercise in a specific thermal environment and the exercise capacity. Previous studies have proposed different views on the effects of heart rate, sweat, etc. on the exercise thermal sensation. However, a more accurate and sensitive measurement of sweat lacks in them. Besides, heart rate, as an important cardiac function parameter, can characterize the metabolic rate under certain circumstances. Can HRV, which is closely related to HR, also responds to thermal sensation?

1.2.3. About the model of the exercise thermal sensation

Tan et al.(Tan et al., 2017) studied the thermal sensation of people who alternated between sedentary exercises and walking on a treadmill at 20 and 25 °C. The experimental results show that when the thermal sensation does not reach a steady-state, PMV is not suitable for predicting the thermal sensation of active individuals. Gagge et al. (Gagge et al., 1969a)studied the relationship between activity levels and the human thermal sensation and thermal comfort under different working conditions. They believe that warmth discomfort is principally related to skin sweating and conductance and is affected either by air temperature and metabolism or by both skin and rectal temperature. The "two-node model" was first proposed by Gagge (Gagge et al., 1971). The SET (Standard Effective Temperature) is an indicator of thermal sensation based on Gagge's model. Gagge et al. (Gagge et al., 1969) conducted a study on four male subjects, and kept them under different temperature conditions, gradually changing from resting to different activity levels. Studies have shown that subjects reached new and stable levels of thermal sensation and thermal comfort 20-30 minutes after a change in activity status. The Fiala model is another more widely used multi-node thermal sensation model. The body is viewed as consisting of 20 spherical and cylindrical body elements with a total of 340 nodes. The model had been used in 90 different thermal environments (temperatures ranging from 5-50°C) and at different exercise intensities (0.8- 10mets), with good agreement with the empirical data(Fiala et al., 1999, 2001). Also, Fiala, in his Ph.D. thesis(Fiala, 1998), obtained a regression-based model of dynamic thermal sensation (DTS). The DTS model includes a term, as a function of the core temperature weighted by the skin temperature, accounting for effects associated with exercise and warm body core temperatures. In the exercise thermal sensation model, researchers have tried to establish the relationship between physiological parameters and thermal sensation using various methods. It had also been noted that thermal sensation adjusts and changes accordingly after a change in exercise status. However, over a relatively short period of time after a change in exercise status, it is unclear how the relationship between detailed changes in physiological indicators and changes in thermal sensation, and whether these detailed changes affect the prediction model.

In terms of the disciplines involved, this work involves multiple disciplines such as exercise physiology, psychology, and architecture. It is an interdisciplinary study.

1.3 Research Questions

1. Physiological parameters adjust and change accordingly after a change in exercise state, which affects thermal sensation. For example, after a change from static to exercise, the physiological parameters may stabilize after a period of time, but what about the shorter period of time before stabilization? Do these subtle changes affect the prediction of exercise thermal sensations? How does the short time after exercise stops, when physiological parameters are in an unstable adjustment phase, affect thermal sensation changes? What are the implications of these for predicting thermal sensation after exercise?

2. Metabolic rate is a common and important measure in the study of exercise thermal sensation. However, the measurement of metabolic rate is complex, and the results are difficult to obtain accurately. Therefore, it is difficult and inconvenient to use the metabolic rate to predict thermal sensation during usual exercise. For practical applications, is it possible to use physiological parameters closely related to metabolic rate and can be easily measured (e.g., with wearable devices), and relate these parameters to thermal sensation to predict thermal sensation? This has important practical implications for the future use of smart bracelets to monitor exercise thermal sensation.

3. In previous studies, the sweating rate and heart rate have impacted exercise thermal sensation. However, the actual measurement of sweating is difficult. Electrodermal activity (EDA) can accurately monitor sweating. Also, heart rate variability (HRV) is closely related to cardiac function. Is it necessary to observe the relationship between the two and the thermal sensation of exercise? There is currently no research on this topic.

4. Are psychological factors significant in the research of exercise thermal sensation?

1.4 Research Objectives

This work is an attempt to observe changes in physiological parameters (using wearable devices) and human thermal sensation (comfort) in common moderate-intensity exercise (e.g., construction sites, gyms, or urban fitness trails), especially before and after a change of exercise status, and to establish a link between the two.

The specific research objectives are:

1. To provide a systematic and detailed overview of the basic concepts, methods, and models related to thermal sensation (in static and exercise) and point out that the dynamic-static steps are inescapable problems in the study of exercise thermal sensation. Examines physiological parameters changes throughout the exercise process (static-dynamic-static), especially around dynamic-static steps.
2. To establish a link with the exercise thermal sensation using physiological parameters closely related to metabolic rate and can be easily measured. The predictive effects are compared.
3. To examine the relationship between physiological parameters that have not been covered in previous studies and exercise thermal sensation, consider the influence of gender, BMI, and psychological factors on exercise thermal sensation.

1.5 Scope of Research

The scope of the research is listed below:

- Considering the practical application of this work, the intensity level is chosen as moderate exercise intensity. In other words, it is the common intensity of people's work, physical exercise, and so on.
- To avoid the interference of excessive environmental factors, this work was chosen to be performed in a controlled climate chamber. The ambient temperature and humidity are set to comfortable conditions for the human body in a static state.
- Subjects were college students of all grades from the same geographical area. They were of similar age and had similar thermal adaptability and thermal experience. However, children and the elderly were not used as subjects.

1.6 Research Outlines

CHAPTER 1:

This chapter aims to explain the background of the study together with problem statement of research. Moreover, the objective and the scope of study are also explained in this chapter.

CHAPTER 2:

Basic terminology related to thermal sensation in the human body is explained in detail and the six important factors that influence thermal sensation. A review of relevant research is also presented. To date, dozens of models of human thermal sensation have been developed. These models can be roughly divided into four categories. In this chapter, representative classical models of thermal sensation are reviewed. The history of famous indicators such as PMV, SET, PET, and UTCI is also reviewed. In Chapters 2 and 3, the effects of changes in external environmental parameters on human physiological parameters and thermal sensation are discussed. Still, under such conditions, the human body is mostly at a static or low metabolic level. Then the human body's thermal sensation in exercise needs further elaboration.

CHAPTER 3:

Four criteria for thermal comfort have been proposed under a static state: a comfortable core temperature, a comfortable skin temperature, a comfortable sweating rate, and a heat load close to zero. However, when used to reflect the true exercise thermal sensation, its feasibility is questionable. This chapter reviews the effects of physiological parameters on thermal sensation when the human body is in exercise. The three physiological parameters closely related to exercise thermal sensation are skin temperature, core temperature, and sweating rate. This also provides a reference for the selection of physiological parameters in experiments. At present, the research on the models of human thermal sensation in exercise can be divided into two categories: one is the research on the accuracy of predicting human thermal sensation using existing models in exercise in a specific thermal environment. The other is to construct a new model according to the exercise's specific characteristics to predict the thermal sensation and verify the model's accuracy by comparing it with the actual thermal sensation. This chapter reviews some of the typical exercise thermal sensation models. The study of thermal sensation models in this work falls into the second category.

CHAPTER 4:

To further study the changes in physiological parameters and thermal sensations in different states of the human body, an experiment was performed with a set of dynamic and static steps. Examines physiological parameters changes throughout the exercise process (static-dynamic-static), especially around dynamic-static steps. Besides, changes and differences in thermal sensation and thermal comfort were observed throughout the experiment by gender and BMI range.

CHAPTER 5:

In this chapter, first, the Stolwijk and Fiala models are reviewed, and the importance of the rate of change of physiological parameters in predicting thermal sensation is explained. A mathematical model was then constructed using original physiological indicators measurement data and the rate of change of physiological indicators, respectively, and the simulation results were compared. Finally, a linear correlation analysis between physiological indicators and subjective perceptions was performed.

CHAPTER 6:

In this work, some physiological indices and thermal comfort have shown some peculiar variations in the experiment. It is, therefore, necessary to explain and discuss these peculiarities in more detail. An attempt was made to analyze the relationship between the HRV index and the thermal sensation of exercise using a "force-directed graph" method; discuss in detail the reasons why the oral temperature drops slightly at the beginning of exercise and continues to rise after exercise; examine the relationship between TSV, TC, EDA, and SFI using linear regression; and discuss the psychological factors that influence the thermal comfort after exercise.

CHAPTER 7:

This chapter first summarizes the core issues of this study and briefly describes the main research work. The overall conclusions of this work are then presented. Since the experiments were conducted in a steady-state environment and moderate exercise intensities were chosen, it is necessary to explain the study's limitations. Finally, a brief explanation of the subsequent research ideas is presented, aiming to contribute to urban fitness trails' rational planning in China.

The chapter names and basic structure of this study are shown in Fig.1.2.

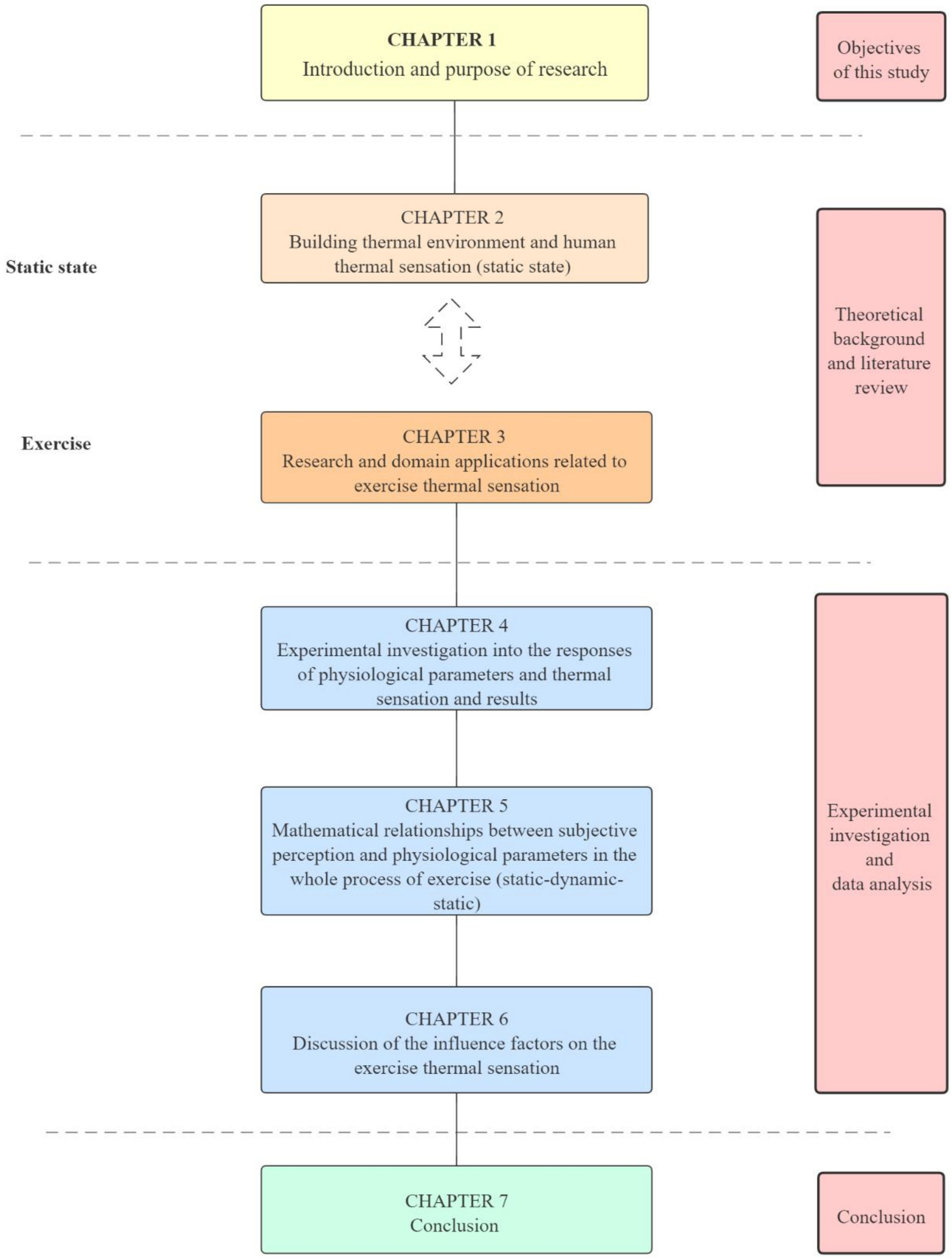

Fig.1.2 Research Outline

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CHAPTER 2

BUILDING THERMAL ENVIRONMENT AND HUMAN THERMAL SENSATION (STATIC STATE)

2.1. Relevant concept 2-1
  2.1.1 Thermal environment 2-1
  2.1.2. Heat stress 2-1
  2.1.3 Thermal adaptation 2-2
  2.1.4 Thermal sensation and thermal comfort 2-3
  2.1.5 Relationship between thermal environment, heat stress, thermal adaptation, and thermal sensation 2-4
  2.1.6 Human thermal balance 2-4
2.2. Factors influencing thermal sensation 2-7
  2.2.1. Air temperature 2-7
  2.2.2 Humidity 2-8
  2.2.3 Air velocity 2-9
  2.2.4 Mean radiation temperature 2-9
  2.2.5 Metabolic rate 2-11
  2.2.6 The clothing factor 2-12
  2.2.7 Other factors 2-15
2.3 Overview of human thermal sensation models 2-17
  2.3.1 The Fanger model 2-17
  2.3.2 The Gagge model 2-19
  2.3.3 The COMFA model 2-21
  2.3.4 Multi-layered multi-node model 2-23
  2.3.5 The Rayman model 2-26
  2.3.6 Wet-bulb globe temperature 2-27
2.4 Evaluating human thermal sensation 2-27
  2.4.1 Thermal sensation scale 2-28
  2.4.2 Skin temperature 2-29
  2.4.3 Human core temperature 2-30
  2.4.4 Heart rate variability 2-31
  2.4.5 Metabolic rate 2-31
  2.4.6 Electroencephalogram(EEG) 2-31

2.4.7 Electromyogram(EMG) *2-32*
2.4.8 Sweating rate *2-32*
2.5 Summary *2-34*
References *2-36*

This chapter explains in detail the basic terminology related to thermal sensation, as well as the six critical influences that affect thermal sensation. A review of relevant research was also presented.

2.1. Relevant concept

2.1.1 Thermal environment

Human beings are always surrounded by their environment, of which four indicators - temperature, relative humidity, thermal radiation, and air velocity - together constitute the "thermal environment" of our daily lives. The impact of the external thermal environment on the human body has attracted the attention of various research fields. In the area of the built environment, the thermal sensation and comfort of the human body in a specific thermal environment is the focus of the researchers. In sports, the effects of the thermal environment on the human body are more complex than in normal conditions. In the field of kinesiology, current research topics related to the thermal environment are mainly focused on heat stress and thermal adaptation during exercise.

2.1.2. Heat stress

Hong and Yan et al. believe that heat stress is a systemic, comprehensive physiological response of the body to the thermal environment (Hong and Yan et al., 2004). It is manifested as increased respiratory rate, increased heart rate, cerebral congestion, pulmonary edema, increased oxidative metabolism in the body, disturbed water and electrolyte balance, and increased urination. These nonspecific physiological responses are exacerbated in the exercise state and are manifested in three main areas: high brain temperature, high muscle temperature, and dehydration (Hong and Yan et al., 2004). However, some scholars believe that heat stress should not only be reflected in physiological indicators but also psychological parameters and exercise capacity. Liu et al. think that heat stress refers to the body's reaction to environmental stimuli when exposed to a thermal environment, which is manifested in both physiological and psychological aspects (Liu and Zheng, 2014). The psychological factors include thermal sensation, thermal comfort, and sweat feeling, and so on.

There has been a lot of research on heat stress in sports. For example, Peter et al. compared the differences in cerebral blood flow in athletes in endurance sports of the same intensity at 39.5°C and 20°C and showed that cerebral blood flow velocity decreased and cerebral blood flow supply was reduced by about 18% at 39.5°C compared to 20°C (Tikuisis and Mclellan et al., 2002). Golbabaei used 32 football players as the subjects studied the effects of heat stress on exercise capacity at four different intensities of exercise (50, 100, 150, 200 w) in summer at a combined temperature index of 21°C and 33°C, respectively. It was found that there were significant differences in oxygen consumption and heart rate at different temperatures, regardless of exercise intensity. The authors suggested that the ambient temperature should be kept below 35°C to avoid the risks associated with heat stress (Golbabaei and Zakerian et al., 2014). Zhou compared the difference in energy consumption during 50 min of aerobic exercise in two thermal environments (high temperature and high humidity, standard temperature and humidity), and found that the energy consumption during exercise was 1.52% higher in the high temperature and high humidity set (Yi and Fan, 2015). These studies indicate that excessive ambient temperature can have a significant impact on the various physiological parameters during exercise, and the heat stress produced during exercise can be exacerbated compared to the normal state.

2.1.3 Thermal adaptation

Thermal adaptation is a series of adaptive reactions of the organism to the thermal environment under repeated thermal effects over a long period (Wei-Bing and Ren-Wei et al., 2013). It is manifested by the gradual improvement of the body's reflex regulation function to heat, and various physiological processes reach a new level. In sports, heat acclimatization is a protective physiological response of the organism to withstand high temperature and resist thermal damage gradually established under the repeated action of thermal stimuli. It can relieve the physiological tension caused by the high-temperature environment, improve the body's exercise ability, and reduce the occurrence of training injuries and excessive fatigue. Chalmers' comprehensive study of eight articles of literature found that long-term heat acclimatization training increases athletes' performance across the board, while short-term heat acclimatization training is more effective for sports that are dominated by aerobic energy supply. It may be achieved a more relaxed subjective feeling during exercise through cardiovascular, thermoregulation, and metabolic rate, as well as by reducing anaerobic energy supply and elevating the lactate threshold to reduce fatigue during exercise (Chalmers and Esterman et al., 2014). Burk found that significant reductions in core temperature, heart rate, skin temperature, and body heat storage when athletes engaged in moderate-intensity exercise at 42°C after 10 days of thermal adaptation training with 21 young men (Burk and Timpmann et al., 2012). Wu used eight middle-distance runners as subjects to observe the changes in various physiological parameters of the body after exercise during ten days of thermal adaptation training. The results showed that the core temperature and heart rate gradually decreased, exercise sweating capacity increased, sweat electrolyte ion concentration decreased significantly, and the post-exercise heat shock protein level increased significantly, which indicated that the 10-day acclimatization training enabled the athletes to establish an effective thermal adaptation(Wei-Bing and Ren-Wei et al., 2013). These studies suggest that a period of thermal adaptation can be useful in altering the level of heat stress in exercise in a thermal environment.

2.1.4 Thermal sensation and thermal comfort

The traditional belief is that thermal sensation is a subjective description of whether the environment is "cold" or "hot" (Hu and Ding, 2007) In reality, however, the body does not feel the ambient temperature directly, but only the stimulation of the nerve endings located under the surface of skin. Therefore, the surrounding thermal environment is only an essential factor in thermal sensation, but the thermal sensation is not exclusively dependent on the surrounding thermal environment. For example, in winter, if you wear enough clothes, you will still subjectively feel hot, but the surrounding thermal environment is cold. So, thermal sensation is the human body's ability to perceive its thermal state, which is influenced by the thermal environment, clothing, metabolic rate, and psychological factors. Conceptually, "thermal sensation" belongs to the scope of psychology(Hu and Ding, 2007), which studies the relationship between sensation and physical stimuli, belongs to "psychophysics", which is one of the earliest branches of psychology. Its purpose is to artificially regulate the thermal environment around the human body, such as the use of air conditioning, natural ventilation, and other means to change the thermal setting in a specific space to create a comfortable thermal environment outside the human body. Therefore, the concept of "thermal comfort" is often used in this field to indicate the level of satisfaction with the thermal environment (Concepts, 2014). However, current research on thermal sensation is almost exclusively in the field of built environment and ergonomics. In these studies, the evaluation of thermal comfort is usually composed of various levels of thermal sensation, such as the 7-point scale of thermal sensation used by Fanger et al., which classifies the degree of thermal sensation into seven levels, from low to high: cold, cool, slightly cool, neutral, slightly warm, warm, and hot.

There are different views on the concepts of "thermal sensation" and "thermal comfort", and some authors, such as Fanger (Fanger, 1998) and Gagge (Gagge, 1981), believe that thermal comfort and thermal sensation are the same. In other words, if the thermal sensation is neutral, it is thermal comfort, or the area corresponding to -1, 0, +1 on a 7-point thermal sensation scale (slightly cool, neutral, slightly warm) is called a thermal comfort zone. Another view, represented by Cabanac, Hensel et al. and Zhao Rongyi (Rongyi, 2000), is that thermal comfort and thermal sensation have different meanings. Thermal comfort does not exist in a steady-state thermal environment, but only during specific dynamic processes, and that thermal comfort is not persistent. Despite the controversy, it is still evident that both thermal sensation and thermal comfort are concerned with heat transfer between the human body and the surrounding thermal environment from the perspective of heat transfer. Thus there is a mutual reference between the two studies. Also, in the fields of architecture and ergonomics research, the purpose of research is usually to study issues related to human thermal comfort in a specific situation, while the actual measurement content is often the measurement of thermal sensation.

2.1.5 Relationship between thermal environment, heat stress, thermal adaptation, and thermal sensation

The relationship between thermal environment, heat stress, thermal adaptation, and thermal sensation can be better understood by looking at the above concepts. During exercise, the combined effects of exercise and the thermal environment can lead to heat stress in the human body. Heat stress is a systemic response of the human body, and changes in thermal sensation and energy expenditure are both manifestations of heat stress during exercise. Thermal adaptation is the adaptive change of the human body to the thermal environment under repeated thermal effects over a long period, i.e., through thermal adaptation, the body can reduce the heat stress in a specific thermal environment. As shown in Figure 2.1.

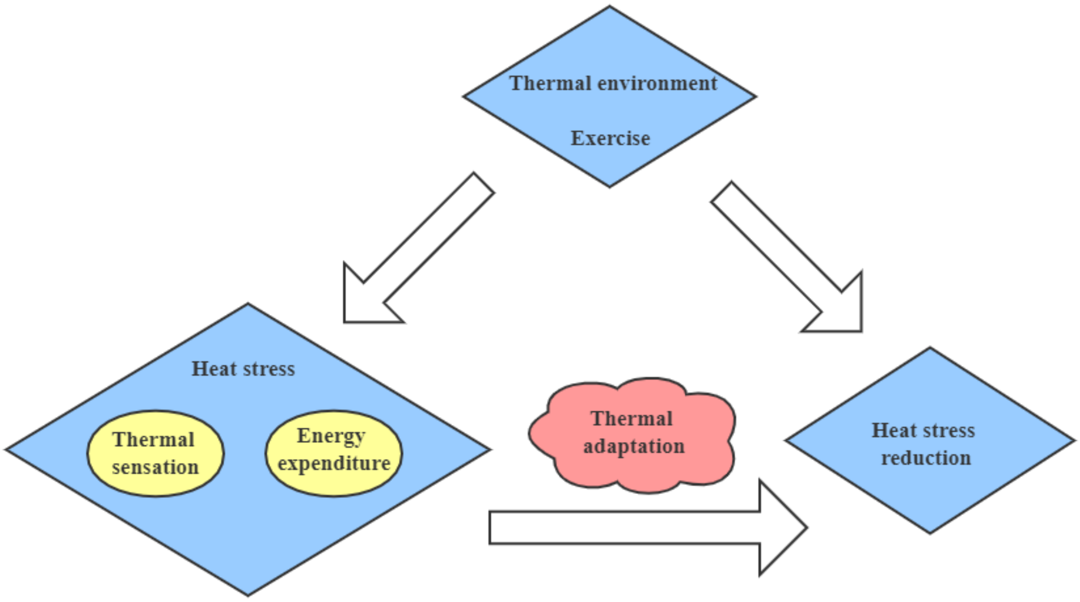


Fig.2. 1 Relationship between thermal environment, heat stress, thermal adaptation, and thermal sensation

2.1.6 Human thermal balance

From the perspective of heat transfer, the human body is regarded as a thermal system, and the energy exchange between the body and the environment follows the law of energy conversion and conservation, i.e., the energy gained by the system minus the energy lost is equal to the energy stored inside the system. As shown in Figure 2.2. According to this principle, the body can establish the equation of thermal balance. No matter what state the human is in, it follows the equation of the thermal equilibrium of the human body. Various models of human thermal sensation are also based on the equation of thermal equilibrium of the human body. The equation of thermal equilibrium of the human body is as follows.

$$M - W = C + R + E_{sk} + C_{res} + E_{res} + S$$

Where, M is the metabolic rate, the concept of "metabolic rate" is often used in the field of heat transfer, but in the field of physiology, the term "energy consumption" or "metabolic equivalent" is more commonly used. They all refer to the energy produced over time through the body's internal energy supply system, but the units differ. The unit of metabolic rate is Watt, metabolic equivalents are METs, and energy expenditure is J.

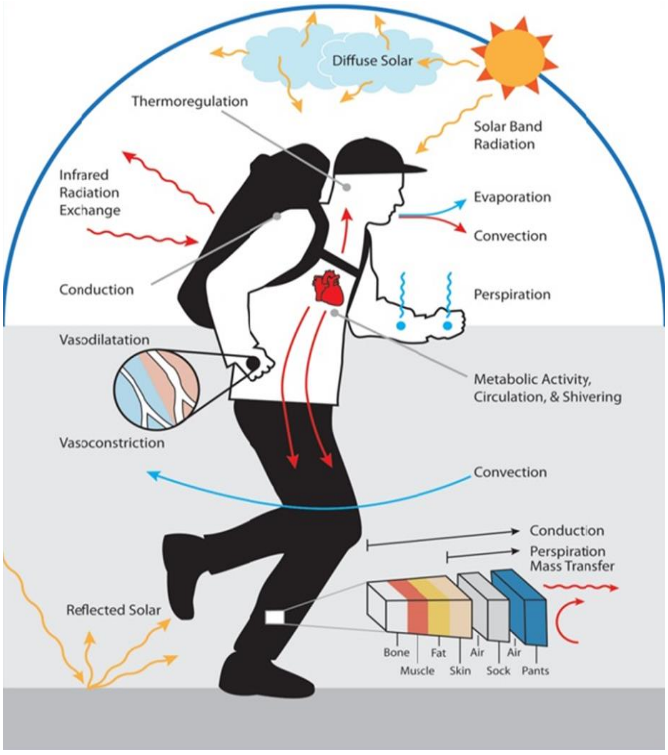


Fig.2. 2 Heat transfer of human body (CLIMATEMEDADMIN, 2020)

W is the energy transferred through the work done by a muscle, i.e., mechanical work. The resistance that a muscle overcomes in performing work includes both internal and external resistance of the muscle. Therefore, the work done by the muscle is accordingly divided into internal and external work. The muscles overcome the external resistance, such as lifting a heavy object, and do external work when the energy of the muscle contraction is transferred to the potential energy of the object. If the muscle work is done to make the body move, it is transformed into kinetic energy of physical movement. Muscle work done by muscles is usually referred to as the external work done by muscles, i.e., mechanical work. The magnitude of the mechanical work done by a muscle depends on the tension produced during muscle contraction and the change in muscle length, the latter being a factor that affects the distance involved in the work done by the muscle.

R is thermal radiation, which is the phenomenon of an object radiating electromagnetic waves due to its temperature. All objects with a temperature higher than absolute zero can produce thermal radiation; the higher the temperature, the greater the total energy of radiation, the more short-wave components. The general thermal radiation mainly by the longer wavelength of visible light and infrared transmission. During sports, heat is usually radiated outwards due to the high body temperature, which is often higher than the temperature of the surrounding objects and environment.

C is convective heat, a process by which the hotter and colder parts of a liquid or gas become homogeneous through a cyclic flow between them. Convection is a unique way of heat transfer in liquids and gases and is more pronounced in gases than in liquids. Convection can be divided into natural convection and forced convection, increase the flow rate of liquid (or gas), can accelerate the convective heat transfer. During exercise, as the surface of the human skin is in contact with the surrounding air, and the relative velocity of flow between the human skin and the air is much higher than in the normal state, convective dissipation occurs and is more pronounced.

E_{sk} is evaporative heat dissipation from the skin. In the thermal balance of the human body, there are two ways to evaporate heat dissipation, namely, insensible perspiration and sweating. E_{dif} is insensible perspiration. Before sweating, when the ambient temperature is low, although the human body does not sweat, but the water in the body will be vaporized, and the water will be evaporated into water vapor and through the skin to dissipate heat. E_{sw} is sweating to dissipate heat, when the ambient temperature is high, the body starts to sweat, and the evaporation of sweat causes heat dissipation.

C_{res} and E_{res} are heat losses due to respiration. The heating or humidification of inhaled air and the loss of heat during respiration through the heating of saliva, causing it to change from a liquid to a gas.

S is the body's heat storage. The value depends on the relationship between the amount of heat produced and heat lost by the body. When the human body is in thermal equilibrium, i.e., the amount of heat produced by the body is equal to the amount of heat lost, $S=0$, the body is in a neutral state. When the body has more heat than it loses, $S>0$, the thermal sensation will shift to the hot side. When the body produces less heat than it fails in a period, $S<0$, thermal sensation turned to the cold side.

In particular, note that for each term in the equation, the sign is positive if the body gains heat and negative if it loses body heat.

2.2. Factors influencing thermal sensation

From the perspective of heat transfer, the various factors that affect human thermal comfort and thermal sensation are influenced by heat transfer through evaporation, convection, and radiation between the human body and the surrounding environment. Among these influences, six factors - air temperature, relative humidity, air velocity, mean radiant temperature, metabolic rate, and garment thermal resistance - are some of the indicators that are of most interest to researchers today (Fig.2.3).

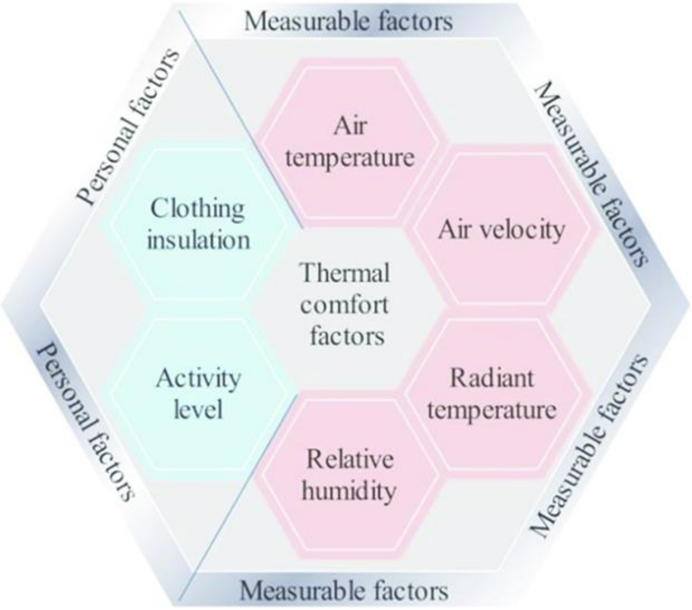


Fig.2. 3 Factors influencing thermal comfort (sensation) (Godbole, 2018)

2.2.1. Air temperature

Many people believe that temperature is the main factor influencing thermal comfort and thermal sensation. Natasha (Natasha and Warland et al., 2009) investigated the actual thermal sensation of runners in an outdoor situation with 27 subjects. He used multiple regression to explore the factors influencing thermal sensation, with predictor variables including gender, age, weight, clothing breathability and thermal resistance, air temperature, radiant temperature, shortwave radiation received and emitted, longwave radiation emitted, air velocity, and metabolic rate. The results indicate that the top three of these predictor variables with the most significant influence on thermal sensation were gender, radiation temperature, and air temperature. Indraganti (Indraganti, 2010) found a linear regression function relationship between indoor temperature and thermal comfort by fitting a linear regression function relationship between temperature and thermal comfort. There was a linear correlation between indoor temperature and both predicted thermal sensation (PMV) as well as actual thermal sensation (AMV) in the presence of natural ventilation, in the range of 26°C-32.45°C. The temperature can explain 86.1% of the variation in PMV and 42.1% of the variation in AMV. Nicol investigated the relationship between temperature and thermal sensation in naturally ventilated buildings in Europe and buildings in tropical hot and humid regions, respectively, and developed linear regression equations. Although not identical, both showed the importance of temperature on thermal sensation and thermal comfort effects (Nicol, 2004; Nicol and Humphreys, 2010). Also, Kenshalo (Kenshalo, 1970) found that thermal sensation depended on the rate of air temperature change (ΔT), but there were inter-individual differences in rate thresholds.

Air temperature is generally measured using thermocouples, semiconductor thermistors, and semiconductor integrated temperature sensors. Besides, mercury thermometers or alcohol glass thermometers can also measure air temperature. Still, their values are affected by radiation when there is a radiation source in the room and corrected by the following equation.

$$t = (1 - g)t_a + gt_r$$

Where, t_a is the thermometer reading, °C; g is the radiation influence coefficient, $g=1/(1+1.13v^{0.6}d^{0.4})$; and t_r is the mean radiation temperature, °C.

2.2.2 Humidity

Humidity is the amount of moisture in the air. The relative humidity of air is the ratio of the actual moisture content of the air to the water vapor content of saturated air at a given temperature and pressure (Lin and Zhan, 2005). Air humidity directly affects the evaporative heat dissipation from the skin, affecting the thermal comfort and thermal sensation. Commonly used methods of expressing humidity include relative humidity RH, absolute humidity d, and water vapor partial pressure Pa (Hui and Lijuan et al., 2016) . The effect of humidity on human thermal comfort and thermal sensation has been studied since the 1920s. 1923, Houghten and Yaglou first studied thermal comfort in humans under different combinations of temperature and humidity and based on this, and they proposed the "effective temperature" (Houghten, 1923). There is a controversy about the effect of humidity on thermal comfort and thermal sensation. Koch conducted an experimental study on human thermal comfort in the thermal environment range of 20-34°C and 20%-90% relative humidity. The result showed that relative humidity on thermal sensation is small in the high-temperature environment (Koch and Jennings et al., 1960). Dong et al. found that when the ambient temperature is moderate (15.5-26.5 ℃), the influence of air relative humidity on human thermal sensation is not enormous; every 50% change in air relative humidity, the impact on human thermal sensation is similar to the air temperature change of 1 ℃ (Zhang, 1995). Nevins studied 72 different temperature and humidity conditions of human thermal sensation. The results show that the influence of relative humidity on human thermal sensation is small, every 10% decrease in relative humidity, which is equivalent to a 0.3°C increase in air temperature (Nevins, 1966). All of these studies concluded that humidity has a small effect on thermal comfort and thermal sensation. Other studies, however, have concluded that humidity has a more significant impact on thermal comfort and thermal sensation. McNall found a modulating effect of metabolic rate, i.e., at lower metabolic rates, air relative humidity has less impact on thermal comfort and heat sensation, but as metabolic rate increases, the effect of air relative humidity becomes more generous. Still, these findings only apply to a comfortable temperature range (McNall, 1967). Tian's results showed that when the ambient temperature is ≥28°C, and relative humidity is ≥70%, humidity significantly affects thermal sensation and thermal comfort (Tian and Xu, 2003). The measurement of humidity mainly includes dry and wet bulb thermometers, hair thermometers, LiCl moisture-sensitive components, and polymer humidity sensors (A. and Bravo et al., 1993). The polymer humidity sensor is divided into capacitive and resistive, which has the characteristics of small error and fast response. It is usually considered that the distribution of humidity in a specific space is relatively uniform, so the humidity value of a point can be used to represent the average level of humidity in the area.

2.2.3 Air velocity

Air velocity will affect the body's convective heat dissipation and skin evaporation heat dissipation, reducing skin surface moistness and skin surface temperature, affecting thermal comfort and thermal sensation. When the human feels hot, a moderate increase in the air velocity around the body can not only improve the heat transfer coefficient between the skin surface and the environment but also accelerate the evaporation of sweat on the skin surface. Rapidly reduce the moistness of the skin surface, and the skin surface temperature can make the thermal sensation subsided. However, if the air velocity is too high, the evaporation rate of sweat will increase too fast, resulting in a cold feeling. In summary, excessive airflow speed can make the human body feel cold, and air velocity is too low will affect the human body to cool down. Tucker (Tucker and Marle et al., 2006) showed that the air velocity on the skin surface during high-intensity exercise could significantly alter the actual thermal environment in which the athlete is exposed, thus affecting the thermal sensation during exercise. The typical instruments used to test air velocities are hot-wire anemometers and hot bulb anemometers, which have the advantage that they can measure wind velocities in different directions. Still, they are not accurate enough at low air velocities.

2.2.4 Mean radiation temperature

The mean radiation temperature is the average temperature of the radiation effect of the environment on the human body. The radiative heat exchange between the body and the inner surface of the enclosure depends on the temperature of each surface and the relative position of the body to the surface. Thermal radiation includes the solar radiation (which heats the body) and the exchange of heat between the human body and the surrounding environment in the form of radiation. Thermal radiation is present between any two objects of different temperatures. Thermal radiation is unaffected by air velocity and always radiates from the higher-temperature object to the lower-temperature object until the temperatures of the two items are equal. Many studies have shown the importance of the average radiation temperature on thermal sensation and thermal comfort. Yang's sensitivity analysis of the factors affecting thermal sensation showed that air temperature has the most significant effect on human thermal sensation, followed by the mean radiation temperature and wind speed, and relative humidity has the weakest impact on thermal sensation (Lin, 1998). Wang's analysis of the variables affecting thermal sensation in a residential thermal environment also showed that the most significant variables during the winter heating period in a severe cold region of China were air temperature, mean radiant temperature, and clothing thermal resistance and their interactive effects (Zhao-Jun and Le-Ming, 2004). Kenny et al. showed that the most influential thermal sensation factors in the outdoor running were gender, radiation temperature, and air temperature (Kenny and Warland et al., 2009). These studies have demonstrated the importance of the effect of radiation temperature on thermal sensation and thermal comfort.

For the calculation and measurement of the mean radiation temperature, the mean radiation temperature was first discovered and proposed by Davie (Davies, 1978) in 1978. The first algorithm for the mean radiation temperature was proposed by Walton(Walton, 1980) in 1980, after which Maloney (Maloney, 1986) modified Walton's algorithm and proposed the BLAST software for radiation heat transfer. Zmeureanu (Zmeureanu and Fazio et al., 1988) revised Maloney's radiative heat transfer model again by introducing favorable terms for different surface coefficients. In 1991, Athienitis et al. (Athienitis, 1991) proposed a model for indoor radiant heat transfer. Later, Sanchez et al. (Sanchez and Bravo et al., 1993) developed a two-dimensional indoor radiation heat transfer model, and Chapman et al. (Chapman and S et al., 1995) further developed a three-dimensional radiation heat transfer model, which can be used to calculate the radiation heat transfer between any two surfaces indoors. The more commonly used method of calculating the average radiant temperature is the black-ball thermometer method and calculation method. The black-ball thermometer method is a thermometer mercury sphere in the center of a 15 cm diameter, black hollow copper sphere to measure the temperature. It reflects the thermal radiation of the environment and is suitable for measuring mean radiant temperature in both indoor and outdoor environments. The custom method consists of the following two primary ways (Hui and Lijuan et al., 2016):

1) Calculation of the mean radiant temperature from the wall temperature of the surrounding maintenance structure.

$$\sigma(\mathrm{t_r} + 273)^4 = \mathrm{B_1F_{p-1}} + \mathrm{B_2F_{p-2}} + \mathrm{B_nF_{p-}}_{n}$$

Where, B_1, B_2, B_n for the significant radiation of the wall, defined as a surface of its radiation of energy and other surfaces of the sum of reflected energy, W/m^2. F_{p-1}, F_{p-2}, and F_{p-n} is the human body and the surface n of the angular plane coefficient.

2) Calculation of mean radiation temperature from planar radiation temperature.

The mean radiant temperature can be calculated in a similar way to the planar radiant temperature. Planar radiation temperature is the thermal radiation in a specific direction, and the mean radiation temperature can be regarded as the common effect of thermal radiation in all directions on the body. According to this principle, the mean radiation temperature can be calculated according to the six directions (front, back, left, right, up, down) of the planar radiation temperature and the body in these six directions of the projected area coefficient. The mean radiation temperature for different human postures is calculated as follows.

Standing:

$$\mathrm{t_r} = \frac{0.08[t_{pr}(\mathrm{up}) + t_{pr}(\mathrm{down}) + 0.23[\mathrm{t_{pr}}(\text{ right }) + \mathrm{t_{pr}}(\text{ left })] + 0.35[t_{pr}(\text{ front }) + \mathrm{t_{pr}}(\text{ back })]}{2(0.08 + 0.23 + 0.35)}$$

Sit up:

$$\mathrm{t_r} = \frac{0.18[t_{pr}(\mathrm{up}) + t_{pr}(\mathrm{down}) + 0.22[\mathrm{t_{pr}}(\text{ right }) + \mathrm{t_{pr}}(\text{ left })] + 0.3[t_{pr}(\text{ front }) + \mathrm{t_{pr}}(\text{ back })]}{2(0.18 + 0.22 + 0.3)}$$

2.2.5 Metabolic rate

The human body is a source of heat, and it generates more heat during activity than when it is resting. Especially during exercise, the metabolic rate is several times higher than usual, and the effect of the metabolic rate on thermal sensation and thermal comfort will be significantly increased. Physiologically, an increase in exercise intensity triggers the thermal stress and thermoregulatory systems, affecting thermal comfort and thermal sensation. Shibasaki et al. (Shibasaki and Wilson et al., 2006) showed that muscle contraction during exercise produces more heat, which affects thermal sensation. The metabolic rate is greater, the more heat produced by muscle contraction, and the higher the thermal sensation. Mora (Mora-Rodriguez and Del Coso et al., 2008) compared the differences in body heat production and heat dissipation between seven subjects at varying exercise intensity (1.5 min of 90% VO_{2max} and 4.5 min of 50% VO_{2max} alternating shifts for 90 min) and fixed exercise intensity (Constant 60% VO_{2max} for 90 min) in a thermal environment with a temperature of 36°C, relative humidity of 29%, air velocity of 2.5 m/s. These subjects were subjected to endurance exercises and thermal adaptation training. Total metabolic heat production was found to be approximately the same between the two exercise modalities. Still, core temperature, heart rate, and heat load were higher at varying exercise intensities than fixed exercise intensities. Prefrontal skin blood flow was lower, and sweating and water loss were higher. These results indicate that at the same total metabolic heat production, exercise at varying intensities produces a more significant heat load and a higher thermal sensation than exercise at a fixed intensity. Besides, a higher metabolic rate leads to greater psychological changes, affecting thermal sensation, as Havenith (Mora-Rodriguez and Del Coso et al., 2008), who showed that psychological changes at high metabolism lead to increased heat tolerance. Liu found that metabolic rate has a significant effect on thermal sensation, with the PMV index accurately predicting thermal trend at a low metabolic rate, but not at a high metabolic rate. There is a large bias in predicting human thermal sensation at high metabolic rates (Rongxiang, 2010). The influence of psychological factors on thermal comfort will be described in detail in a later section.

The measurement of metabolic rate is often difficult. During exercise, the body is powered by three major systems, namely, the phosphorogenic system, the glycolytic system, and the aerobic energy system. The first two systems are anaerobic and rely on them for instantaneous exertion, while slow exertion depends mainly on aerobic energy supply. Therefore, in most sports, both anaerobic and aerobic energy supply is present. The energy produced in these ways cannot be measured directly, only indirectly through oxygen, carbon dioxide, or other indicators of physical activity. These indirect indicators have not been able to predict the metabolic rate during different sports accurately. However, the energy consumption and metabolic rate generated during exercise can be measured by gas metabolism instruments such as the Cosmed $K4b^2$ during specific modes of practice, e.g., running within a certain speed range. The most commonly used method to calculate the metabolic rate in exercise is by estimation. Ainsworth et al. (B E and W L et al., 2000) estimated and classified a variety of sports and their corresponding metabolic equivalents, resulting in a physical activity level metabolic equivalency table, which is widely accepted in the field of human health and sports science.

2.2.6 The clothing factor

Clothing is the second layer of "skin" for heat exchange between the human body and the outside. In the process of the heat balance of the human body, clothing mainly plays the role of keeping warm and preventing moisture diffusion, increases heat convection and water exchange, plays the role of interface between the body and the surrounding environment, and plays a vital role in influencing the thermal sensation of the human body. When the body is maintained at room temperature, 10% of the heat generated by the body is lost through respiration, and 90% is lost through skin and clothing. The exchange of heat and humidity between the human body and the external environment mainly occurs through convection, conduction, radiation, and evaporation. Clothing can carry out heat and humidity regulation between the human body and the environment, forming a micro-climate between the human body and the clothing, thus changing the human thermal sensation and thermal comfort. For example, a study of office workers by Humphreys (Rev. and Humphreys, 1994) found that despite the massive difference in average indoor temperatures between summer and winter, most people were comfortable with the hot indoor environment, mainly due to changes in clothing. In 1941, Gagge (Gagge and Burton et al., 1941) and others studied the effect of garment regulation on skin temperature. They proposed the garment insulation index. Its physical meaning is the ratio of the temperature difference between the two sides of the garment layer, and the heat flow perpendicular to the unit area through the garment ($m^2 \cdot °C/W$). It reflects the insulating and warming capacity of the garment. It defines the insulating value of a garment worn by a sedentary or lightly mentally active human being in a thermally neutral state in a standard thermal environment as 1clo. In 1962, Woodcock (Woodcock and A., 1962) proposed the clothing moisture permeability index **im** in the study of moisture transfer in textile materials and clothing. And the physical significance is the ratio of the water vapor pressure difference between the two sides of the clothing layer and the evaporative heat flow perpendicular to the unit area through the clothing ($m^2 \cdot Pa/W$). These two metrics lay the foundation for clothing research, which is known as garment thermal resistance and hot suit moisture resistance.

