USING A MULTIMODAL SENSING APPROACH TO CHARACTERIZE HUMAN THERMAL COMFORT LEVEL

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A method to distinguish human level of comfort has been developed by using a thermal camera, physiological sensors, and a surroundings sensor. The method has successfully collected data from hominal facial features, breathing rate, skin temperature, room temperature, blood volume pressure, relative humidity, and air velocity. Participants from all genders and races were involved in two sessions of a human comfort experiment including a psychology survey session. The variables, such as room temperature and clothing are controlled to maintain steady test conditions. The region of interest was determined by body temperature and facial temperature as registered by the thermal imaging camera.

To experience different levels of discomfort, participants were required to perform two different activities. The first session included an activity on the air resistance elliptical and the second session required the subjects to remain steady in front of a fan. The data was subsequently compared on all subjects to determine whether human discomfort and comfort can be predicted by using various approaches. The parameters of discomfort and comfort were simulated to characterize human levels of comfort. According to arrangement of correlation among thermal comfort responses, blood volume pressure, skin temperature, respiration, and skin conduction, we are be able to predict discomfort and comfort affective states.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

About one third of the world's energy consumption is used to provide humans comfort. The ability to provide thermal comfort is one the most important functions of a building. Human level of comfort has been studied for decades. There are many methods to distinguish comfort. Two tests such as the PMV (predicted mean vote) method by Fanger [1, 2] and the psychology test of human behavior [8] may be performed to evaluate human comfort.

When adjusting a thermostat, a person is setting a goal for comfortable air temperature. Optimal thermal comfort requires the heat loss of the hominal (with hominal being equivalent to human) body to be in