The reference values for the thermal resistance of clothing are usually derived from data obtained from static dummy measurements while being in a specific external thermal environment, i.e., no airflow (air velocity) or experimental conditions maintained at a low wind speed (Havenith and Holmér et al., 2002). Jones(Jones, 2002) suggested that the thermal resistance values obtained at low wind velocities produce large errors when applied to high wind velocities. Therefore, Kenny et al. (Kenny and Warland et al., 2009) proposed a formula for calculating the thermal resistance of clothing during a physical activity at different wind speeds, the formula is as follows.

$$r_c = r_{co}(-0.37\left(1 - exp^{-\frac{V_{ac}}{0.72}}\right) + 1)$$

Where, $r_{co}$is the static garment thermal resistance, due to the number of factors influencing the garment thermal resistance, accurate estimation is difficult. In recent years, researchers mainly based on the ISO7730 standard and ASHRAE55 standard provides a list to estimate the static garment thermal resistance. v_{ac} is the body activity velocity, v_{ac} applies to the calculation of garment thermal resistance under dry conditions, first proposed by Havenith (Havenith and Heus et al., 1990) and Nielsen (Nielsen and Olesen et al., 1985), who found that air velocity does not reduce garment thermal resistance, but even at lower activity velocities, garment thermal resistance is reduced to a large extent.

Besides, Zhou Xiang's (Xiang and Mei et al., 2003) study also showed that the exercise, in addition to the air velocity and the activity speed, that is, the existence of relative velocity between the human body and the air, will significantly reduce the thermal resistance of clothing. The following formula can estimate the value of thermal resistance.

$$I_{cl} = 0.496 I_{cl^0} + 0.24 - 0.00281 v_{\omega}$$

Where, I_{cl} is the actual thermal resistance of the garment in motion; I_{cl}^0 is the static garment thermal resistance. v_{ω} is the relative velocity between the body and air during the move.

Similar to clothing thermal resistance, the measurement of evaporative resistance of clothing was obtained from static “biothermal manikin” at low or no air velocity. According to Havenith et al. (Havenith and Heus et al., 1990), the maximum reduction in evaporative resistance during physical activity compared to static was about 80%. The specific relationship between clothing evaporative resistance during exercise and static is as follows.

$$r_{cv} = r_{cvo}\left(-0.80\left(1 - exp^{-\frac{v_r}{1.095}}\right) + 1\right)$$

Where, r_{cvo} is the static evaporative resistance of clothing, v_r is the relative air velocity calculated according to the wind speed and activity speed, v_r applies to the calculation of evaporative resistance; by Havenith (Havenith and Heus et al., 1990) and Havenith first proposed, they found that the wind speed and activity speed will have a significant impact on the evaporative resistance of clothing, static evaporative resistance of clothing query ISO9920 table can be seen.

Differences in the color of clothing can also affect thermal sensation. Nielsen (Nielsen, 1990) measured the difference in solar radiation on human heat load between subjects wearing black (reflectance 0.28) and white (reflectance 0.45) clothing after 60 min of outdoor cycling and found that the mean skin temperature MT_{sk} was 3 to 4 times higher in black clothing compared to white. Kenny (Kenny and Warland et al., 2009) also found that the heat load was more significant on dark surfaces, with an average change in thermal radiation of 115 to 157 W/m^2 for garments with reflectance in the range of 0.21 to 0.57. The average change in thermal radiation was 0.21 to 0.57 W/m^2.

2.2.7 Other factors

In addition to the six main factors that affect the thermal sensation mentioned above, several other factors can also have an impact on thermal sensation. According to Jones' study(Jones, 2002), the most significant limitation of the thermal sensation model is the accuracy of the relationship between thermal sensation and thermal environmental variables as well as human physiological variables, especially in outdoor situations, where this uncertainty is particularly pronounced, i.e., it is still not possible to accurately predict the actual thermal sensation of the human using the above six factors (Johansson and Emmanuel, 2006). Among other studies of factors affecting thermal sensation, Jones (Jones, 2002), Hoppe (Hoppe, 1984), Nikolopoulou (Nikolopoulou and Lykoudis, 2006), Metje (Metje and Sterling et al., 2008), and Knez (Knez and Thorsson et al., 2009)have shown that anticipation of the weather affects actual thermal sensation in humans.

Nikolopoulou (Nikolopoulou and Lykoudis, 2006) collected more than 10,000 questionnaires and corresponding meteorological data to investigate individuals' psychological evaluation of the thermal environment and showed that recent experiences and expectations of the weather could cause a difference of more than 10 degrees in thermal sensation, with a comfort range of 17.6 and 13.5°C in spring and autumn, and 5.9 and 9.6°C in summer and winter. Of course, the clothing factor also plays an essential role in this regulation. Besides, psychological factors such as psychological adaptation, seasonal changes, sensory control, and the amount of time spent in the environment can affect human thermal sensation. A study by Knez et al. (Knez and Thorsson et al., 2009) found that comfort in outdoor activities was significantly correlated with ambient temperature and sunny weather. Although, in some cases, the thermal environment was not objectively comfortable.

Also, it has been shown that age factors may affect human thermal sensation, with younger people being more heat receptive than older people in the same thermal environment (Knez and Thorsson et al., 2009). However, it has also been suggested that although the basal metabolic rate decreases gradually with age, the evaporation rate of skin surface sweat also decreases slowly with age. That is, the body's heat production and heat dissipation reduce simultaneously so that the effects due to age cancel each other out (Hui and Lijuan et al., 2016).

Many studies have shown that gender factors may also affect human thermal sensation. Tanabe's research showed that the neutral temperature was 1°C higher in women than in men. Environmental changes had a more significant effect on thermal sensation in women than in men(Tanabe and Kimura et al., 1987). Modera (Modera, 1993) tested the difference in skin temperature between men and women at the same intensity of exercise. The results showed that the optimal ambient temperature for women was 1.2°C lower than that for men when the exercise intensity was higher.

The optimal ambient temperature was the same when the exercise intensity was lower. The study by Nevins (Nevins and Gonzalez et al., 1975) measured a neutral temperature of 25.5°C for females and 26.1°C for males. The slope of the linear regression between thermal sensation and temperature was 0.37 units/k for females and 0.3 units/k for males, indicating that females are more sensitive to changes in temperature than males.

Studies by Dear (Richard J De Dear, 1998), Fanger (Fanger and Toftum, 2002), and Yao (Yao and Li et al., 2009) all found a deviation between the PMV indicator and the actual thermal sensation in Fanger's model. They suggest that this deviation is mainly due to a combination of factors such as geographic location, gender, age, climate adaptation, ethnicity, and anticipation of the weather. Considering the combined effect of these factors, they proposed the concept of modified PMV (aPMV). For example, Yao et al. (Yao and Li et al., 2009) used the "black box" correction model, taking the thermal environmental stimuli as the system input and the observed results as the system output, and found the correction coefficients between the actual and predicted thermal sensations under hot and cold environmental conditions, as shown below.

Under hot ambient conditions： $aPMV = \frac{PMV}{1+0.293\times PMV}$

Under cold ambient conditions： $aPMV = \frac{PMV}{1-0.125\times PMV}$

Before the 1960s, most studies only considered the influence of a single or part of factors on thermal sensation. However, the body does not have specific receptors for each thermal environmental parameter, which can only be expressed through thermoreceptors and thermally; they regulate skin temperature and blood flow through the hypothalamus. The human body's thermal sensation is affected by thermal environmental factors, and there are complex interactions between different environmental factors. Such as in the low wind speed, the mean radiation temperature and air temperature for the human heat balance almost the same impact, and the high air velocity, air temperature for the human heat balance than the average radiation temperature impact is much greater. It is because the air temperature is the main factor that causes an increase in convective heat exchange. Therefore, only through the establishment of the human thermal sensation model, can we quantify the complex interactions among the various thermal influences and predict the thermal sensory state of the human body in different complex thermal environments. In 1962, Macpherson (Macpherson, 1962) proposed six main factors influencing thermal sensation: air temperature, relative humidity, air velocity, mean radiation temperature, metabolic rate, and clothing thermal resistance. Many scholars have since begun to model human thermal sensation based on these factors and analyze their effects on thermal sensation

2.3 Overview of human thermal sensation models

Up to now, dozens of human thermal sensation models have been born. These models can be roughly divided into four categories: the first category is the Fanger model, focusing on the correspondence between human heat load and thermal sensation, which is the earliest human thermal sensation model. The model proposed a Predicted Mean Vote (PMV) index. The second category is a two-node model. The human body is divided into the core layer and the skin layer of two nodes. Representative models include the Gagge model, MEMI model, and COMFA model. Based on the Gagge model, the Standard Equivalent Temperature (SET) index is proposed, and the Physiological Equivalent Temperature (PET) index is proposed based on the MEMI model. The third type is the multilayer multi-node model, which divides the human body into multiple layers and parts with various nodes. The division form varies, so different thermal sensation models have been generated, including the Stolwijk, Wissler, KSU, Tanabe, Berkeley, and Fiala models. The Universal Thermal Climate Index (UTCI) is proposed based on the Fiala model. The fourth category is a comprehensive model, and a new model is built by integrating the above types of models. The Rayman model is based on the Fanger model and the MEMI model, as in recent years. In this section, we will not go through all the human thermal sensation models one by one but only review the representative models.

2.3.1 The Fanger model

To establish a comfortable indoor thermal environment, Fanger from the Technical University of Denmark developed a predictive model of human thermal sensation based on the human thermal equilibrium equation (Eq. 2-11) in 1967. He investigated the thermal sensation of 1396 subjects from Kansas State University and proposed the PMV (Predicted Mean Vote) evaluation index (Fanger, 1967). He obtained a regression equation between thermal sensation and heat load, metabolic rate, and body surface area (Eq. 2-12).

$$L = M - W - R - C - E_D - E_{\mathrm{Re}} - E_{sw}$$

Where, M is the heat generated by metabolism; W is the rate of work; R is radiation cooling; C is convective cooling; E_D is heat loss from body surface diffusion; E_{Re} is heat loss from respiration; E_{sw} is heat loss from sweat evaporation; L for the human body heat load, reflecting the human body per unit of time per unit area of energy absorbed or produced and dissipated energy rate balance between, L less than 0 means that the heat dissipation rate is greater than the rate of heat production, L greater than 0 means that the heat dissipation rate is less than the rate of heat production. The unit of all terms in the formula is the watt.

$$PMV = [0.303\exp\left(-\frac{0.036\mathrm{M}}{\mathrm{A}}\right) + 0.0275]\mathrm{L}$$

PMV is the predicted thermal sensation value calculated according to the regression equation. L is the human body heat load (watt), M is the metabolic rate (watt), and A is the human body surface area (m^2). The correspondence between PMV and thermal sensation calculated by the Fanger model is shown in Table 2.1.

Table 2. 1 Categorization of PMV for different levels of thermal perception and physiological stress.

PMV	Thermal perception	Grade of physiological Stress
-3	Very cold	Extreme cold stress
-2.5	Cold	Strong cold stress
-1.5	Cool	Moderate cold stress
-0.5	Slightly cool	Slight cold stress
0	Comfortable	No thermal stress
0.5	Slightly warm	Slight heat stress
1.5	Warm	Moderate heat stress
2.5	Hot	Strong heat stress
3	Very hot	Extreme heat stress

Meanwhile, due to differences in thermal sensation between individuals, PMV does not accurately reflect the heat sensation of all individuals. There will be a small number of individuals who are dissatisfied with heat-neutral that are satisfactory to the vast majority of individuals. Thus the Predicted Percentage of Dissatisfied (PPD) index was proposed to indicate the population that is dissatisfied with the thermal environment. A relationship between PPD and PMV was presented as follows.

$$PPD = 100 - 95^{*}\, exp[-(0.03353PMV^{2} + 0.2179)^{*} PMV^{2}]$$

The Fanger model is the earliest model of thermal sensation, which has played a pioneering role in guiding the subsequent research on the thermal sensation model and become the common standard in this field. What is more valuable is that compared with the later models (which focus on the prediction of thermophysiological indicators and ignore the psychological), the Fanger model establishes a regression equation between heat load and thermal sensation by collecting a large amount of experimental data. It takes into account the possible influence of psychological factors on thermal sensation. Although this consideration is in its infancy, i.e., treating psychological factors as a black box, considering only the correspondence between input heat load and output thermal sensation, it is unclear which specific psychological factors influence thermal sensation. Due to the above advantages of the Fanger model, in 1994, the International Organization for Standardization

(ISO) proposed the ISO 7730 standard based on the Fanger thermal sensory model. The standard specifies the environmental elements and control values for high indoor comfort (Dis, 1985) . It has become the internationally recognized gold standard in thermal environments in buildings and research on thermal comfort.

2.3.2 The Gagge model

In 1971, Givoni (Givoni and Goldman, 1971) was the first to propose the single-node model, which treats the entire human body as a node. Still, this model was only developed experimentally and is only suitable for hotter thermal environments. In the same year, Gagge (Gagge, 1971) proposed the "two-node model" for the first time, which divides the human body into a core layer and a skin surface layer, and consists of two subsystems, i.e., the control system and the controlled system. The principle is that part of the heat produced by metabolism in the core layer is dissipated directly into the environment through respiration. The rest is transferred to the surface of the skin. The heat transferred to the surface of the skin is lost by evaporation of sweat, while the rest is transferred to the surface of the garment through the clothing and then lost to the environment by radiation and convection. The thermal equilibrium equations for the core and skin layers are shown in Equations 3-4 and 3-5, respectively, from which skin temperature and skin moisture can be calculated.

$$M_{cr}c_{cr}\frac{dT_{cr}}{dt} = M + M_{sh} - W - Q_{re} - (K + m_{bl}c_{p,bl})(T_{cl} - T_{sk})$$

$$M_{sk}c_{sk}\frac{dT_{sk}}{dt} = (K + m_{bl}c_{p,bl})(T_{cl} - T_{sk}) - Q_{dr} - Q_{ev}$$

Where, M_{cr} and M_{sk} are the core and skin masses of the unit surface (kg), c_{cr} and c_{sk} are the mean specific heat capacity of the core and skin layers (J/kg·°C), T_{cr} and T_{sk} are the temperatures of the core and skin (°C), t is the time (s), M is the metabolic rate of the unit surface (W/m^2), M_{sh} is shivering heat production per body surface area (W/m^2), W is the external mechanical work performed per unit of body surface area (W/m^2), Q_{re} is the respiratory heat loss per unit of body surface area (W/m^2), Q_{dr} is the sensible heat transfer per unit of body surface area to the environment (W/m^2), Q_{ev} is the latent heat transfer per unit of body surface area to the environment (W/m^2), K is the thermal conductivity between the core and skin (W/m^2·°C), m_{bl} is the blood flow between the core and skin (m/s), and $C_{p,bl}$ is the specific heat capacity of the blood (J / m^3·°C).

After solving the skin temperature and skin moisture using the above formula, substituting its value into Eq. 3-6, the Standard Effective Temperature (SET) can be calculated.

$$Q_{sk} = h_{cSET}(t_{sk} - SET) + wh_{eSET}(p_{sk} - 0.5p_{SET})$$

Where, Q_{sk} is the total heat dissipation from the skin,(W/m^2); h_{cSET} is the integrated convective surface heat transfer coefficient considering the sensible heat resistance of the garment in a standard environment,(W/ m^2·°C); t_{sk} is the skin temperature, °C; w is the skin humidity; h_{eSET} is the integrated convective mass exchange coefficient considering the latent heat resistance of the garment in a standard environment, (W/m^2·kPa); p_{sk} is the corresponding saturated water vapor partial pressure at the skin surface temperature, (kPa); p_{SET} is the saturated water vapor partial pressure at SET, (kPa).

SET is an indicator of human thermal sensation based on the Gagge model. It is defined as a person wearing standard clothing (heat resistance is 0.6 clo) in an environment where the relative humidity is 50%, the air is approximately stationary, and the air temperature is the same as the average radiant temperature. If the average skin temperature and skin humidity are the same as under some actual environment and actual garment thermal resistance conditions, the human body will have the same heat dissipation in both the standard and actual environments. The standard ambient air temperature is the standard effective temperature of the actual environment (Gagge and Fobelets et al., 1985). According to the correspondence between the standard effective temperature and human thermal sensation (Table 2.2), we can predict the thermal sensation under different actual thermal environments.

Table 2. 2 Categorization of SET for various levels of thermal perception and physiological stress.

Category	Thermal sensation	Grade of Physiological Stress
<17	Cool	Moderate Hazard
17-30	Comfortable	No Danger
30-34	Warm	Caution
34-37	Hot	Extreme caution
>37	Very Hot	Danger

Smith et al. (SMITH and C. et al., 1991) found that the Gagge model was applicable at moderate exercise intensities and homogeneous thermal environments but had limitations in humans exposed to specific thermal environments for less than 1 hour and in non-homogeneous thermal environments. Hoppe's MEMI model (Munich Energy-balance Model for Individuals), developed in 1984, is also based on the two-node division of the human body and is now widely used in biometeorology. The principle of the MEMI model is based on the equation of heat balance in the human body, plus two equations of the heat transfer process, namely: process equations for heat transfer from the core of the body to the skin (equation 3-7) and from the surface of the skin to the surface of the garment (equation 3-8), coupled with the above three equations, you can solve the clothing surface temperature T_{cl}, skin surface temperature T_{sk} and the body's core temperature, T_c, are the three key indicators that determine the body's thermal sensation and then predict the body's thermal state.

$$F_{cs} = v_b \times \rho_b \times c_b \times (T_c - T_{sk})$$

Where, F_{cs} is the heat from the core to the skin, v_b is the blood flow from the core to the skin (L/s/m^2), which is determined by the grade of skin temperature and core temperature, ρ_b is the density of blood (kg/l), c_b is the specific heat capacity of blood (Ws/K/kg), T_c is the body core temperature (°C), and T_{sk} is the skin temperature (°C).

$$F_{cs} = (1/I_{cl}) \times (T_c - T_{sk})$$

Where, F_{cs} is the heat flowing from the skin surface to the clothing surface, I_{cl} is the clothing thermal resistance (Km^2/W), T_{sk} is the skin surface temperature (°C), and T_c is the clothing surface temperature (°C).

Based on the MEMI model, Hoppe proposes the Physiologically Equivalent Temperature (PET) metric, which is defined as the core and skin temperature of the human body when in an environment equal to that of a standard environment, where the mean radiant temperature is equal to the air temperature, the water vapor pressure is 1200 Pa, and the air velocity is 0.1m/s. At this point, the air temperature in the standard environment is equal to the PET. This is good for translating different actual thermal environments to standard environments and predicting thermal sensations. For example, a person under the summer sun, the air temperature is 30°C, the mean radiation temperature is 60°C, the air velocity is 1m/s, and the water vapor partial pressure is 2100Pa. The PET calculated using the MEMI model is 43°C, which means that the human thermal state is the same as in a standard 43°C environment. The specific evaluation criteria for PET are shown in Table 2.3.

2.3.3 The COMFA model

The COMFA model, proposed by Brown and Gillespie in 1986 (Brown and Gillespie, 1986). The model is based on the two-node theory and the equation of the body's thermal balance, and the four criteria of thermal comfort satisfaction. These are a comfortable core temperature, a comfortable skin temperature, a comfortable sweating rate, and a heat load close to zero. And they conducted experiments under 59 different outdoor natural conditions with different temperature, radiation, and air velocity to investigate the correlation between the calculated value of the model (W/m^2) and the measured thermal sensation, and the results show that the correlation coefficient between the two is 0.91, showing a high correlation. The equations for human thermal equilibrium during exercise in an outdoor thermal environment are shown below.

$$B = M + R_{RT} - C - E - L$$

Table 2. 3 Categorization of PET for various levels of thermal perception and physiological stress.

PET	Thermal perception	Grade of physiological Stress
＜4	Very cold	Extreme cold stress
4~8	Cold	Strong cold stress
8 ~13	Cool	Moderate cold stress
13 ~ 18	Slightly cool	Slight cold stress
18 ~ 23	Comfortable	No thermal stress
23 ~ 29	Slightly warm	Slight heat stress
29 ~ 35	Warm	Moderate heat stress
35 ~ 41	Hot	Strong heat stress
> 41	Very hot	Extreme heat stress

Where, B is the heat load, M is the metabolic heat production transferred to the surface of the body, R_{RT} is the heat absorbed by the body by short-wave and long-wave radiation (such as solar radiation), C is the convective heat dissipation, E is the evaporative heat dissipation, and L is the body's long-wave radiation heat dissipation.

The COMFA model and the MEMI model have in common that they both focus on the clothing surface temperature(T_{cl}), the skin temperature(T_{sk}), and the core temperature(T_c). However, there are significant differences in calculating the metabolic rate and the sweating rate of individuals of different ages and genders. Besides, there are significant differences in body surface area, blood flow density from the core region of the body to the skin, blood density, and blood heat capacity, and differences in these parameters give rise to differences in the calculation of heat flow from the core region of the body to the surface of the skin. For the COMFA model, scholars have applied it to exercise to predict the body's thermal sensation during exercise, and the model has been modified and improved based on this model to incorporate specific features in the exercise.

2.3.4 Multi-layered multi-node model

In addition to the single-node and two-node thermal sensation models, the multi-layered multi-node model is one of the representative thermal sensation models first proposed by Stolwijk and mainly used in the aerospace field. The model adopts the grid division method to divide the human body horizontally from inside to outside into four different layers: the core layer, the muscle layer, the fat layer, and the skin layer. Meanwhile, it divides the human body vertically from top to bottom into six different parts: head, torso, arms, hands, legs, and feet, to analyze the human body layer by layer and part by part (Figure 2.4). Since Stolwijk built a predictive model of thermal sensation based on the physiological structure of the human body and the heat transfer process in each part can be simulated, the model is more accurate than single and two-node models, which is still a milestone even though the model is only applicable in stable thermal environments.

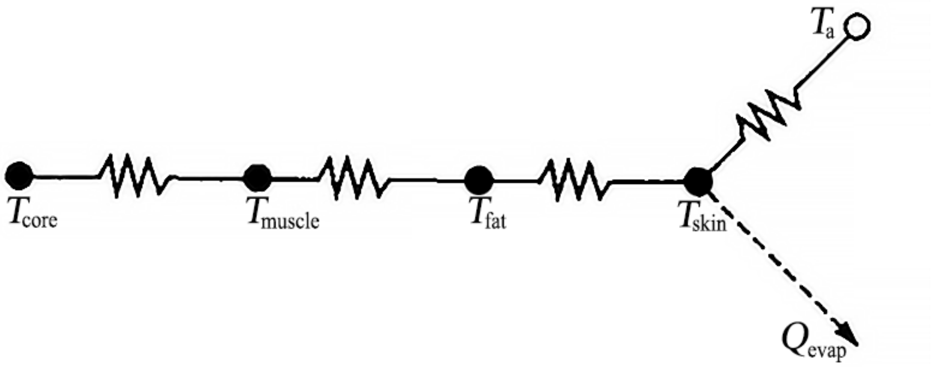


Fig.2. 4 Simplified schematic diagram of the multi-layered multi-node model (STOLWIJK, 1966).

Munir (Munir and Takada et al., 2009) found the Stolwijk model to predict local accurately and mean skin temperatures at low temperatures in a variable thermal environment and low physical activity intensity. However, when the human body is in a high-temperature environment or a state of intense physical activity, radiating heat by evaporation is the primary way to maintain a stable core temperature (Parsons, 2014), which at the same time causes a decrease in the mean skin temperature (Fanger and Toftum, 2002). The calculation of the mean skin temperature in the Stolwijk model does not consider the accumulation of sweat on the skin surface, which results in a lower MT_{sk} calculated by the model compared to the real value. So, using the Stolwijk model to predict the MT_{sk} of a human body during exercise at high temperatures will result in large errors.

The multi-layered multi-node models proposed after this were modifications and refinements of the Stolwijk model (Kuznetz, 1979; Tanabe and Kobayashi et al., 2002). The main difference lies in the improvements and innovations in body division, which also produced several thermal sensation models. For example, Jones (Jones, 2002) divided the human body into 225 finite element nodes and thus established the Wissler thermal sensation model; Smith (SMITH and C. et al., 1991) used more than 3000 limited element nodes to divide the human body into three dimensions and thus invented the KSU thermal sensation model; based on the Stolwijk model, Tanabe divided the human body into 4 layers of 16 parts with 65 nodes, including head, chest, back, pelvis, shoulders, arms, hands, thighs, calves, feet. The blood system is added to the body's core layer to analyze the role of blood circulation in the body's physiological and thermal regulation, and radiation analysis and computational fluid dynamics (CFD) analysis are also added.

The results show that the model can predict the thermophysiological parameters of "thermal manikin" in a complex thermal environment with high accuracy. Thus the Tanabe thermal sensation model is established. Huizenga (Huizenga and Hui et al., 2001) considered the body as composed of infinite parts and divided the body into five layers: the core layer, the muscle layer, the fat layer, the skin layer, and the clothing layer, and evaluated the effects of blood flow, sweating, and metabolic rate on the thermal sensation of a sedentary population in a complex thermal environment. It shows that the classification method had good accuracy under different thermal environments, and thus the Berkeley thermal sensation model was established (Figure 2.5).

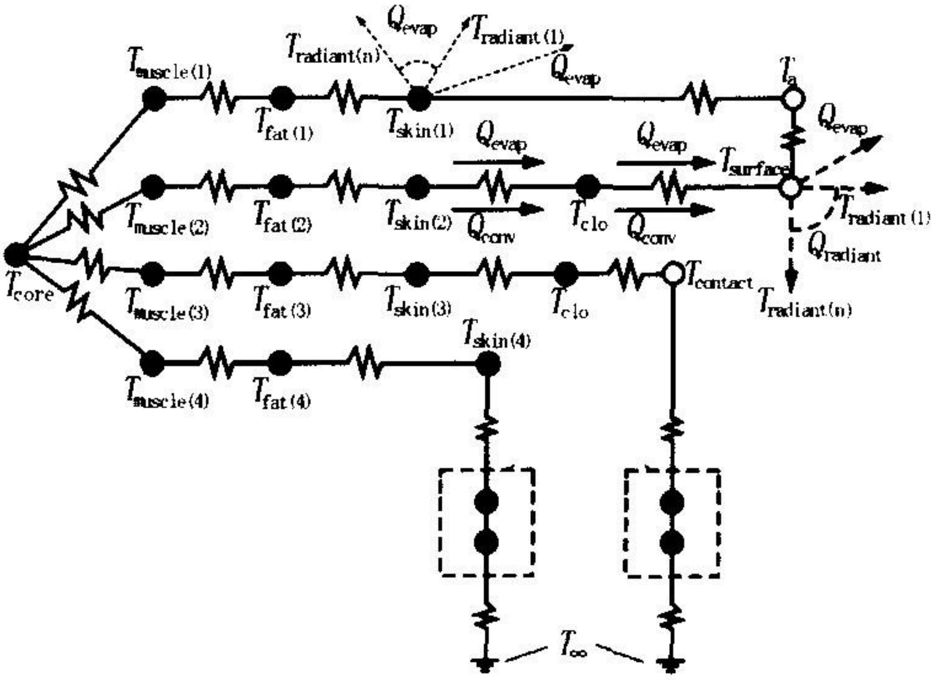


Fig.2. 5 Schematic diagram of the Berkeley thermal sensation model.

The Fiala model is a widely used multi-node thermal sensation model based on the Stolwijk model (Figure 2.6). The model consists of two interacting systems, the passive control system, and the active control system. The body consists of 20 spherical and cylindrical body elements with a total of 340 nodes. The passive system partially simulates heat exchange in the human body and between the body surface and the surrounding environment, surface convection, directional radiation exchange, evaporation and moisture transfer from the skin, and local differences non-uniform distribution of clothing.

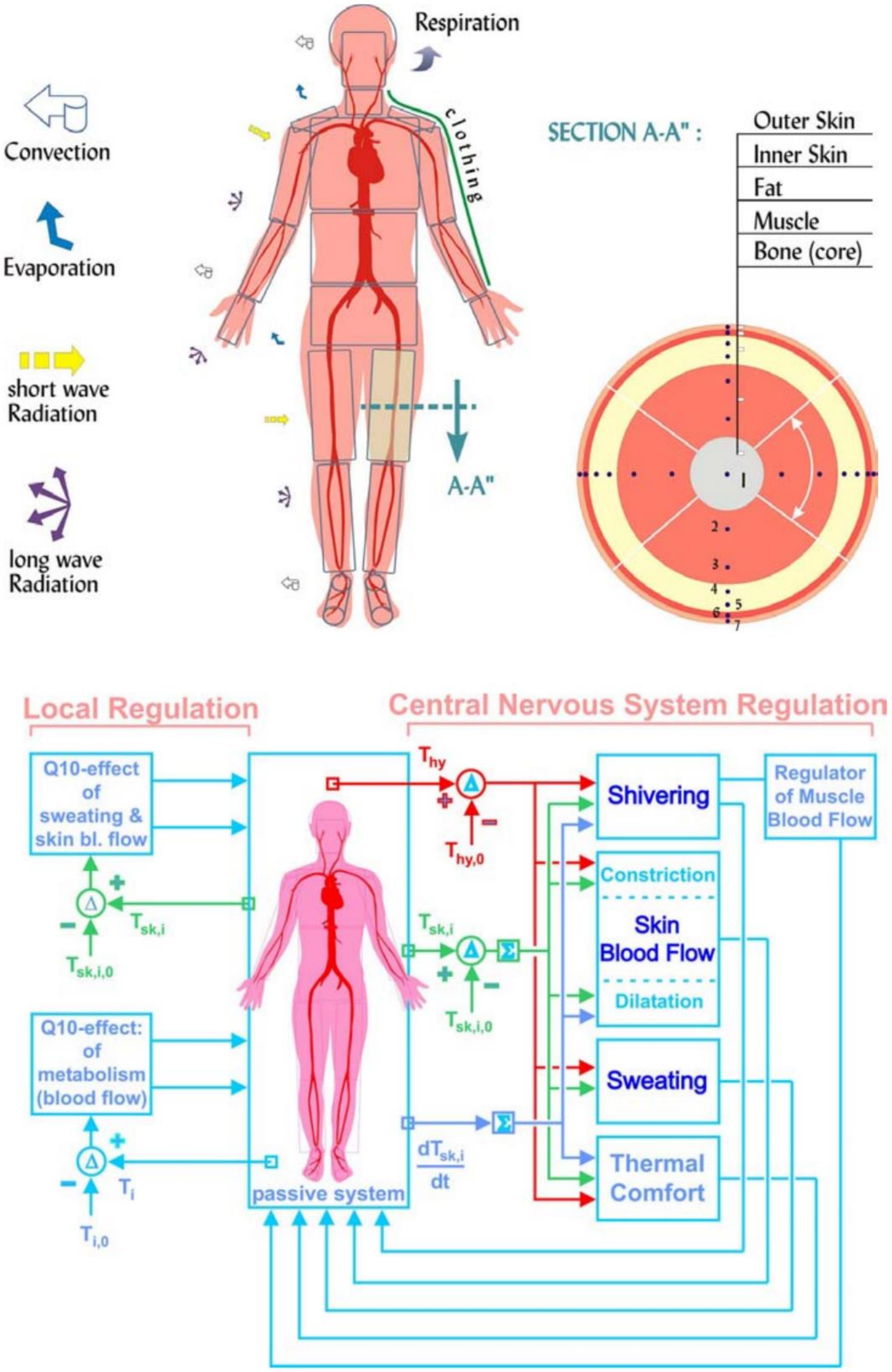


Fig.2. 6 Schematic diagram of the Fiala thermal sensation model (Fiala and Psikuta et al., 2012)

The active system simulates complex human physiological phenomena in four ways: vasoconstriction, vasodilation, shivering and sweating (Dusan and Lomas et al., 1999). Cheng et al. concluded that the Fiala model is more accurate at different metabolic rates, even at very high exercise intensities. This, coupled with the fact that it can be applied in non-stationary thermal environments, makes it a compelling thermal sensation model (Cheng and Niu et al., 2012). It has been shown that the Fiala thermoregulation model has good consistency with empirical data in 90 different thermal environments (temperatures ranging from 5-50°C) and at different exercise intensities (0.8-10mets), both in steady-state and transient thermal environments (Fiala and Lomas et al., 2001).

Since 2000, the International Society of Biometeorology (ISB) has organized the development of the UTCI based on the Fiala model to develop an indicator for predicting weather extremes, mapping biometeorology, and planning urban development in the field of biometeorology. The correspondence between the UTCI and thermal sensation is shown below.

Table 2. 4 Thermal sensation and different groups of UTCI.

UTCI range (℃)	Stress Category
Above +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress
+9 to 0	Slight cold stress
0 to -13	Moderate cold stress
-13 to -27	Strong cold stress
-27 to -40	Very strong cold stress
Below -40	Extreme cold stress

2.3.5 The Rayman model

The Rayman model was developed by Matzarakis et al. based on a combination of the Fanger model and the MEMI model to reflect the human body's thermal state using two thermal sensory predictors, PMV and PET (Matzarakis and Rutz et al., 2010). Lin found that the Rayman model could accurately predict hourly PET and mean radiant temperature (Lin and Matzarakis et al., 2010). Pezzoli (Pezzoli and Cristofori et al., 2012) used the Rayman model to perform a detailed analysis of field thermal sensations in cyclists to prevent possible adverse effects of climatic conditions at the World Road Cycling Championships on athletes. With the analysis of PMV and PET indicators throughout the exercise, he found patterns of variation in thermal sensation and related physiological parameters in cyclists at different exercise stages.

2.3.6 Wet-bulb globe temperature

WBGT was developed by Yaglou and Minard in 1957 and is regarded as one of the main experimental indices for measuring heat stress (Yaglou and Minard, 1957). It can be used to assess heat stress both indoors and outdoors. Depending on where a person is, different variables, including natural wet temperature, radiation temperature, and metabolic rate, are used in calculating this index. For indoor spaces, natural wet temperature and bulb globe temperature are utilized in calculating this index, while, for outdoor spaces, dry temperature is also taken into account. Table 2.5 provides necessary recommendations for being involved in outdoor activities according to WBGT values (Blazejczyk et al., 2012).

Table 2. 5 Necessary recommendations for outdoor activities according to WBGT values.

WBGT (°C)	Recommended sporting activity
<18	Unlimited
18-23	Keep alert for possible increases in the index and for symptoms of heat stress
23-28	Active exercise for unacclimatized persons should be curtailed
28-30	Active exercise for all but the well-acclimated should be curtailed
>30	All training should be stopped

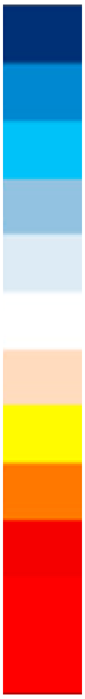
Comparing thermal perceptions of UTCI, SET, PET, PMV, PPD, and WBGT according to standard values for each index. Table 2.6 presents comparison of thermal perceptions based on the abovementioned indices.

2.4 Evaluating human thermal sensation

The use of appropriate evaluation methods to evaluate thermal sensation accurately is the basis for in-depth research on thermal sensation. It also directly affects the evaluation and creation of thermal environments in actual situations. The evaluation methods of thermal sensation include thermal sensation scale method, skin temperature method, metabolic rate method, heart rate variability method, electromyography method, EEG method, sweating rate method, etc.

Table 2. 6 Comparing thermal perceptions in various bioclimatic indices (Blazejczyk et al., 2012)

Thermal perception	Indices				
	UTCI	WBGT	SET	PMV	PET
Very cold[1] (Txtreme cold stress[1,2])	< -40			-3	< 4
(very strong cold stress[2])	-40 to -27				
Cold[1] (Strong cold stress[1,2])	-27 to -13			-2.5	4 ~ 8
Cool[1,3] (Moderate cold stress[1,2]/ Moderate Hazard[3])	-13 to 0		<17	-1.5	8 ~ 13
Slightly cool[1] (Slight cold stress[1,2])	0 to +9			-0.5	13 ~ 18
Comfortable[1,3] (No thermal stress[1,2]/ No Danger[3,4])	+9 to +26	< 18	17~30	0	18 ~ 23
Slightly warm[1] (Slight heat stress[1])				0.5	23 ~ 29
Warm[1,3,4] (Moderate heat stress[1,2]/ Laution[3,4])	+26 to +32	18 ~ 23	30~34	1.5	29 ~ 35
Hot[1,3,4] (Strong heat stress[1,2]/ Extreme caution[1,4])	+32 to +38	23 ~ 28	34~37	2.5	35 ~ 41
(very strong heat stress[2])	+38 to +46				
Very hot[1,3,4](Extreme heat stress/ Danger[3,4])	>+46	28 ~ 30	> 37	3	＞41
Sweltering[4] (extreme danger[4])		>30		-3	



[1]PET and PMV [2]UTCI [3]SET [4]WBGT

2.4.1 Thermal sensation scale

The thermal sensation scale is a simple and convenient method to obtain human thermal sensation and has been widely used in thermal sensation study. Fanger (Fanger, 1967) first used a 7-level scale in his 1967 thermal comfort model, Table 2.7.

Table 2. 7 Fanger 7-Point Scale

Thermal sensation	cold	cool	slightly cool	neutral	slightly warm	warm	hot
PMV	−3	−2	−1	0	+1	+2	+3

Based on Fanger's 7-point scale, Spagnolo et al.(Spagnolo, 2003) concluded that the three thermal sensations of slightly cool (-1), neutral (0), and slightly warm (+1) could be combined into thermal neutral, but only if the subject could accurately describe their thermal sensations. As in Table 2.8.

Table 2. 8 Spagnolo 5-Point Scale

Thermal sensation	hot	warm	neutral	cool	cold
PMV	+2	+1	0	−1	−2

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) introduced the TSENS index in 2009, which classifies thermal sensation into 11 levels, as shown in Table 2.9.

Table 2. 9 TSENS 11-Point Scale

TSENS	extreme cold	very cold	cold	cool	slightly cool	neutral	slightly warm	warm	hot	very hot	extreme hot
Thermal sensation	−5	−4	−3	−2	−1	0	+1	+2	+3	+4	+5

2.4.2 Skin temperature

It has been found that changes in physiological parameters caused by thermoregulatory activity can effectively reflect thermal sensation in the human body. Bulcao et al. argued that thermal sensation depends largely on skin temperature and is closely related to heart rate, sweating rate, and core temperature (Bulcao and Frank et al., 2000). Yao pointed out that the actual thermal sensation depends directly on the skin temperature, and that the change in human thermal sensation is achieved through the changes of the temperature receptors under the skin, and the actual thermal sensation change is more significant when the temperature change (ΔT) is fast (Yao and Lian et al., 2007). Wang's study found that finger skin temperature or finger-forearm skin temperature difference could be used to reflect thermal sensation in humans (Wang and Hui et al., 2007). However, Liu's study showed that the correlation between mean skin temperature and the thermal sensation was strong when there was no significant sweating but weakened when there was significant sweating when the ambient temperature increased, or the metabolic rate increased (Guodan and Feng et al., 2014).

However, skin temperature varies between parts of the body and between individuals. Stolwijk (Stolwijk and Hardy, 2011), Sakoi (Sakoi and Tsuzuki et al., 2007), and Munir(Munir and Takada et al., 2009) suggesting that differences in mass, volume, and blood flow in various parts of the body are responsible for differences in skin temperature. Besides, there is a significant difference in skin temperature between men and women. It has been shown that heart rate and local skin temperature are higher in men because their metabolic rate is approximately 11% higher than in women(Yao and Lian et al., 2007) (Parsons, 2014). Stolwijk (Stolwijk and Hardy, 2011) and Parsons (Parsons, 2014) studied the thermal conductivity, blood flow, and heat production of various body parts (head, trunk, arms, hands, legs, feet) and the tissues of each part (core, muscle, fat, skin) and found that blood flow and heat production were highest in the center of the trunk. A study by Munir et al.(Munir and Takada et al., 2009) found that the standard deviation (SD = 1.4°C) of the skin temperature of the feet in the seated position was the largest in thermal neutral, followed by the abdomen (SD = 0.8°C). Similar results were obtained in a study by Yao (Yao and Lian et al., 2007), who found that the feet' skin temperature was significantly lower than the rest of the body's skin temperature, while the skin temperature of the forehead was the highest.

Due to the uneven distribution of skin temperature in various parts of the human body, many studies have begun to use the MT_{sk} as an objective indicator of thermal sensation in the human body. The contraction or dilation of blood vessels in the human skin leads to a decrease or increase in skin temperature. Therefore, MT_{sk} is an important physiological parameter reflecting the degree of heat and cold stress and the state of heat exchange between the body and the environment. So, many methods of measuring the average skin temperature have been developed, and the method usually used is to find out which parts of the body (local skin temperature) changes will have an important impact on the overall skin temperature, and then measuring the skin temperature in these parts of the body and weighting them to calculate the mean skin temperature. Burton (Burton, 1934) proposed the 3-point method as early as 1934, which involves measuring the skin temperature of the chest (weight = 0.50), forearm (weight = 0.14), and foreleg (weight = 0.36), and then calculating the MT_{sk} based on the weight of each part. Yao (Yao and Lian et al., 2007) tested 12 different weighted MT_{sk} and two unweighted MT_{sk} measurements in a control room using thermocouples in a steady-state environment. The results show no significant differences between the Burton method and the other measurement methods, and it is concluded that the Burton method should be preferred for ease of use.

Another weighted formula to predict MT_{sk} more easily was proposed by Ramanathan (Ramanathan, 1964), which measures four points on the body, including the chest, thigh, leg, and arm. Based on 112 measurements on 3 subjects over the course of a year, Ramanathan proposed the following formula for calculating MT_{sk}.

$$MT_{sk} = 0.3t_{chest} + 0.3t_{arm} + 0.2t_{thigh} + 0.2t_{leg}$$

After proposing the 4-point method to calculate MT_{sk}, Ramanathan correlated the method with Hardy's (Hardy, 1938) 7-point method and Burton's 3-point method, respectively. The results show that the correlation coefficients are 0.94 and 0.98, respectively, with very high significance and low standard error.

2.4.3 Human core temperature

The core temperature is the temperature of the thoracic cavity, abdominal cavity, and central nervous system inside the body, known as body temperature. Benzinger (Benzinger and Kitzinger, 1961) showed that the core temperature could represent the metabolic heat production variation and thermal sensation variation compared to the skin temperature. Bulcao (Bulcao and Frank et al., 2000) showed that the proportional contribution ratio of T_{sk} / T_c to thermal comfort was ≈1:1. This represents a much greater T_{sk} / T_c contribution ratio for thermal comfort than previous studies have shown for sweating (1:20) or vasoconstriction and shivering (1:4). Wyss (Wyss and Brengelmann et al., 1974) showed that humans' sweating rate depends almost on core temperature with little correlation with skin temperature. Parsons (Parsons, 2014) showed that for a seated person, blood flow is normally 1.75 $gs^{-1}m^{-2}$ in thermo-neutral conditions. For every 1°C increase in core temperature, blood flow increases by 56 $gs^{-1}m^{-2}$ due to vasodilation, which ultimately leads to increased convective heat dissipation from the skin surface and affects the body's thermal sensation. Therefore, core temperature can be used as one of the indicators to evaluate thermal sensation effectively.

Methods of measuring human core temperature can be divided into two main categories. The first is the direct measurement of temperature. Approximating the temperature of a part of the human body in place of the core temperature while ignoring certain errors, including nuclear magnetic temperature, rectal temperature, auditory canal temperature, oral temperature, esophageal temperature, and pulmonary artery temperature. The second is the indirect estimation method, which mainly uses human body surface temperature modeling to calculate and analyze core temperature. The estimation of body surface temperature includes a single-channel heat flow model, two-channel heat flow model, two-node measurement model of the human body, and multi-node measurement model of the human body (Liu and Tang et al., 2017) .

2.4.4 Heart rate variability

Thermoregulatory activity in humans is governed by the autonomic nervous system (sympathetic and parasympathetic nervous system). Heart rate variability (HRV) is a valid method used to evaluate the autonomic nervous system's activity. It, therefore, can also be used to evaluate the thermal sensation in humans (Mohr and Langbein et al., 2002). Liu (Liu and Lian et al., 2008) found an association between HRV and thermal sensation, showing that when the human body is in a non-thermal neutral, the LF/HF values are significantly higher than those in a thermally neutral.

2.4.5 Metabolic rate

The metabolic rate is also a physiological indicator of the body's thermal sensation. The body's metabolic rate is lowest at thermo-neutral ambient temperatures. In the hot environment, the body's respiratory and circulatory systems are at a high level leading to a higher metabolic rate. Ye (Ye, 2005) compared the human body's metabolic rate in the cold and thermo-neutral environment and found that the human body's metabolic rate in a cold environment was significantly higher than that thermo-neutral environment.

2.4.6 Electroencephalogram(EEG)

It has been shown that EEG is closely related to changes in thermal sensation in humans. The brain temperature changes when the thermal sensation changes, which affects the frequency of EEG and, thus, its power density spectrum (Kanosue and Sadato et al., 2002). Therefore, different types of EEG can reflect the thermal sensation of the human body. Yao (Yao and Lian et al., 2008) measured the EEG of the human body at different thermal sensations. The results showed that the power ratio of α-wave was significantly higher when the human body felt slightly cool, neutral, and warm than at other thermal sensations. The power ratio of β-wave was significantly higher when the human body felt hot or cold than other thermal sensations.

2.4.7 Electromyogram(EMG)

EMG is also associated with thermal sensation. When the human body feels cold, it produces heat (e.g., shivering) through increased muscle activity to maintain thermal balance (Mohr and Langbein et al., 2002). EMG at this time is quite different from the thermo-neutral state. This has been verified in animal studies. Ye Xiaojiang (Ye, 2005) measured the EMG response of limb and trunk muscles in rats at different ambient temperatures and showed that limb and trunk muscles' discharge activity increased significantly at lower ambient temperatures. When the ambient temperature was 26-28°C, the discharge activity decreased to a minimum; when the ambient temperature was higher, the discharge activity increased again, but the increase was smaller.

2.4.8 Sweating rate

The sweat rate can also be used as an indicator of the body's thermal sensation. The rate of perspiration is lower in the thermal neutral and cold sensation. When the ambient temperature rises or the intensity of exercise increases, the amount of heat emitted by the body through radiation and convection is insufficient to remove the heat generated by the body. To maintain the body's thermal balance, the sweat glands begin to produce sweat, and the rate of sweating is higher.

Liu (Liu and Lian et al., 2011) compared the physiological factors related to thermal sensation, the significance of the difference between different thermal sensations (sensitivity), and the accuracy of the evaluation of thermal sensation (reliability), and the results are shown in Table 2.10. In his opinion, overall, the sensitivity of the mean skin temperature in reflecting the thermal sensation is high and has high reliability. Its measurement and calculation are simple, so it can be used as an objective index to evaluate the human body's thermal sensation.

Table 2. 10 Comparison of physiological indicators for evaluating thermal sensation

Physiological coefficient	Skin temperature	Heart rate variability (LF/HF)	Metabolic rate	EEG	Electromyogram	Sweating rate
Physiological mechanisms	Retraction and dilation of skin vessels	Sympathetic/vagal state of excitation	Energy consumption in the body	Brain temperature, mental state	Muscle activity	Sweat gland secretion
Relationship to thermal comfort	Approximate linear	Lower in comfort	Lower in comfort	α wave power increases under comfortable conditions; β wave changes reverse trend	Higher cold discomfort	Higher warm discomfort
Sensitivity	Cold discomfort /comfort/ warm discomfort	Discomfort /comfort	Discomfort /comfort	Discomfort /comfort	Cold discomfort /comfort	Warm discomfort /comfort
Limitation	Sweating has a major effect on skin temperature	Does not reflect thermal sensation, more complex measurement and analysis	Does not reflect thermal sensation, making accurate measurement difficult	More complex to measure and analyze, with more influencing factors	Just a reflection of cold discomfort	Just a reflection of warm discomfort

2.5 Summary

According to the concept of thermal sensation, the study of heat sensation in sports belongs to the research area of sports psychology from a conceptual point of view. The changes in human thermal sensation in sports are the psychological manifestations of thermal stress in the human body. Still, in psychology, the research on thermal sensation is rarely involved. Current research on thermal sensation is concentrated in the fields of the built environment and ergonomics. Still, the purpose of the study is primarily to regulate the thermal environment artificially or to create a comfortable thermal environment. These fields are more concerned with the thermal environment influencing thermal sensation and less concerned with the critical influences on thermal sensation during exercise. Therefore, this study draws on the methods and results of research on heat sensation in the built environment and ergonomics to study thermal sensation in exercise in sports psychology based on the different exercise states of the human body itself.

From the perspective of heat transfer, the factors that affect human thermal comfort and thermal sensation during exercise are influenced by heat conduction such as evaporation, convection, and radiation between the human body and the surrounding environment, which have an impact on thermal comfort and thermal sensation. Among these influencing factors, air temperature, relative humidity, air velocity, average radiation temperature, metabolic rate, and clothing thermal resistance are the factors that researchers are most concerned about. Numerous studies have shown that these six factors have a significant impact on thermal comfort and thermal sensation. Besides, factors such as geographic location, gender, age, climate adaptation, ethnicity, and anticipation of the weather can also influence thermal sensation. During the exercise, in addition to the factors as mentioned above under normal conditions, the preparation before exercise, the anticipation of exercise before exercise, the sense of control over the exercise process, the adaptation to the heat environment during exercise, the difficulty of breathing during exercise, the previous exercise experience and the frequency of exercise will affect the thermal sensation during exercise.

Up to now, dozens of human thermal sensation models have been developed. These models can be roughly divided into four categories. The first is the Fanger model, which focuses on the correspondence between human heat load and thermal sensation, and is the earliest human thermal sensation model. Based on this model, the Predicted Mean Vote (PMV) is proposed. The second is the two-node model, which divides the human body into two nodes: the core and skin layers. Based on the Gagge model, the Standard Equivalent Temperature (SET) index is proposed, and based on the MEMI model, the Physiological Equivalent Temperature (PET) index is proposed. The third is the multi-layered multi-node model, which divides the human body into multiple nodes into multiple layers and parts. Still, with different division forms, thus different thermal sensation models have been developed, including the Stolwijk model, Wissler model, KSU model, Tanabe model, Berkeley model, and Fiala model. The Universal Thermal Climate Index (UTCI) has been proposed based on the Fiala model. The fourth model is the comprehensive model, which integrates the above models to build a new model. In recent years, the Rayman model has been developed based on the Fanger model and MEMI model.

At present, two evaluation methods are used for human body thermal sensation: subjective and objective. In the subjective evaluation method, Fanger's 7-point thermal sensation evaluation scale has the advantages of simplicity and accuracy and has been widely used in a large number of studies; in the objective evaluation method, the mean skin temperature is currently the ideal objective evaluation index of thermal sensation, its relationship with thermal sensation is approximately linear, and the difference of skin temperature between different thermal sensations in the non-obvious sweating state is more significant. However, the disadvantage is that sweating has a greater impact on skin temperature when the correlation between the mean skin temperature and thermal sensation is weakened. Studies have shown that the correlation between skin temperature and thermal sensation is significantly lower in exercise situations than in normal conditions. However, which evaluation method is used ultimately depends on the situation, and Fanger's 7-point scale is the best choice when conditions allow. However, under certain circumstances, the human body's actual thermal sensation cannot be obtained through questioning or questionnaires, e.g., it is difficult to obtain the thermal sensation of an astronaut in an aircraft cabin through subjective evaluation. These models are reasonable under normal conditions because these indicators are positively correlated with thermal sensation under normal conditions. However, in the study of physiological indicators related to the exercise thermal sensation, the use of these models may produce bias in predicting exercise thermal sensation.

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CHAPTER 3

RESEARCH AND DOMAIN APPLICATIONS RELATED TO EXERCISE THERMAL SENSATION

3.1 Physiological mechanisms of thermal sensation during exercise 3-1

3.2 Thermophysiological responses of the human body during exercise 3-3

3.3 Physiological indicators related to thermal sensation during exercise 3-4

- *3.3.1 Correlation between skin temperature and thermal sensation during exercise 3-4*
- *3.3.2 Correlation between core temperature and thermal sensation during exercise.............. 3-5*
- *3.3.3 Correlation between sweating rate and thermal sensation during exercise 3-7*

3.4 Influence of psychological factors on human thermal sensation during exercise....................... 3-8

3.5 Several models for predicting thermal sensation during exercise 3-9

- *3.5.1 COMFA model predicts thermal sensation during exercise 3-10*
- *3.5.2 Fanger model predicts thermal sensation during exercise 3-11*
- *3.5.3 Kenny's model of human thermal sensation during exercise 3-12*
- *3.5.4 Reviews of other models of thermal sensation during exercise..................................... 3-12*

3.6 Reviews of exercise thermal sensation studies in different research domains 3-14

- *3.6.1 Case study of exercise thermal sensation in indoor thermal environment..................... 3-14*
- *3.6.2 Research in the domain of sports science and medical science 3-19*

3.7 Summary 3-22

***References** 3-24*

The human body's response to the thermal environment includes both subjective sensation and objective physiological responses. The subjective response, i.e., thermal sensation, objective physiological response, i.e., the body's autonomous thermoregulation. In the case of low metabolic rate, maintaining the balance of heat production and heat dissipation through autonomous thermoregulation is the main pathway and mechanism for the generation of thermal sensation in the human body; however, in exercises with a high metabolic rate, in addition to the influence of autonomous thermoregulation, psychological factors can also have a significant impact on the thermal sensation of the human body during exercise (Maw and Boutcher et al., 1993; SPARKS and CABLE et al., 2005; Brotherhood, 2008). A four-point thermal comfort criterion was proposed in a static state: a comfortable core temperature, a comfortable body skin temperature, a comfortable sweating rate, and a heat load close to zero. However, these criteria' feasibility is questionable when used to reflect the true thermal sensation during exercise.

3.1 Physiological mechanisms of thermal sensation during exercise

As shown in Figure 3.1, the combined effects of thermal environment, clothing, and exercise first cause changes in human skin temperature and core temperature in an exercise situation. Changes in skin temperature and core temperature can be sensed by the presence of temperature receptors sensitive to temperature changes in the skin layer and free nerve endings in the body's internal organs. The temperature receptors can be divided into heat receptors and cold receptors based on their response characteristics to dynamic stimuli. Regardless of the initial temperature, heat receptors always produce a large excitation pulse in response to a hot stimulus, and the cold stimulus signal is inhibited; similarly, cold receptors only produce a pulse signal in response to a cold stimulus, and the hot stimulus signal is inhibited. Strughold's study showed that the human body's cold and heat receptors are distributed in different locations. The number of cold receptors is significantly higher than the heat receptors, which leads to a more sensitive response to cold sensations(Levine, 1997). When a change in core and skin temperature is felt, temperature receptors send corresponding impulses to the brain.

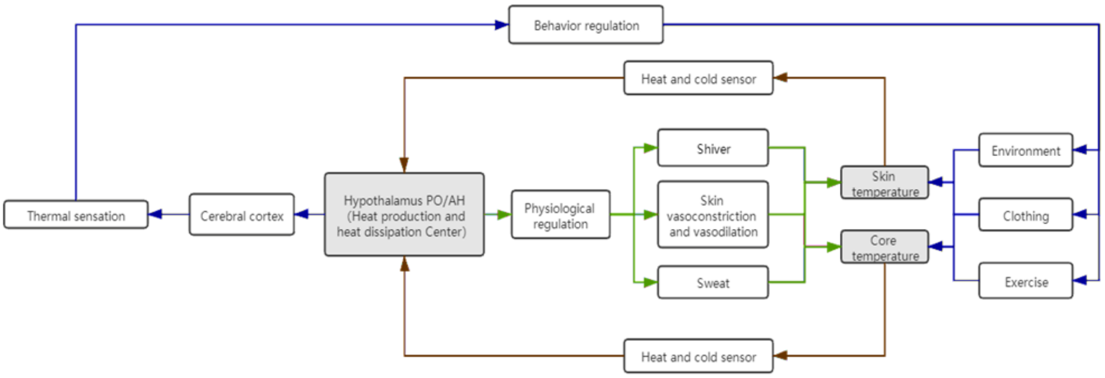


Fig.3. 1 The physiological mechanism of thermal sensation during exercise in a thermal environment

The center responsible for temperature regulation in the brain is located in the hypothalamus. Animal experiments found that when the preoptic - the anterior hypothalamus (PO/AH) is cooled, the excitation of the cold-sensitive neurons in this region will promote heat production and inhibit heat dissipation. However, when heating this region, it will stimulate the excitation of heat-sensitive neurons in this region to promote heat dissipation and inhibit heat production. This suggests that the PO/AH is the center of the central mechanism of the thermoregulatory system. Mekjavic's research shows that the central temperature-sensitive neurons in the PO/AH play a role as a set point in the thermoregulatory center, and the set temperature value determines the body temperature level.

However, this setpoint is not constant, but rather a temperature region that changes in response to physiological regulation(Mekjavic and I., 2006). Research has shown that the setpoint of the thermoregulatory system is induced to increase when exercise intensity is high .

After the hypothalamus receives the signal from the temperature receptors, it starts to change the human body's core temperature and skin temperature through three physiological regulation methods: skin vasoconstriction and expansion, shivering, and sweating. When the body temperature is lower than the body temperature regulation point, skin vasoconstriction, and skin blood flow decrease. The body to the environment of radiation and convective heat dissipation decreased. When the body's internal temperature drops to a point where the skin's constriction and blood vessels are insufficient to maintain thermal balance, the body's skeletal muscles generate heat to maintain body temperature using shivering. When the body temperature is above the body temperature set point, the blood vessels in the skin dilate, and the blood flow to the skin increases, and the radiation and convective heat dissipation from the body to the environment increases. When the blood flow in the skin is not enough to exchange the excess heat in the body to the outside of the body, the human body starts to sweat. Figure 3.2 shows human thermoregulatory responses in exercise.

The sweat gland discharges the sweat to the surface of the skin to evaporate. Evaporative cooling becomes the main heat dissipation method to achieve the purpose of cooling the skin and increasing heat dissipation in the body. At this time, the loss of water and salt in the body is accelerated, leading to water and salt metabolism disorder if it lasts too long. Simultaneously, the hypothalamus transmits information about cold or heat to the cerebral cortex, creating a thermal sensation, which is used to maintain body temperature by changing the thermal environment, clothing, and behavioral regulation of physical activity levels.

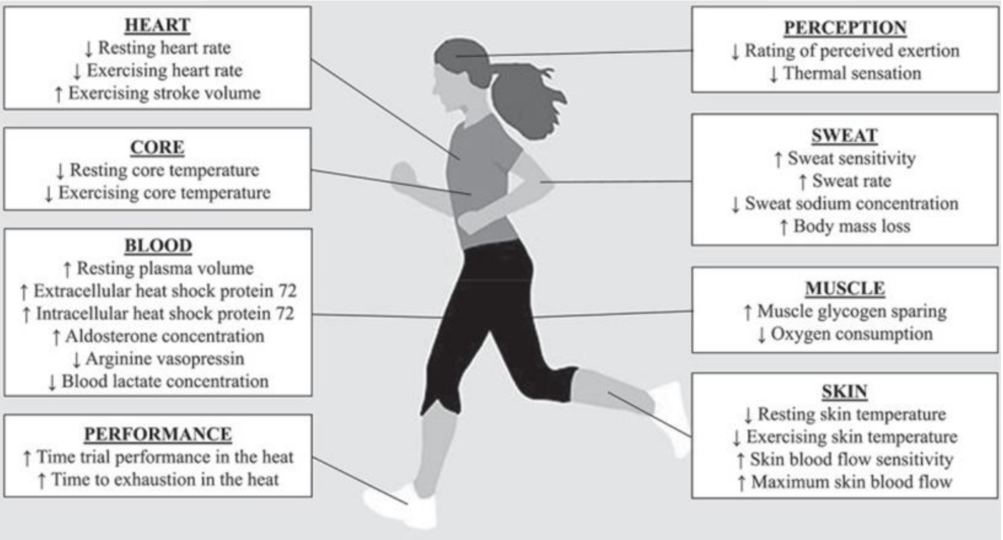
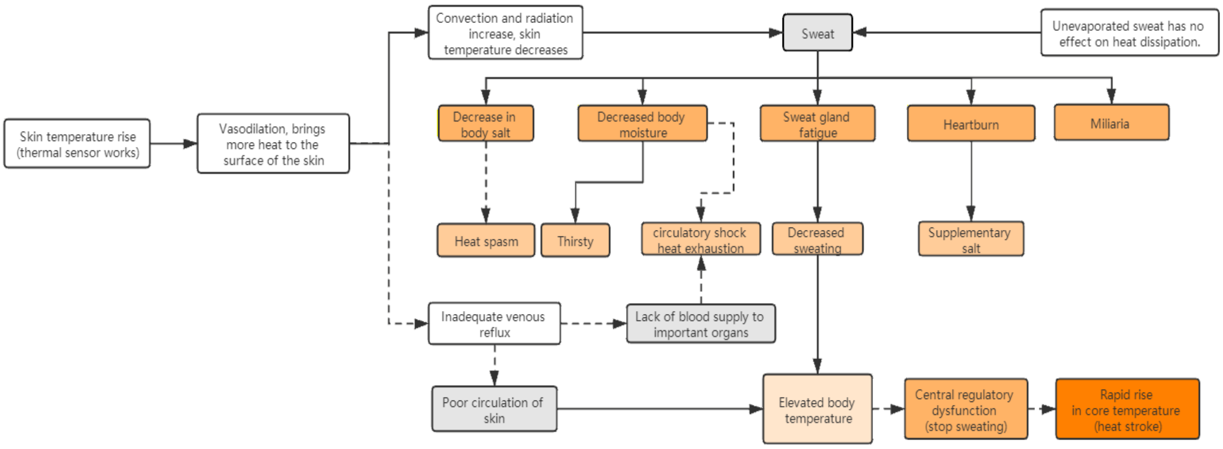


Fig.3. 2 Human thermoregulatory responses during exercise (Pryor JL et al., 2019)

3.2 Thermophysiological responses of the human body during exercise

In the exercise, when the heat produced by the human body through evaporation, radiation, convection, work, etc. is not enough to dissipate out of the body, it will produce a heat load. Fanger believes that it is due to the heat load in the human body that leads to the thermal sensation (Fanger, 1967). The heat load in the exercise is usually greater than 0, that is, the human body produces more heat than dissipated heat, at this time, the human body will feel warm or hot. This also shows that the thermal sensation in exercise is an effective indicator to measure the human body's thermal physiological state and prevent thermal and physiological adverse reactions in exercise. When the heat load is



The solid line indicates the normal physiological response during exercise. The dotted line is the possible adverse response when the heat load exceeds the human body's normal regulation range.

Fig.3. 3 The thermophysiological response of the human to exercise in a thermal environment

greater than 0, the human body will produce a series of physiological and even pathological reactions, as shown in Figure 3.3.

3.3 Physiological indicators related to thermal sensation during exercise

Yao et al.(Yao and Lian et al., 2007) pointed out that at a low metabolic rate, the thermal sensation is strongly correlated with three physiological parameters: mean skin temperature (MT_{sk}), core temperature (T_c), and sweating rate. Therefore, the correlation between thermal sensation and these three physiological indexes deserves special attention in the exercise with a high metabolic rate. From the physiological mechanism, the generation of thermal sensation during exercise is realized by the thermoregulatory system. The thermoregulatory system's key indicators are the core temperature and skin temperature, so it is essential to study skin temperature changes and core temperature to study the exercise's thermal sensation. Besides, a large amount of perspiration during exercise causes evaporative cooling, so the sweating rate is also an important physiological indicator of thermal sensation.

3.3.1 Correlation between skin temperature and thermal sensation during exercise

To understand the correlation between skin temperature and thermal sensation during exercise, it is the first to understand the pattern of skin temperature changes during exercise. A study by Huizenga (Huizenga and Hui et al., 2001) found that blood flow regulation significantly affects MT_{sk} in exercise. Blood flow regulation affects thermal distribution throughout the body, leading to vasodilation, sweating, and higher MT_{sk}.

Yang Hailan (Hailan, 2014) conducted a more detailed study on the changes in skin temperature during exercise. The subjects exercised on a power bicycle for 25 min at two intensities: high and low and tracked the changes of skin temperature at four points: chest, upper arm, thigh, and lower leg during exercise. The results showed that skin temperature change during exercise was very different between the points and significantly different between high and low-intensity exercise. Specifically: every 5 min as a time point, the skin temperature of the chest in the first 5 min under low-intensity changes flat, and then 5-25 min showed a trend of increasing, decreasing, increasing, decreasing again; in the first 5 min under high-intensity changes flat, and then 5-25 min showed a trend of decreasing, increasing, increasing, decreasing also. For the lower leg point measurements, it was found that the lower leg skin temperature showed a decreasing trend throughout exercise at a low intensity; it showed a rising, rising, rising, and stable trend under high-intensity exercise. Very different trends of change were also observed at the other two observation points and different intensities. Besides, at the upper arms point, under high-intensity exercise, the skin temperature was significantly lower than low-intensity exercise; at the chest point, the skin temperature was approximately the same under high- and low-intensity exercise; and at the thigh and lower leg points, the skin temperature was significantly higher under high-intensity exercise than low-intensity. This suggests that there is no strong correlation between exercise intensity and skin temperature.

Numerous studies have shown a high correlation between skin temperature and thermal sensation in static state. Still, in exercise situations, many studies have shown that this correlation weakens with increasing exercise intensity. For example, Liu Rongxiang (Rongxiang, 2010) showed that thermal sensation increases at higher exercise intensities, but the correlation between skin temperature and thermal sensation decreases. Wang (Wang and Hu, 2016) measured skin temperature, sweating rate, and thermal sensation in 16 subjects who participated at the moderate-intensity exercise. The results showed that the correlation between skin temperature and the thermal sensation was not significant. Furthermore, the entire process of sweating affects the mean skin temperature, which, compared to the static state, results in lower thermo-neutral skin temperature during moderate-intensity exercise. Laviana (Laviana, 1988) also showed that when the metabolic rate is high, the skin temperature required to achieve thermal comfort is generally lower than that of thermal neutrality in static state. Davies(Davies and Brotherhood et al., 1976) found no correlation between skin temperature and metabolic rate, total heat production, heat evaporation from perspiration, or maximum oxygen uptake in a study of 11 subjects after 1 hour of high-intensity exercise. The skin temperature of all subjects reached a similar value at the end of the exercise period. This suggests that the correlation between skin temperature and heat and thermal sensation is weak at high metabolic rates.

However, human skin temperature can be significantly affected by the external thermal environment during exercise. A study by Sparks (SPARKS and CABLE et al., 2005) on the mean skin temperature of athletes performing moderate to high-intensity exercise in different thermal environments showed that the mean skin temperature was 26-30°C when in a cold environment (T_a=8-10°C) and 31°C when in a neutral environment (T_a=20-24°C). The mean skin temperature is 33-37°C when in a hot environment (T_a=30-40°C). Studies by Adams(Adams, 1977) have shown the ambient temperature significantly alters that skin temperature. Also, Davies(Davies, 1979) showed that human skin temperature is influenced by air velocity during exercise, only to a lesser extent than in static state. Brotherhood (Brotherhood, 2008) argued that air relative humidity during exercise also affects skin temperature and is second only to ambient temperature. Among the thermal environmental factors in exercise, ambient temperature has the most significant influence on skin temperature, followed by air relative humidity and the air velocity.

3.3.2 Correlation between core temperature and thermal sensation during exercise

Changes in core temperature have a significant impact on human function and exercise capacity. The body produces a lot of heat during exercise. If the rate of heat production exceeds the rate of heat dissipation, body heat accumulates over time. It increases core temperature, which is considered high core temperatures of kinematic properties when the core temperature exceeds 38°C. When the body's core temperature exceeds 41.5°C, it will lead to the thermoregulatory system's failure and heat illness. The body loses thermal rapidly in a cold environment. If the thermally produced amount during exercise is less than the amount of thermal dissipated, core temperature drops, and human function decreases when the temperature falls below 36°C. In most cases, high core temperature happens during exercise, which is an essential cause of reduced exercise capacity and fatigue. When the core body temperature reaches the upper limit, neurotransmitters in the brain block the central nervous system from controlling the skeletal muscles and then terminate the exercise to avoid fatal thermal damage.

From the physiological mechanism, human core temperature and heat load are highly correlated within a certain range, and thermal sensation mainly depends on physiology's heat load. Therefore, it can be inferred that there is a high correlation between core temperature and thermal sensation within a certain range in exercise. However, there are not many studies on the relationship between core temperature and the human body's thermal sensation during exercise.

The pattern of changes in human core temperature during exercise has received extensive scholarly attention. Noakes's (Noakes and Myburgh et al., 1991) study showed that the rectal temperature was between 40-41°C in long-distance endurance running. Maughan's (Maughan and Leiper, 1994) study showed that the core temperature of the human body in soccer is about 39.5℃, and it is a normal physiological response when the core temperature is within this range during intense exercise. Adams's(Adams and Mack et al., 1992) study showed that: if the intensity of the exercise is kept constant, the core temperature and sweating rate of the human body will continue to rise and reach a steady-state 20min after starting the exercise, and evaporation reaches equilibrium. Saltin (Saltin and Hermansen, 1966) showed that the thermoregulatory system's core temperature under normal operating conditions depends on the exercise intensity expressed as a percentage of the maximum aerobic capacity. Galloway(Galloway and Maughan, 1997) showed that the human body's core temperature during exercise depends on the self-perceived fatigue level and is independent of changes in thermal conditions. However, a study by Maw et al.(Maw and Boutcher et al., 1993) found that when subjects exercised at an intensity of 60-69% of maximum heart rate, self-perceived fatigue level were lower in the colder environment (8°C) compared to the hotter environment (40°C). This may be due to vasodilation at higher ambient temperatures causing uncomfortable physiological responses such as excitation, hypotension, and dyspnea. It can be inferred from this that at sufficiently large differences in ambient temperature, differences in human core temperature still exist. Lind(Lind, 1963) called the range of thermal environmental conditions in which the body's core temperature does not change with the thermal environment the "presciptive zone" (PZ), and found that the range of the PZ changes with metabolic heat production. The range of the PZ during exercise is not known. Davies (Davies, 1979) showed that in a thermal environment with an air temperature of 21°C, the relative humidity of 50%, and air velocity equal to the running speed, a person in a static state would feel comfortable. However, when running at an exercise intensity of 85% VO_2max for 1 hour, the body never reached thermal equilibrium, and the rectal temperature gradually increased to 40°C within 1 hour. Therefore, PZ's range is very narrow when running at an exercise intensity of 85% VO_2max.

3.3.3 Correlation between sweating rate and thermal sensation during exercise

Nielsen(Nielsen and Nielsen, 1965) conducted an in-depth study of the sweating rate of the human body during exercise. He found that the mean skin temperature does not change when exercising at different exercise intensities (540kpm/min-1440kpm/min) at a fixed ambient temperature. The sweating rate at this time is linearly correlated with the body's core temperature, and the higher the exercise intensity, the higher the body's core temperature, and the higher the sweating rate. When exercising with fixed intensity at different ambient temperatures (5°C and 30°C), the core temperature remains unchanged, and the sweating rate increases linearly with the increase of the mean skin temperature. Thus, the external thermal environment mainly affects skin temperature but has less influence on core temperature in exercise. Exercise primarily affects core temperature, but less skin temperature, and the sweating rate is a combined reflection of the effects of exercise and thermal environment on human thermoregulation. In addition, Pugh's (Pugh and Corbett et al., 1967) study showed that during marathon running, the sweating rate is related to the metabolic rate; Nielsen's (Nielsen and Kassow et al., 1988) research on the human thermal balance during exercise in the sun found that the sweating rate is closely related to radiation thermal exchange; Nadel's (Nadel and Bullard et al., 1971) study showed that the sweating rate is related to air temperature, air velocity, and convective thermal exchange, as well as the sweating rate with the temperature of the air, airflow rate, and convective thermal exchange. These studies suggest that the sweating rate reflects the combined effects that the heat load induced by heat production during exercise and the thermal environment.

Wang (Wang and Hu, 2016) investigated the relationship between sweating and thermal sensation at moderate-intensity exercise. In a climate chamber, 16 subjects were asked to participate in two types of exercise, treading in situ and up-and-down a step. The metabolic rate, skin temperature, thermal sensation, sweat feeling index, and air velocity were measured. It was found that the correlation between the thermal sensation and the sweat feeling index was strong, and the sweating process during the exercise would have a significant influence on the thermal sensation. The increase in the air velocity would reduce the sweat feeling index and thermal sensation. However, the human body's actual sweating rate was not measured in this experiment, but rather the subjective index (sweat feeling index) was used. In a study by Pezzoli (Pezzoli and Cristofori et al., 2012) , it was found that during bicycling at high air velocity, the body's internal thermal production increased greatly, and the sweating rate increased significantly. Still, due to the wind's cooling effect on sweat, the body did not subjectively feel the actual increase in sweating. Thus, there is a distinction between the sweat feeling index and the sweating rate. Besides, Wang's research focuses on the relationship between sweat and thermal sensation in low- to moderate-intensity exercise. The relationship between sweat and thermal sensation in high-intensity exercise needs further study.

3.4 Influence of psychological factors on human thermal sensation during exercise

It has been shown that psychological factors can have a significant effect on thermal sensation during exercise. Havenith (Havenith and Holmér et al., 2002) suggested that thermal sensation changes significantly during exercise, with psychological factors including: first, the exercising body is psychologically prepared for the uncomfortable exercise conditions that it will face; second, the hormones produced by the hypothalamus during exercise cause the body to pleasure. This suggests that, in addition to the thermal environment and exercise factors, psychological changes in exercise can also significantly impact thermal sensation. Based on Nikolopoulou's (Nikolopoulou and Steemers, 2003) study on the possible psychological adaptations involved in human thermal sensation in urban space design, Vanos(Vanos and Warland et al., 2011) argued that: factors such as current climate change (changing seasons), preparation for per-exercise, the anticipation before exercise, control over the exercise process, adaptation to the thermal environment during exercise, previous exercise experience, and frequency of exercise all influence the body's thermal sensation during exercise. Yao et al.(Yao and Lian et al., 2007) argued that overall thermal sensation is closely related to local sensations in the body, such as leg pain and breathing difficulty. The effects of these factors are more pronounced during exercise. From this, it can be inferred that there is a correlation between the rating of perceived exertion (RPE) during exercise and the actual thermal sensation. The study by Kenny (Kenny et al., 2009) on the human body's thermal sensation during exercise in an outdoor environment showed that the actual thermal sensation and RPE are closely related. The factors mentioned in the above study are mainly influencing the psychology of the human during exercise and thus changing the body's thermal sensation.

Unfortunately, research on the influence of psychological factors on thermal sensation in exercise is still only in its preliminary stages. No studies have been conducted using scientific research methods to prove which specific psychological factors influence exercise's thermal sensation. There is only speculation on the psychological factors that may be involved in certain phenomena. Ahmed's

(Ahmed, 2003) study in the tropics showed that the human body feels more comfortable at an exercise intensity of 3METs than at 2METs. Still, only meteorological and physical parameters cannot be used to make a reasonable explanation for thermal sensation. Possible psychological factors influencing thermal sensation in humans during exercise are shown in Figure 3.4.

In this experimental study, it was found that thermal alliesthesia occurs at the end of the exercise, resulting in a higher thermal comfort level after exercise than before. This will be described in detail in a later chapter.

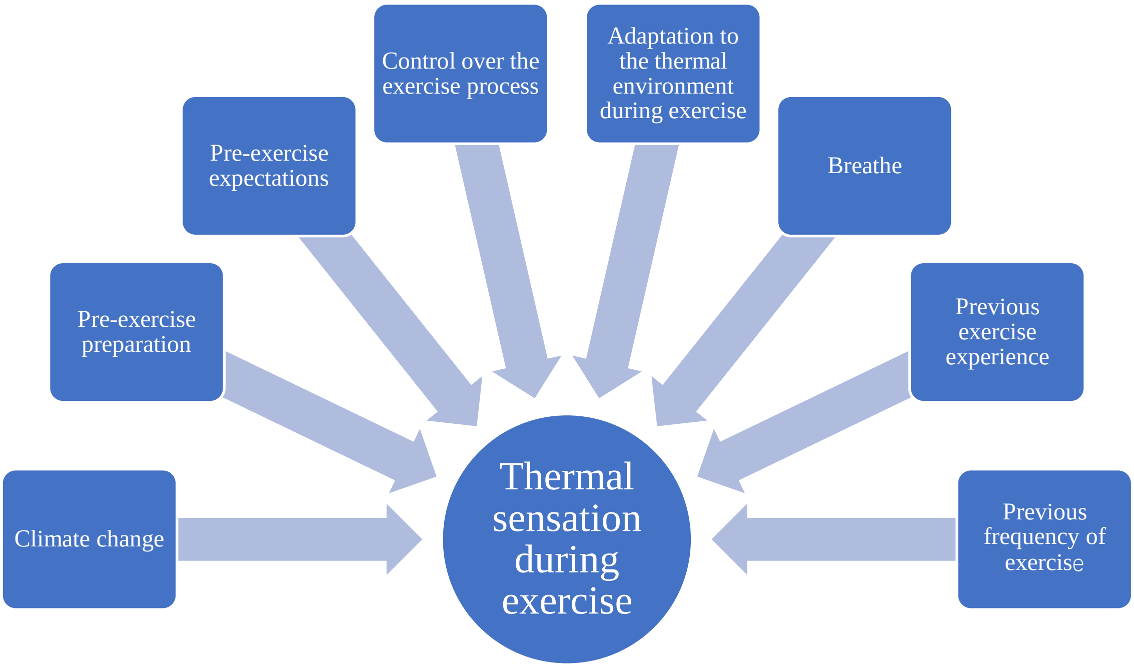


Fig.3. 4 Psychological factors influencing thermal sensation in the human body during exercise

3.5 Several models for predicting thermal sensation during exercise

Based on the equation of body thermal balance, a mathematical model can be established by integrating the parameters that affect human body thermal sensation in exercise, such as thermal environment, radiation temperature, metabolic rate, clothing, etc. These models can effectively predict the actual state of thermal sensation in different thermal environments, so it is of great significance to prevent excessive thermal stress and thermal damage during exercise. At present, the research on the models of human thermal sensation in exercise can be divided into two categories: one is the research on the accuracy of predicting human thermal sensation using existing models in exercise in a specific thermal environment. Wang (Wang and Hu, 2016) and Liu (Rongxiang, 2010) used the Fanger model to predict the thermal sensation of the human body during exercise and compared it with the actual thermal sensation, and Kenny(Kenny and Warland et al., 2009) used the

COMFA model to predict the thermal sensation of the human body during exercise and compared it with the actual thermal sensation. The other is to construct a new model according to the exercise's specific characteristics to predict the thermal sensation and verify the accuracy of the model by comparing it with the actual thermal sensation. Kenny (Kenny and Warland et al., 2009) and Vanos (Vanos and Warland et al., 2010) established a prediction model for human thermal sensation in outdoor exercise based on the COMFA model proposed by Brown (Brown and Gillespie, 1986) , and Kenny (Kenny and Warland et al., 2009) also verified the accuracy of his model for human thermal sensation in exercise by comparing it with the actual thermal sensation in outdoor.

The study in this thesis falls into the second category. The difference from previous studies is that this study examines the patterns of thermal sensation changes before, during, and after exercise. It also attempts to establish a link between physiological parameters and thermal sensation and construct a mathematical model. The predicted thermal sensation was compared with the actual thermal sensation.

3.5.1 COMFA model predicts thermal sensation during exercise

The study by Kenny et al. used the COMFA model to predict thermal sensations during three types of exercise outdoor: fast walking, running, and cycling, and compared them with those derived from actual thermal sensation. Spearman's correlation analysis between actual and predicted thermal sensations showed a significant positive correlation with a correlation coefficient of 0.574. In the overall distribution of actual thermal sensation, 82% of the votes for thermal sensation were between 0 and +2, with +1 receiving the most votes, 0 and +2 receiving about the same number of votes, +3, -1, and -2 receiving a tiny percentage. In the overall distribution of the predicted thermal sensation, the similarity with the actual thermal sensation is that 84.7% of the votes are between 0 and +2. In the overall distribution of the predicted thermal sensation, 84.7% of the votes were between 0 and +2, similar to the actual thermal sensation. However, the predicted thermal sensation votes did not follow a normal distribution and were mainly distributed at 0 and +2 points, with percentages of 36.8% and 29.8%, respectively. The percentage of +1 is 18.1%, and the percentages of +3, -1, and -3 are small. Compared to the actual thermal sensation, the predicted thermal sensation was 36% equal, 30% overestimated by 1 rating, 23% underestimated by 1 rating, 7% underestimated or overestimated by two ratings, and 4% underestimated or overestimated by three ratings.

Besides, Kenny plotted the interquartile range (IQR) and the median of heat load values at the actual thermal sensation level, based on the two parameters of heat load and actual thermal sensation calculated by the COMFA model. This is because the IQR and median are less affected by outliers and extremes than the arithmetic mean. The median of the heat load under each actual thermal sensation level is shown in Table 3.1.

Table 3. 1 Correspondence between actual thermal sensation and median of heat load (Kenny et al., 2009)

thermal sensation level	description	heat load(W/m^2)
-2	Cool	-50
-1	Slightly cool	16
0	Neutral	40
+1	Slightly warm	70
+2	Warm	152
+3	Hot	219

The study shows that IQR is smallest at thermal sensation level of 0 and +3, 59W/m^2, and 72W/m^2, respectively; and largest at +1 and -1, 149W/m^2, and 116W/m^2, respectively. There was a clear overlap of IQR at all levels except when the thermal sensation was +3. In 6% of cases, the COMFA model predicted and actual values deviated significantly, i.e., outliers exceeding 1.5 IQR. The largest number of outliers occurred when the thermal sensation level was zero.

The above studies indicate that the COMFA model's accuracy for predicting thermal sensation during exercise outdoor needs to be improved, and the model itself needs to be modified and refined.

3.5.2 Fanger model predicts thermal sensation during exercise

Wang (Wang and Hu, 2016) studied the thermal sensations of 16 subjects (8 males and 8 females) in two types of exercise (treading in situ and up-and-down a step) in different thermal environments (22°C, 24°C, and 26°C) in a climate chamber, and measured the difference between the actual thermal sensations after 20 min of exercise and the predicted thermal sensations calculated using the Fanger model. The results showed that the actual and predicted thermal sensations were very close under resting conditions, with a mean deviation of only 0.23. Still, the mean deviation increased as the activity level increased, with a mean deviation of 0.8 for the actual and predicted thermal sensations for the treading in situ and 1.24 for the up-and-down a step. This shows that the Fanger model is a strong predictor of human thermal sensation at low exercise intensities but overestimates the actual thermal sensation when the exercise intensity increases. For the up-and-down a step, the PMV calculated by the Fanger model exceeded +3 at 24 and 26°C, indicating that the Fanger model was no longer able to accurately predict the human body's thermal sensation when the exercise was performed. A similar conclusion was reached in the study of Liu (Rongxiang Liu, 2010). He found that the PMV calculated by the Fanger model was very close to the actual thermal sensation of the human body when static. Still, with the increase of metabolic rate, the difference between the PMV and the human body's actual thermal sensation increased. The Fanger model over-predicted the actual thermal sensation during exercise in the thermal environment.

3.5.3 Kenny's model of human thermal sensation during exercise

Kenny modified the calculation methods of skin tissue resistance, clothing thermal resistance and evaporative resistance, and air velocity in the COMFA model based on exercise's specific characteristics. He made them applicable to the prediction of human thermal sensation in exercise in outdoor environments. Comparing the distribution of the predicted thermal sensations in exercise by the modified model with the actual thermal sensations, the results showed that the modified model had better accuracy in predicting the overall distribution of human thermal sensations in exercise. However, comparing the correlation between the values of the COMFA model (and the values of the modified model) and the actual thermal sensation, respectively, revealed that the Spearman correlation coefficient between the COMFA model and the actual thermal sensation was 0.574 ($p<0.01$). In contrast, the modified model was 0.531 ($p<0.01$), which appeared slightly decreases. Also, there are still 4.5% of cases where the new modified model significantly over- or underestimates the actual thermal sensation. 78% of the outliers occurred at ambient temperatures ranging from 24 to 29°C, radiation temperatures ranging from 27 to 30°C, and exercise at high metabolic rates (694-814 W/m2), with equal numbers of males and females experiencing outliers. This indicates that the applicability of Kenny's new model modified from the COMFA model in the exercise needs to be further improved, especially under the high ambient temperature and metabolic rate.

3.5.4 Reviews of other models of thermal sensation during exercise

Nielsen et al. (Nielsen B, 1979) noted that the human preferred comfortable skin temperature decreases with increasing activity (heat production), while preferred skin moistness increases linearly with activity. Diyi Tan et al.(Tan et al., 2017) studied the thermal sensation of people who alternated between sedentary exercises and walking on a treadmill at 20 and 25 ℃. The experimental results show that when the thermal sensation does not reach a steady-state, PMV is not suitable for predicting the thermal sensation of active individuals. Gagge et al. (Gagge et al., 1969a)studied the relationship between activity levels and the human thermal sensation and thermal comfort under different working conditions. They believe that warmth discomfort is principally related to skin sweating and conductance and is affected either by air temperature and metabolism or by both skin and rectal temperature. The "two-node model" was first proposed by Gagge (Gagge et al., 1971). The SET (Standard Effective Temperature) is an indicator of thermal sensation based on Gagge's model. Gagge et al. (Gagge et al., 1969b) conducted a study on four male subjects, and kept them under different temperature conditions, gradually changing from resting to different activity levels. Studies have shown that subjects reached new and stable levels of thermal sensation and thermal comfort 20-30 minutes after a change in activity status. The Fiala model is another more widely used multi-node thermal sensation model. The body is viewed as consisting of 20 spherical and cylindrical body elements with a total of 340 nodes. The model had been used in 90 different thermal environments (temperatures ranging from 5-50°C) and at different exercise intensities (0.8- 10mets), with good agreement with the empirical data(Fiala et al., 1999, 2001). Also, Fiala, in his Ph.D. thesis(Fiala, 1998), obtained a regression-based model of dynamic thermal sensation (DTS). The DTS model includes a term, as a function of the core temperature weighted by the skin temperature, accounting for effects associated with exercise and warm body core temperatures. The ISB (International Society of Biometeorology) has been developing UTCI indicators based on the Fiala model since 2000, which was completed in 2009.

For research models of thermal sensation and thermal comfort, the calculation of the metabolic rate is critical. McNall et al. (McNall, 1967) found a modulating effect of metabolic rate, i.e., at lower metabolic rates, relative humidity on the thermal comfort and thermal sensation is less affected. However, as the metabolic rate increases, the effect of relative humidity on the body becomes more magnificent. These findings apply to a comfortable temperature range. Goto et al. (Goto et al., 2006) investigated the changes in physiological parameters and subjective responses caused by changes in metabolic rate. Thermal sensations began to increase or decrease immediately (within 1 min) after a change in metabolic rate, suggesting that a transient change in metabolic rate affects thermal sensations. After about 15-20 min of exercise, the subjective thermal response was very similar to that at steady state, and thermal sensation and skin temperature could be stabilized. The body's metabolic rate can reach stability after 5 min of sustaining the same activity level. They also proposed a model to estimate the transient thermal sensation after metabolic changes. Hasan et al. (Hasan et al., 2016) showed the application of the human-in-the-loop sensor data of wearable devices to provide continuous feedback for the averaged metabolism value of building occupants. However, in this experiment, the subjects were asked to perform similar everyday activities while working at the office or home, and the metabolic rate under moderate or high-intensity exercise was not considered—however, the metabolic rate changes over time with exercise. Research by Zhang et al. (Zhang et al., 2020) revealed a specific relationship between thermal sensation votes and physiological indexes. The human body typically takes 3–5 min to reach a new metabolic level after walking and 4–5 min to return to a normal sedentary state after exercise. Choi et al. (Choi et al., 2012)believe that the heart rate is significantly related to the human metabolic rate and maybe a potential parameter that directly (or indirectly) affects the cause of thermal comfort. The purpose of the research by Wang et al. (Wang and Hu, 2016) is to understand better the real thermal sensation of individuals performing moderate activities. They found that the thermal sensation of the subjects was related to sweat activity. As the activity intensified, the subjects expected higher air velocity. Thermal stress has been involved in previous studies (Golbabaei et al., 2014; Meeusen and Roelands, 2010; Racinais and Oksa, 2010). The main concerns are the changes in the physiological and biochemical indexes of the human body in exercise in a specific thermal environment and the exercise capacity.

However, in the current study, the determination of the metabolic rate was relatively complicated and not very accurate. The use of the metabolic rate to predict thermal sensation in daily exercise is difficult and inconvenient.

3.6 Reviews of exercise thermal sensation studies in different research domains

Activity is an important factor affecting the comfort of the thermal environment. For example, in the same building environment, the human thermal sensation differences will be larger at different activity levels. Thermal physiological adjustment and heat dissipation methods differ when the body is at a higher activity level and lower. The thermal environment in which the human body feels comfortable at higher activity levels will also differ from the normal building thermal environment. Thus the required evaluation methods will be different.

When the ambient temperature is high, the efficiency of work that requires neural operation and decisive ability will be significantly reduced. In contrast, low temperature will affect the flexibility of hand operation. Therefore, creating a suitable indoor thermal environment is an important function that the building should have. And, it can also impact social production and the economy by improving work efficiency and psychological satisfaction, etc. However, the creation of a specific indoor thermal environment requires artificial and energy consumption (Akimoto et al., 2013) .

3.6.1 Case study of exercise thermal sensation in indoor thermal environment

In the early 20th century, ASHRAE conducted the first study of indoor thermal environment on human thermal comfort in the Pittsburgh laboratory (Houghton and Yaglo, 1923). Macpherson, in 1962 identified six factors influencing human thermal comfort: air velocity, ambient temperature, mean radiation temperature, relative humidity, thermal resistance of clothing, and activity level (metabolic rate). Gagge et al. studied four male subjects at 10°C, 20°C, and 30°C, gradually changing from a resting state to different levels of physical activity, and showed that the subjects were able to reach new static levels of thermal sensation and thermal comfort in 20-30 minutes after changing their activity state. Nielsen et al. put subjects in alternating work-rest mode, and when the ambient temperature was neutral, the subjects' voting values fluctuated around "neutral". The thermal sensation of the working mode will be increased, and the skin temperature is decreasing. Kashimura conducted a research study on 5 subjects exposed to 20°C, 25°C, and 30°C environments and found that thermal sensation voting was related to rectal temperature and was not significantly related to mean skin temperature. Rowe collected staff activity reports and did a study, which affirmed the importance of the recent activity before thermal sensation generation on the effect of thermal sensation.

Li WenQiang (Li, 2016) simulated the climatic conditions of industrial buildings and conducted thermal comfort experiments for three activity levels under different ambient temperature conditions, respectively. In addition, subjects' physiological parameters and questionnaires were collected during the experiments. The results are shown in Fig.3.5

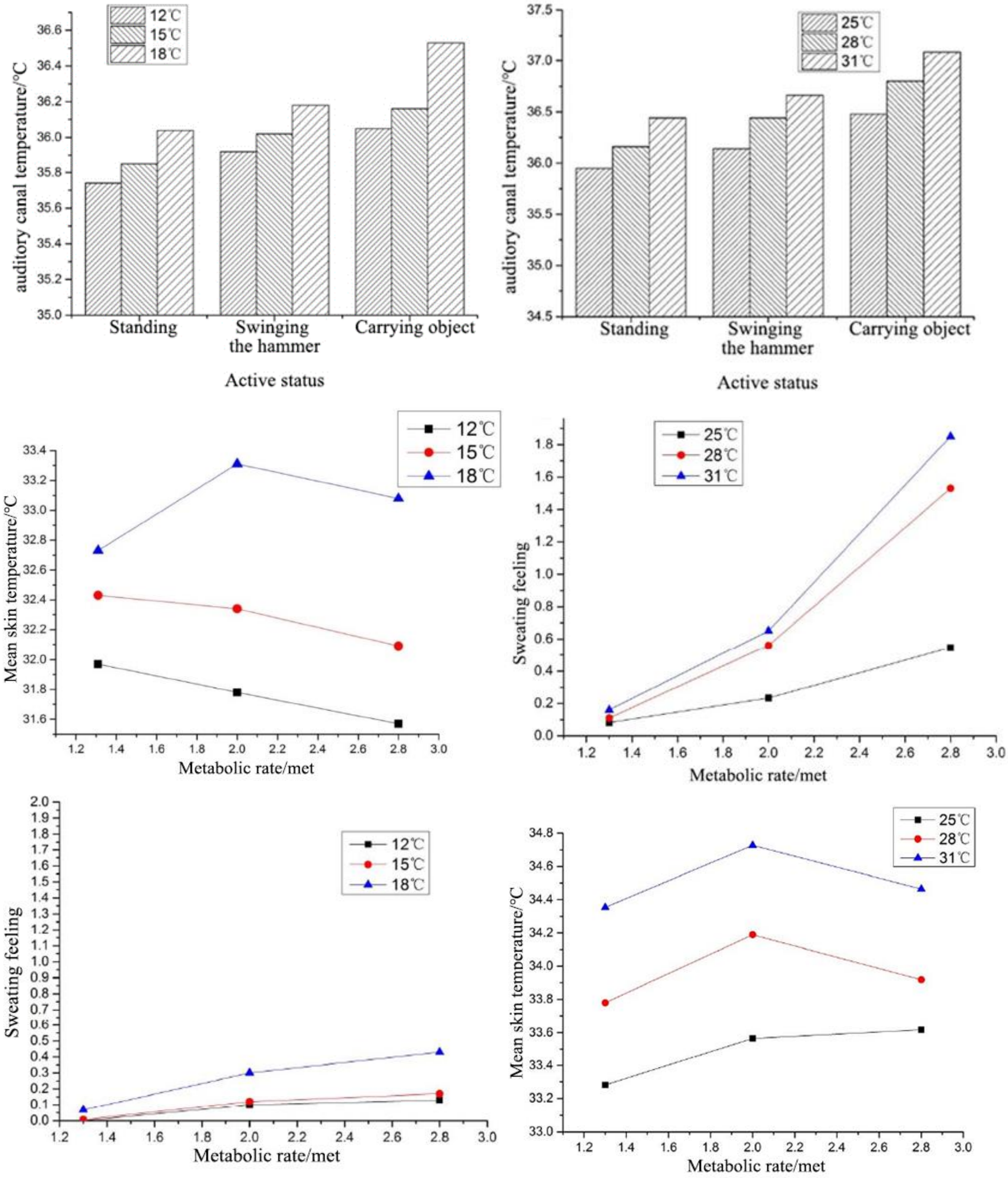
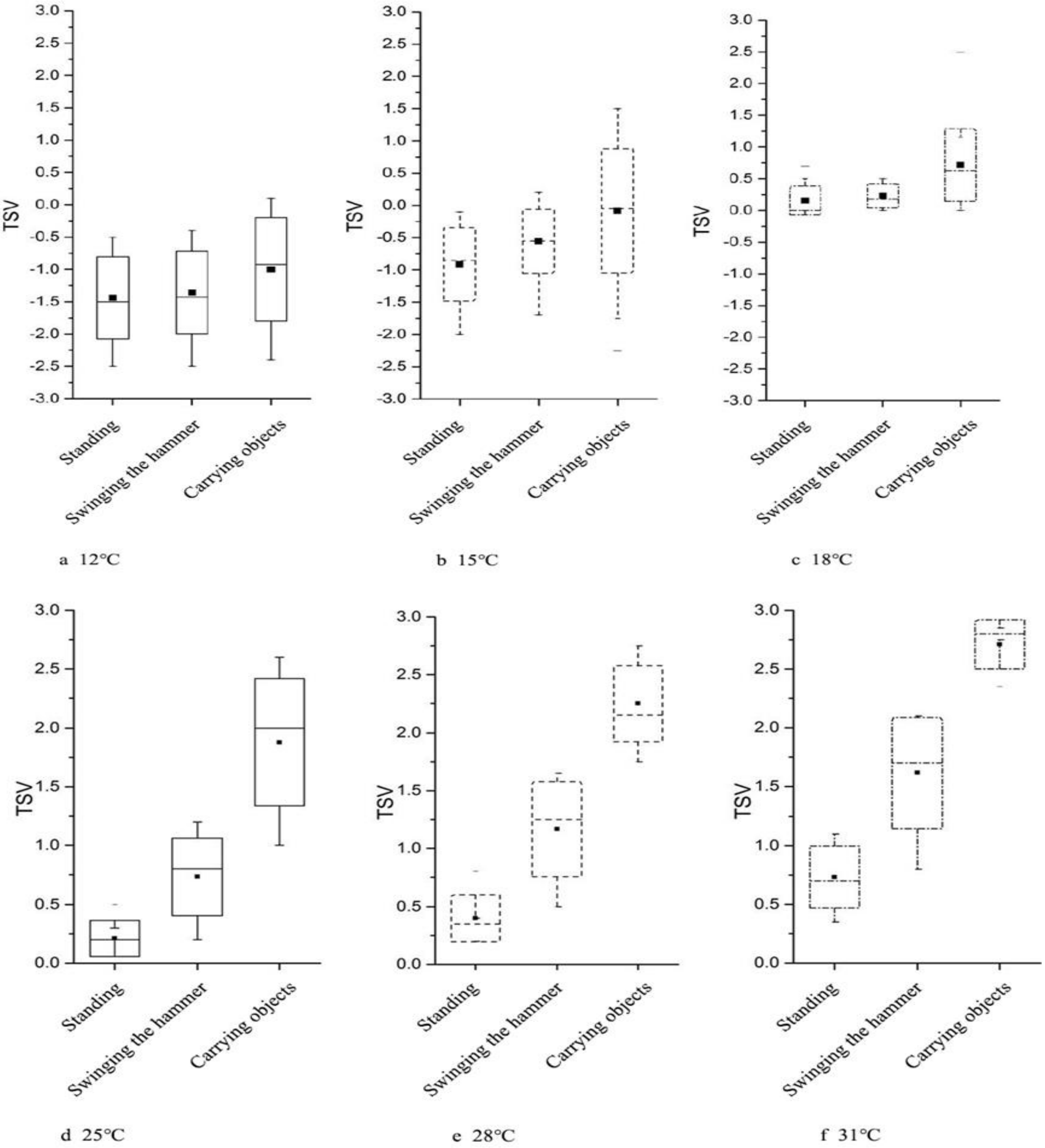


Fig.3. 5 Changes in physiological indicators at different ambient temperatures and metabolic levels (Li, 2016)

The results showed that the trend of the auditory canal temperature with ambient temperature was approximately the same as that standing, except that when the human body was at a higher metabolic level, the auditory canal temperature was higher than that at a lower metabolic level. At ambient temperatures of 12°C and 15°C, the skin temperature decreased as the metabolic rate increased; at ambient temperatures of 18°C to 31°C, the skin temperature first increased and then decreased with the increase of metabolic rate. The skin temperature increases first because of the slight sweating when the metabolic rate increases, insufficient evaporative heat dissipation. When the metabolic rate increases to a certain level, the body increases the evaporative heat dissipation by sweating a lot, which leads to a decrease in skin temperature. Figure 3.6 shows the comparison of TSV at different ambient temperatures and metabolic levels.



a 12°C b 15°C c 18°C

d 25°C e 28°C f 31°C

Fig.3. 6The comparison of TSV at different ambient temperatures and metabolic levels (Li, 2016)

The comparison of the three figures of a,b,c revealed that the TSV of the subjects was more concentrated when the ambient temperature was higher. From the d,e,f figures, it can be seen that the TSV of the subjects increased significantly with the increase of metabolic level. Also, when subjects were at the same activity intensity at different ambient temperatures, the TSV was different, and when the ambient temperature increased, the TSV increased.

Preferred temperature method is a way to determine the comfortable temperature directly by allowing subjects to change the chamber temperature based on their preferences. Numerous studies using this method have been conducted to evaluate the validity of PMV model for different geographic locations, different times of the day, aged and gender. It was found that PMV prediction matched preferred temperature well under sedentary activity, and there was no difference in terms of preferred temperature for different geographic locations, age, and gender, or times of the day. However, at higher levels of office activity, PMV predictions can be seriously biased. In the study by Nielsen et al. (B. Nielsen et al., 1979) on validating Fanger's comfort equations, they asked the exercising subjects every 10 min throughout the experiment whether he would prefer the environment to be warmer, cooler, or the same, and then altering the ambient temperature accordingly.

Gao (Siru Gao et al., 2018) studied thermal sensation and preferred temperature at elevated office activity levels in their experiments and determined the suitable ambient temperatures. The study showed that The active workstation significantly increased human metabolic level and reduced preferred temperature. PMV model was found to predict too cool temperature than needed for higher metabolic rates. As shown in Fig.3.7 and 3.8.

Zhang carried out an experimental study in a badminton gym. Subjects were asked to walk at different speeds for 20 min and sit for 10 min. The thermal parameters were recorded during the experiments, and the thermal perceptions of the subjects were collected (Yuchun Zhang et al., 2020). The results revealed a certain relationship between thermal sensation votes and physiological indexes. As shown in the fig.3.9. and 3.10.

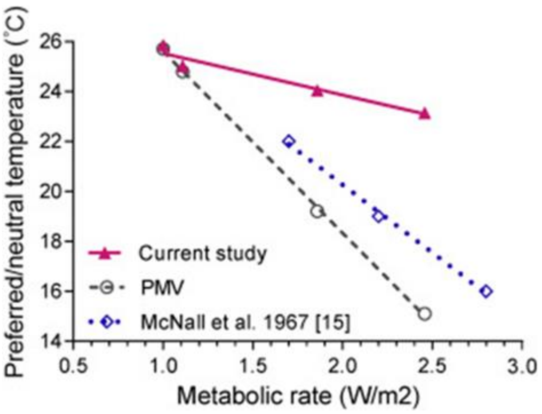
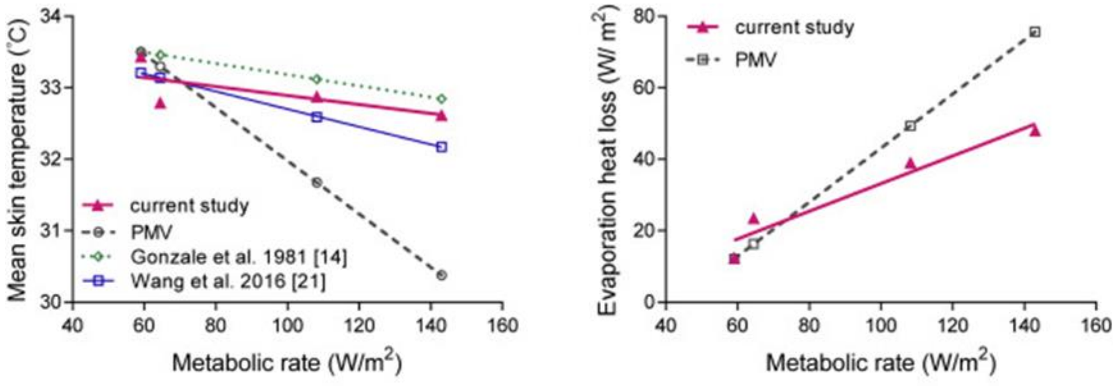


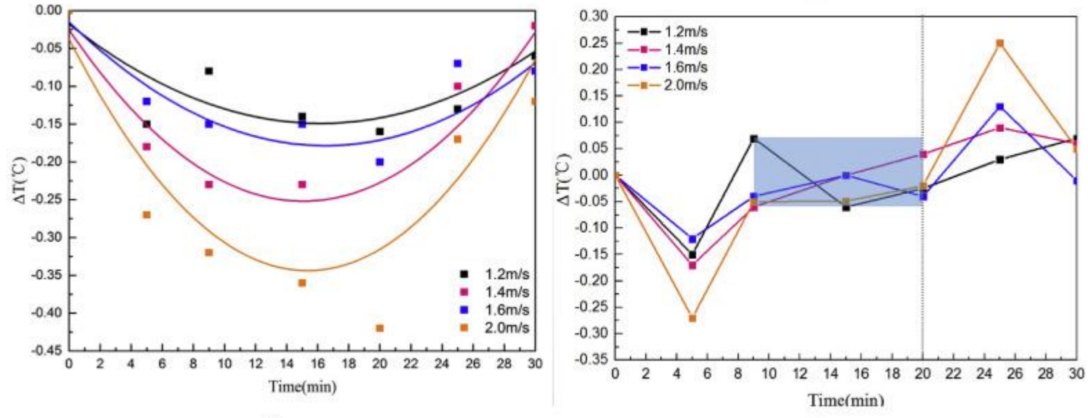
Fig.3. 7 The relation between metabolic rate and preferred temperature (Siru Gao et al., 2018)



a. Mean skin temperature and activity level for people in thermal comfort.

b. Evaporative heat loss and activity level for people in thermal comfort.

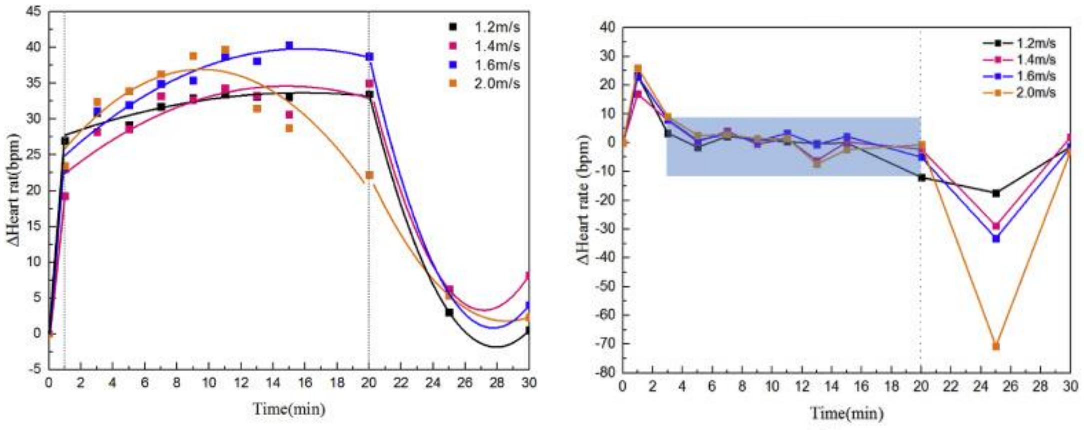
Fig.3. 8 Comparisons with PMV model (Siru Gao et al., 2018)



(a)

(b)

Fig.3. 9 The average changes of auditory canal temperature: (a) Compare with the initial value, (b) Compare with the last value. (Yuchun Zhang et al., 2020)



(a)

(b)

Fig.3. 10 The average changes of heart rate: (a) Compare with the initial value, (b) Compare with the last value (Yuchun Zhang et al., 2020)

3.6.2 Research in the domain of sports science and medical science

In sports science, there is a risk to the health of athletes if they are exercising in a hot and humid environment. Heat-related illness (HRI) is an ever present threat to athletes, military personnel, and occupational athletes, as the combination of physical exertion in hot environments makes individuals susceptible to heat stroke, heat exhaustion, and heat cramps (Casa DJ, 2007; Wallace RF et al., 2006). Also, Heat acclimation is a more important study in sports science. Heat acclimation requires moderate-intensity exercise in a hot environment (~40°C) be performed repeatedly over 5–14 d to improve heat tolerance and performance in the heat (Racinais S et al., 2015). This potential performance benefit is appealing for elite athletes seeking a competitive advantage in hot weather competition, but many athletes live and train in areas of the world with more temperate climates and do not have access to the resources (i.e., environmental chamber) necessary for exercise–heat acclimation. High temperature (muggy) meteorological condition has a great influence on competitions, especially the open-air competitions. The accidents caused by sports calenture during Olympic Games are all related to high temperature weather. It can be seen that sports ability has close relationship with environmental temperature, especially the endurance sports. The dehydration and core body temperature rise will accelerate the generation of fatigue, weaken the willpower, reduce the exercise ability, and even cause thermal spasm, heat exhaustion and heatstroke. This is exactly the situation I described in Chapter 1. The author, therefore, argues that the building thermal environment greatly affects the exercise thermal comfort. The study of the exercise thermal sensation in the thermal environment of buildings should be more in-depth and detailed.

In medical science, researchers have compared the changes of body core temperature and catecholamine neurotransmitters in human body from incremental exercise to exhaustion in the environments of high temperature and normal temperature, and probed into the sensitive indicators affecting the increase of body core temperature . Nine athletes were executed incremental load exercise in laboratories with temperature 30°C, relative humidity 80%, temperature 20 °C and relative humidity 40%. The continuous changes of body core temperature were recorded, and the changes of blood adrenaline (E), norepinephrine (NE) and dopamine (DA) were detected under the two experimental conditions. Compared with the environment of 20 °C and 40 % relative humidity, the body core temperature rises faster and E, NE and DA increase more, when the temperature is temperature 30°C, relative humidity 80% (Wang Z et al., 2018). But, the time of movement is shorter. Exercise dehydration is also a topic often discussed in medical research. The dehydration is caused by the decrease of extracellular fluid caused by the loss of water and sodium ions in the body. Many researches show that dehydration of body can aggravate the premature occurrence of exercise fatigue during exercise at high temperature. With the aggravation of dehydration, the body temperature will increase accordingly (Xing et al.2017). When dehydration rate is 1% of the body, the core body temperature rises by 0.10-0.23°C. The excessive body temperature caused by dehydration can inhibit the frequency of central fatigue, and thus to restrict the contractility of skeletal muscles and directly lead to the fatigue.

By examining current research on related topics in sports science and medical science, the author identified 2 issues that have been overlooked by these studies.

1. When physiological parameters are measured, the observation of changes in physiological parameters and thermal sensation in a short period of time before and after the change of exercise state is missing. No prediction model of the exercise thermal sensation was formed. The following figures shows the experimental procedure in the study case (Fig.3.11, 3.12,and 3.13). There was no increase in the density of time points before and after the state change.

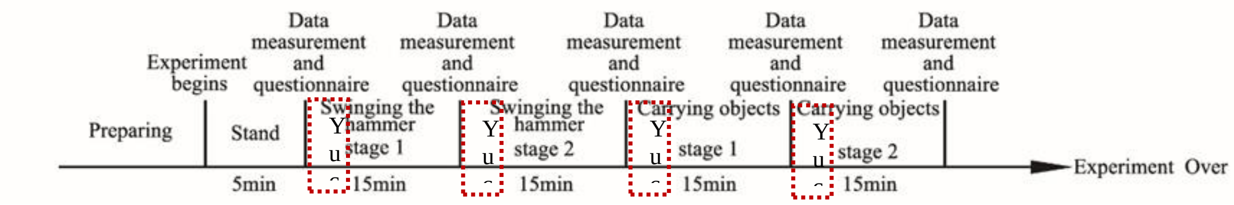


Fig.3. 11 Experiment procedure (Li, 2016)

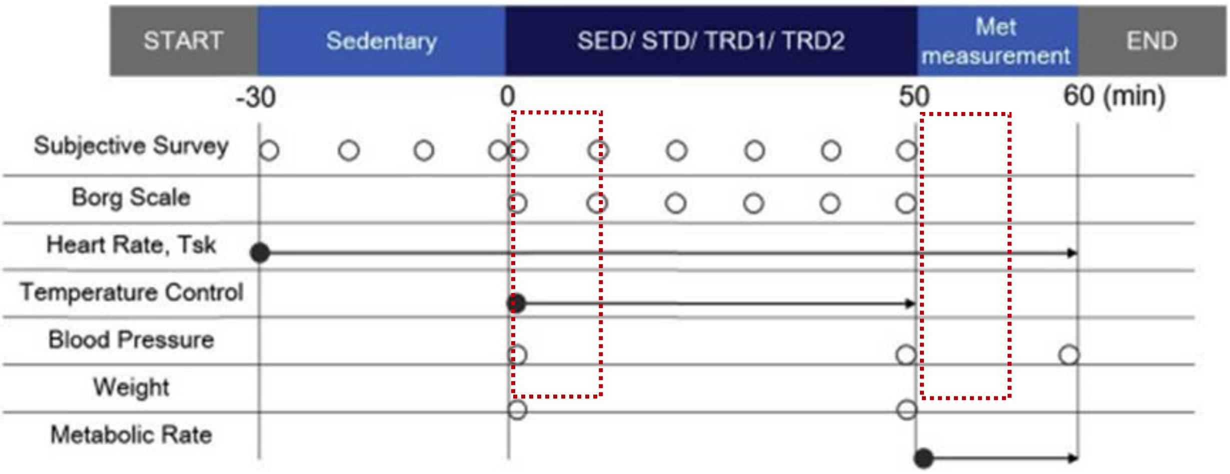


Fig.3. 12 Experimental procedure, (open circles indicate time to fill out the questionnaire or to measure physiological response, and the dot and arrow means continuous measurement) (Siru Gao et al., 2018)

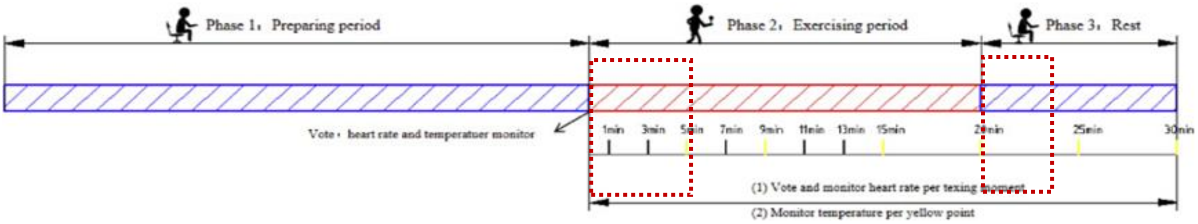


Fig.3. 13 Experiment procedure (Yuchun Zhang et al., 2020)

2. Exercise science and medical science focus on the changes of thermal sensation and physiological indicators of the human body in extreme environments, thus threatening health. In contrast, the exercise thermal sensation (comfort) in normal thermal environments is less covered.

It is important to predict thermal comfort in a built environment because the thermal comfort model has great potential for energy saving. If the comfort temperature in different environment can be predicted accurately, a reasonable set temperature can be determined. Human beings can be exposed to different environments with various thermal environment. However, to create a comfortable thermal environment for buildings in exercise, studying and predicting exercise thermal sensation is an important fundamental research. By thermal comfort model, comfortable environment can be predicted for different environment. Therefore, human thermal comfort model is an important part of built environment research.

3.7 Summary

According to previous studies, thermal stress induced by exercise and thermal environments leads to many thermoregulatory responses in the human body. The three physiological parameters most likely to be associated with exercise thermal sensation are skin temperature, core temperature, and sweating rate. The study of these three indicators revealed that changes in the core temperature are closely related to the metabolic rate in an exercise and are minimally affected by the thermal environment. But the research on the relationship between human core temperature and thermal sensation is scarce. The thermal environment dramatically affects human skin temperature. Still, the metabolic rate has little influence, and research has shown that the correlation between skin temperature and thermal sensation during exercise is substantially weaker than in the static state. The sweating rate is influenced by both the thermal environment and the intensity of exercise. Therefore it effectively reflects the combined effect of thermal environment and heat production during exercise on body temperature regulation. However, the relationship between sweating and thermal sensation during exercise needs to be further investigated, especially the relationship between sweating rate and thermal sensation in medium (high)-intensity exercises.

In conclusion, previous studies on physiological parameters related to thermal sensation during exercise have focused on the correlation between skin temperature and thermal sensation because of the high correlation between skin temperature and thermal sensation in a static state. However, it has been shown that this is not the case in exercise. The correlation between these three physiological indicators and thermal sensation during exercise, whether skin temperature, human core temperature, or sweating rate, needs to be further investigated.

Analysis of existing thermal sensation models shows that, except for the Fanger model, all existing models are based on thermophysiological indicators, focusing on predicting several physiological indicators related to thermal sensation. That is thermal comfort to four criteria: a comfortable core body temperature, a comfortable skin temperature, a comfortable sweating rate, and a heat load close to zero. These models are reasonable under normal conditions because these indicators are positively correlated with thermal sensation under normal conditions. However, in the study of physiological indicators related to the thermal sensation in exercise, it has been found that the correlation between the physiological indicators and thermal sensation in the human body during exercise is significantly reduced compared to the normal conditions. Therefore, the use of these models may produce bias in predicting thermal sensation in humans in exercise. Besides, many models use "biothermal manikin" to construct thermal sensation models, but "biothermal manikin" cannot simulate many psychological factors that affect the thermal sensation in exercise, which may also cause deviations in the prediction of thermal sensation.

But the Fanger model is not like that. It is based on the equation of the heat balance of the human body by collecting a large number of experimental data to establish a regression equation between heat load and thermal sensation, which considers the possible influence of other factors on the human body's thermal sensation. Although this consideration is only in its infancy, that is, other possible factors are treated as a "black box", and only the correspondence between the input heat load and the output thermal sensation is considered, it is not clear which specific factors influence the human body's thermal sensation. In 1994, the International Organization for Standardization (ISO) proposed the ISO7730 standard based on the Fanger thermal sensation model, which has become the accepted standard in building the thermal environment and the research related to human thermal comfort.

Analysis of existing thermal sensation models shows that Current research on models of exercise thermal sensation in thermal environments is divided into two categories. One is the research on the accuracy of existing models in predicting exercise thermal sensation in specific thermal environments. The other is to construct a new model to predict exercise thermal sensation and to verify the accuracy of the model by comparing it with actual thermal sensation. The research approach of this work belongs to the second category.

Finally, the author reviewed the research on exercise thermal sensation in different domains. The similarities, differences, and deficiencies are presented, and experimental designs are conducted for a more in-depth exploration of exercise thermal sensation.

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CHAPTER 4

EXPERIMENTAL INVESTIGATION INTO THE RESPONSES OF PHYSIOLOGICAL PARAMETERS AND THERMAL SENSATION IN THE WHOLE EXERCISE PROCESS OF DIFFERENT INTENSITIES

4.1 Experimental method *4-2*
  4.1.1 Subjects *4-2*
  4.1.2 Experimental conditions and measurements *4-3*
    4.1.2.1. Experimental environment *4-3*
    4.1.2.2 Measurement of physiological parameters *4-3*
    4.1.2.3. Subjective voting *4-8*
  4.1.3 Experimental procedure *4-9*
  4.1.4 Data processing and analysis methods *4-10*
4.2 Results and analysis *4-11*
  4.2.1 The impact of dynamic-static step changes on physiological parameters in exercise. ...*4-11*
    4.2.1.1 Skin temperature *4-11*
    4.2.1.2 Oral temperature *4-12*
    4.2.1.3 HR and HRV *4-13*
    4.2.1.4 Electrodermal activity *4-15*
  4.2.2 The impact of dynamic-static step changes on subjective sensation in exercise. *4-18*
    4.2.2.1 Thermal sensation *4-18*
    4.2.2.2 Thermal comfort *4-19*
    4.2.2.3 SFI *4-20*
    4.2.2.4 Fatigue index *4-21*
  4.2.3 Differences in the impact of gender and BMI on TSV and TC *4-23*
4.3 Summary *4-25*
References *4-26*

With technology development, indoor temperature regulators such as air conditioners and electric heaters have become essential appliances in homes and provide year-round temperature adjustment to a comfortable range. To reasonably evaluate the indoor thermal environment and create a suitable indoor environment, a lot of research has been conducted worldwide, and familiar thermal environment comfort evaluation indexes and models such as PMV have been developed. These research results are mainly based on lower activity levels. However, the thermal sensation and the comfort of the human body often change greatly because of changes in thermal environmental conditions or the different activities of people in the building. In buildings such as production workshops, construction sites, gyms or stadiums, there is a high activity level, such as labour, physical exercise, etc. For example, in a gym, if the indoor thermal environment is set to be comfortable or slightly warmer for people at static, the thermal sensation caused by exercise is intensified, people sweat sooner, tiredness increases, and comfort during exercise is reduced. There is even a great increase in the proportion of energy consumption caused by the thermal environment, so exercise loses its significance. Therefore, it is necessary to change the exercise place's thermal environment to improve the exercise thermal comfort. It is important to study the exercise thermal sensation in-depth to control the thermal environment effectively.

Predicting thermal comfort in the thermal environment is essential because thermal comfort models also have a great potential for energy saving. If the comfort temperature in different environment can be predicted accurately, a reasonable set temperature can be determined. Human beings can be exposed to different environments with various thermal environment. Yet, to create a comfortable building thermal environment in an exercise state, the study and prediction of exercise thermal sensation is important fundamental research. By thermal comfort model, a comfortable environment can be predicted for different environment. Therefore, the human thermal comfort model is an important part of built environment research.

The relationship between physiological indicators and thermal sensation has been described in the previous chapters. It has been found that the variation of thermal sensation in exercise is complex and difficult to study. Nevertheless, previous researchers have attempted to explore various aspects of thermal sensation in exercise, including the relationship between physiological parameters and thermal sensation in exercise and mathematical models. However, the author believes that the human body undergoes at least three exercise stages, i.e. static-dynamic-static. And, the first state may have a significant, even decisive, influence on the later states. In addition, the physiological indicators respond differently in different states, thus complicating the changes in thermal sensation in each state. The author attempts to decompose the whole process of exercise and observe the relationship between human thermal sensation and physiological indicators in each state to provide a new perspective and method for the study of exercise thermal sensation.

Compared with the human body in a static state, various physiological indicators of the human body in exercise have more complicated changes. The relationship between the subjective and objective indicators of the dynamic-static steps (static - dynamic - static) changes and each stage in the whole process are different and sometimes even damage health. Various physiological indicators in an exercise state are significantly different compared to the static state. In particular, the changes in the physiological parameters are more involved around the dynamic-static step. Therefore, it is necessary to conduct an in-depth investigation of the dynamic response of physiological parameters (densified monitoring points near the steps) and changes in thermal sensation (comfort) pre-, during, and post-exercise at moderate intensity. Among these physiological indices, in addition to some parameters that have been considered in previous studies to be closely related to thermal sensation, attempts investigated some of the physiological indices that are rarely used but easy to collect (ex. EDA, SDNN, and RMSSD, etc.).

This experimental study was divided into 4 parts: first, two exercise intensities were performed separately on a treadmill (speeds in the two sets of experiments were v_1 = 4.5 km/h and v_2 = 6 km/h). The activity intensities of V_1 and V_2 are approximately 3.4, and 4.9 met, respectively, and belong to medium intensity exercise. Core temperature, skin temperature, heart rate, HRV, and EDA were used as the subjects to observe the changes in these physiological parameters in the whole exercise. Changes in thermal sensation and thermal comfort were observed. Correlation analysis between subjective perception and objective physiological indices was performed. Second, two types of mathematical models are developed. A mathematical model between physiological indicators and thermal sensation in exercise, and a mathematical model between the rate of change of physiological indicators and thermal sensation. The actual thermal sensation is compared with the predicted thermal sensation calculated by the model to experimentally verify the accuracy of the newly developed model of human thermal sensation in exercise. After explaining the reasonableness and accuracy of the model, the two types of models' simulation effects are then compared to illustrate their advantages and disadvantages (see Chapter 5). Third, a detailed discussion of the exercise thermal sensation and the peculiarities of certain physiological parameters during the experiments is presented, along with a detailed analysis of the psychological factors that influence thermal comfort (thermal homeostasis) (See Chapter 6).

4.1 Experimental method

4.1.1 Subjects

Experiments were conducted with sixteen subjects recruited from cities in northern China using physiological measuring instruments and subjective questionnaires.

Table 4.1 shows basic information, including age, gender, body mass index (BMI)(American Society of Heating, 2017; Organization, 2000), and body surface area (As)(Yu et al., 2003). All subjects wore regular clothes (underclothes, long-sleeved T-shirts, thin trousers, socks, and sneakers) with clothing insulation of 0.8 clo. Clothing insulation values were calculated using the ASHRAE standard 55(Iso, 2007).

To avoid the influence of age and social background on the results, the subjects were all college students from the same province. Subjects were required to remain healthy and free of underlying diseases and were not allowed to take drugs before or during the experiment. Vigorous exercise and overeating were not allowed within 24h before the test. Subjects were not allowed to eat or drink for 2h before the test. All protocols had been approved by the University Ethics Committee (approval number SXULL2019069). Before participating in the experiment, verbal and written informed consent was obtained from each subject.

Table 4.1 Basic information on the subjects

Gender	**No.**	**Age (years)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/cm^2)**
Male	9	20.5 ± 2.5	175.1 ± 11.9	66.3 ± 15.7	21.6 ± 3.8
Female	7	20 ± 1	165.6 ± 6.4	59.7 ± 11.3	21.8 ± 5.3
All	16	20 ± 3	170.9 ± 12.1	63.4 ± 18.6	21.7 ± 5.4

Note: BMI and As are the for body mass index and body surface area, respectively.

4.1.2 Experimental conditions and measurements

4.1.2.1. Experimental environment

The test was performed in a climate chamber (Fig. 4.1). The indoor environment has a temperature of 26 ℃, the relative humidity of 60%, average radiation temperature equal to the indoor temperature, and air velocity $v_a < 0.1$ m / s.

4.1.2.2 Measurement of physiological parameters

Physiological parameters were monitored throughout the experiment. Special attention was given to changes in the exercise state changes (dynamic-static steps). The physiological parameter measuring instrument was portable, and the indicators of the device are shown in Table 4.2. The arithmetic mean of all data collected within 5s before and after the measurement of each physiological parameter was calculated to improve the validity of the data.

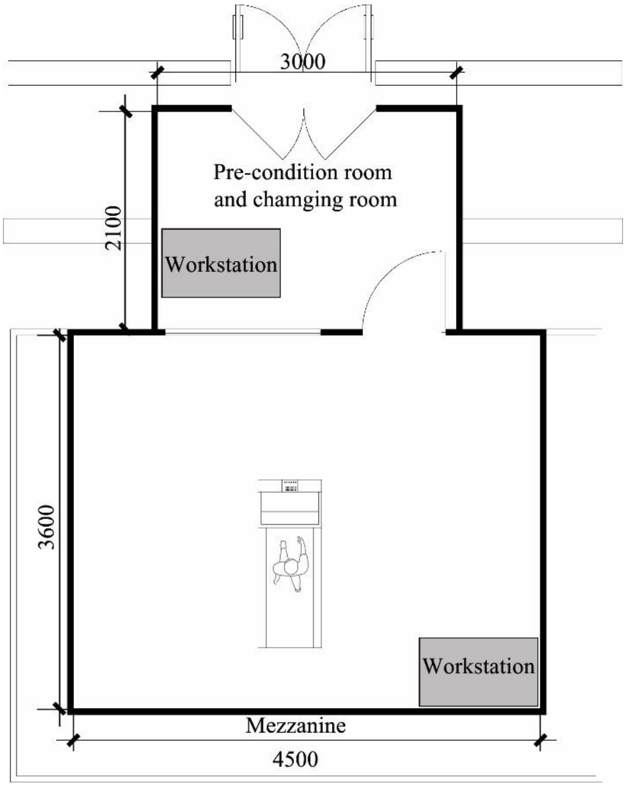

Fig.4. 1 Climatic chamber diagram

This experiment uses the ErgoLAB Human-Machine Environment Cloud Platform, capable of real-time and synchronous acquisition of human-machine-environment multi-dimensional data, and transmit the data via Bluetooth RF. Data processing and analysis were performed on the ErgoLAB Multimodal data synchronization Cloud Platform.

Before and after the experiments, it has been ensured that all measuring equipment has been carefully calibrated. Firstly, it was confirmed with the manufacturer that the error of the instruments in the test is constant and that the instruments themselves would not affect the experiment results. Before the experiment started, seven temperature sensors were placed side-by-side in the same skin area and observed for 5 minutes to confirm that each sensor's results were the same (the allowable error was 0.1°C). During the experiment, the author made sure that each sensor was used in the same part. Each sensor was wiped with alcohol after the experiment and left it to stand for at least 20 minutes before being allowed to be used again. However, the most crucial influence on the experiment results is the preparation work before the test. The author has ensured that the following preparations have been performed before the operation. When performing skin temperature measurements, the measurement area's skin must be cleaned or wiped with alcohol, and the sensing probe was attached to the surface with vapor-permeable surgical tape. The sensor probe was firmly attached to the skin. Wiped or cleaned the skin area to which the sensor electrodes need to be connected before performing EDA measurement measurements. Apply the conductive paste to the skin area. Attach the two sensor electrodes separately to the skin area to which the conductive paste is applied. For PPG measurements, the pulse sensor's black ear clip needs to be attached to the earlobe. The earlobe needs to be gently massaged before the experiment to promote blood flow. The purpose was to prevent any noise or interference with the acquisition signal.

Table 4. 2 Measurement instruments of this experiment.

Instrument	**Parameter**	**Measuring Range**	**Accuracy**	**Sensor Pic.**	**Wearing Style**
Wireless skin temperature sensor	T_{sk}（℃）	10–60℃	± 0.1℃		
ireless skin electrodermal activity sensor	EDA（μS）	0–30 μS	± 0.3 μS		
PPG Ear Tip Pulse Sensor	ECG (HR, HRV）	25~240bpm	± 1bpm		

1) Skin and oral temperatures

Skin temperature is closely related to the human thermal sensation and should be used as an essential indicator in human activity experiments. The instrument automatically records the data of 7 body parts and performs weighted calculations according to equation (Fig.4.2) (Yao et al., 2008).

$$T_{sk} = 0.07T_{forehead} + 0.35T_{chest} + 0.14T_{lowerarm} + 0.05T_{hanback} + 0.19T_{thigh} + 0.13T_{lowerleg} + 0.07T_{instep}$$

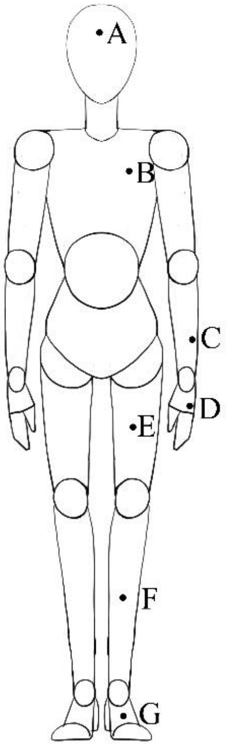

Fig.4. 2 Test points on the body

Current measurements of the core temperature probably include oral temperature, auditory canal temperature, oesophageal temperature, tympanic membrane temperature, and rectal temperature. Xiong et al. (Xiong et al., 2016) used oral and skin temperature as markers of the thermal metabolism system. Zhang et al. (Zhang et al., 2020) used the auditory canal temperature as the core temperature in the dynamic test. Zhai et al. and Gao et al. used telemetry pills to measure the core temperature (Gao et al., 2018; Zhai et al., 2019). The author chose oral temperature as the core temperature for this experiment for reasons:

a) The original purpose of the study was to select some parameters that are easy and convenient to measure. It is challenging to measure rectal temperature, tympanic membrane temperature, etc. in dynamic testing. And it is hoped that in the future, with the progress of the research, these easily measurable parameters, which can predict and show thermal sensation, comfort, and health, will be incorporated into smart devices, such as smart bracelets. This is basic research for future practical applications.

b) The author has also tried to use telemetry pills at the same time to find out if there is a significant relationship with oral temperature. But unfortunately, the author currently lacks this device, so the author is considering using it to measure core temperature in a future study.

c) More importantly, the author found support for this experiment in previous authors' researches.

Xiong et al. (Xiong et al., 2016) used oral temperature as core temperature. Relatively speaking, the accuracy of temperature accuracy in clinical practice is relatively high, and Greenleaf et al. (Greenleaf and Castle, 1972) have suggested that auditory canal temperature is the most appropriate way to reflect the mean body temperature. Chappuis et al.(Chappuis et al., 1976) found that sublingual temperature (T_{or}) was somewhat higher than tympanic membrane temperature (T_{ty}) at 25 and 30°C at rest. During exercise, the difference between T_{or} and T_{ty} became smaller. Figure 4.3 shows a good correlation between these two measurements during the 90W exercise.

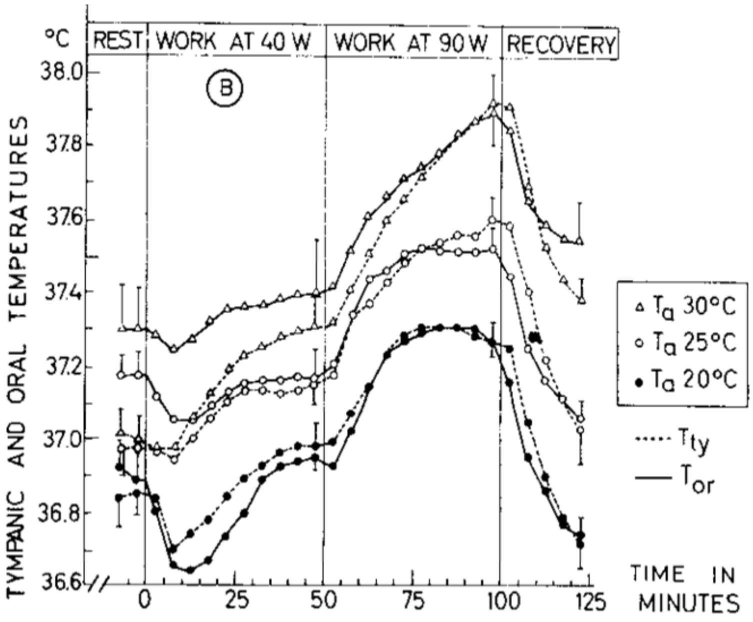

Fig.4. 3 Tympanic (T_{ty}) and Sublingual (T_{or}) temperature at 20, 25, and 30°C (Chappuis et al., 1976)

When measuring the oral temperature, the sensor probe is sterilized and placed under the tongue. The subject is required to breathe through the nose during the whole process to avoid errors caused by mouth breathing during exercise. Breathing through the nose satisfies the oxygen demand of the body as the exercise intensity is moderate in this experiment. Ear canal or anal temperatures are recommended for high-intensity exercise testing.

2) HR and HRV

The heart rate (HR) reflects the activity of the heart. Heart rate variability (HRV) is a non-invasive method for assessing the effects of the autonomic nervous system(Malik et al., 1996). HRV consists of time and frequency domain metrics. The frequency domain is a method of separating the waveforms in the heart rate graph according to different frequencies and analyzing and researching in a specific frequency range (this experiment uses LF/HF as the primary indicator). The time-domain method analyzes the time-domain heart rate and heartbeat interval within the test and studies its change over time(Liu et al., 2008). The heart rate variability index in the time domain analysis primarily reflects the function and state of the parasympathetic nerve (this experiment uses SDNN and RMSSD as the primary indicator).

3) EDA (electrodermal activity)

EDA is the physiological response of an individual related to the sympathetic nervous system and maybe a useful indicator of the sympathetic branch activity of the autonomic nervous system because sweat glands are innervated by sympathetic nerve activity (Poh et al., 2010; Schumm et al., 2013). EDA can also be used as an indicator of sweat secretion.

4.1.2.3. Subjective voting

These indices include thermal sensation (TSV), thermal comfort (TC), and the sweat feeling index (SFI) (Table 4.3). The thermal sensation was investigated according to the ASHRAE Thermal Sensitivity Scale (Zolfaghari and Maerefat, 2011), and subjects answered questions regarding thermal sensation on a 9-point scale (ASHRAE 7-pt scale with very hot and very cold added as endpoints), during the experiments. Thermal comfort rating scores range from −3 to +3. The levels of SFI are 0, 1, and 2 (Wang and Hu, 2016). Fatigue was assessed using Japanese subjective fatigue symptoms (2002 version) listed in Table 4.4 (Geng, 2009). The fatigue check-list contains 25 items and is divided into 5 subtypes. The participants answered each items using 5 point scale from þ1(none) to þ5(extremely severe). Fatigue subtype score ranges from 5 to 25 because it is the summation of corresponding five items. Similarly, the total score ranges from 25 to 125 since it is the summation of all 25 items.

Table 4. 3Voting scale for the thermal sensation, thermal comfort, and sweat feeling indices

Thermal sensation	−4 Very cold	−3 Cold	−2 Cool	−1 Slightly cool	0 Neutral	1 Slightly warm	2 Warm	3 Hot	4 Very hot
Thermal comfort	0 No feeling of sweating	1 Slightly feeling of sweating	2 Strong feeling of sweatong						
Sweat feeling indices	−3 Very uncomfortable	−2 uncomfortable	−1 Slightly uncomfortable	1 Slightly comfortable	2 comfortable	3 Very comfortable			

Table 4. 4 Sakai Kazuhiro, items of Japanese subjective fatigue symptoms (2002 version).

Type 1: insecurity	**Type 2:discomfort**	**Type 3: tiredness**	**Type 4: fuzziness**	**Type 5: soreness**
Feel nervous	Have a headache	Feel sleepy	Feel slightly hard to keep eyes	Feel arms feeble
Feel bad in mood	Feel heavy in the head	Want to lie down	Feel the eyes tired	Feel a pain in the back
Feel restless	Feel bad	Give a yawn	Feel sore in the eyes	Feel a pain in the hands or fingers
Have a quick temper	Feel mind wandering	Lack motivation	Feel dry in the eyes	Feel acid leg pain
Feel confused in thinking	Feel dizzy	Feel general weakness	Feel blurred in vision	Feel soreness in the shoulders

4.1.3 Experimental procedure

The experiment was conducted in October 2018 and was divided into two sets (V_I and V_2). Each subject was required to participate in the two sets of experiments; the experimental procedures of the two sets were precisely the same. Each subject participated test at an interval of more than 72h to ensure adequate acclimatization to the experimental conditions, to prevent biases in the results owing to any one set of the experiment. Before and after the experiments, we have ensured that all measurement equipment was carefully calibrated. We have assured that the following preparations have been performed before the test. When performing skin temperature measurements, the skin of the measurement area must be cleaned or wiped with alcohol, and the sensing probe was attached to the surface with vapor-permeable surgical tape. The sensor probe was firmly attached to the skin. Wiped or cleaned the skin area to which the sensor electrodes need to be connected before performing EDA measurement measurements. Apply the conductive paste to the skin area. Attach the two sensor electrodes separately to the skin area to which the conductive paste is applied. For PPG measurements, the black ear clip of the pulse sensor needs to be attached to the earlobe. The earlobe needs to be gently massaged before the experiment to promote blood flow. The purpose was to prevent any noise or interference with the acquisition signal.

The subjects were asked to wait 15 min outside the climate chamber before the test to avoid entering the chamber with an elevated metabolic rate. Each set of experiments lasted 50 min and was divided into three phases (Fig. 4.4). In the first stage (15 min), the subjects stood still in the climatic chamber. In the second stage, the subjects walked for 20 min on a treadmill at a certain speed (speeds in the two sets of experiments were v_1 = 4.5 km/h and v_2 = 6 km/h). In the third stage, the subjects stopped exercising and continued to stand for 15 min. A sitting position may wrinkle or fold clothing and yield different clo values. Therefore, the standing posture was maintained to avoid the formation of an air layer between the clothing layers. The ASHRAE Standard 55-2017 table (American Society of Heating, 2017) and the study by Zhai et al. (Zhai et al., 2018) are used to estimate the metabolic rate value. The activity intensities of V_1 and V_2 are approximately 3.4, and 4.9 met, respectively, and belong to medium intensity exercise.

As shown in Fig.4.4, thermal sensation and SFI voting were conducted during the experiment at the 13th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 25th, 29th, 33rd, 35th, 36th, 37th, 40th, 43rd, 46th, and 49th min (red |). The 12 thermal comfort questionnaire times (violet |) were at minutes 13th, 17th, 21st, 25th, 29th, 33rd, 35th, 37th, 40th, 43rd, 46th, and 49th min. The exercise was stopped at the 35th minute. The questionnaire of thermal sensation and thermal comfort was completed at 10s after the exercise to study the immediate subjective changes in the human body.

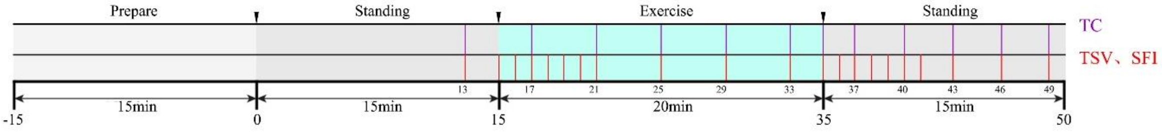

Fig.4. 4 Experimental procedure

|: Thermal sensation and SFI questionnaire were filled out at the 13th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 25th, 29th, 33rd, 35th, 36th, 37th, 40th, 43rd, 46th, and 49th min.

|: The thermal comfort questionnaire was filled for 13th, 17th, 21st, 25th, 29th, 33rd, 35th, 37th, 40th, 43rd, 46th, and 49th min.

4.1.4 Data processing and analysis methods

Raw data were input into Excel 2019 for organization and sorting. All data description analysis was performed in Origin 2018, including data splitting and summarization. In this study, the data were described through line charts and histograms, and the boxplot determined the outliers. The differences and correlations of the data were studied with IBM SPSS Statistics 25. The Shapiro-Wilk method was used to conduct the normality test; the sample T-test was performed on the test V_1 and V_2 data. The Pearson correlation coefficient was calculated, and the double-tail test was performed. The objective and subjective indexes were quantitatively analyzed by stepwise regression algorithm, the model was established, and the significance test was carried out. The stepwise regression method is a multiple linear regression analysis method. The stepwise regression algorithm is adopted to fit the regression model. The selection of independent variables is determined automatically by the stepwise algorithm. In each step, a variable is considered for addition to or subtraction from the set of explanatory variables based on some prespecified criterion. Statistical analyses were performed at the 95% significance level.

4.2 Results and analysis

4.2.1 The impact of dynamic-static step changes on physiological parameters in exercise.

4.2.1.1 Skin temperature

Fig.4.5 shows skin temperature over time. In the early stages of exercise, the skin temperature decreased slightly. It can be explained by the thermal balance equation of the human body.

$$M - W = C + R + E_{sw} + C_{res} + E_{res} + S$$

SHL is defined as sensible heat loss; SHL = C + R. LHL is the loss of latent heat. At the beginning of the exercise, M began to change but did not stabilize immediately. The human body took 5–6 min to reach a new exercising metabolic level (Ji et al., 2018). LHL, C_{res}, and S did not change significantly in a short time. M-W was reduced, thereby reducing SHL, and SHL reflects the situation of T_{sk}. Later, as the metabolic rate increased, the skin temperature gradually rose. This situation can also be explained based on physiology (Johnson, 1992; Kenney and Johnson, 1992). Blood flows to the exercise muscles at the beginning of the exercise to meet the energy requirements of the working muscles, and the blood vessels in the skin begin to contract, causing the skin temperature to drop. In the later stages of exercise, the body generates abundant heat. In order to maintain normal body temperature, the skin blood vessels begin to relax to increase heat loss, causing the skin temperature to begin to rise. It is important to note that the skin temperature overshoots at 36 min. The human body indicators in exercise fluctuate widely when compared to the static state. Equation shows the average changes in skin temperature. It is introduced to reflect the change of the indicators better and to facilitate the acquisition of useful statistical comparisons. To estimate the change of each T_{sk}, the T_{sk} at the 35th min was used as a benchmark to normalize the change of the data of each subject.

$$T_{sk}\,(36^{th}\ min - 35^{th}\ min)\ (\%) = (T_{sk}\ at\ 36^{th}\ min - T_{sk}\ at\ 35^{th}\ min) / (T_{sk}\ at\ 35^{th}\ min)$$

The results show (Fig. 4.6) that changes greater than 0, indicating that the skin temperature experiences an overshoot phenomenon after the exercise. The change in the V_2 experiment is greater than that of the V_1 experiment; this phenomenon is more obvious after the increase in exercise intensity (the change at 36 min).

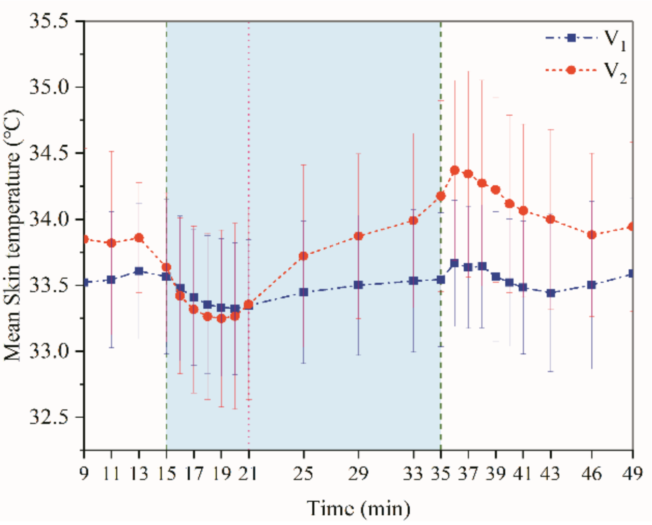

Fig.4. 5 Multiple line of mean skin temperature (95% CI) by time and phase

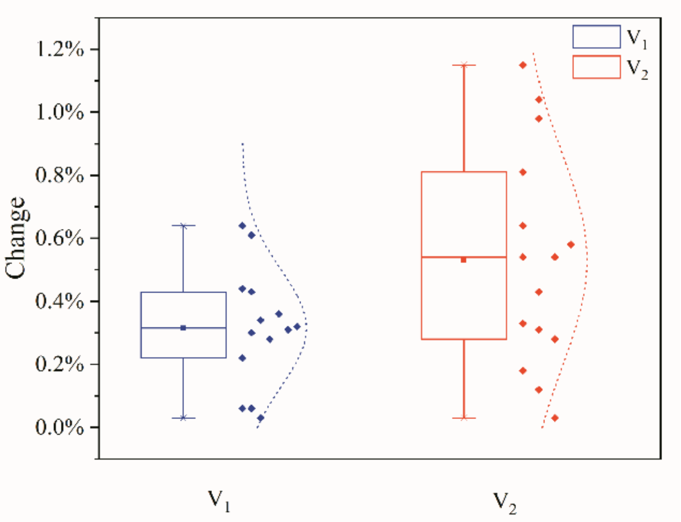

Fig.4. 6 Multiple line of mean skin temperature by time and phase

4.2.1.2 Oral temperature

Both oral and skin temperatures reflect the function of the thermal metabolic system of the body. Fig.4.7 shows that the oral temperature was maintained at approximately 37.2–37.4 °C before exercise. At the beginning of the exercise, the oral (core) and skin temperatures showed a downward trend. In the V_2 test, T_{or} differed significantly between the initial and final stages of the exercise periods ($P < 0.001$) as shown in Fig.4.11. After the end of the exercise, the core temperature continued rising and was practically the same as the initial temperature.

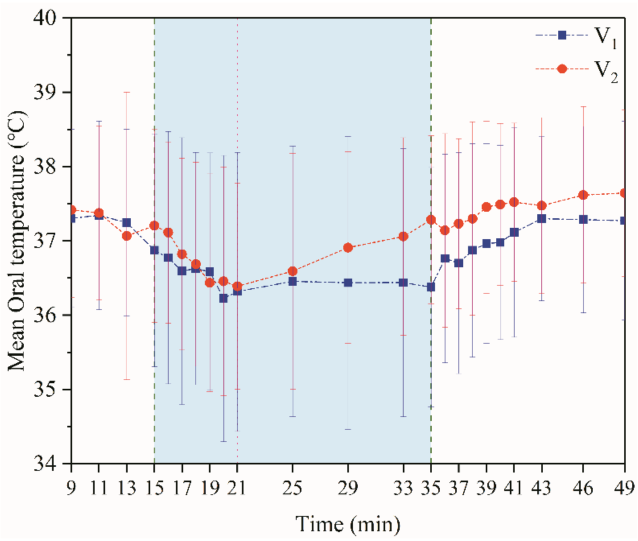

Fig.4. 7 Multiple line of mean oral temperature (95% CI) by time and phase

4.2.1.3 HR and HRV

Previous studies found a significant correlation between HR and energy metabolism. Load intensity, especially during exercise, increased gradually, and energy metabolism demand became higher; thus, heart rate also increased. Therefore, it is possible to use heart rate to reflect exercise intensity and metabolism(Strath et al., 2000). Fig.4.8 shows that the heart rate before exercise is practically maintained at 75–80 BMP. The heart rate began to fluctuate at the start of the exercise and was higher in the V_2 stage than in V_1. Studies show that increased sympathetic nerve activity and decreased vagal nerve activity are necessary mechanisms that cause a rise in heart rate to rising and vasoconstriction during exercise. The vagus nerve is activated again during the recovery period after exercise to restore the heart rate and vasodilation (P. Kaikkonen, 2008; Sarmiento et al., 2013). The sympathetic nerve dominates the sympathetic and vagus nerve balance during exercise, vagal nerve tension is suppressed, and adrenaline secretion increases and acts on the myocardium to strengthen myocardial glycogen breakdown and accelerate energy metabolism, thus increasing heart rate (Xiao-nan, 2015). It is illustrated by the rise in heart rate and the continuous decrease in the RMSSD and SDNN index during exercise. The upward rush of the heart rate within 2 min after the exercise is a phenomenon that becomes more obvious as the exercise intensity increases. This trend is also found in the LF/HF index changes. Studies have shown that changes in sympathetic and vagus nerve activity during exercise are highly correlated with cardiovascular disease risk and mortality (Agaty et al., 2017). In the 6-min walk test for healthy older people over 40 years of age, HRV and heart rate indicators can more sensitively reflect the functional status of the subjects. These indicators are more helpful in analyzing the effects of interventions on the autonomic nervous regulation and cardiopulmonary function of the elderly (Corrêa et al., 2013).

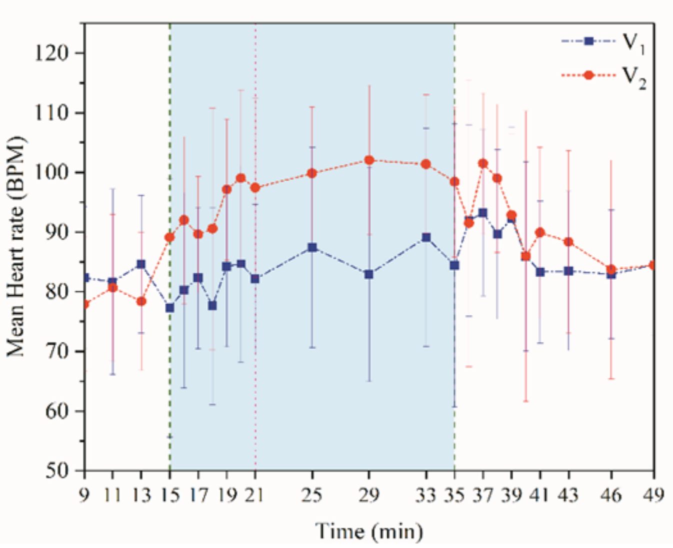

Fig.4. 8 Multiple line of mean heart rate (95% CI) by time and phase

The metabolic rate does not stop immediately when the exercise stops for moderate or intense activities. This reaction may also affect the thermal sensation, a finding even more important for the frail, especially the elderly. After moderate and high-intensity exercises, a sudden spike in the heart rate may cause harm to the body, accompanied by a temporary reduction in thermal comfort.

The HRV analyzes the time domain index SDNN, RMSSD, and frequency domain index LF/HF. SDNN reflects the total change of heart rate variability and the total activity of the sympathetic and vagus nerves. RMSSD is primarily used to evaluate the cardiac vagus nerve regulatory function in the high-frequency field and is commonly employed as a parameter for assessing the parasympathetic nervous system activity (Malik et al., 1996; Malliani et al., 1991). According to the HRV analysis theory, LF is related to sympathetic and parasympathetic nerve activity, and HF indicates vagus nerve activity. Therefore, LF/HF indicates the dominant activity and potentially affects thermal comfort by acting on the vagus and sympathetic nerves of the human body (Yao et al., 2008).

Fig.4.9 shows the changes over time for each indicator in the HRV. The change patterns of the time domain indicators are similar. At the beginning of the exercise, the time-domain index increased rapidly. During the exercise, SDNN and RMSSD trended downward and recovered to the pre-exercise levels with a more significant drop after the exercise. It shows that the parasympathetic tone gradually decreases, indicating that the comfort level progressively worsens. The values of SDNN and RMSSD in the V_2 experiment during exercise are significantly higher than those in the V_1 experiment ($P < 0.001$). It shows that the human body was more uncomfortable in the V_2 experiment. A study by Spring et al.(Spring et al., 2018) showed that the subjects experienced a decrease in

RMSSD and HF during exercise compared to in a resting state and that the sympathetic-vagal nerve was imbalanced. Maraes V R et al. (Maraes et al., 2013) found that RMSSD and HF decreased after walking, while LF increased. The increase in LF/HF and the decrease in RMSSD after exercise in this test are consistent with the results of the above study. There was no significant change before and during exercise in the frequency-domain indicator LF/HF, indicating that the active degree of difference between the sympathetic and parasympathetic nerves is the same; thus, the balance of the entire autonomous audit system remains unchanged. However, the data visualization revealed that the index has some relationship with thermal sensation and thermal comfort.

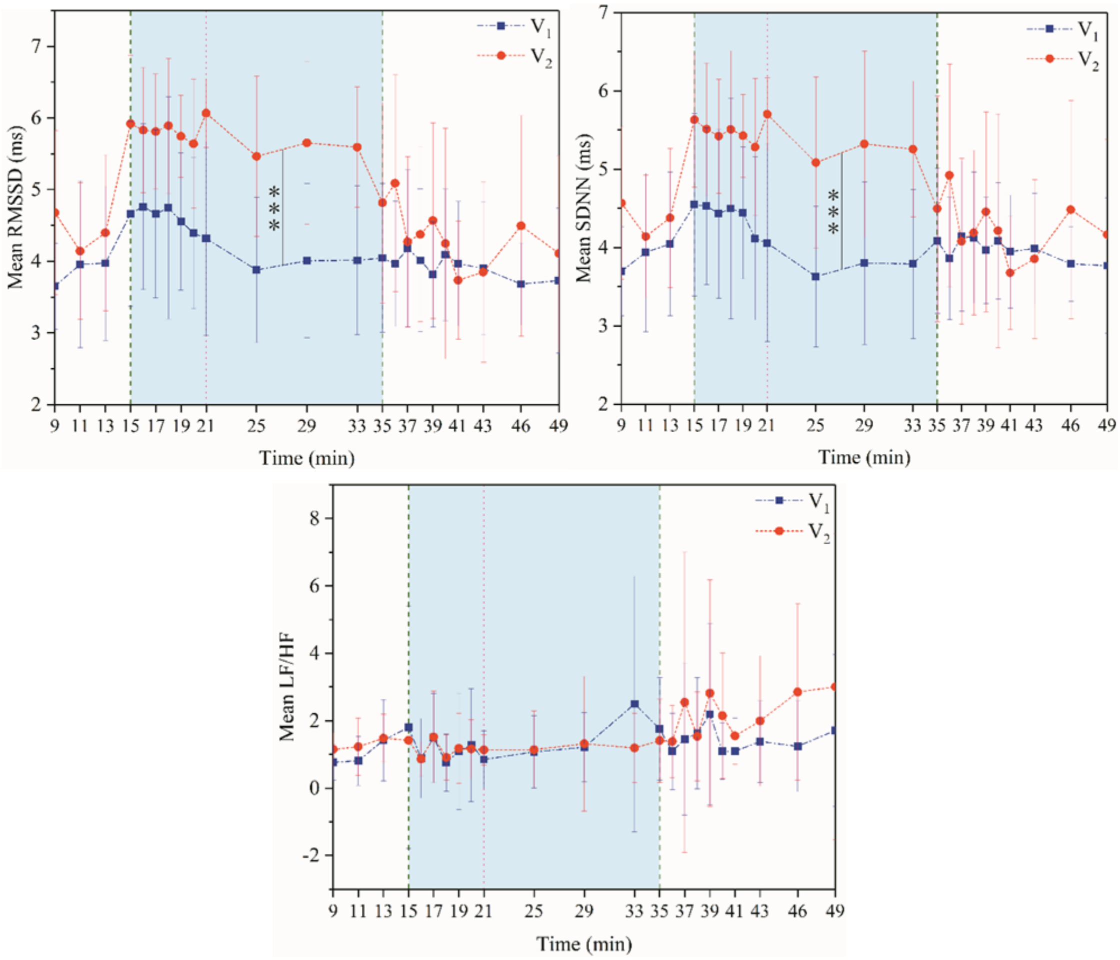

Fig.4. 9 Multiple line of mean each indicator in the HRV (95% CI) by time and phase

4.2.1.4 Electrodermal activity

EDA is an autonomous change in the electrical characteristics of the skin caused by sweat secretion (Benedek and Kaernbach, 2010). EDA can reflect the degree of sweat secretion. It may be a useful indicator of the sympathetic nerve activity of the autonomic nervous system because sweat glands are innervated by sympathetic nerve activity. The EDA value suddenly changed at the moment when the exercise started (Fig.4.10). This phenomenon is more evident in the V_2 experiment and is a physiological stress response because of the sudden changes in exercise status. The value is very sensitive because the EDA sensor probe is fixed to the tip of the index finger, the part of the human that first sweats after being stimulated by external stimuli or sudden changes in mood. Higher EDA can reflect the stimulation of sympathetic nerves by external stressors, which is the result of feedback from the autonomic nervous system (Epstein, 1994). This mutation result is consistent with the time-domain indicators (SDNN and RMSSD) in the HRV. After the stress level was lowered, the EDA index decreased and returned to normal levels. However, the EDA index of the V_2 experiment is generally higher than V_1, indicating that the amount of sweat in the V_2 test is higher than in V_1. By the last stage of the exercise, the EDA index gradually increased with the increase in sweating and reached a peak at the end of the exercise. The sympathetic nerve is more active at this time, and the discomfort is stronger. The EDA index decreased after exercise in the V_2 experiment but did not return to pre-exercise levels. Because this experiment was performed in a steady-state environment, the subjects exercised in situ and dressed in long-sleeved clothing and trousers to allow sweat to evaporate slowly. The EDA indicator takes longer to return to its initial value before the exercise.

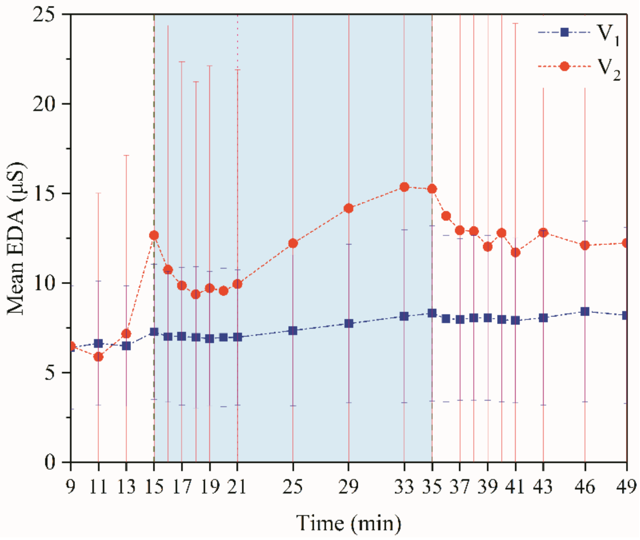

Fig.4. 10 Multiple line of mean EDA (95% CI) by time and phase

Interestingly, in a comparison of multiple physiological parameter figures, it was found that 21st minutes after the start of the exercise was the inflection point moment for physiological indicators. To further illustrate this point, we calculate the change value. The physiological parameters of different subjects will not be exactly the same at the same moment. Therefore, even under identical environmental conditions and experimental procedures, we can expect different physiological parameters (Choi and Loftness, 2012). Hence, we conducted a detailed investigation using numerical change rates to obtain a valid statistical comparison. Several important physiological parameters were selected for analysis. To estimate the change of a certain physiological parameter, the parameter at the 21st (or 15th) min was used as a baseline to normalize the change of the physiological index of each subject. Equations use skin temperature (T_{sk}) as an example; the change obtained in (4) is denoted as CR_1, and the change obtained in is denoted as CR_2.

CR_1 : $T_{sk}(21^{th}\ min - 15^{th}\ min)(\%)$

$=(T_{sk}\ at\ 21^{th}min - T_{sk}\ at 15^{th}\ min) / (T_{sk}\ at\ 15^{th}\ min)$

CR_2: $T_{sk}(35^{th}\ min - 21^{th}\ min)(\%)$

$=(T_{sk}\ at\ 35^{th}\ min - T_{sk}\ at\ 21^{th}\ min) / (T_{sk}\ at\ 21^{th}\ min)$

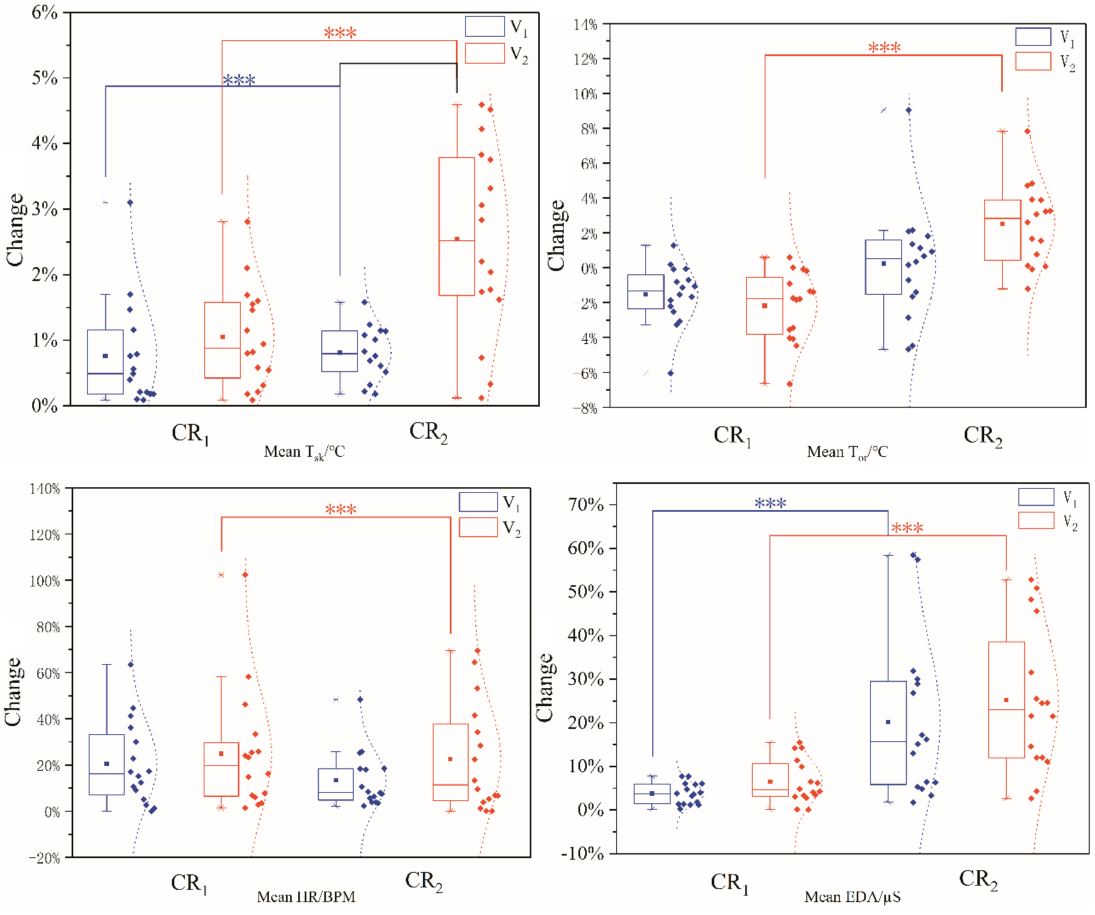

Fig.4. 11 Comparison of CR_1 and CR_2 between V_1 and V_2

CR_1 and CR_2 are generally lower in the V_1 experiment than in the V_2 experiment (Fig.4.11), showing that increasing the exercise level will bring greater changes to the physiological indicators. For the V_2 experiment, the CR_2 of the four parameters T_{sk}, T_{or}, HR, and EDA, was significantly greater than CR1 ($P < 0.001$). For the EDA index, significant differences were observed between CR_1 and CR_2 in the V_I experiment ($p < 0.01$). For the Tsk index, it was also observed that the CR_2 in the V_2 was significantly greater than in the V_1 ($p<0.001$). This result indicates that the various physiological indices reached a new level about 6 minutes after the start of the exercise. It is consistent with previous research conclusions (Ji et al., 2018; Zhang et al., 2020). Additionally, this conclusion provides a reference for designing experimental procedures and optimizing the time of future data collection and questionnaires.

4.2.2 The impact of dynamic-static step changes on subjective sensation in exercise.

4.2.2.1 Thermal sensation

Fig.4.12 shows the change in the mean human thermal sensation vote (MTSV) throughout the experiment. Overall, V_2 has a higher thermal sensation than V_1. Over time, the metabolic rate of the body gradually increases, and the body heat load gradually increases, which makes the thermal sensation increase progressively. TSV, TC, and SFI were asked about 10s after the exercise stopped (35^{th} min). The thermal sensation does not weaken immediately after the exercise stops but instead reaches its peak. Hence, at the moment when the continuous exercise is completed, the thermal sensation overshoots. This phenomenon becomes more evident with the increased intensity of the activity and can be explained by the thermal balance equation of the human body. Because the experiment was performed in a steady-state environment, and the subjects were exercising in place (mainly considering indoor labor or sports), the wind speed brought by the exercise was not significant to LHL. The moment the subject stopped exercising, W stopped immediately, and SHL and LHL did not change significantly in a short time. The metabolic amount did not stop immediately, which can be judged by HR(Shaw, 1972). Therefore, the thermal load S of the human body is pushed up instantaneously, forming a thermal sensation overshoot within a short time after the end of the exercise. From the thermal balance equation, it is known that when W=0, LHL and SHL remain constant, S is pushed up instantaneously. Due to the increase in heat storage in the body, the core temperature rises for a short period of time. It makes the oral temperature have an "overshoots" a short time at the end of the exercise. When the exercise intensity is high, this phenomenon will be more obvious. Simultaneously, to maintain the body's thermal balance, the hypothalamus sends out instructions, vasodilation in a short period of time, blood flow increases, resulting in the skin temperature "overshoot" after exercise. Therefore, this "overshoots" of skin and oral temperature leads to an " overshoots" of the thermal sensation in a short time after the exercise. However, we believe that this phenomenon may be unfavorable to the frail or the elderly and may even be dangerous or cause damage. For example, under certain environmental conditions, after intense exercise (at a higher intensity than in this experiment), due to the thermal sensation in a short time " overshoot" may occur, which may lead to an instantaneous collapse of the body's autonomic regulation function, resulting in heat damage such as "heat stroke". Also, the HR and LF/HF may increase temporarily after high-intensity exercise, which may also pose a risk to the frail and elderly. In recent years, there have been incidents of sudden death after long-distance running among young people in China. Therefore, we suggest that the frail and the elderly should avoid strenuous exercise. The hazards of heat injury after vigorous exercise should also be paid more attention to and studied in depth. Additionally, the thermal sensation declines faster after exercise than it rises during exercise. It is more evident for the V_2 experiment.

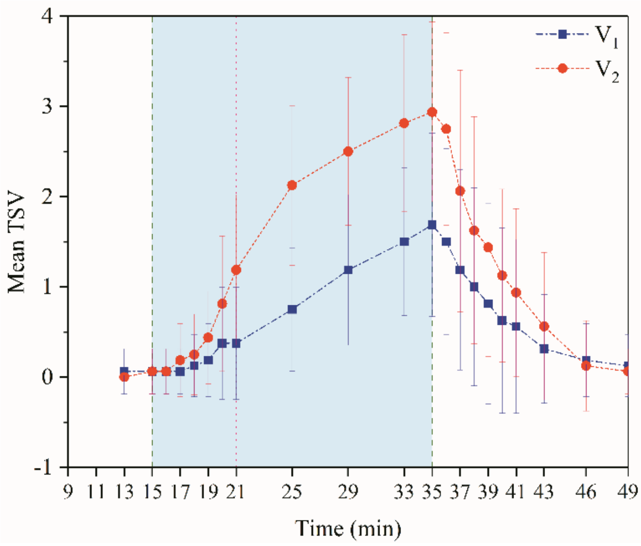

Fig.4. 12 Multiple line of mean TSV (95% CI) by time and phase

4.2.2.2 Thermal comfort

Fig.4.13 shows the change in thermal comfort. Increased duration or intensity of the exercise causes thermal comfort to decrease gradually. The comfort vote was conducted 10s after the exercise ended, at which time thermal comfort reached its lowest level.

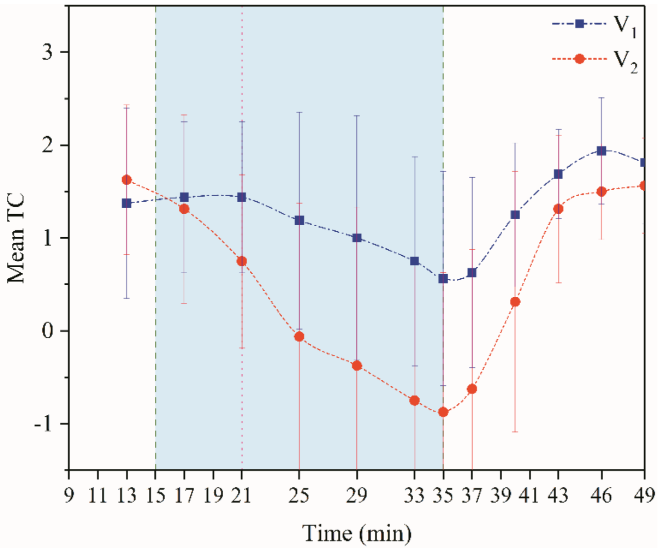

Fig.4. 13 Multiple line of mean TC (95% CI) by time and phase

The thermal comfort at the end of the V_1 experiment was higher than at the beginning of the test, likely because of the "thermal alliesthesia" factor (Cabanac, 1971). Based on daily experience, the human body generally feels comfortable and relaxed after the exercise. At the end of the V_2 experiment, although the thermal comfort was lower than at the beginning of the experiment, the curve showed an upward trend. If the experiment time is increased, the same results as V_1 will likely appear. Thus, with increased exercise intensity, the recovery of thermal comfort will be slower and eventually higher than before exercise, a reminder that studying the thermal comfort of human movement must consider the effects of the thermal sensation and pay attention to thermal delight.

4.2.2.3 SFI

The SFI is practically 0 at the beginning of the exercise (Fig.4.14), and a weak sweaty feeling appeared approximately 3 min after the start of the exercise. Within a minute after the exercise stopped, the sweaty feeling did not stop and experienced an overshoot similar to the change in thermal sensation.

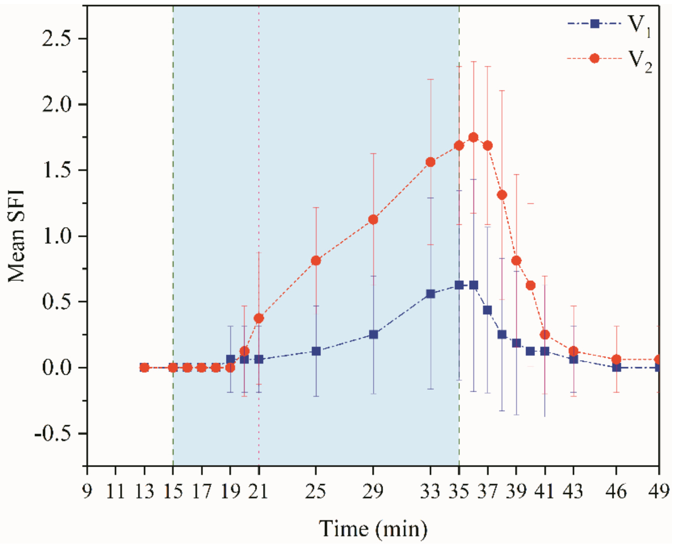

Fig.4. 14 Multiple line of mean SFI (95% CI) by time and phase

Because the subjective voting value is a discrete quantity, the concept of change value is introduced. The average change (Δ) in equation (4) illustrates the amount of SFI change denoted as ΔSFI.

Average change at (36th min – 35th min) SFI = SFI at 36th min - SFI at 35th min

ΔSFI is greater than 0 in both the V_1 and V_2 experiments, indicating that the sweaty feeling experiences overshoot after the exercise stops and that the duration is longer than that of the thermal sensation (Fig.4.15). The subjective sensation lags more than that of the EDA index. The sweaty feeling after exercise takes shorter to subside than it takes to grow.

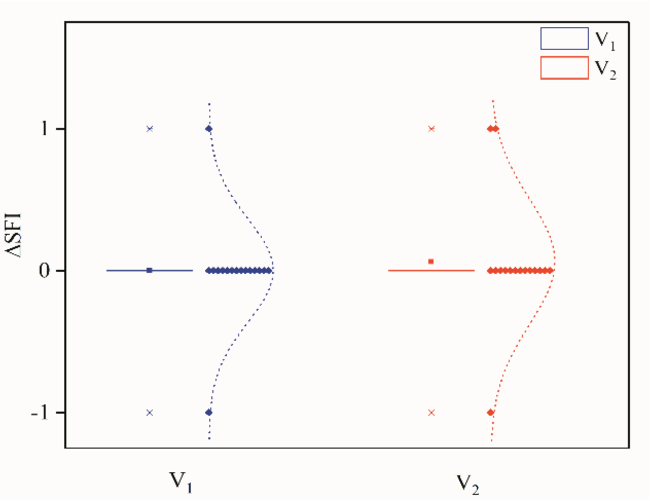

Fig.4. 15 Comparison of ΔSFI between V_1 and V_2

The parameter at the 21st (15th) min is used as a baseline to calculate the change value to examine the amount of change in a subjective perception vote. Equations use thermal sensation as an example; the change obtained by is recorded as Δ_1, and the change obtained by is recorded as Δ_2.

Δ_1: *Change value at (35 min - 21 min)TSV = TSV at 35 min - TSV at 21 min*

Δ_2: *Change value at (21 min - 15 min)SFI = TSV at 21 min - TSV at 15 min*

Sample T-tests for experiments V_1 and V_2 showed significant differences in the Δ_1 and Δ_2 for TSV, TC, and SFI ($P < 0.01$), except TSV of the V_2 experiment (Fig. 4.16). Significant differences were also observed in Δ_1 and Δ_2 between the V_1 and V_2 experiments ($P < 0.05$), showing that subjective feelings have obvious differences in the same exercise stage under different exercise intensities.

4.2.2.4 Fatigue index

The left axis in Fig.4.17 represents the fatigue index, and the right axis represents the number of subjects who are fatigued as a percentage of the total. The highest fatigue value occurs after the exercise has stopped. The amount of subjects suffering from fatigue at the same time is also the largest. Fatigue is relieved faster after exercise than it occurs during exercise. The number of subjects whose fatigue disappeared was higher than the number of subjects whose fatigue increased.

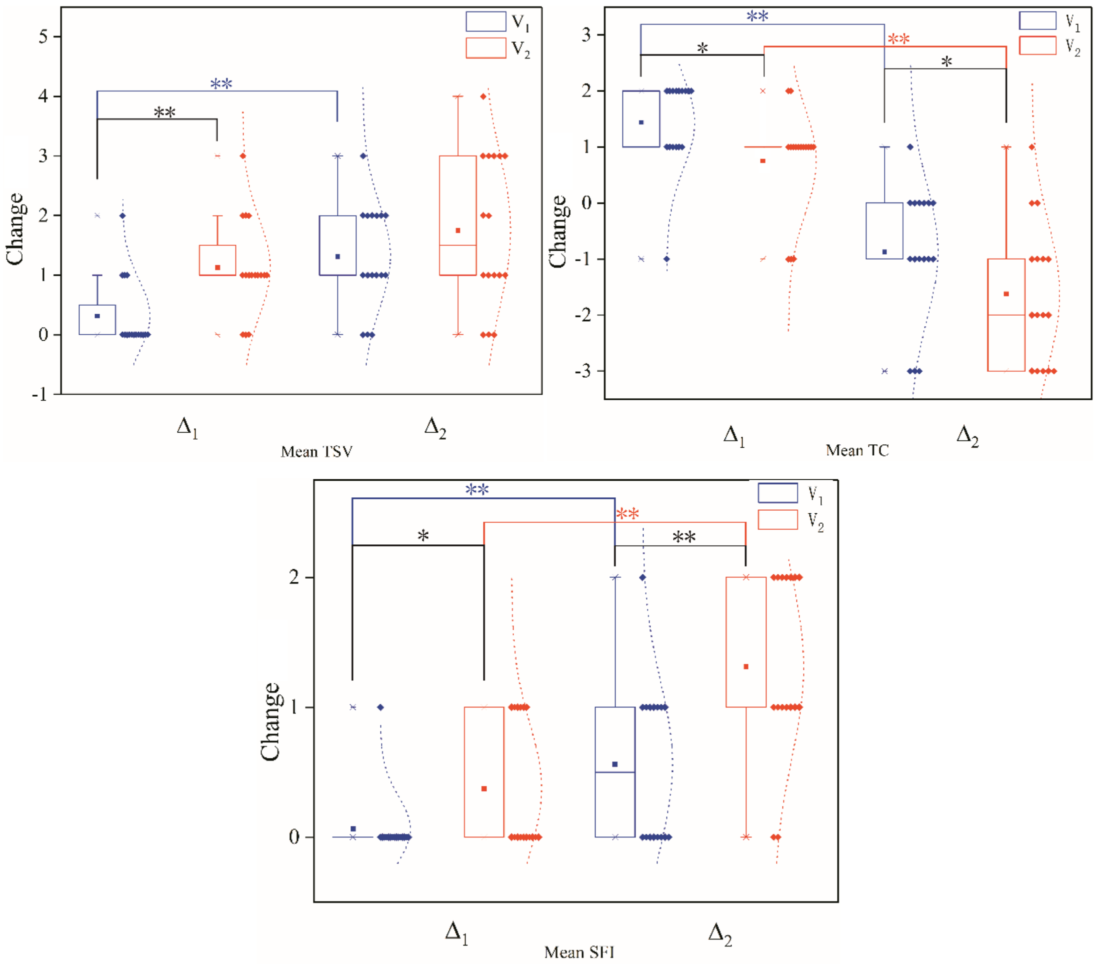

Fig.4. 16 Comparison of the change value of Δ_1 and Δ_2 between V_1 and V_2

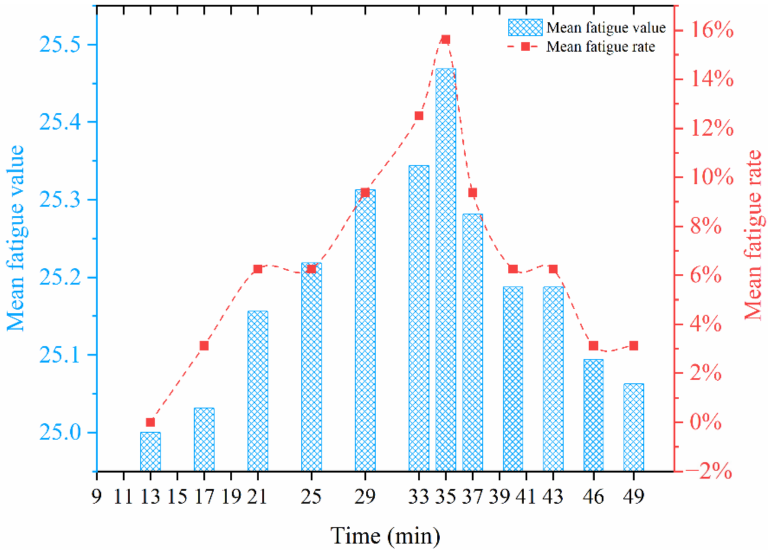

Fig.4. 17 The biaxial plot of mean fatigue value and fatigue rate

4.2.3 Differences in the impact of gender and BMI on TSV and TC

Gender and BMI were verified as factors that make a significant difference in physiological signals and subjective responses, as confirmed via many related studies (Chaudhuri et al., 2018; Choi and Yeom, 2017; Thapa, 2019). However, the subjects in these studies were in a static state. So what would be the effect of gender and BMI on exercise thermal sensation (comfort)? Fig. 4.18 shows the effects of gender and BMI on TSV and TC, respectively. The increase of male and female thermal sensations is not significantly different in the V_1 experiment. When the exercise stopped, the male thermal sensation was slightly higher than that of females, but there was no significant difference. However, the female thermal sensation subsided faster than that of the male after exercise, and MTSV practically returned to the initial state of the experiment after exercise. For the higher-intensity V_2 experiment, males seemed to feel hotter than females after the experiment started. The male MTSV was slightly higher than that of the female when the exercise was stopped, but there was no significant difference. However, the male MTSV subsided faster than that of the female after exercise, returning to pre-experiment levels. In the V_2 experiment, male comfort decreased faster than female after the 21st minute. At the end of the exercise, male mean thermal comfort was significantly lower than that of female, indicating that female heat tolerance is higher than that of males in higher intensity exercise. In general, there is an effect of gender on the exercise thermal sensation, and this effect tends to increase as the level of exercise intensity increases. However, there is no statistically significant difference in this experimental condition.

The World Health Organization (WHO) classifies BMI in four levels: underweight (≤18.5), normal weight (18.5–24.9), overweight (25–29.9), and obese (≥30). In this study, two participants were overweight, and the remaining 14 were normal. Considering the balance of comparison and significance, the BMI threshold was set as 21, which divided participants into a high BMI group (7 participants, ≥ 21) and a low BMI group (9 participants, < 21). After the 21st min, both the V_1 and V_2 experiments showed that the MTSV in the low BMI group was higher than that in the high BMI group (There was a significant difference in the V_1, $P < 0.05$, Fig.4.18). The exercise thermal sensation at 35th min was higher in the low BMI group than in the high BMI group (There was a significant difference in the V_1, $p<0.05$). However, this gap became smaller as the intensity of exercise increased. Therefore, the exercise thermal sensation tends to be consistent after increasing the intensity of the exercise, and the effect of BMI on the thermal sensation becomes smaller. The thermal comfort of the low BIM group is generally lower than that of the high BMI group in the V_1 experiment ($P < 0.05$). In the V_2 test, the comfort of the two groups of subjects showed alternation, showing that with the increase of exercise intensity, the impact of BIM on comfort becomes smaller, and the deterioration of comfort is relatively rapid. At 35th min, the comfort of the low BMI group was lower than that of the high BMI group. At 35th minutes, we still observed lower MTC in the low

BMI group than in the high BMI group, but no significant differences were observed. In general, for the exercise thermal comfort, BMI had a greater effect on comfort at lower exercise intensities, but the effect became smaller with increasing exercise intensity.

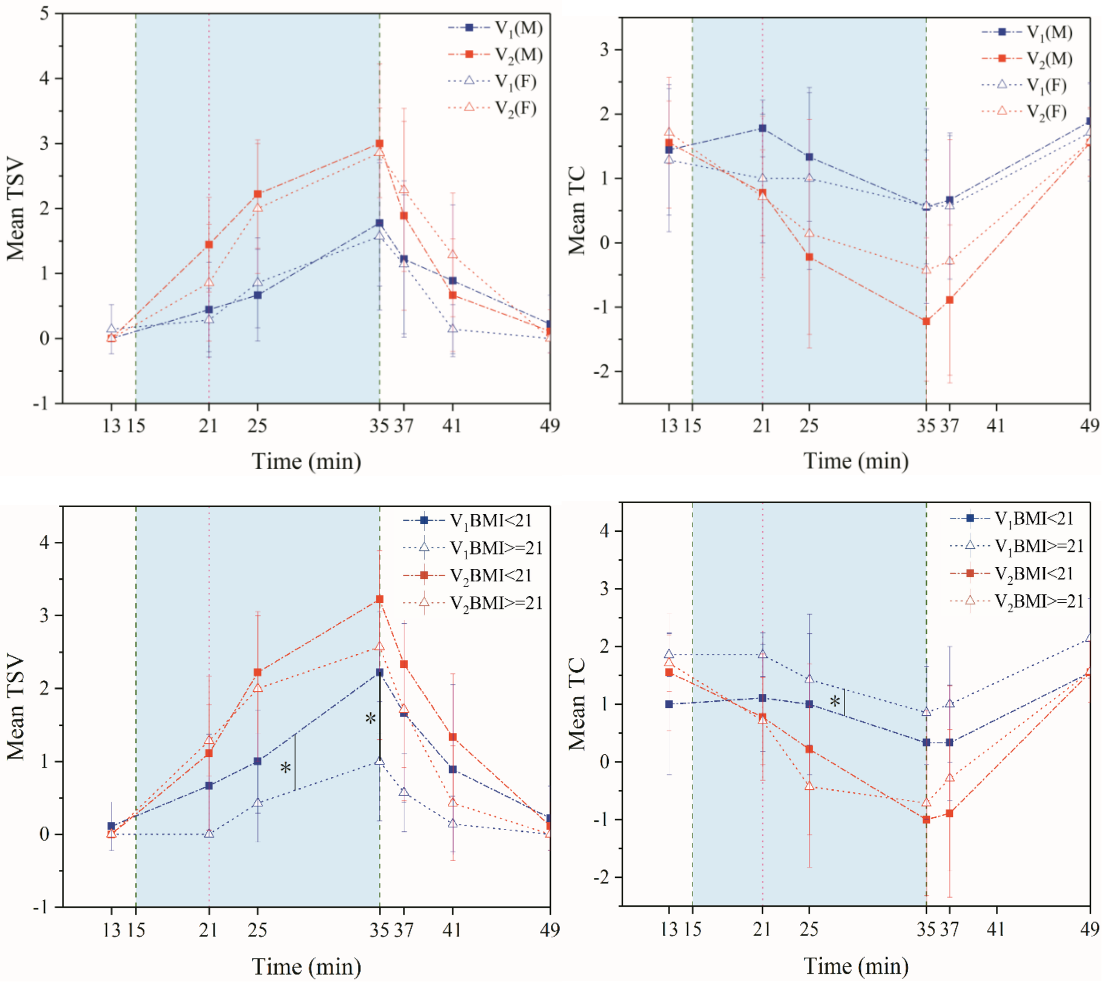

Fig.4. 18 Line chart of TSV and TC (95% CI) for different genders and BMI

4.3 Summary

Two exercise intensities were performed separately on a treadmill (speeds in the two sets of experiments were v_1 = 4.5 km/h and v_2 = 6 km/h). The activity intensities of V_1 and V_2 are approximately 3.4, and 4.9 met, respectively, and belong to medium intensity exercise. Core temperature, skin temperature, heart rate, HRV, and EDA were used as the subjects to observe the changes in these physiological parameters during the whole exercise. Changes in thermal sensation and thermal comfort were observed. The following conclusions were reached.

In physiological parameters, T_{sk}, T_{or}, and HR were all observed to overshoots after exercise. In subjective sensations, TSV and SFI also showed similar overshoots.

The physiological indicators are in the adjustment stage at the beginning of the exercise and reach stability after about 6 minutes. Simultaneously, 6 minutes is also the cutoff point for many indicators to turn the corner.

The HRV index and HR differed significantly with increasing exercise intensity. After the end of exercise, this difference gradually disappears and returns to the initial state.

Gender and BMI are also factors that influence the exercise thermal sensation (comfort). When exercise is stopped, the mean thermal sensation is higher for men than for women. As the intensity of exercise increases, female heat tolerance is higher than that of males and the effect of BMI on thermal sensation becomes smaller. At the end of the exercise, the thermal sensation was higher in the low BMI group compared to the high BMI group, and the opposite was true for comfort.

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CHAPTER 5

MATHEMATICAL RELATIONSHIPS BETWEEN SUBJECTIVE PERCEPTION AND PHYSIOLOGICAL PARAMETERS IN THE WHOLE PROCESS OF EXERCISE (STATIC-DYNAMIC-STATIC)

5.1 A comparison of the dynamic thermal sensation between the modified Stolwijk model and the Fiala thermal physiology 5-1

5.1.1 Stolwijk model 5-2

5.1.1.1. Passive part 5-2

5.1.1.2. Active part 5-3

5.1.1.3 Modifications Stolwijk model 5-3

5.1.2 Dynamic thermal sensation (DTS) 5-4

5.1.3 Fiala model 5-5

5.1.4 Variant calculations 5-5

5.1.5 The rates of change in mean skin temperature ($T_{sk,m}$) (Fiala, 1998) 5-6

5.2 Mathematical models 5-9

5.2.1 Stepwise regression analysis between physiological indicators and TSV 5-9

5.2.2. Stepwise regression analysis between physiological indicators and TC 5-11

5.2.3. Average change and rate of change of physiological parameters 5-12

5.2.4 Stepwise regression analysis of TSV using average change and rate of change of physiological parameters 5-15

5.3 Correlation analysis 5-19

5.3.1 The correlation coefficients between T_{sk}, T_{or}, HR, and HRV parameters (between objective physiological parameters) 5-19

5.3.2 Correlation analysis between objective physiological parameters and subjective perception 5-20

5.3.3 Correlation between subjective perceptions 5-22

5.4 Summary 5-23

References *........ 5-24*

There has been a growing demand from research and the industry for detailed models predicting human thermophysiological responses. Thermophysiological models are necessary for the design of the indoor thermal climate. In the Fiala model, the mean skin temperature, the core temperature and the rate at which the mean skin temperature changes are the parameters affecting the thermal sensation under dynamic conditions. Since this work draws on the aforementioned thermal sensation parameters, it is necessary to review the Fiala model.

5.1 A comparison of the dynamic thermal sensation between the modified Stolwijk model and the Fiala thermal physiology

Stolwijk and Hardy (1966) developed a thermophysiological human model which, to day, is still the basis and inspiration for many other thermophysiological human models (Katic, Zeiler, and Boxem, 2014). The multizonal Stolwijk model as compared to the better known two-node Gagge model (Gagge, Fobelets, and Berglund, 1986) was more extensive in scope, e.g. because the heat balance of the body is divided into the head, the trunk, arms, hands, legs and feet. Some later on developed thermophysiological models are usually tailored to specific applications, for instance the cold side of the comfort zone (Gordon, 1974) or Chinese people (Zhou et al., 2014). Often the source code of the computer programs of these models are not released and the computer programs are not made available for the professional practice. The Stolwijk model is made available by NASA and, precisely because of the availability of the source code, still used for research in the industry and research community by among others NASA (Miskovish, Byerly, and Miller, 2014), the Biophysics and Biomedical Modeling Division US Army Research Institute of Environmental Medicine (Berglund, Yokota, and Potter, 2013) and universities (Munir, Takada, and Matsushita, 2009; Munir et al., 2010; Ingegneria medica Universita' di Tor Vergata Roma, 2016). The Stolwijk model used in this study is improved with regard of the calculation of the skin temperature and equipped with clothing as well as thermal sensation, as described by Roelofsen (Roelofsen and Vink, 2016; Roelofsen, 2016).

In 1998 Fiala also developed a thermophysiological model (Fiala, 1998), based on the Stolwijk model and is currently considered to be the latest development in thermophysiological human models. The current version of the Fiala model is managed and operated by the company Ergonsim and is known in practice as the Fiala thermal Physiology and Comfort (FPC) model. In the FPC model an equation is included to predict the thermal sensation under dynamic conditions, the so called Dynamic Thermal Sensation (DTS), based on the simulated core temperature and the mean skin temperature. Fiala's DTS-model was developed based on the subjects' votes in early studies carried out at the Kansas State University, which did not involve physiological measurements; instead, he used his physiological model to predict the skin and the core temperatures from environmental variables measured in the tests. Fiala’s regression analysis is therefore based on the votes of human subjects and simulated skin and core temperatures. The correlations are therefore specific to Fiala’s physiological model (Zhang, 2003).

5.1.1 Stolwijk model

5.1.1.1. Passive part

The passive part of the model consists of five cylinders and a sphere with adjusted dimensions (the dimensions are determined by measurements on subjects) (Figure 5.1). The cylinders represent the trunk, arms, hands, legs and feet, the sphere represents the head. Each element consists of four concentric layers or compartments that comprise the core, the muscle tissue, the fat and the skin layers. The model also contains a central blood compartment, which represents the large arteries and veins. In this compartment heat is exchanged with the other compartments by convective heat distribution (this occurs when blood flows to the other compartments).

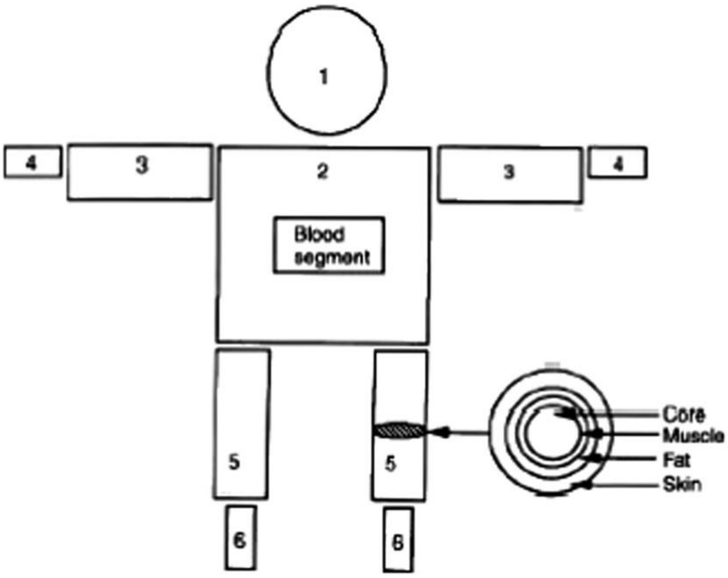


Fig.5. 1 Schematic representation of the passive part of the Stolwijk model (Stolwijk and Hardy, 1977)

The model assumes that the body is symmetrically built up; the legs are represented by one cylinder. The total passive system consists of 25 nodes: five cylinders and a sphere, each consisting of four layers, and one central blood compartment.

In this chapter, a linear correlation between physiological parameters and subjective perception is first examined to examine how the correlation between the two differs in exercise compared to the static state. Next, a stepwise regression algorithm was used to quantitatively analyze subjective and objective indicators, establish a model, and perform a significance test. This study established models for the two exercise intensity experiments. The regression model in this article did not include the evaluation of TSV and TC before exercise.

5.1.1.2. Active part

The active part of the model is the thermoregulation system (Figure 5.2) which perceives the ambient temperature and consists of an integrated and regulatory system. It is a simplified representation of the actual human thermoregulation system and is based on set point values. The set point value is basically the temperature for each node that a node would have in a neutral condition. If the value in a node is different from this set point value then the regulatory mechanisms are used.

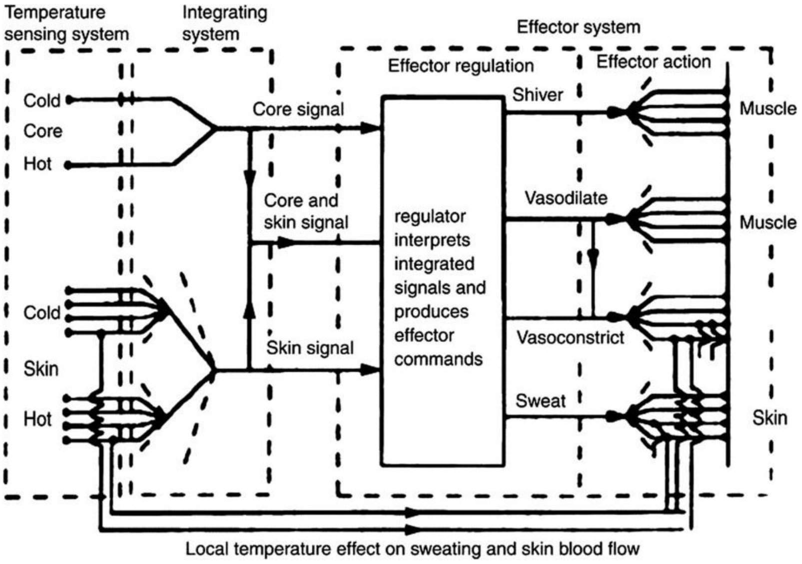


Fig.5. 2 Schematic representation of the active part of the Stolwijk model (Stolwijk and Hardy, 1977).

5.1.1.3 Modifications Stolwijk model

1. Skin temperature

The characteristics of the multi-segmented human thermal model of Stolwijk were evaluated by Munir, Takada, and Matsushita (Munir, Takada, and Matsushita, 2009) using skin temperature measurements at low activity in transient environments by comparing the results of two series of experiments, involving ten and seven subjects. The subjects were exposed to stepwise changes in environmental conditions, including neutral, low, and high ambient temperatures. It was concluded that the original Stolwijk model accurately predicted the absolute value of and the tendency of the transient mean skin temperature. This suggests that the original Stolwijk model was valid for the prediction of the transient mean skin temperature of an 'average' person in low-activity conditions. Some of the body segments showed deviations of local skin temperature. Modification of the distribution of the basal skin blood flow and the distributions of vasoconstriction and workload significantly improved the predicted results of both thermally neutral condition and thermal-transient conditions (Munir, Takada, and Matsushita, 2009).

The above mentioned modifications are displayed in (Munir, Takada, and Matsushita, 2009) and included in the modified Stolwijk model (Roelofsen and Vink, 2016).

2. Clothing

The original Stolwijk model was not equipped with clothing. In order for the model to be useful in the evaluation of the thermal comfort within the built environment it is necessary that clothing can be included in the assessment. For that reason, the Stolwijk model, for all body segments, is modified, as described in (Roelofsen and Vink, 2016). In this study the calculation of the clo value is executed with a computer program, based on a model of J. Lotens (Woerlee, 1982). It calculates the clothing insulation values for a four cylindrical model of the human body. The model is covered with a clothing layer except for head and hands.

5.1.2 Dynamic thermal sensation (DTS)

In the FPC model an equation is included to predict the thermal sensation under dynamic conditions, the so called Dynamic Thermal Sensation (DTS), based on the simulated core temperature and the mean skin temperature. DTS (Fiala, Lomas, and Stohrer, 2003)

$$\mathrm{DTS} = 3 * \tanh(f_{\mathrm{sk}} + ø + \psi)$$

Where:

$f_{\mathrm{sk}} = 1.08 * \Delta T_{\mathrm{sk,m}}$	[-];	for $\Delta T_{\mathrm{sk,m}} > 0$
$f_{\mathrm{sk}} = 0.30 * \Delta T_{\mathrm{sk,m}}$	[-];	for $\Delta T_{\mathrm{sk,m}} < 0$
$\Delta T_{\mathrm{sk,m}} = (T_{\mathrm{mean\ skin}} - 34.4)$	[K]	
$ø = 7.94 * \exp(-0.902/(\Delta T_{\mathrm{hy}} + 0.4) + 7.612/(\Delta T_{\mathrm{sk,m}} - 4))$	[-];	$ø = 0$ when $\Delta T_{\mathrm{hy}} + 0.4 \leq 0$ or $\Delta T_{\mathrm{sk,m}} - 4 \geq 0$
$\Delta T_{\mathrm{hy}} = (T_{\mathrm{hypothalamic}} - 37.0)$	[K]	
$\psi = (\tau_{-} + \tau_{+}) / (1 + ø)$	[-]	
$\tau_{-} = 0.11 * \mathrm{d}T_{\mathrm{sk,m}}/\mathrm{d}t$	[-];	for $\mathrm{d}T_{\mathrm{sk,m}}/\mathrm{d}t < 0$
$\tau_{+} = 1.91 * (\mathrm{d}T_{\mathrm{sk,m}}/\mathrm{d}t)_{\mathrm{max}} . \exp(-0.681 * \Delta t)$	[-];	for $\mathrm{d}T_{\mathrm{sk,m}}/\mathrm{d}t > 0$
$\Delta t = t – t_{0}$	[h]	
t_{0} = time of occurrence of highest rate $\mathrm{d}T_{\mathrm{sk,m}}/\mathrm{d}t$	[h].	

The equation for predicting the thermal sensation is based on a large number of independent experiments. Using a multivariate analysis it was found that the mean skin temperature, the core temperature and the rate at which the mean skin temperature changes are the parameters affecting the thermal sensation under dynamic conditions. The thermal sensation was assessed on the basis of the ASHRAE seven-point scale. Experiments showed that the predicted DTS and the Predicted Mean Vote (PMV) (NEN-EN-ISO-7730, 2005) were in agreement (Fiala, 1998). In the studies of Fiala two versions of the Dynamic Thermal Sensation (DTS) were published. Both versions are included in the modified Stolwijk computer model, but the one used for this study is published in (Fiala, Lomas, and Stohrer, 2003) and is calculated as above equation.

5.1.3 Fiala model

In 1998 Fiala developed a thermophysiological model (Fiala, 1998), based on the Stolwijk model. As with the Stolwijk model, the model of Fiala is split into passive and active parts. The original model of Fiala also assumes a standard male person weighing 73.5 kg, a body fat percentage of 14%, a Dubois area of 1.9 m^2 and a basal metabolic rate of 87.1 Watt.

The current FPC model (version 5.3) however has undergone significant changes, modifications and extensions. In the FPC model the human body is modelled as 20 compartments consisting of 366 tissue nodes; the active system has been further developed and optimized. The passive system incorporates a reference humanoid model, which reproduces an average person obtained from anthropometric field studies. The new reference model represents a 35 years old, unisex person weighting 71.4 kg, 169.7 cm tall, with a skin surface of 1.83 m^2, and body fat content of 22.6% (Ergonsim, 2016).

5.1.4 Variant calculations

In order to find out to what extent the DTS calculation results of the modified Stolwijk model deviate from the current FPC model, a number of variant calculations were carried out. Three well described and known scientific experiments from the professional literature are used for this, for a homogenous step-change transient thermal environment and for sedentary activity. In graphs below, three phases can be identified with an environmental condition that deviates from the environmental condition in the subsequent phase, as once explicitly shown in Figure 5.3.

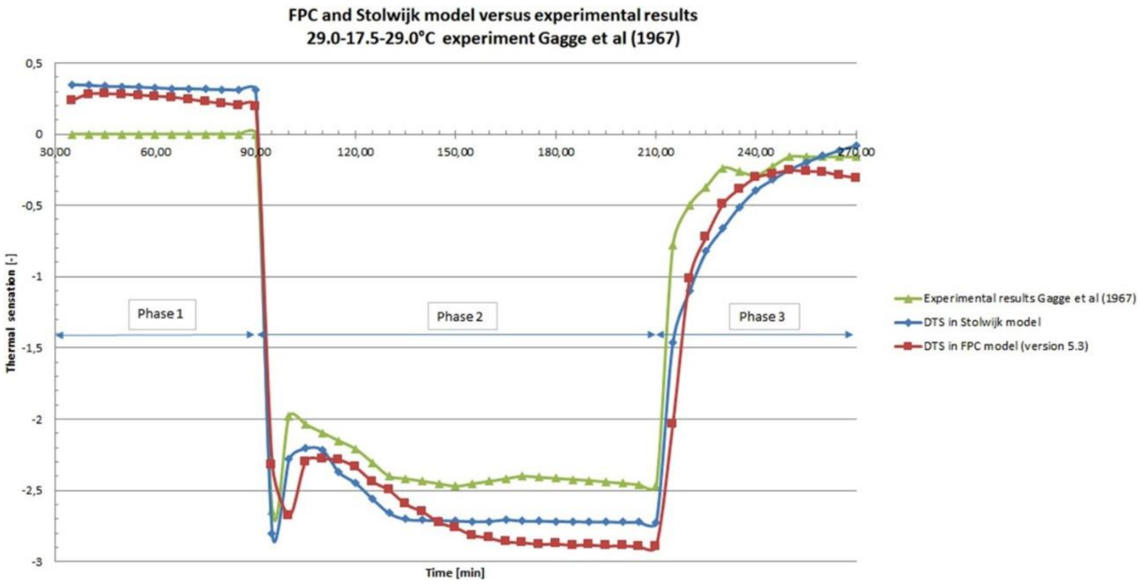


Fig.5. 3 Neutral: 29°C/RH = 40%, Cool:17.5° C/RH = 31%, Neutral: 29° C/RH41%

5.1.5 The rates of change in mean skin temperature ($T_{sk,m}$) (Fiala, 1998)

In Fiala's DTS model, rates of change in physiological parameters appear. For example, the rate of change in $T_{sk,m}$. Any transient change in ambient conditions which cause a sudden cooling of the skin is characterized by an abrupt decrease in thermal sensation. This 'overshoot'-response can occur because of a fall in ambient temperature or any other environmental parameter including relative humidity.

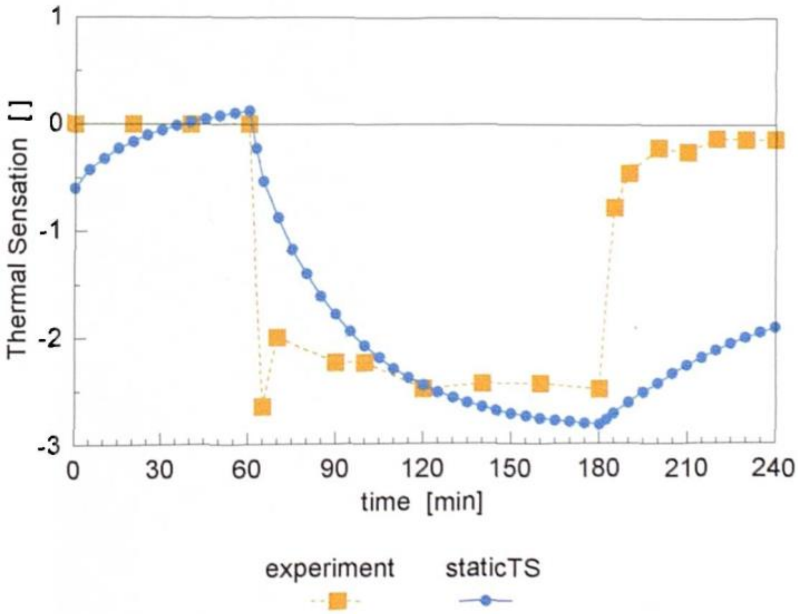


Fig.5. 4 Discrepancy between the static comfort model and the dynamic response of subjects exposed to sudden changes in ambient temperature of Ta (28 - 18 - 28°C)

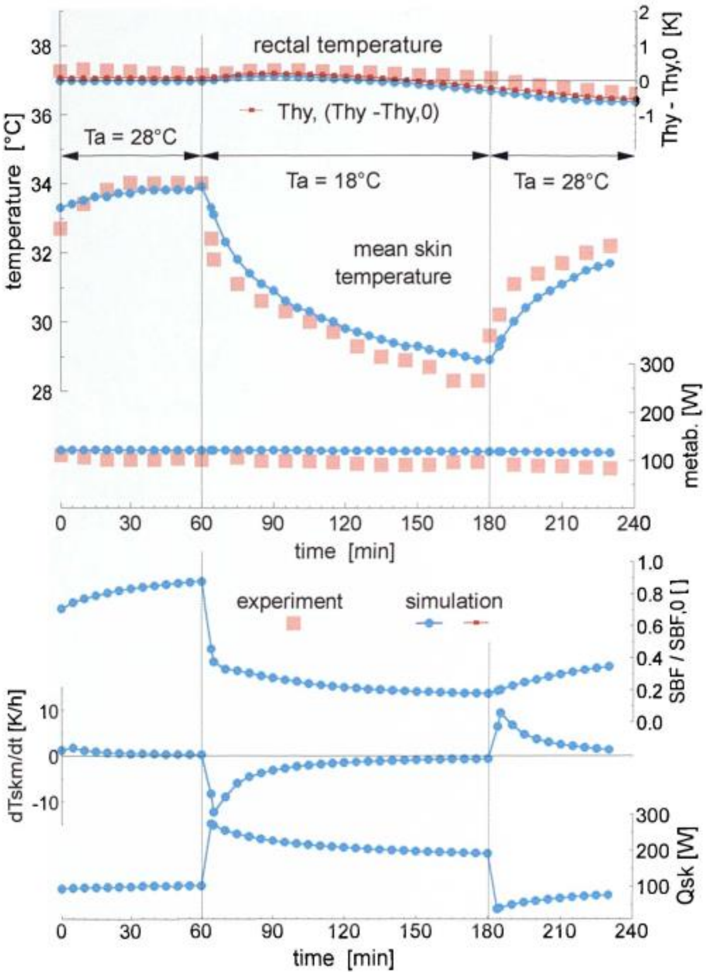


Fig.5.5 Parameters of the bodily thermal state as predicted by the model for sudden changes from a thermally neutral environment to a cold climate of Ta 18°C and back to neutral. Predicted rectal temperature, mean skin temperature and the metabolic heat product

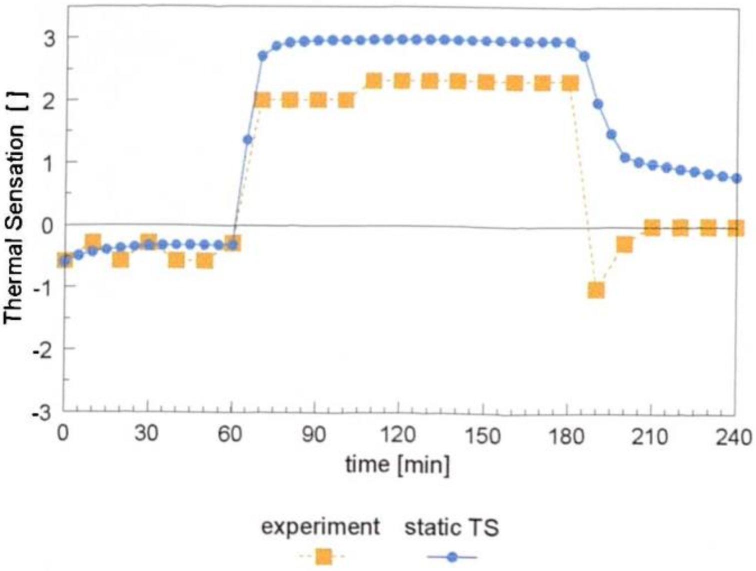


Fig.5. 6 Discrepancy between the static comfort model and the dynamic response of subjects exposed

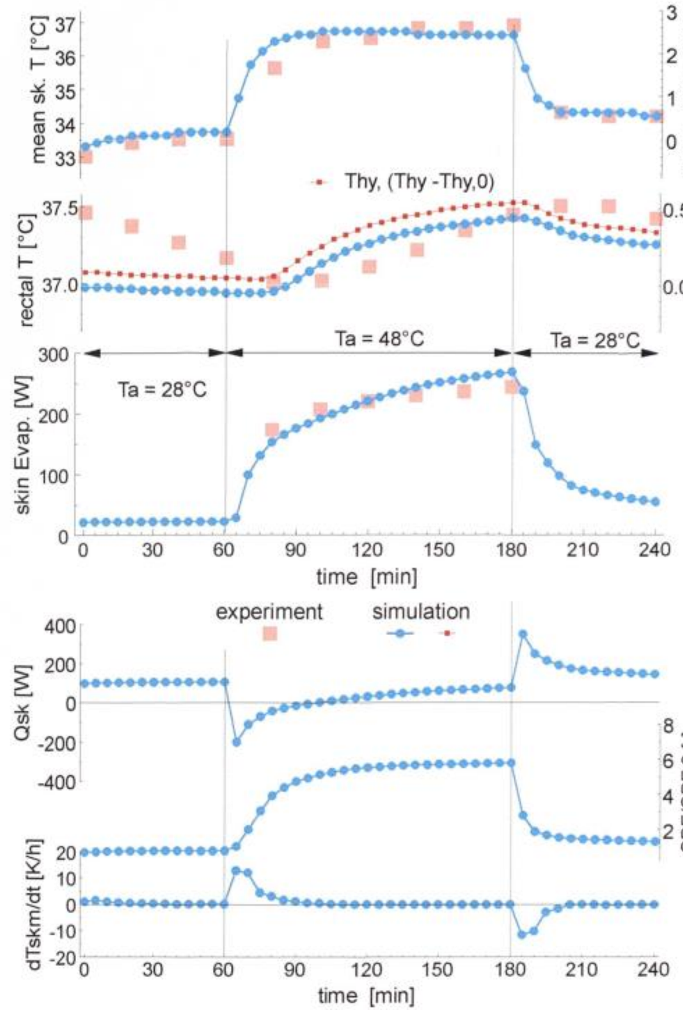


Fig.5. 7 Parameters of the bodily thermal state as predicted by the model for sudden changes from a thermally neutral environment to a hot climate of T_a=48°C

Analysis of the rate of change of the TS-votes and the predicted rate of change of skin temperature (i.e., 60<t<90 mm. in Fig.5.4 and Fig.5.5; and 180<t<210 mm. in Fig.5.6 and Fig5.7) reveals that the $dT_{sk\ ,m}/dt$ -signal is the physiological origin of dynamic effects on thermal sensation which occur when changes in environmental parameters cause transient cooling of the skin. The appearance of this 'overshoot'-response is not restricted to conditions where cutaneous thermoreceptors send warnings of 'cold' skin temperature. The sensation of 'warm' and 'hot' might also be subject to this transient effect as demonstrated for t > 180 mm in Fig.5.6. Fig.5.7 shows that parameters of the bodily thermal state as predicted by the model for sudden changes from a thermally neutral environment to a hot climate of T_a=48°C (and hack to neutral. Predicted mean skin temperature, rectal temperature, and the evaporative skim, heat loss - from top to bottom - are compared with the corresponding measured values. Further simulated variables (not measured in the experiment) are plotted: tile hypothalamus temperature (and tile corresponding error signal T_{hy} - $T_{hy,0}$), skim, heal flux O_{sk}, relative skin blood flow SBF/SBF0, and rate of change of the mean skin temperature $dT_{sk,m}/dt$.

Can the same thermal sensory overshoot that occurs in this work also be described by the rate of change of physiological indicators? In section 7.2 the authors make an attempt.

In this chapter, a linear correlation between physiological parameters and subjective perception is first examined to examine how the correlation between the two differs in exercise compared to the static state. Next, a stepwise regression algorithm was used to quantitatively analyze subjective and objective indicators, establish a model, and perform a significance test. This study established models for the two exercise intensity experiments. The regression model in this article did not include the evaluation of TSV and TC before exercise.

5.2 Mathematical models

5.2.1 Stepwise regression analysis between physiological indicators and TSV

The relationship between TSV and various physiological indicators under different exercise intensities, including T_{or}, T_{sk}, RMSSD, SDNN, LF/HF, and EDA, was investigated. Table 5.1 shows the stepwise regression results of TSV for T_{or}, T_{sk}, RMSSD, SDNN, LF/HF, and EDA in the V_1 and V_2 experiments. In the V_1 experiment, EDA, T_{or}, and T_{sk} remained in the model after calculation, F = 47.88 (p-value < 0.001), indicating that the model is statistically significant. The p-values of significance tests corresponding to EDA, T_{or}, and T_{sk} are < 0.001, < 0.001, and 0.026, which means that the regression relationship is significant. EDA entered the model first and produced an R^2 of 38.1%, indicating that EDA has an explanatory power of 38.1% for the dependent variable. T_{or} and T_{sk} entered the model next, and R^2 increased by 48.1% and 3.81%, respectively. Thus, the ability of the model to interpret TSV reached 90%, and the model can express 90% of the information volume of the V_1 data set. RMSSD, SDNN, and LF/HF were excluded from the model variable set due to insufficient significance. In the V_2 experiment, after automatic selection, EDA, T_{or}, and T_{sk} increased R^2 by 52.2%, 24.8%, and 15.5%, respectively. The interpretation ability of EDA and T_{sk} of the thermal sensation gradually strengthens as exercise intensity increases, while the interpretation ability of T_{or} weakens. Equations are the results of two experimental stepwise regression algorithms. EDA and T_{sk} have a positive effect on TSV, and T_{or} has a negative effect on TSV. Skin temperature and oral temperature are relevant physiological indicators of the thermal metabolic system that partially reflect the individual metabolic rate. Results also show that the parameters related to metabolic rate are still indispensable in the evaluation of the exercise thermal sensation.

$$V_1: TSV = -15.284 + EDA * 0.846 - T_{or} * 1.299 + T_{sk} * 1.711$$

$$V_2: TSV = 14.010 + EDA * 0.325 - T_{or} * 2.446 + T_{sk} * 2.189$$

Table 5. 1 Stepwise analysis of objective indicators and TSV

V_1	Step 1		Step 2		Step 3		V_2	Step 1		Step 2		Step 3	
	Coef.	P	Coef.	P	Coef.	P		Coef.	P	Coef.	P	Coef.	P
EDA	0.64	0.004	1.013	0.000	0.846	0.000	EDA	0.409	0.000	0.582	0.000	0.325	0.000
T_{or}			-1.277	0.000	-1.299	0.000	T_{or}			-1.459	0.001	-2.446	0.000
T_{sk}					1.711	0.026	T_{sk}					2.189	0.000
R-sq	38.1%		86.2%		90.0%		R-sq	52.2%		77.0%		92.5%	
△R-sq			48.1%		3.8%		△R-sq			24.8%		15.5%	

Fig. 5.8 shows that by analyzing the residual Q-Q diagram and scatter plots, the residual reveals the characteristics of "White Noise" and obeys the standard normal distribution.

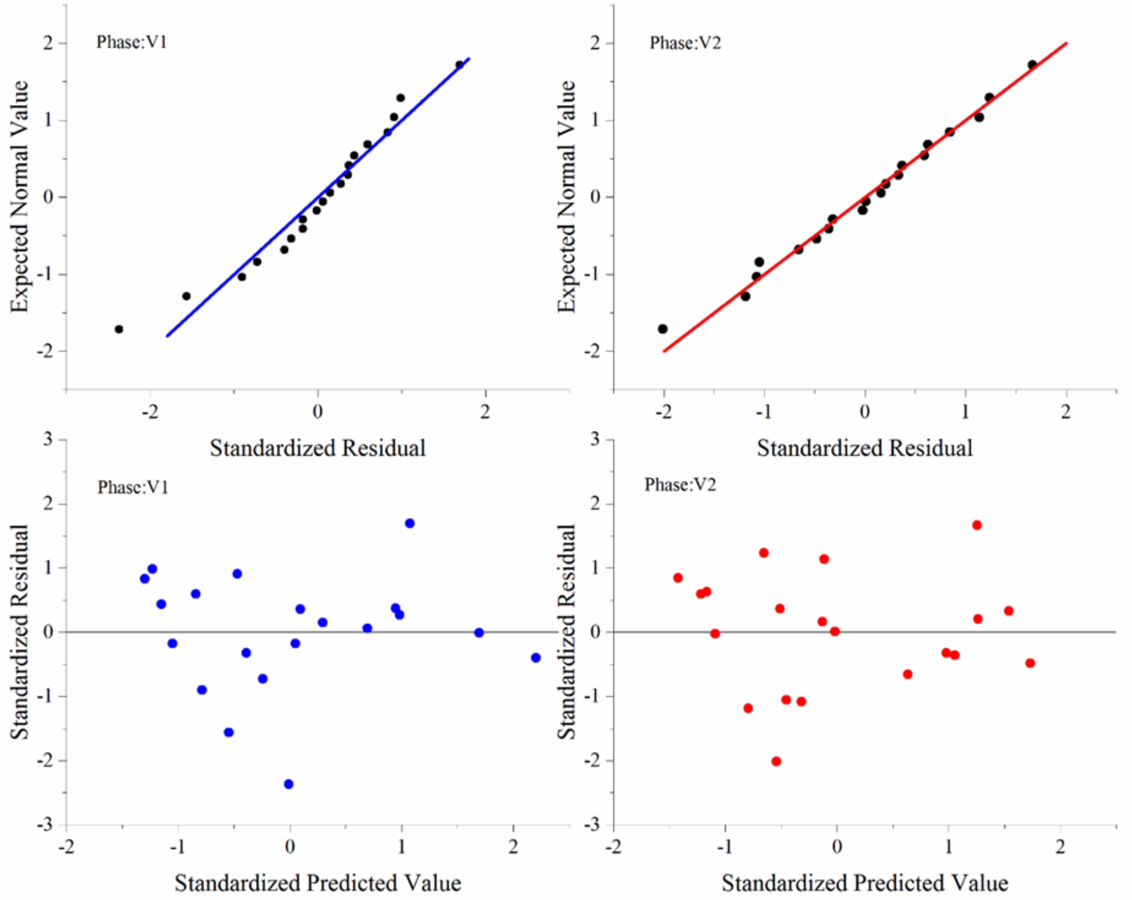


Fig.5. 8 Normal Q-Q Plot and Scatterplot of the Regression Standardized Residual of TSV

5.2.2. Stepwise regression analysis between physiological indicators and TC

The author further examined the relationship between TC and various physiological indicators, including T_{or}, T_{sk}, RMSSD, SDNN, LF/HF, and EDA. Table 5.2 shows the results of the stepwise regression. In the V_1 experiment, T_{or} and T_{sk} remained in the model, and the model significance test p-value = 0.001, indicating that the model has statistical significance. The p-values for the significance test of the corresponding coefficients of T_{or} and T_{sk} are < 0.001 and 0.007, respectively, indicating that the regression coefficient is significant. T_{or} and T_{sk} increased the R^2 of the model by 51.8% and 27.9%, respectively, increasing the model's ability to interpret TSV to 79.7%. EDA, RMSSD, SDNN, and LF/HF were excluded from the model variable set due to insufficient significance. In the V_2 experiment, EDA, T_{or}, and T_{sk} remained in the model. Significance test p-values < 0.001 for EDA, T_{or}, and T_{sk} produced coefficient significance test p-values of 0.044, <0.001, and 0.005, respectively, indicating that the model and coefficient are significant. The R^2 corresponding to EDA, T_{or}, and T_{sk} increased by 43.2%, 27.9%, and 18.8%, respectively. Equations are the results of two experimental stepwise regression algorithms. T_{or} has a positive effect on TC, and T_{sk} and EDA have a negative effect on TC. With the increase of exercise intensity, EDA is still an essential parameter for predicting comfort.

$$V_1: TC = 88.827 + T_{or} * 0.967 - T_{sk} *3.801$$

$$V_2: TC = 1.418 - EDA * 0.229 + T_{or} * 2.438 - T_{sk} *2.7$$

Table 5. 2 Stepwise analysis of objective indicators and TC

V_1	Step 1		Step 2		V_2	Step 1		Step 2		Step 3	
	Coef.	P	Coef.	P		Coef.	P	Coef.	P	Coef.	P
T_{or}	0.862	0.008	0.967	0.000	EDA	-0.376	0.020	-0.489	0.002	-0.229	0.044
T_{sk}			-3.801	0.007	T_{or}			1.377	0.016	2.438	0.000
					T_{sk}					-2.700	0.005
R-sq	51.8%		79.7%		R-sq	43.2%		71.1%		89.9%	
△R-sq			27.9%		△R-sq			27.9%		18.8%	

Analyzing the residual Q-Q diagram and scatter plots reveals that the residuals have the characteristics of "white noise" and obey the standard normal distribution, further verifying the validity of the model establishment (Fig.5.9).

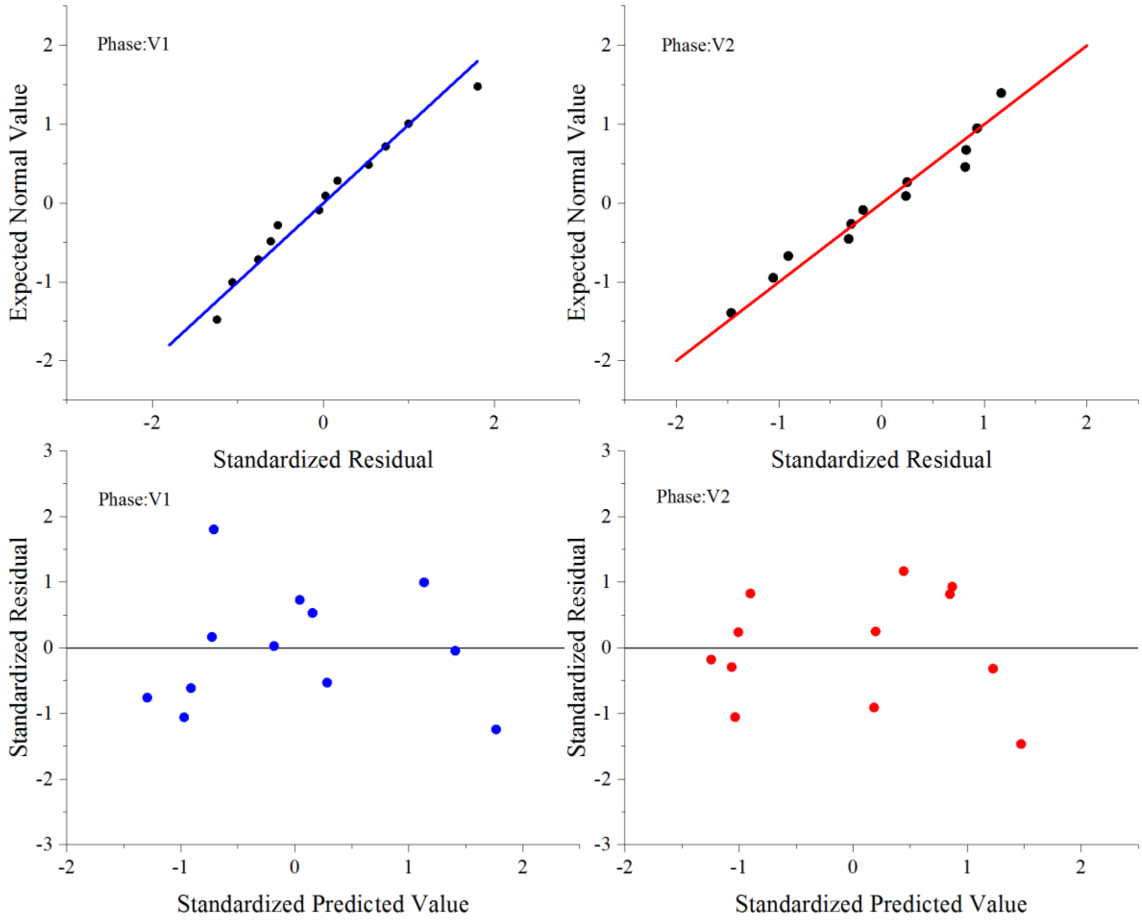


Fig.5. 9 Normal Q-Q Plot and Scatterplot of Regression Standardized Residual of TC

5.2.3. Average change and rate of change of physiological parameters

Fig.5.10 shows the average changes in skin temperature, oral temperature, and EDA. The author compared the value of each testing moment with the initial value. That is, ΔT_{sk}=T(time(i))-T (time(i = 15)), ΔT_{or}=T(time(i))-T (time(i = 15)), ΔEDA=EDA(time(i))-T (time(i = 15)). The average change of each physiological parameter in V_2 was greater than in V_1. i.e., skin temperature: V_1 (-0.25 to 0.05), V_2(-0.4~0.7); Oral temperature:V_1(-0.65~0.45), V_2(-0.8~ 0.47); EDA: V_1(-0.4~1.2), V_2(-3.4~2.9). When about 6 minutes since the exercise, the turning points of each parameter come to appear. After the end of the exercise, the function of change of each parameter over time is more complex.

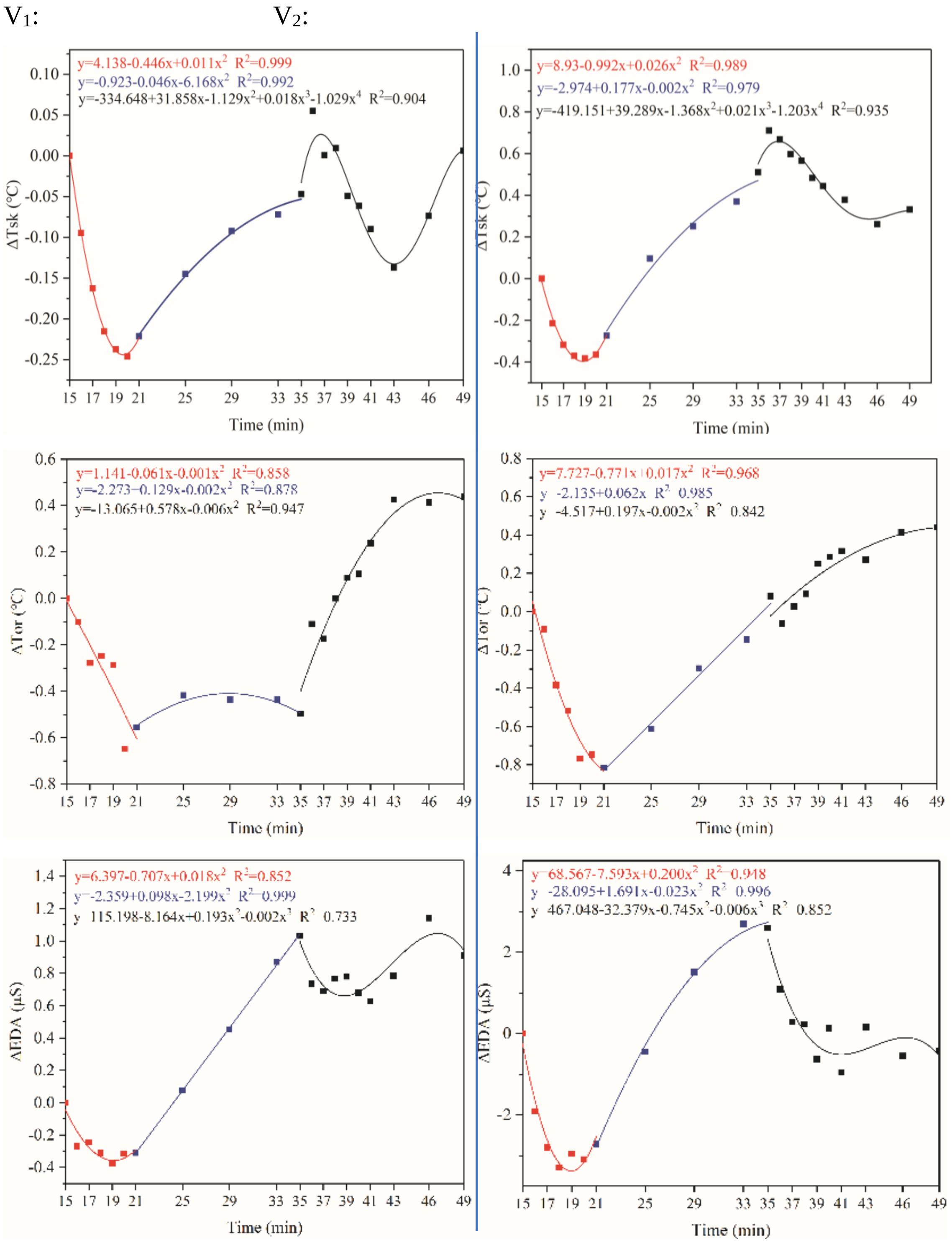


Fig.5. 10 The average change of physiological parameters

Fig.5.11 shows an example of the values corresponding to the rates of change for the three parameters and TSV. In general, the rate of change of each parameter fluctuates considerably during the first 6 minutes of the exercise and also in the early period of the post-exercise. And as the exercise intensity increases, the rate of change is more significant. It is interesting to note that at 6 minutes after exercise, the rate of change becomes relatively stable(with a drift toward 0). Is the "symmetry" worthy of attention? That is, the timing of adjustment of physiological parameters and TSV are always similar after a mutation in metabolic levels(static-dynamic-static), which deserves further study. It means that after a sudden change in the activity state(dynamic-static steps), there is a dynamic process of adjustment of the physiological parameters. This adjustment process is more complex and lasts longer than the physiological adaptation caused only by changing the ambient conditions. Also, "overshoot" was observed for each rate of change. It was found that "overshoot" occurs in a short time after the exercise, while it was not noted at the beginning of the exercise.

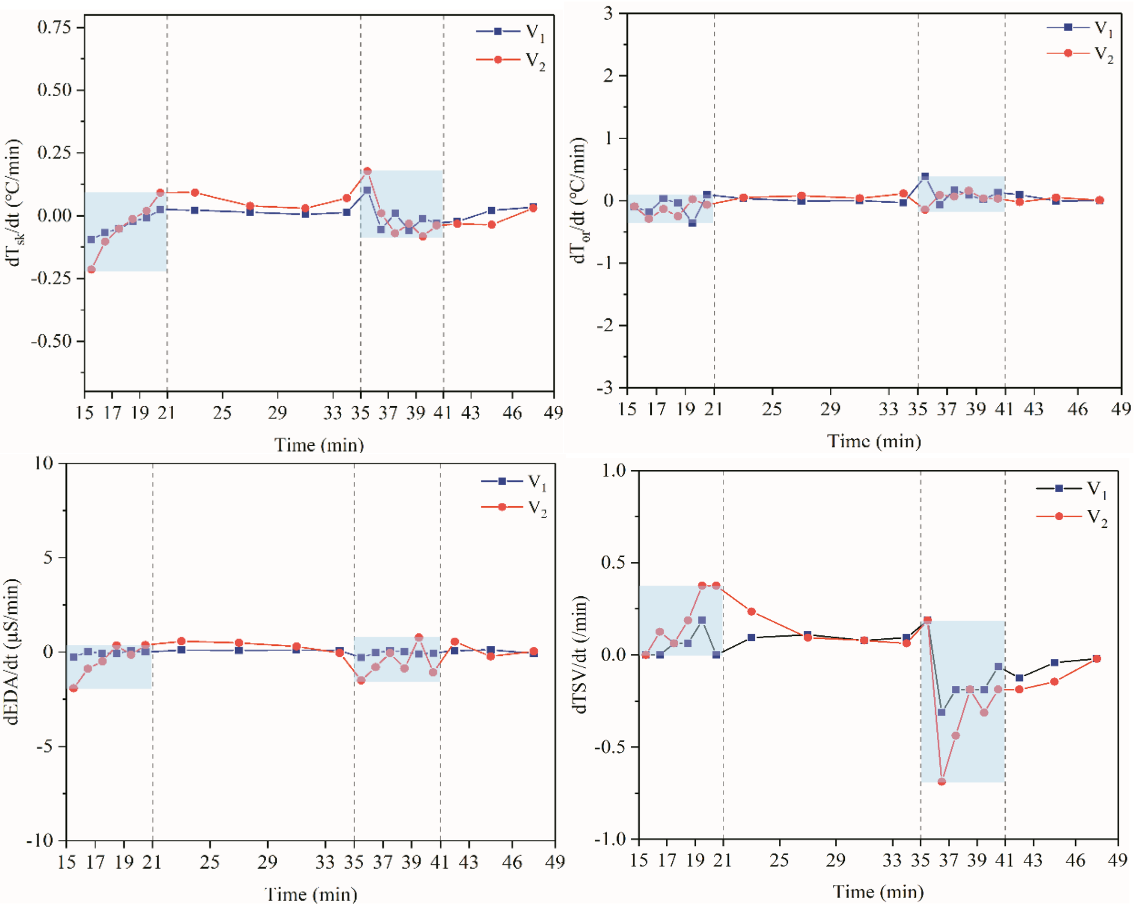


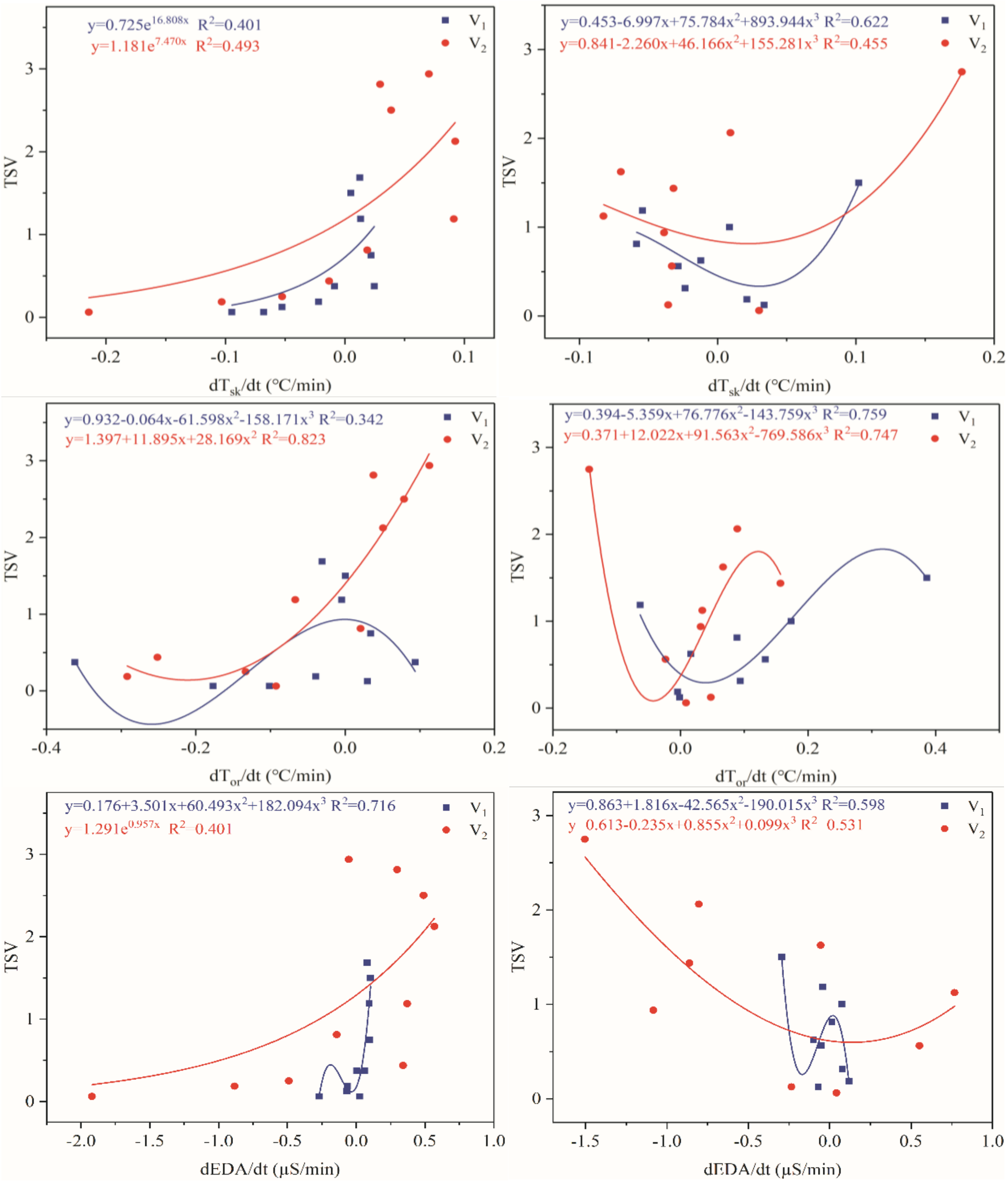
Fig.5. 11 The rate of change of physiological parameters and TSV

Besides, at about the 37th min, there was a cold sensation overshoot in the rate of change of thermal sensation. This shows that the decrease in thermal sensation is very rapid in the short time after exercise. In fact, three subjects (2 subjects in the V_1 experiment and 1 subject in the V_2 experiment) reported thermal sensation TSV=-1 at a certain point time after exercise (between the 35th to 41st min), i.e., there was one cold sensation overshoot and then recovered. Further analysis of the data found that the three subjects' skin and oral temperature at that point times were about the same or slightly lower than the original temperature at the static state. Still, the EDA and SFI were higher than the original values. Therefore, the reason for this phenomenon was judged to be due to a large amount of evaporation of sweat after exercise, and the rapid decrease in thermal sensation, causing some subjects to experience significant cold sensation overshoot. Also, the higher the exercise intensity, the more pronounced this phenomenon may be. Later, as sweat's evaporation decreased, this phenomenon disappeared, and the thermal sensation returned to a neutral state.

Based on the above analysis, the author selected several physiological parameters closely related to the exercise thermal sensation and examined the regression between the rate of change and thermal sensation. Fig.5.12 shows thermal sensation as a function of the rate of change of physiological parameters, separately for during and post-exercise. It shows that TSV is rapidly elevated after a positive rate of change in physiological parameters during exercise (i.e., a derivative greater than 0). That is, as the rate of change of physiological parameters accelerates during exercise, the TSV changes rapidly as well. It becomes more pronounced with increasing exercise intensity. From the regression equation, it can be seen that when the rate of change is equal to 0, $TSV_2 > TSV_1$. This means that the higher the intensity of exercise during exercise, the greater the effect of the change rate of physiological parameters on TSV. When the rate of change of physiological parameters was 0 at post-exercise, the thermal sensation was all near the lowest point of the curve (0.3–0.8). In other words, thermal sensation returned to the comfort range when the physiological index was not changing over time. Besides, it can be observed that the curves appear to be symmetrical during and post-exercise. That is, TSV is approximately similar to the changes in each physiological index in both phases, so it may be more reasonable to use the rate of change to predict the thermal sensation of exercise. It is then necessary to explore the use of the rate of change of physiological parameters to perform stepwise regression analysis of TSV.

5.2.4 Stepwise regression analysis of TSV using average change and rate of change of physiological parameters

Stepwise regression continues to be used to examine the relationship between objective indicators and TSV, i.e., ΔT_{or}, ΔT_{sk}, ΔEDA, dT_{sk}/dt, dT_{or}/dt, and $dEDA/dt$. Tables 5.3 and 7.4 show the results of the separate stepwise regressions during(DE) and post-exercise(PE) for the two sets of experiments.



During exercise Post-exercise

Fig.5. 12 Thermal sensation as a function of the rate of change of physiological parameters

The Q-Q plots and scatters plots have been carried out for these models. It was evident that the residuals show "White Noise" characteristics and obey the standard normal distribution, thus further verifying the validity of the model(Fig.5.13, Fig.5.14)

V_1: DE: $TSV=0.637+0.995\times\Delta EDA+3.536\times dT_{sk}/dt$,

PE: $TSV=0.883-1.748\times\Delta T_{or}+1.025\times dT_{or}/dt$,

Table 5. 3 Stepwise analysis of objective indicators and TSV

V_1 DE	Step 1		Step 2		V_1 PE	Step 1		Step 2	
	Coef.	P	Coef.	P		Coef.	P	Coef.	P
EDA	1.124	0.000	0.995	0.000	ΔT_{or}	-1.946	0.000	-1.748	0.000
dT_{sk}/dt			3.536	0.001	dT_{or}/dt			1.025	0.002
R-sq	94.4%		99%		R-sq	91%		98.4%	

V_2: DE: $TSV=0.896+4.255\times\Delta T_{sk}-1.696\times\Delta T_{or},$

PE: $TSV=2.328 - 4.975\times\Delta T_{or},$

Table 5.4 Stepwise analysis of objective indicators and TSV

V_2 DE	Step 1		Step 2		V_2 PE	Step 1	
	Coef.	P	Coef.	P		Coef.	P
ΔT_{sk}	3.171	0.000	4.255	0.000	ΔT_{or}	-0.475	0.000
ΔT_{or}			1.696	0.000			
R-sq	88.2%		98.9%		R-sq	92.1%	

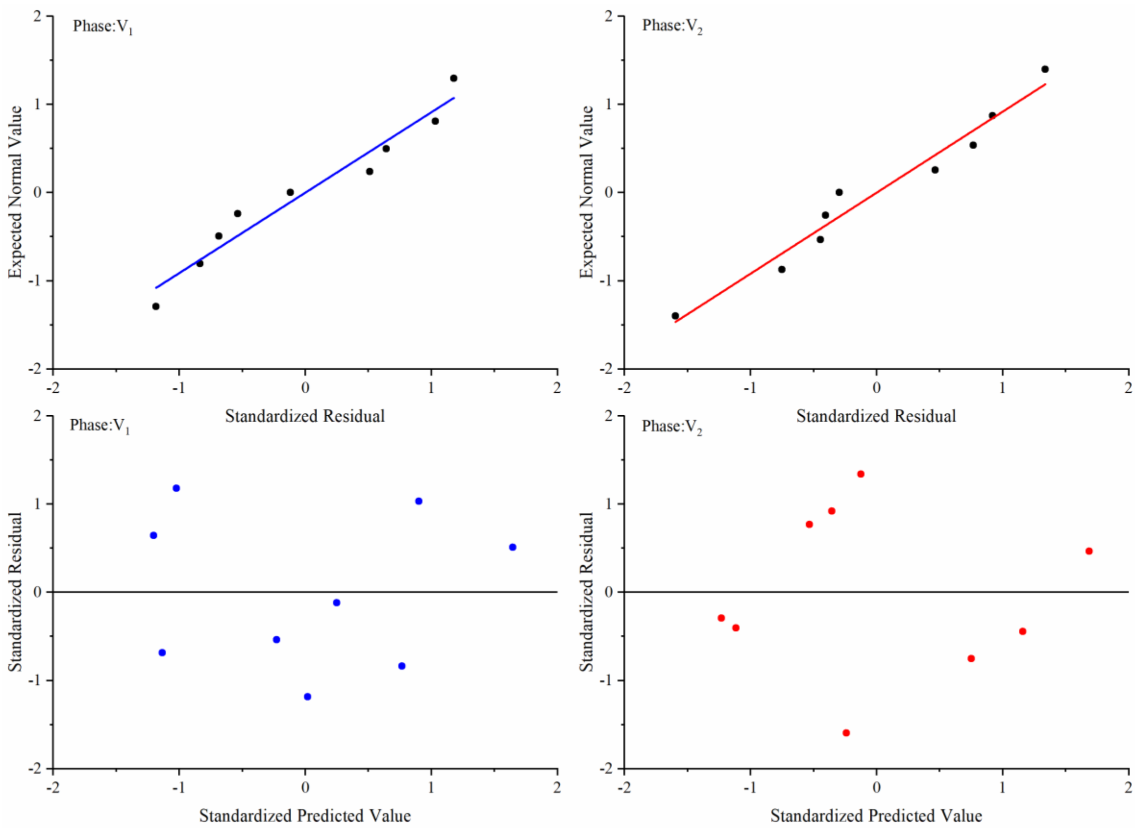


Fig.5. 13 Normal Q-Q Plot and Scatterplot of Regression Standardized Residual of DE

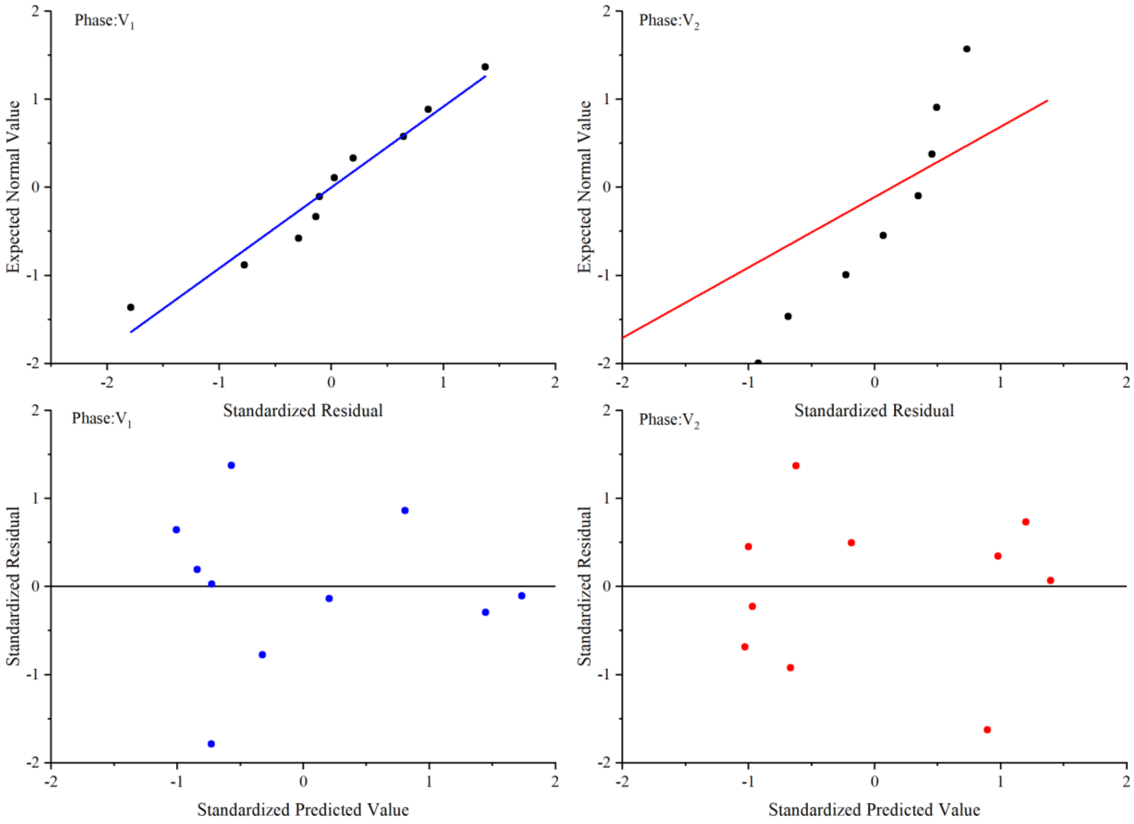
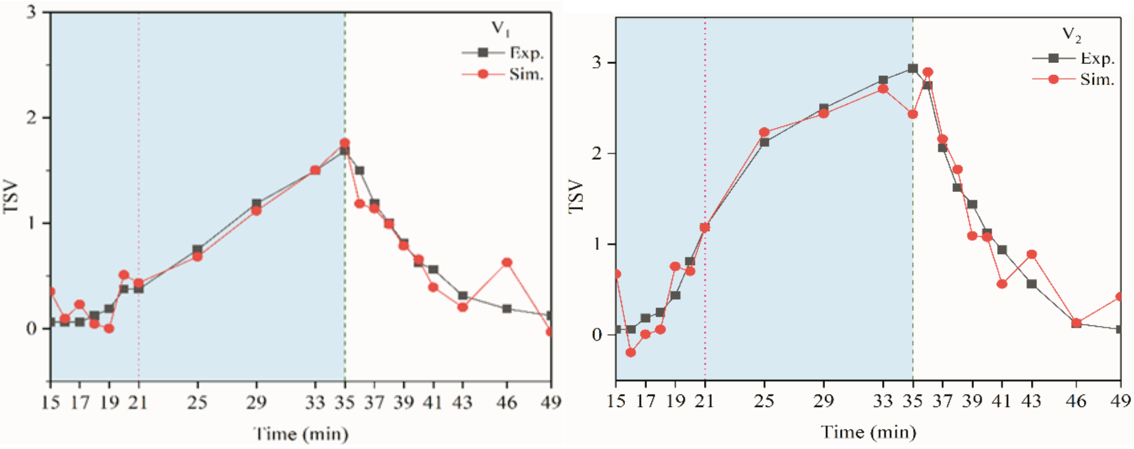


Fig.5. 14 Normal Q-Q Plot and Scatterplot of Regression Standardized Residual of PE

Fig. 5.15 shows a comparison of the model simulation results from sections 3.3.1(original model) and 3.3.4(improved model) with the experimental data. The original model was found to fit poorly at the beginning of the exercise and at the end of the experiment. The improved model fit was better. It indicates that the average change of physiological parameters and their rate of change may be significant factors in predicting the exercise thermal sensation. Also, it is necessary to separate the dynamic and static phases to construct the model better.

Original model:



Improved model:

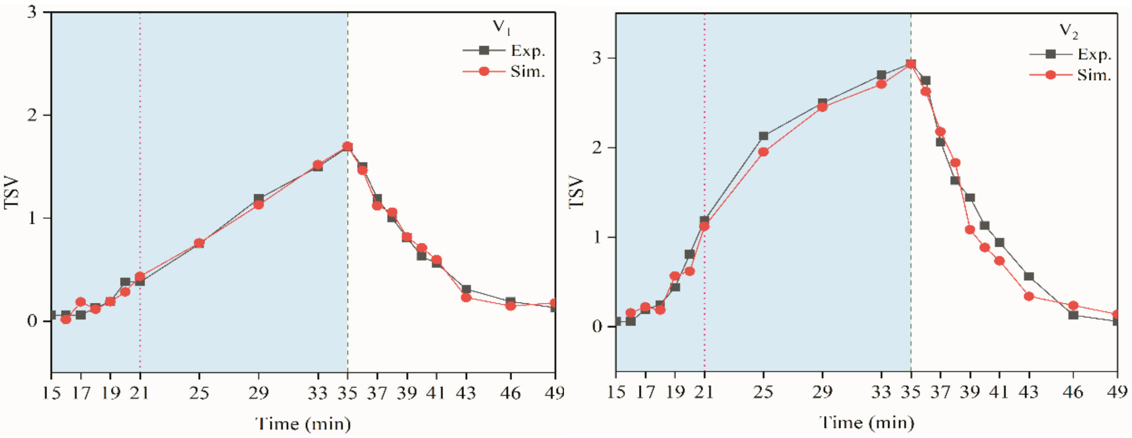


Fig.5. 15 Comparison of the model simulation results

5.3 Correlation analysis

5.3.1 The correlation coefficients between T_{sk}, T_{or}, HR, and HRV parameters (between objective physiological parameters).

Table 5.5 shows the Pearson correlation coefficients between objective physiological parameters. In the V_1 experiment, only T_{sk} has a significant correlation with T_{or}. HR has a significant correlation with other objective indicators except for T_{sk}. There was a high negative correlation with the indicators in HRV ($P < 0.01$) and a significant positive correlation with LF / HF. This shows that as HR becomes larger, LF / HF also becomes larger, sympathetic nerves dominate, and comfort will deteriorate. In the V_2 experiment, due to the increase in exercise intensity (medium-intensity exercise), it was observed that the skin temperature showed a significant correlation with other physiological indicators ($P < 0.01$).

T_{sk} is positively correlated with T_{or} and negatively correlated with HRV parameters. From the overall data of view, the correlation coefficient of the V_2 experiment has been further improved compared to

V_1. However, no significant correlation was observed between T_{sk} and LF / HF, and it only reflected the changing trend in the same direction (positive direction). There is still a strong correlation between various parameters in HRV.

It was also found that as the intensity of exercises increased, the correlation between objective parameters began to appear, and it gradually increased. Although only two intensity activities were arranged in the experiment, it is reasonable to believe that as the exercise's intensity increases, the correlation between the parameters will still change accordingly, and the correlation between some parameters will strengthen. However, compared with the human body in a quiet state, each parameter's statistical correlation worsens and even disappears for low-intensity exercises(Xiong et al., 2016). Therefore, this conclusion can indicate that the PMV model is biased in evaluating the human thermal sensation in exercise, and the bias will become larger as the exercise level increases (Humphreys and Fergus Nicol, 2002; Mochida and Sakoi, 2003). With the gradual increase of exercise level, many physiological parameters of the human body will be dynamically adjusted and rebalanced. During this period, the correlation will be gradually broken and re-established. Because the human body is complex, and the mechanisms for changing various physiological parameters are also complicated, the correlation will be weaker when performing correlation analysis in exercise than in a static state, which needs further discussion and analysis.

Table 5. 5 The Pearson correlation coefficients between objective physiological indicators

	T_{sk}	T_{or}	HR	SDNN	RMSSD	LF/HF
T_{sk}		$.423^{**}$	$.325^{**}$	$-.360^{**}$	$-.398^{**}$	$.131^{*}$
T_{or}	$.163^{**}$		.085	$-.173^{**}$	$-.206^{**}$	.001
HR	-.081	$-.122^{*}$		$-.626^{**}$	$-.589^{**}$	-.005
SDNN	.082	.067	$-.435^{**}$		$.979^{**}$	-.088
RMSSD	.081	.055	$-.431^{**}$	$.958^{**}$		$-.183^{**}$
LF/HF	-.114	$-.158^{**}$	$.152^{**}$	$-.139^{*}$	$-.264^{**}$	

The lower triangle indicates the V_1 experiment's correlation coefficient, and the upper triangle (the shaded portion) indicates the V_2 correlation coefficient.

Note: * and ** denote P < 0.05 and P < 0.01, respectively

5.3.2 Correlation analysis between objective physiological parameters and subjective perception

In this study, T_{sk}, T_{or}, HR, LF / HF, and EDA were selected for correlation analysis with TSV. In the previous analysis, the 21st minute was the inflection point location for each index's change. To compare the change in the correlation between the two at different stages in each set of experiments, the 21st minute was used as the cutoff time point. The Pearson correlation analysis was performed for the three phases, namely, phase1 (15 ~ 21thmin), phase 2 (21 ~ 35thmin), and phase 3 (35 ~ 49thmin, after exercise). Table 5.6 shows that in phase1, no significant correlation was observed between these indicators and subjective perceptions because the physiological parameter changes were not stable. However, it can be roughly seen that in phase1, T_{sk}, T_{or}, LF / HF, and TSV have a negative change trend.

Table 5. 6 Correlation coefficients between physiological parameters and TSV in different steps in V_I and V_2

	TSV					
	Phase1		Phase 2		Phase3	
	V_1	V_2	V_1	V_2	V_1	V_2
T_{sk}	-.066	-.219	.108	.259**	.037	.342**
T_{or}	-.351**	-.326	-.163*	.425**	-.421**	.287**
HR	-.121	.142	.037	.194*	.171	.314**
LF/HF	-.033	-.249	.225	-.175	.055	-.100
EDA	.144	.295	.125	.409**	.133	.600**

Note: * and ** denote $P < 0.05$ and $P < 0.01$, respectively

Because of the high sensitivity of the two indicators, HR and EDA, the correlation shows a change from positive to negative or negative to positive. Judgment is caused by unstable changes in physiological parameters in the early stages of exercise. In phase2, the correlation between each parameter and TSV is improved. This phenomenon is more obvious in the V_2 experiment. In the V_2 experiment, T_{or}, T_{sk}, EDA, and TSV showed a significant positive correlation ($P <0.01$). In phase3, the correlation is further enhanced. T_{sk}, T_{or}, HR, and EDA showed a significant positive correlation with TSV in the V_2 experiment ($P <0.01$).

I also performed a general correlation analysis on the two sets of experiments (V_1 and V_2) without any phase (removing the static state before exercise). The purpose is to compare which of the correlation coefficients in Table 5.6 and Table 5.7 (without any phases) in each experiment set is more ideal. At the same time, we also performed a correlation analysis of physiological parameters with TC and SFI. Table 5.3 shows that as exercise intensity increases, so does the correlation. Overall, compared with the above results, the correlations all show varying degrees of improvement. Among them, T_{sk}, T_{or}, HR, and EDA all showed significant positive correlations. Still have to point out that although there is a significant correlation, the correlation coefficient was not very large compared with that in a static state. It is consistent with the conclusions of previous studies (Davies et al., 1976). There is a significant positive correlation between Tsk and SFI. During more intense exercise, sweat feeling also increases with increasing skin temperature (Nielsen and Nielsen, 1965). Among the correlation with TC, the correlation between LF / HF and HR was significant. It fully shows that there is a close relationship between comfort and sympathetic nerves. Both of them showed a significant negative correlation with TC. This shows that the greater the HR, the greater the LF / HF, and the lower the comfort level. There is a significant positive correlation between EDA and SFI.

Table 5. 7 Correlation coefficients between physiological parameters and subjective perception in V_1 and V_2

	TSV		**TC**		**SFI**	
	V_1	V_2	V_1	V_2	V_1	V_2
T_{sk}	.143	.264**	-.024	-.002	.295**	.276**
T_{or}	-.251**	.262**	.079	-.176	.250**	.113
HR	.166**	.193*	-.298**	-.242**	.007	.155
LF/HF	.065	.068	-.209**	-.245**	.062	.083
EDA	.124	.334**	-.038	-.332**	.240**	.200**

Note: * and ** denote $P < 0.05$ and $P < 0.01$, respectively

All the correlation coefficients in the TSV and TC groups were reversed. This indicates that TSV and TC tend to be negatively correlated. Therefore, it is necessary to proceed to analyze the correlation between subjective perceptions.

5.3.3 Correlation between subjective perceptions

Table 5.8 shows the Pearson correlation coefficient among subjective perceptions. The correlation among subjective perceptions increased with increased exercise intensity. TSV, SFI, and TC were significantly negatively correlated. SFI and TSV were significantly positively correlated, showing that as the thermal sensation increases, the sweaty feeling also increases, while the thermal comfort decreases.

Table 5. 8Pearson correlation coefficient among subjective perceptions.

	TC		**SFI**	
	V_1	V_2	V_1	V_2
TSV	-.530**	-.719**	.208**	.682**
TC			-.302**	-.528**

Note: ** denotes $P < 0.01$

The human body is complex, and the mechanism of change of various physiological indicators in exercise is also complex. When correlation studies are carried out, the correlation coefficients may not be as ideal as when the human body is static. For example, the correlation between HRV indicators and thermal sensations during the exercise is weaker than in the static state. An important reason for this phenomenon is that the exercise largely affects cardiac function, making its representation of subjective sensations weaker. Also, the absence of significant correlations between parameters in these analyses only means that the linear correlation is not significant but does not exclude other correlations.

5.4 Summary

In this chapter, first, the Stolwijk and Fiala models are reviewed. A mathematical model was then constructed using original physiological indicators measurement data and the rate of change of physiological indicators, respectively, and the simulation results were compared. Finally, a linear correlation analysis between physiological indicators and subjective perceptions was performed. The main findings were as follows.

Skin temperature, oral temperature, and EDA are important indicators related to exercise thermal sensation. The rate of change in physiological parameters can be used to predict the exercise thermal sensation better.

The rate of change of each parameter fluctuates considerably during the first 6 minutes in the exercise and the early post-exercise period. The timing of physiological parameters adjustment and TSV adjustment are always similar after a mutation in metabolic levels(static-dynamic-static).

"overshoot" was observed for each rate of change. It was found that "overshoot" occurs quickly after the exercise, while it was not noted at the beginning of the exercise. This also indicates that overshoot of skin and oral temperature is an important cause of thermal sensation overshoot.

There is a significant correlation between thermal sensation and core temperature, T_{sk}, EDA, and HR. And with the increase in exercise intensity, the correlation has gradually strengthened. But, compared with the static state, the correlation becomes weaker. The correlation between subjective perception is stronger than the correlation between subjective and objective physiological parameters.

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CHAPTER 6

DISCUSSION OF THE INFLUENCING FACTORS ON THE EXERCISE THERMAL SENSATION IN THE EXPERIMENTS

6.1 HRV indicators and exercise thermal sensation (comfort) 6-1
6.2 Oral temperature during exercise 6-3
6.3 Thermal alliesthesia 6-7
6.4. The relationship between TSV, TC, EDA and SFI. 6-8
    6.4.1 TSV and TC 6-8
    6.4.2. TSV and EDA 6-9
    6.4.3 TSV and SFI 6-10
    6.4.4 EDA and SFI 6-10
6.5 LF/HF and thermal sensation and comfort..6-11
6.6 Indoor environment and exercise thermal sensation... 6-12
6.7 Summary 6-15
References *6-17*

In Chapter 6, it provides a detailed description of the changes over time in objective physiological indicators and subjective perceptions in exercise. In this chapter, the author attempts to discuss in depth the relationship between thermal sensation and objective physiological indicators in exercise and the influence of psychological factors on thermal comfort before and after exercise. In particular, the changes in the physiological parameters are more involved around the dynamic-static step. Therefore, it is necessary to conduct an in-depth investigation of the dynamic response of physiological parameters (densified monitoring points near the steps) and changes in thermal sensation (comfort) pre-, during, and post-exercise at moderate intensity. As the author increased the density of test points in this experiment, some specific physiological phenomena and results related to thermal sensation were found. Although a few scholars have mentioned similar results in previous studies, few specific and reasonable explanations have been given. Therefore, in this chapter, the author also tries to explain these phenomena. The author also examines the thermal sensations using the HRV index in exercise for the first time and analyzes and discusses the possible intrinsic connection between them.

6.1 HRV indicators and exercise thermal sensation (comfort)

In the stepwise regression analysis, no significant linear relationship between HRV indicators and TSV was shown. To further investigate the cause, a visual analysis was performed between HRV and TSV. The HRV indicator and its corresponding thermal sensation were sorted out to form a Force-Directed Graph. A Force-Directed Graph, or Force-Based Graph, is used to visualize the connections between objects in a network. By grouping the objects connected to each other in a natural way, a Force-Directed Graph also makes it possible to discover subtle relationships between groups. Each set of experiments was divided into during- and post-exercise, and the TSV rating and the corresponding HRV parameters were statistically classified. The data were divided into three sections. Namely, high-valued section (HS), mid-valued section (MS), and low-valued section (LS), and these values were proportionally calculated. Besides, three value sections were indicated using different colors to visualize the correspondence. Table 6.1 shows the Force-Directed Graph with the proportional distribution of value sections between HRV and TSV, and the following analysis was obtained：

(1) Overall, RMSSD and SDNN distribution trends were similar, with a higher proportion of HS in the DE (During exercise) phase than LS. It indicates that the cardiac load increases during exercise, and the autonomic nervous system are transformed from a state of mutual equilibrium between the sympathetic and vagus nerves at rest to a direction where the sympathetic nerves are dominant(Lucini et al., 1994). It indicates that the human body is in a state of "excitement". In particular, in the V_2 experiment, the proportion of HS was as high as 84.1%, suggesting that increasing exercise intensity has a more significant impact on HRV (Michael et al., 2016).

(2) For time-domain indicators, MS accounts for the highest proportion except for the IE phase of the V_2 experiment. Under normal conditions, the SDNN and RMSSD values for Chinese are about 3-5 (expressed in natural logarithm transformed values) (Group, 2000). The experimental results showed that the time domain indicators returned to standard values after the exercise.

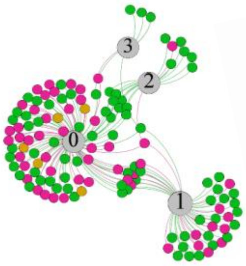
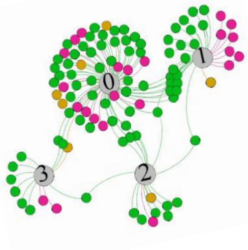
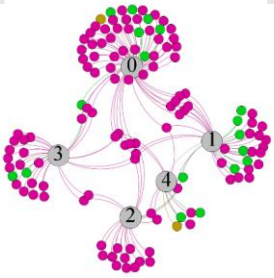
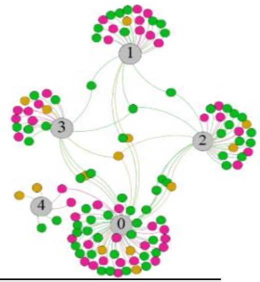
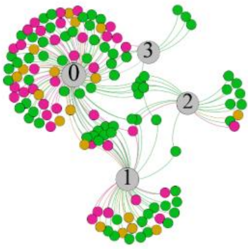
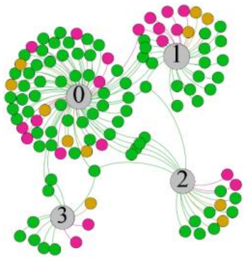
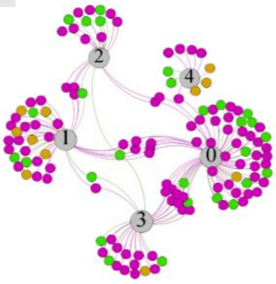
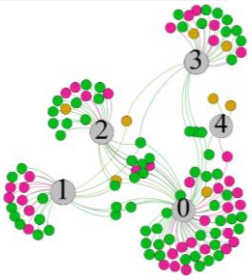
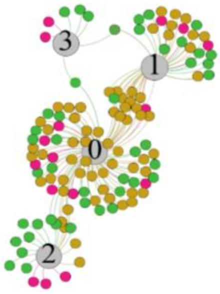
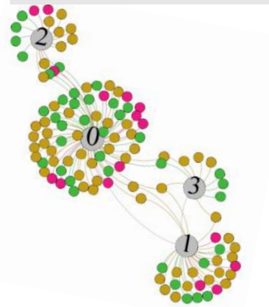
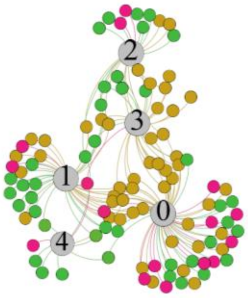
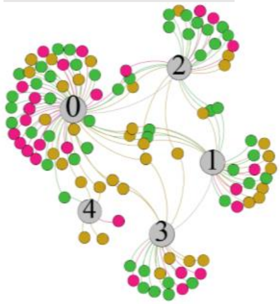
(3) SDNN indicators reflect the overall HRV situation. Table 6.1 shows that both HS and LS decreased, and MS increased after the exercise, indicating a gradual return of HRV to the standard range.

(4) As can be seen from the force-directed graph, LS is more likely to be found in the low thermal sensation area. For HS and MS, no significant distribution patterns were observed at the corresponding individual thermal sensation nodes. It also explains, to some extent, the absence of time-domain indicators as an independent variable in the stepwise regression analysis.

(5) For the frequency domain indicator (LF/HF), there was almost no LS distribution in the region of the highest thermal sensation node during exercise. It indicates that sympathetic activity was dominant, and the body is in a state of excitement, tension, or discomfort. After exercise, the proportion of LS in the high thermal sensation area increased rapidly, indicating that HF increased, and parasympathetic nerves were activated after exercise, which is consistent with the results of previous studies (Martinmäki and Rusko, 2008; Michael et al., 2016). Parasympathetic nerves were activated, indicating that the " excitement " state began to be inhibited, and comfort began to increase. But, as a whole, we still do not observe a more pronounced regular change in the distribution of each value segment in LF/HF with increasing thermal sensation. It may be related to the fact that the body is in exercise and the heart functions are in a complex state.

In summary, changes in cardiac function during and after exercise are complex. It makes changes in the HRV indicator more complicated than in the resting state. In a sense, changes in HRV during and after exercise may be more dependent on changes in body status and consequent changes in heart function. But the effect on the characterization of thermal sensation and thermal comfort is negligible. Therefore, the desire to evaluate exercise thermal sensation using HRV indicators may be difficult to achieve. This analysis was carried out for the reason that the HRV indicator did not enter the multivariate regression equation. Still, it was not possible to prove the existence of other mathematical relationships, which can be further investigated in future studies by attempting to use a computer theory.

Table 6. 1The force--directed graphs between HRV and TSV

	V₁						V₂					
	During exercise			Post-exercise			During exercise			Post-exercise		
Range of values	> 5 🟥 (HS)	3 ~ 5 🟩 (MS)	2 ~ 3 🟨 (LS)	> 5 🟥 (HS)	3 ~ 5 🟩 (MS)	2 ~ 3 🟨 (LS)	> 5 🟥 (HS)	3 ~ 5 🟩 (MS)	2 ~ 3 🟨 (LS)	> 5 🟥 (HS)	3 ~ 5 🟩 (MS)	2 ~ 3 🟨 (LS)
Scale	38.3 %	57.9 %	3.8 %	21.5 %	72.0 %	6.5 %	84.1 %	14.3 %	1.6 %	35.9 %	53.0 %	11.1 %
RMSSD												
Scale	28.3 %	58 %	13.7 %	17.9 %	73.2 %	8.9 %	69.7 %	21.2 %	9.1 %	31.9 %	61.2 %	6.9 %
SDNN												
Range of values	> 3 🟥 (HS)	1 ~ 3 🟩 (MS)	0 ~ 1 🟨 (LS)	> 3 🟥 (HS)	1 ~ 3 🟩 (MS)	0 ~ 1 🟨 (LS)	> 3 🟥 (HS)	1 ~ 3 🟩 (MS)	0 ~ 1 🟨 (LS)	> 3 🟥 (HS)	1 ~ 3 🟩 (MS)	0 ~ 1 🟨 (LS)
Scale	12.8 %	35.2 %	52 %	13.92 %	33.04 %	53.04 %	13.34 %	36.19 %	50.47 %	23.64 %	43.64 %	32.72 %
LF/HF												

6.2 Oral temperature during exercise

The oral temperature is decreased during the initial phase of exercise. A similar phenomenon was also found in the studies of Zhang et al.(Zhang et al., 2020)and P. Chappuis et al.(Chappuis et al., 1976). Zhang et al. found that the subjects' average auditory canal temperature showed a downward trend at each walking velocity. The faster they walked, the faster the average auditory canal temperature dropped (Fig.6.1). A similar phenomenon was observed in the experiments of Zhai et al.

The core temperature did not change immediately after the beginning of the exercise, and only after 5 minutes did the core temperature begin to change (Fig.6.2) . A closer look at Fig.6.2 reveals a slight downward trend in T_{cr} in HEx and Mex. After the end of the exercise, T_{cr} remained elevated for some time and then decreased. It is similar to the results of our experiment.

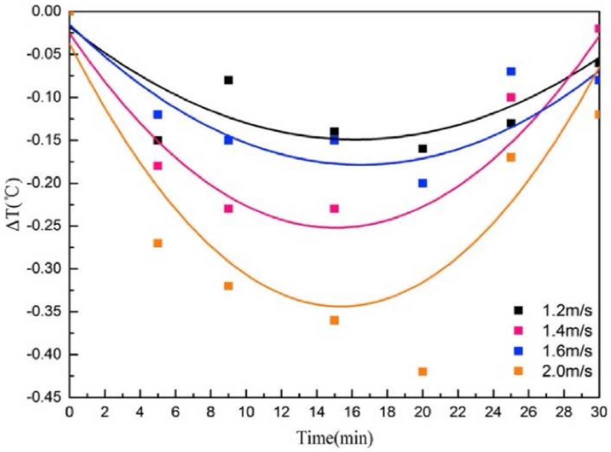


Fig.6. 1 The average changes of auditory canal temperature

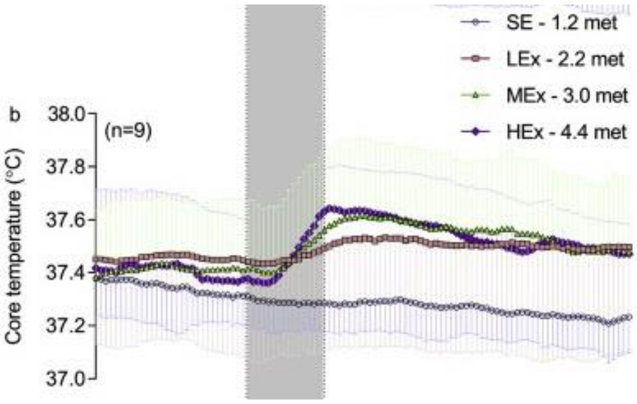


Fig.6. 2 Measured means core temperature (n = 9)

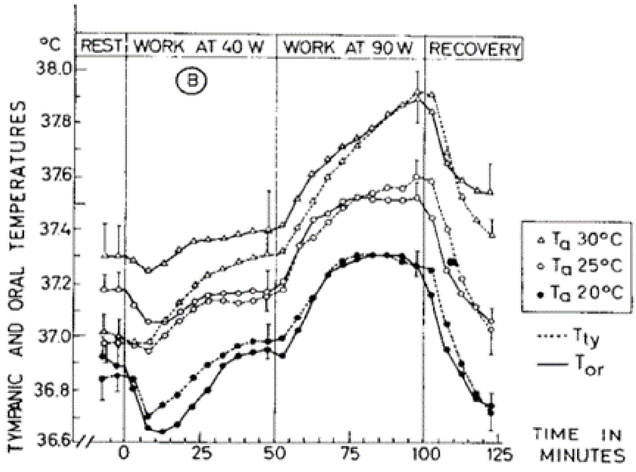


Fig.6. 3 Tympanic (T_{ty}) and sublingual (T_{or}) temperatures at 20, 25, and 30°C

But unfortunately, there is no explanation for this phenomenon in the above articles. In the study by P. Chappuis et al., the dual decrease in core and skin temperature during the initial phase of exercise was more intuitive (Fig.6.3).

I believe that the event may be due to the following reasons.

(1) In the study by P. Chappuis et al., it is mentioned that at the beginning of exercise, movement of the legs decreased air insulation and caused an increase in C of about 16W at 20°C, 14W at 25°C, and 4W at 30°C. After 10 min of exercise, (R + C) did not change appreciably until the end of the exercise period. Hence, the movement of the legs decreases air insulation and increases convective heat dissipation, thereby reducing the core temperature at the beginning of the exercise.

(2) At the beginning of exercise, this observation was also noticed by Äikäs et al. (Karvonen Äikäs et al., 1962), who measured esophageal temperature, and by Jéquier et al. (Jéquier et al., 1970) for tympanic temperature. This fall in temperature is best explained by a cooling of central blood due to mobilization of colder blood coming from the extremities. Well, The author believed that because the mouth, auditory canal, and tympanic are in direct contact with the outside, temperature fluctuations may be more significant in these areas, and blood temperature is also more affected by the outside environment.

(3) In section 6.1 of Fiala's doctoral thesis (Fiala, 1998), it is mentioned that the effect of core temperature on the model's vasoconstriction appeared to be practically negligible(Fig.6.4). The initial phase of cold exposure was accompanied by a rapid decrease in mean skin temperature and no significant increase in metabolic heat. It shows that the rise in core temperature brought about by vasoconstriction is limited.

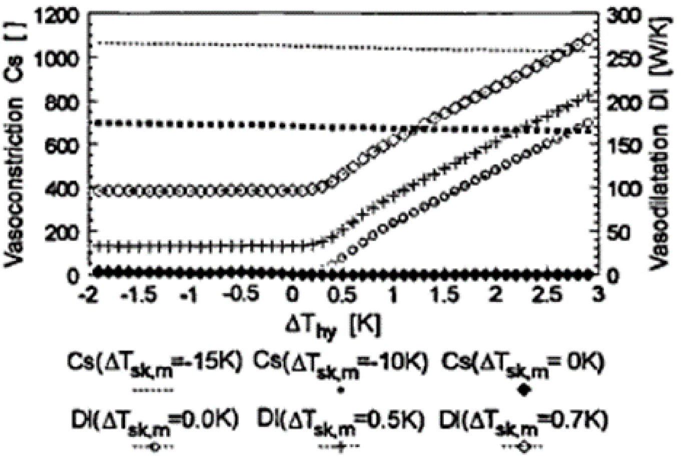


Fig.6. 4 Cutaneous vasomotor responses Cs and D_I, against the temperature error signal from the head core ΔT_{hy} (for three different skin temperatures)

In the study by P. Chappuis et al. the following is stated. "Metabolic free energy production (M) partially results from anaerobic reactions at the onset of exercise, or after a change in work intensity. Under these conditions, the rate of metabolic energy production exceeds that indicated by oxygen consumption, and an oxygen deficit is created. The anaerobic energy production mainly arises from the splitting of high-energy phosphates of ATP and creatine phosphate.” ATP is available directly to the body and is dissipated from the body through work, convection, radiation, and evaporation. Yet the total amount of ATP pre-programmed by the body is low and is maintained for a short time. Then at the beginning of exercise, when there is a sudden change in activity intensity, it is the body heat that is most easily converted into the required energy. Therefore, I believe that the energy consumption caused by exercise maybe prevent the increase of core temperature caused by vasoconstriction. All the power produced by the human body is converted from chemical energy. When it is necessary to regulate body temperature, it is released in the form of heat; when it is required to power, it is expressed in the form of mechanical energy. The brain completely controls the type and timing of the energy needed by the human body. The entire conversion process requires the consumption of chemical energy stored in the body. In the early stages of exercise, the body's metabolism increases gradually, and there are no significant changes in the way the body heat exchanges with the environment. There is no substantial change in the amount of heat stored. Then to meet the suddenly intensified workload, the body needs to convert heat into much-needed mechanical energy. As metabolic levels increase, aerobic exercise predominates, and this condition will disappear.

In his doctoral thesis, Fiala mentioned that the human body might be shivering at low temperatures, when it must increase its metabolic rate to produce heat. And then, the core and skin temperatures are both decreasing (Fig.6.5).

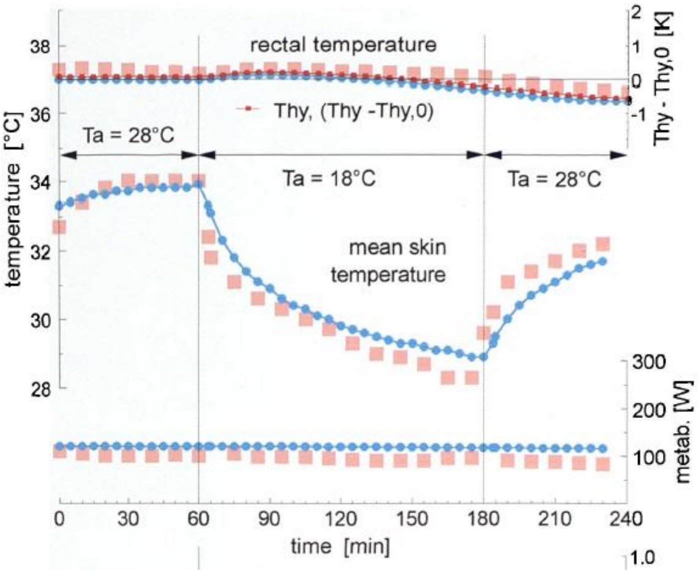


Fig.6. 5 Parameters of the bodily thermal state as predicted by the model for sudden changes from a thermally neutral environment to a cold climate of T_a 18°C and back to neutral.

So can I argue that vasoconstriction is not necessary to cause an increase in core temperature, especially during exercise? In experiments, a sudden workout and "shivering" were the same in some sense identical. In the study by Goto et al. it was also found that the metabolic rate of the human body reached a stabilization after 5 min of continuing the same activity state. This coincides with the timing of the decline of T_{or} and T_{sk} in this experiment. In the study by Goto et al., it was also found that the metabolic rate of the human body reached a stabilization after 5 min of continuing the same activity state. It coincides with the timing of the decline of T_{or} and T_{sk} in experiment.

In fact, different outside temperatures and humidity, different exercise intensities, different exercise durations, and different measurement areas can cause different trends in core temperature. But in any cases, when the exercise is over, the core temperature will eventually return to near the initial temperature, and the process of change will be different. A similar phenomenon was observed in Zhai et al. (Zhai et al., 2019) and Zhang et al. (Zhang et al., 2020b). The core temperature begins to fall, then rises, and eventually returns to the initial temperature. In the study by Chappuis et al. (Chappuis et al., 1976), the oral temperature returns to near the initial temperature at the end of the exercise. It can also be observed that the oral temperature first decreases and then increases during the 40W work, and this exercise lasts up to 50 minutes. In our work, the exercise lasted 20 minutes. The oral temperature was lower than the initial temperature at the end of the exercise, so the oral temperature will continue to rise after the exercise until it is near the initial temperature.

6.3 Thermal alliesthesia

In the article titled: “Physiological role of pleasure” published in Science in 1971, Cabanac used “alliesthesia” to describe the dependence of a pleasant or unpleasant sensation on the subject's interior milieu (internal state) (Cabanac, 1971) , depending on the subject's internal state. The article also argued that the alliesthesia to different extents existed in thermal, gustatory, olfactory, luminous, or auditory stimuli sensations. In Richard's study (Richard, 2011), alliesthesia is proposed as the logical framework of a new approach to thermal comfort modeling by him, the phenomenon of alliesthesia is used to differentiate thermal pleasure from thermal neutrality and acceptability. Richard summarized the simple concept of alliesthesia: any external or environmental stimulus that has the prospect of restoring the regulated variable within the milieu interieur to its set-point will be perceived as pleasant (positive alliesthesia), while any environmental stimulus that will further displace the error between the regulated variable and its set-point will be perceived as distinctly unpleasant, or even noxious in more extreme cases (negative alliesthesia). Alliesthesia leads us to seek pleasant stimuli and avoid unpleasant ones. Thermal alliesthesia has been studied in greater depth by Thomas et al. (Thomas and Richard, 2015). They elaborated on the thermophysiological hypothesis of alliesthesia with a particular focus on set-point control and the origins of thermoregulatory load-error signals, and then discussed them within the broader context of thermal pleasure. In their subsequent research, it was found that the psychophysiological principle of thermal alliesthesia operates within the thermoneutral zone, making it equally relevant to quotidian indoor environments as it is to the extremes found in traditional physiological research. Non-steady-state built environments could potentially offer spatial alliesthesia through carefully managed contrasts between local and mean skin temperature trends. Transitional zones were suggested as design solutions.

In this experiment, it was observed that post-exercise thermal comfort was higher than pre-exercise under the same ambient. The author believed that the intensity of exercise governs sensation and delight after exercise rather than not just the ambient conditions. After experiencing thermal discomfort during exercise, subjects experienced an increase in comfort brought about by a decrease of thermal and sweat sensations in a static state, which would indicate the perception of conditions that could trigger thermal delight, also provide the conditions for thermal alliesthesia. Due to alliesthesia, an asymmetry in thermal comfort before and after exercise is created. Therefore, it is necessary to consider thermal delight and alliesthesia in future studies of thermal comfort during exercise.

6.4. The relationship between TSV, TC, EDA and SFI.

The author further discussed subjective perceptions and EDA in the experiment. The following analysis explains the changes in the exercise states during and after the exercise.

6.4.1 TSV and TC

There is always a close relationship between thermal sensation and thermal comfort in the human body's static state, and a significant correlation also exists during exercise. TSV and TC show a good linear relationship during and after exercise (Fig.6.6). As thermal sensation rises, thermal comfort decreases linearly. The post-exercise slope was higher than during exercise. When the post-exercise thermal sensation was neutral (TSA=0), comfort was higher than during exercise (1.775>1.532). This means improved thermal comfort after exercise. Havenith et al. (Havenith et al., 2002) believe that the human body's thermal sensation during exercise greatly changes because of psychological factors. First, the human body is psychologically prepared for uncomfortable exercise conditions while exercising. Second, the hormones produced by the hypothalamus during exercise can cause a sense of pleasure in the body, showing that in addition to the thermal environment and exercise factors, psychological changes during exercise will also have an important effect on the thermal sensation (Nikolopoulou and Steemers, 2003; Vanos et al., 2011). Therefore, I think that the influence of "thermal alliesthesia" cannot be ignored when studying thermal comfort in exercise.

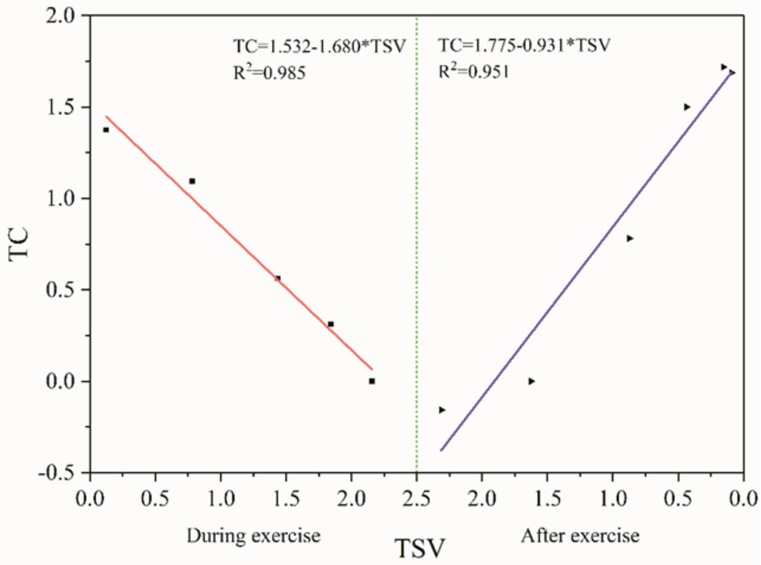


Fig.6. 6 Relationship between thermal sensation and thermal comfort during and after exercise

6.4.2. TSV and EDA

Fig.6.7 shows a quadratic curve relationship during and after exercise. However, R² is lower in the regression curve after exercise. From the figure, it can be seen that the value of EDA is 8 -9 when TSV <0.5 at the start of exercise, which means that the thermal sensation at the early stage of exercise is similar to the thermal sensation when the body is static. And after exercise, the curve decreases more rapidly. When the TSV returned to near neutral (0 ~ 0.5), the EDA value was around 10, and the dispersion degree was larger. After exercise, the specific gravity of LHL increases, and the evaporation of sweat is larger, which makes the thermal sensation decrease.

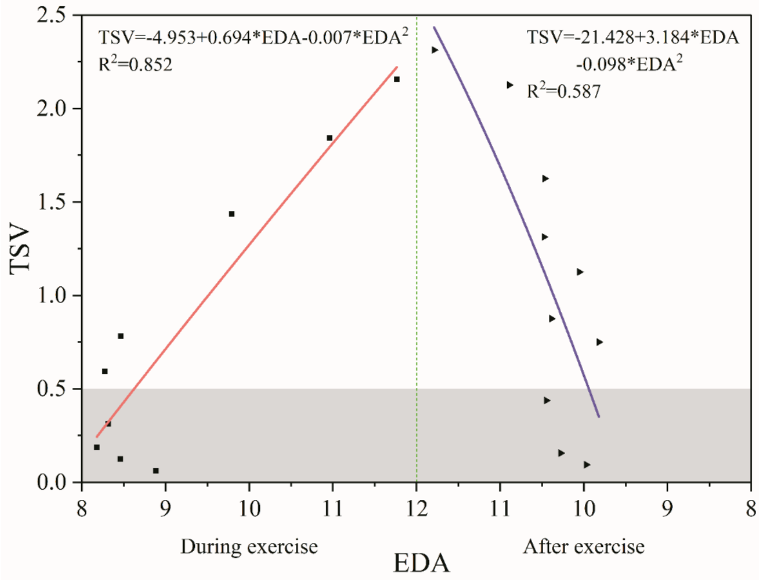


Fig.6. 7 Relationship between thermal sensation and EDA during and after exercise

6.4.3 TSV and SFI

Fig.6.8 shows the relationship between the thermal sensation and the sweating index. When SFI = 0 in the early stage of exercise, 0 < TSV < 0.5. As SFI increases, the rate at which the thermal sensation increases gradually slows, showing that LHL becomes larger during exercise and slows heat storage (S) and thermal sensation growth. When the thermal sensation is the same during and after the exercise, the SFI after exercise is greater. This indicates that LHL has a greater effect on thermal sensation after exercise than during exercise. When TSV < 0.5, SFI is generally equal to 0. The above discussion shows that the correlation between subjective perception indicators remains high, and the regressions are good during exercise.

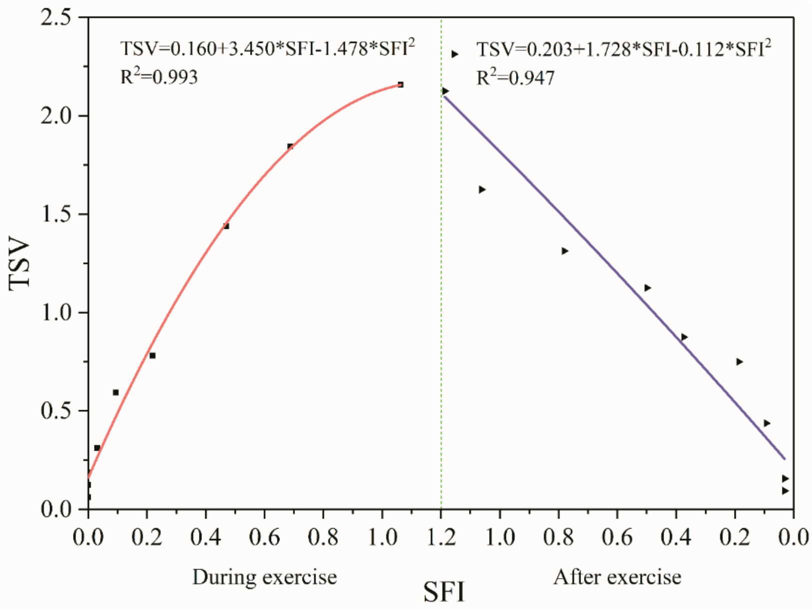


Fig.6. 8 Relationship between thermal sensation and SFI during and after exercise

6.4.4 EDA and SFI

Fig. 6.9 compares the relationship between the sweat feeling index and EDA. The R² of the fitted curve was smaller after exercise. During exercise, EDA changed faster than SFI. This means a time difference between the objective measurement (EDA value) and subjective sensation, and subjective sensation has a lag during exercise. After the exercise, the decline rate of subjective sensation is greater than the EDA, and subjective sensation has a lead. It was judged to be related to the increased evaporation of sweat after exercise, so the somatosensory and physiological index responses were not synchronized.

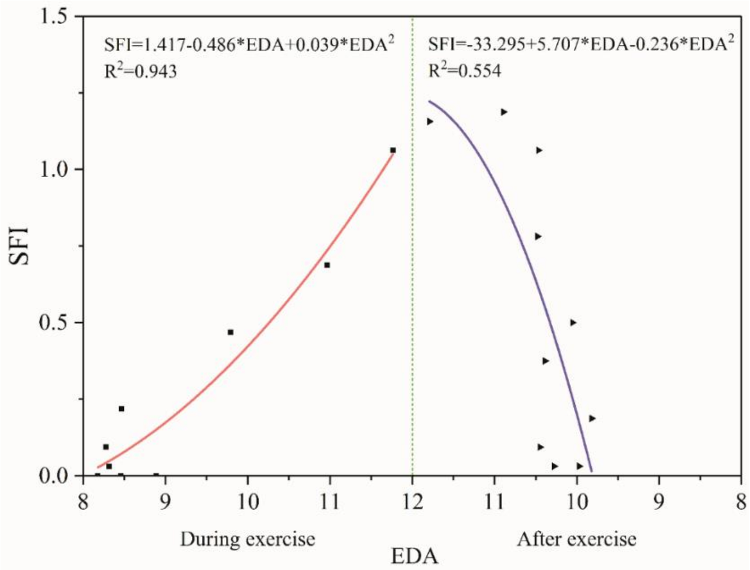


Fig.6. 9 Relationship between EDA and SFI during and after exercise

In summary, the author found more significant differences in the subjective-objective interrelationship during and after exercise. In other words, the subjective-objective interrelationship becomes more complex after the exercise.

6.5 LF/HF and thermal sensation and comfort

LF/HF represents the degree of activity between sympathetic and parasympathetic nerves, that is, the balance of the entire autonomous audit system. This value is directly proportional to sympathetic nerve activity and inversely proportional to parasympathetic nerve activity.

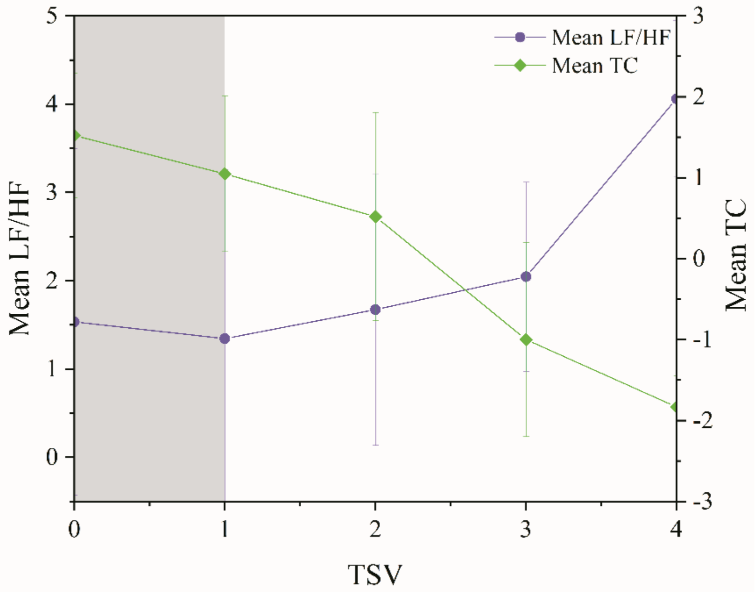


Fig.6. 10 Biaxial chart of the relationship between the LF/HF index, TSV, and TC

Fig.6.10 shows that TSV is between 0 and 1, and LF/HF is at its lowest point when the thermal sensation is low. According to the scatter plot of TSV and TC, comfort is highest when the value of TSV is between 0 and 1. This shows that when people feel comfortable, parasympathetic nerves dominate. Exercise states can also presumably affect the vagus and sympathetic nerve activities of the body and affect thermal sensation and comfort levels. The correlation coefficient table shows a significant correlation between LF/HF and TC (see Table 5. 7). However, because the human body is in motion, LF/HF is not as stable as in a static state. These results are derived from larger fluctuations. Also, because EDA is also an indicator of sympathetic nerve activity, an increase (decrease) in EDA causes an increase (decrease) in TSV and the sympathetic nerve activity and a worsening (or improvement) in the comfort level. LF/HF and EDA can also be used as auxiliary reference indices to measure and evaluate human comfort while exercising.

6.6 Thermal environment and exercise thermal sensation

In this experiment, the author chose 26 °C as the ambient temperature based on two main reasons.

1. We asked subjects to be thermal sensation neutral in a static state (pre-exercise), simulating a typical work environment. In Zhai's study, Room A, (measuring 4.5 m × 3.9 m × 2.7 m) was used to simulate a typical office environment (26 °C) (Zhai et al., 2019) . Yao created 4 ambient temperatures (21°C, 24°C, 26°C and 29°C) in his study. As is shown in Fig. 1, when the ambient temperature rises from 21 °C to 26 °C, the LF power will decrease, and when the ambient temperature continues rising till 29 °C, it will increase. For the HF power, it will have a big increase at first, but changes little after 26 °C in the ambient temperature. The change pattern of LF/HF with the ambient temperature was similar to that of LF. LF/HF represents the degree of activity between sympathetic and parasympathetic nerves. This value is proportional to sympathetic activity and inversely proportional to parasympathetic activity. The lower this value is, the lower the thermal sensation and the higher the comfort level. The minimum value of LF and LF/HF occurred under the neutral thermal environment (Ye Yao et al., 2007).

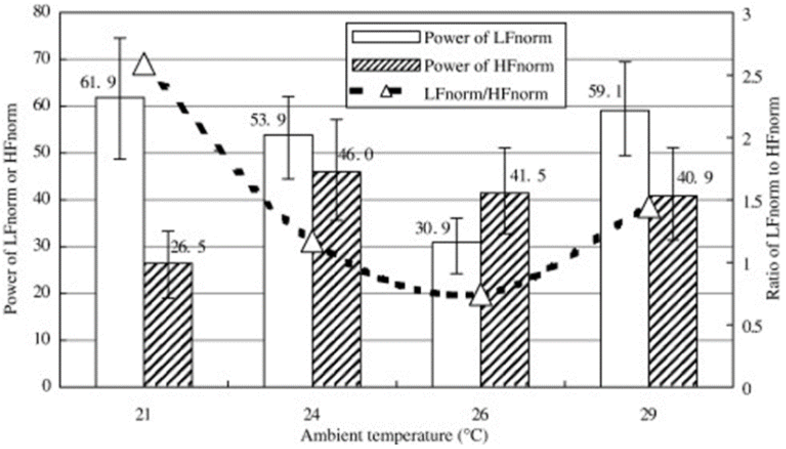


Fig.6. 11 HF, LF and LF/HF under different ambient temperatures (Ye Yao et al., 2007)

In Gao's study (Siru Gao et al., 2018), the test room temperature was also set at 25.7 °C, which is the neutral temperature predicted by the PMV model for sedentary activity (1.0 met). As shown in Figure 2, the neutral temperature was approximately 26 °C when the subjects were in a static state.

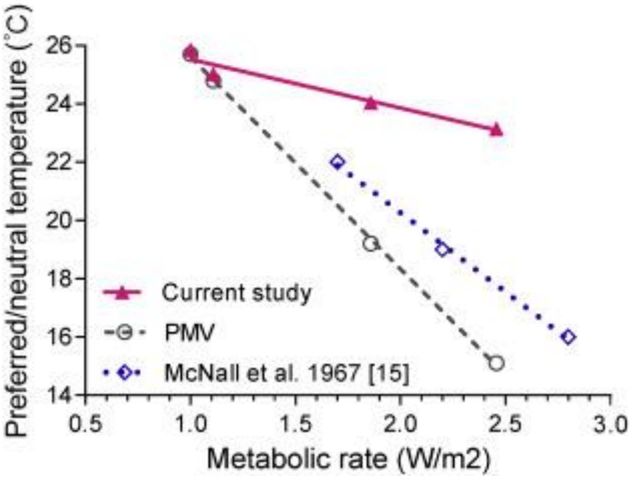


Fig.6. 12 The relation between metabolic rate and preferred temperature (Siru Gao et al., 2018)

Also, 26 °C was analyzed as an important environmental parameter or neutral temperature in Wang and Zhai's study (Wang et al., 2016; Zhai et al., 2019).

2. Another reason for choosing 26 °C as the ambient temperature is to make the fluctuation of thermal sensation more obvious for the subjects. As the exercise intensity is not high, if the temperature setting is low, some subjects in the experiment physiological indicators, thermal sensation, and sweating index change little, which may reduce the significance of this work. Wang, in his study, that when the air temperature was kept at 26 °C, people would feel a little hot if they took moderate activities (Wang et al., 2016).

Therefore the author chose a high value of temperature in the thermal neutral range as the ambient temperature.

In addition, if the ambient temperature is lowered to, for example, 22, 24 °C. Then, the subject's thermal sensation will be reduced during the same exercise time. Changes in certain physiological parameters may be insignificant. In other words, as the exercise intensity increases, the neutral temperature of the environment will decrease. It was confirmed in the study by Yang (Yang et al. 2020). Subjects were exposed to four ambient temperatures (20, 23, 26, 29 °C) while conducting four activities (sitting, standing, walking at 1.0 km/h, and walking at 2.0 km/h). Physiological responses, including metabolic rate, skin temperature, and skin wettedness, were measured continuously, while subjective thermal comfort responses were surveyed. Treadmill workstation significantly increased human metabolic levels and reduced the associated environmental neutral temperatures.

However, increasing the ambient temperature and humidity may be detrimental or even dangerous to the body. Tian (Xiaoyu Tian et al. 2021) noted in his study that when air temperature ranged from 26 °C to 37 °C, the eardrum temperature, heart rate, skin temperature, weight loss, systolic blood pressure, respiratory flow, and respiration rate increased significantly. Thermal sensation reported by subjects was slightly hot at 26 °C and close to very hot when the temperature increased to 37 °C. The intensity of headache, dizziness, fatigue and sleepiness increased with increasing temperatures. People performing moderate activities should avoid sustained exposure under temperature of 37 °C, which was estimated to have significant health risks. Within the temperature range of 26 °C to 33 °C, acceptability of thermal environment can be maintained by thermoregulatory responses and thermal acclimatization. Tamm reported that perceived fatigue and exertion increased significantly with increasing activity levels at high temperature of 42 °C (Tamm et al. 2014).

Also, increasing the intensity of exercise (raising the level of metabolism) is also an important factor that affects thermal sensation. If the speed in the experiment is increased, then the subjects may experience more severe thermal sensations. Thermoregulatory balance during strenuous exercise depends on the interaction of metabolic heat production and exchange with the environment (Kenefick RW et al., 2007). Heat-related illness (HRI) is an ever present threat to athletes, military personnel, and occupational athletes, as the combination of physical exertion in hot environments makes individuals susceptible to heat stroke, heat exhaustion, and heat cramps.

The changes in indoor environment can cause changes in the exercise thermal sensation, and thus it can be considered that the prediction methods and models of exercise thermal sensation will also change in different thermal environment ranges. Even extreme thermal environments can produce extreme physiological changes and thermal sensations. However, the author still believe that it is most important and significant to study thermal sensation in everyday buildings (e.g., stadiums, gyms) or construction sites in a normal range of thermal environments and moderate activity intensities.

6.7 Summary

In this work, some physiological indices and thermal comfort have shown some peculiar variations in the experiment. It is, therefore, necessary to explain and discuss these peculiarities in more detail. For example, the oral temperature decreased for a short time after the start of exercise and increased after the end of exercise. There was no significant correlation between the HRV index and the thermal sensation of exercise, but are there other relationships? Post-exercise comfort is higher than pre-exercise, so psychological factors cannot be neglected in exercise thermal comfort studies. The main results are as follows.

Changes in cardiac function during and after exercise are complex. In a sense, changes in HRV during and after exercise may depend on changes in body status and consequent changes in heart function. But the effect on the characterization of thermal sensation and thermal comfort is negligible.

Oral temperature may drop for a short time after the start of exercise. Different outside temperatures and humidity, different exercise intensities, different exercise durations, and different measurement areas can cause different trends in core temperature. But in any case, when the exercise is over, the core temperature will eventually return to near the initial temperature, and the process of change will be different.

Exercise's intensity governs sensation and delight after exercise rather than not just the ambient conditions. Due to thermal alliesthesia, an asymmetry in thermal comfort before and after exercise is created.

By examining the regression function of thermal sensation and TC, EDA, and SFI, it is found that the regression of thermal sensation and other subjective sensation is good. The relationship between thermal sensation and EDA was found to be better during exercise and worse after exercise. Similar results were found in the regression functions of EDA and SFI.

When the LF/HF value is low, the thermal feeling is also low, and comfort is high. This demonstrates that physiological parameters measuring sympathetic and parasympathetic nerves can be used as auxiliary reference indicators to measure and evaluate human thermal comfort while exercising.

The changes in the indoor environment can cause changes in the exercise thermal sensation, and thus it can be considered that the prediction methods and models of exercise thermal sensation will also change in different thermal environment ranges. Even extreme thermal environments can produce extreme physiological changes and thermal sensations.

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CHAPTER 7

CONCLUSION

7.1. Conclusion of Research 7-1
7.2 Further Research 7-4

7.1. Conclusion of Research

The study of exercise thermal sensation is more difficult than that of static thermal sensation in the human body. This research provides a comprehensive and systematic review of the concepts, evaluation methods, and the evolution of classical models of exercise thermal sensation. The author obtained data on physiological indicators and subjective perceptions by experiments. The experimental data were analyzed and processed using Origin 2018, IBM SPSS Statistics 25, and Gephi, including linear correlation analysis, stepwise regression analysis, etc. The specific physiological parameters and thermal comfort changes during the experiment were explained and discussed in more detail. The author seeked to understand the relationship between the human thermal sensation and its related physiological parameters in more detail in the whole exercise process. The results of the study can provide an provide an important reference for the study of exercise thermal sensation nowadays. Besides, the study is highly practical as it attempts to use physiological indicators that are easily measurable and can effectively predict thermal sensation. It also provides basic research for the further development of smart bracelets. The main work and results can be summarized as follows:

In chapter one, INTRODUCTION AND PURPOSE OF RESEARCH. Research background and significance of exercise thermal sensation were demonstrated. Moreover, the objective and the scope of study are also explained in this chapter.

In chapter two, BUILDING THERMAL ENVIRONMENT AND HUMAN THERMAL SENSATION (STATIC STATE). From the perspective of heat transfer, the factors that affect human thermal comfort and thermal sensation during exercise are influenced by heat conduction. Air temperature, relative humidity, air velocity, average radiation temperature, metabolic rate, and clothing thermal resistance are the factors that researchers are most concerned about. Numerous studies have shown that these six factors have a significant impact on thermal comfort and thermal sensation. During the exercise, in addition to the factors as mentioned above under normal conditions, the preparation before exercise, the anticipation of exercise before exercise, the sense of control over the exercise process, the adaptation to the heat environment during exercise, the difficulty of breathing during exercise, the previous exercise experience and the frequency of exercise will affect the thermal sensation during exercise. Up to now, dozens of human thermal sensation models have been developed. In this chapter, these models can be roughly divided into four categories. That is the Fanger model, the two-node model, the multi-layered multi-node model, and the comprehensive model. In recent years, the Rayman model has been developed based on the Fanger model and MEMI model. Two evaluation methods are used for human body thermal sensation: subjective and objective. In the subjective evaluation method, Fanger's 7-point thermal sensation evaluation scale has the advantages of simplicity and accuracy and has been widely used in a large number of studies. In the objective evaluation method, some physiological indicators are often used to evaluate thermal sensation. These models are reasonable under normal conditions because these indicators are positively correlated with thermal sensation under normal conditions. However, in the study of physiological indicators related to the exercise thermal sensation, the use of these models may produce bias in predicting exercise thermal sensation.

In chapter three, RESEARCH AND DOMAIN APPLICATIONS RELATED TO EXERCISE THERMAL SENSATION. According to previous studies, thermal stress induced by exercise and thermal environments leads to many thermoregulatory responses in the human body. The three physiological parameters most likely to be associated with exercise thermal sensation are skin temperature, core temperature, and sweating rate. Previous studies on physiological parameters related to thermal sensation during exercise have focused on the correlation between skin temperature and thermal sensation because of the high correlation between skin temperature and thermal sensation in a static state. However, it has been shown that this is not the case in exercise. The correlation between these three physiological indicators and thermal sensation during exercise, whether skin temperature, human core temperature, or sweating rate, needs to be further investigated. Analysis of existing thermal sensation models shows that, except for the Fanger model, all existing models are based on thermophysiological indicators, focusing on predicting several physiological indicators related to thermal sensation. Current research on models of exercise thermal sensation in thermal environments is divided into two categories: one is the research on the accuracy of existing models in predicting exercise thermal sensation in specific thermal environments. The other is to construct a new model to predict exercise thermal sensation and to verify the accuracy of the model by comparing it with actual thermal sensation.

In chapter four, EXPERIMENTAL INVESTIGATION INTO THE RESPONSES OF PHYSIOLOGICAL PARAMETERS AND THERMAL SENSATION IN THE WHOLE EXERCISE PROCESS OF DIFFERENT INTENSITIES. Two exercise intensities were performed separately on a treadmill (speeds in the two sets of experiments were v_1 = 4.5 km/h and v_2 = 6 km/h). In physiological parameters, T_{sk}, T_{or}, and HR were all observed to overshoots after exercise. In subjective sensations, TSV and SFI also showed similar overshoots. The physiological indicators are in the adjustment stage at the beginning of the exercise and reach stability after about 6 minutes. Simultaneously, 6 minutes is also the cutoff point for many indicators to turn the corner. The HRV index and HR differed significantly with increasing exercise intensity. After the end of exercise, this difference gradually disappears and returns to the initial state. Gender and BMI are also factors that influence the exercise thermal sensation (comfort).

In chapter five, MATHEMATICAL RELATIONSHIPS BETWEEN SUBJECTIVE PERCEPTION AND PHYSIOLOGICAL PARAMETERS IN THE WHOLE PROCESS OF EXERCISE (STATIC-DYNAMIC-STATIC). There is a significant correlation between thermal sensation and core temperature, T_{sk}, EDA, and HR. And with the increase in exercise intensity, the correlation has gradually strengthened. But, compared with the static state, the correlation becomes weaker. The correlation between subjective perception is stronger than the correlation between subjective and objective physiological parameters. Skin temperature, oral temperature, and EDA are important indicators related to exercise thermal sensation. The rate of change in physiological parameters can be used to predict the exercise thermal sensation better. The timing of physiological parameters adjustment and TSV adjustment are always similar after a mutation in metabolic levels(static-dynamic-static). Overshoot was observed for each rate of change. It was found that overshoot occurs quickly after the exercise, while it was not noted at the beginning of the exercise. This also indicates that overshoot of skin and oral temperature is an important cause of thermal sensation overshoot.

In chapter six, DISCUSSION OF THE INFLUENCE FACTORS ON THE EXERCISE THERMAL SENSATION IN THE EXPERIMENTS. In this work, some physiological indices and thermal comfort have shown some peculiar variations in the experiment. Changes in cardiac function during and after exercise are complex. In a sense, changes in HRV during and after exercise may depend on changes in body status and consequent changes in heart function. But the effect on the characterization of thermal sensation and thermal comfort is negligible. When the exercise is over, the core temperature will eventually return to near the initial temperature, and the process of change will be different. Exercise's intensity governs sensation and delight after exercise rather than not just the ambient conditions. Due to thermal alliesthesia, an asymmetry in thermal comfort before and after exercise is created. By examining the regression function of thermal sensation and TC, EDA, and SFI, it is found that the regression of thermal sensation and other subjective sensation is good. The relationship between thermal sensation and EDA was found to be better during exercise and worse after exercise. Similar results were found in the regression functions of EDA and SFI.

In chapter seven, CONCLUSION. The whole summary of each chapter has been presented.

7.2 Further Research

The research that has been undertaken for this thesis has highlighted a key point on which further research would be beneficial. This work is done indoors. In future studies, the relationship between physiological parameters and thermal sensation (thermal comfort) during exercise in an outdoor environment could be explored. Subjects are placed in a walkway (or similar to fitness trails) with different canopy cover. At the same time, temperature, humidity, wind speed, and solar radiation will be recorded. The distance and time to fatigue (or sweat) are measured for different canopy cover percentages. Mathematical statistics and calculations will be performed in an attempt to find the most economical canopy cover. The research results will be used in combination with simulation software to further optimize vegetation planning for fitness trails.

APPENDIX I
Informed Consent Form

Informed Consent Form

Research Topic		
Principal Investigators	**Tel**	**Email**
Co-Investigator	**Tel**	**Email**
Emergency Contact	**Tel**	

We invite you to participate in this study. Your participation in this study is completely voluntary, and you may refuse to participate or withdraw from the experiment at any time without penalty.

Before deciding whether to participate, you will need to understand what the research is about, the risks and benefits of participating in the study, and what you will be expected to do. You may also discuss this study and this consent form with your family, friends, or doctor. If you have any questions about this research or this consent form, please contact the Principal Investigator and Co-Investigator. If you decide to participate in this study, you must sign this consent form. We will provide a signed copy of this consent form for your records.

What is the purpose of the research?

This questionnaire is designed solely to carry out investigation on the topic of Exercise Thermal Sensation (comfort) in a Steady-state Building Environment for a PhD Research in Architecture, The University of Kitakyushu, Japan.

How long does it take to participate in the research?

This experiment was designed with dynamic-static steps (static-dynamic-static) with durations of 15 minutes, 20 minutes, and 15 minutes, respectively. The total duration of each experiment is 65 minutes. You are required to participate in two experiments, each with different moderate exercise intensity. The interval between the two experiments is more than 3 days.

What are the possible risks or discomforts?

This experiment was conducted in a steady-state environment with varying levels of intensity for 20 minutes. The exercise time in this study is relatively short, and we have been paying attention to your thermal sensation and physical condition during the exercise. If you feel extremely hot, shortness of breath, or even unable to hold on, the experiment will be terminated immediately to ensure your safety.

What are the possible benefits of participating in the research?

You will not benefit directly, but this experiment will help investigate and understand the patterns of exercise thermal sensation and physiological parameters. It is important to design thermal environmental comfort in stadiums, gyms, fitness trails, etc.

Will you be compensated for your participation in the research?

You will be paid 30 RMB for each experiment. If you give up in the middle of the exercise, the previous compensation will not be refunded, and you will not be paid for the remaining experiments you did not participate in. If you have already completed an experiment, we will pay you the usual fee if the researcher has operational problems. If you feel discomfort during exercise and terminate an experiment, we will also pay for that experiment as usual.

Can I leave the experiment midway?

You may opt-out at any time throughout the experiment without penalty if you experience any special conditions or discomfort during exercise. When the experimenters notice heat stress symptoms such as exhaustion, difficulty breathing, or heavy sweating, we will ask you to stop the experiment immediately to prevent further harm to your body.

How will the study protect your privacy?

In this experiment, your personal data involved include your name, age, height, weight, dress, exercise thermal sensation, and thermal comfort vote. All of your data will be used only for this study. If your data appears in future publications such as journals, books, etc., it will be anonymized or coded so that your data cannot be directly identified by anyone other than the researcher. The data will be stored in Excel format on the researcher’s private computer in the “Building Energy Efficiency” lab with a password. No one else will have access to it except the researcher. The researcher will store the data in the computer for 5 years. The researcher promises that the data will never be shared with others. The data will continue to be anonymized or code-named if they appear in any published material. The researcher also stores paper copies of the informed consent forms in a locked cabinet with a key in the “Building Energy Efficiency” lab, which cannot be accessed by non-lab researchers. The researcher will keep the informed consent forms for 3 years, after which they will be destroyed in a paper shredder.

University Human Subjects Ethics Committee and how does it protect you?

This committee will review all research involving human subjects, such as the study you are considering participating in.

Responsible for protecting the rights and welfare of research participants. The committee adheres to state legal requirements and guidelines and reviews each study to ensure that all research projects are conducted with the least possible risk.

The University Human Subjects Ethics Committee is composed of the following individuals.

- Physicians
- Researchers
- Non-scientific Staff
- Attorneys
- Community members

If you have any questions about a subject's rights, or if you believe you have been treated unfairly, or if you have any concerns about this booklet, you should contact us.

If you have any questions about the research, you can contact the committee.

Who can you contact if you have any questions?

If you have any questions, concerns, or complaints about your participation in the study, or if you have any questions about your rights as a research subject, you may contact the principal investigator and contact person listed on the first page of this consent form.

Tel: +8613703516280, Email: xuqinghao@sxu.edu.cn.

I have read this consent form, and all of my questions have been answered.

I have voluntarily agreed to participate in this research and have received a copy of the above.

Name of subject Signature of subject Date

Name of Issuer of Consent Signature of Issuer of Consent Date

APPENDIX II

Questionnaire Survey

Dear Respondent,

This questionnaire is designed solely to carry out investigation on the topic of Exercise Thermal Sensation (comfort) in a Steady-state Building Environment for a PhD Research in Architecture, The University of Kitakyushu, Japan. Your prompt cooperation in responding to the questions appropriately shall be highly appreciated. All information provided will be treated with strict confidentiality.

Thank you.

Part A: Personal Information

1. Gender Male ○ Female ○

2. Age……………………………years

3. Height……………………… cm Weight…………………………kg

4. Dress Code

○ Underclothes ○ Long-sleeved T-shirts ○ Thin trousers

○ Socks ○ Sneakers

5. Does you have an underlying disease?

No ○ Yes ○

6. Did you take medication before the experiment?

No ○ Yes ○

7. Did you engage in strenuous exercise within 24 hours?

No ○ Yes ○

8. Did you eat or drink in the 2 hours before the experiment?

No ○ Yes ○

Part B: Thermal Sensation Voting

Thermal Sensation										
		Very hot	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold	Very cold
		+4	+3	+2	+1	0	-1	-2	-3	-4
Rest	**13**									
Exercise	**15**									
	16									
	17									
	18									
	19									
	20									
	21									
	25									
	29									
	33									
	35									
Rest	**36**									
	37									
	38									
	39									
	40									
	41									
	43									
	46									
	49									

Part C: Thermal Comfort Voting

Thermal Comfort

		Very comfortable	Comfortable	Slightly comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable
		+3	+2	+1	-1	-2	-3
Rest	13						
Exercise	17						
	21						
	25						
	29						
	33						
	35						
Rest	37						
	40						
	43						
	46						
	49						

Part D: Sweat Feeling Index Voting

Sweat Feeling Index

		No feeling of sweating	Slight feeling of sweating	Strong feeling of sweating
		0	1	2
Rest	13			
Exercise	17			
	21			
	25			
	29			
	33			
	35			
Rest	37			
	40			
	43			
	46			
	49			

Part E: Fatigue Voting

Fatigue was evaluated using a Japanese subjective fatigue checklist, which consists of 25 items and is divided into five subtypes. Participants answered each item using a five-point discrete scale from +1 (none) to +5 (extremely severe).

Type 1: Insecurity											
	Rest	Movement						Rest			
Symptom Measurement point	13	17	21	25	29	33	35	37	40	46	49
Feel nervous											
Feel bad in mood											
Feel restless											
Have a quick temper											
Feel confused in thinking											

Type 2: Discomfort											
	Rest	Exercise						Rest			
Symptom Measurement point	13	17	21	25	29	33	35	37	40	46	49
Have a headache											
Feel heavy in the head											
Feel bad											
Feel mind wandering											
Feel dizzy											

Type 3: Tiredness											
	Rest	Exercise						Rest			
Symptom Measurement point	13	17	21	25	29	33	35	37	40	46	49
Feel sleepy											
Want to lie down											
Give a yawn											
Lack motivation											
Feel general weakness											

Type 4: Fuzziness											
	Rest	Exercise						Rest			
Symptom Measurement point	13	17	21	25	29	33	35	37	40	46	49
Feel slightly hard to keep eyes open											
Feel the eyes tired											
Feel sore in the eyes											
Feel dry in the eyes											
Feel blurred in vision											

Type 5: Soreness											
	Rest	Exercise						Rest			
Symptom Measurement point	13	17	21	25	29	33	35	37	40	46	49
Feel arms feeble											
Feel a pain in the back											
Feel a pain in the hands or fingers											
Feel acid leg pain											
Feel soreness in the shoulders											

-Thank you for your assistance-

APPENDIX III

University Ethics Commission Approval Form (Approval No. SXULL2019069)

山西大学伦理审查申请表

——涉及人体生物医学研究项目（药物及器械临床试验、新技术应用等）的申请

项目依托单位	山西大学	序号（由委员会统一填写）	SXULL2019069
项目名称	在稳定建筑环境下人体动态热感觉（热舒适度）与生理参数指标相关性研究	项目起止时间	2019.11.5-2022.11.5

项目类别　A. 新药物临床试验　B. 新器械临床试验　C. 新技术应用　D. 人体标本收集

E. 其他（请注明）：生理指标测定

申请人（项目负责人）简要信息

姓名	徐清浩	性别	男	学历	研究生	科室	土木工程系
办公电话	0351-2646291	传真		移动电话	13703516280	电子邮箱	35818239@qq.com
通信地址	山西省太原市杏花岭区山西大学大东关校区					邮政编码	071000
目前主要研究方向	人居环境工程						

联系人简要信息（如无，可不填）

姓名		性别		学历		科室	
办公电话		传真		移动电话		电子邮箱	
通信地址						邮政编码	

申请人（项目负责人）承诺：

以上所填内容（包括各附件材料）均属实，如获批准，我将严格按照提供的方案进行研究，并遵守山西大学医学伦理委员会的相关规定。

申请人（项目负责人）签字：徐清浩　日期：2019.11.5　所在院系名称：土木工程系

山西大学医学伦理委员会审批意见：

同意申报！

主任委员（签章）：董川印　日期：2019.11.25　山西大学医学伦理委员会（盖章）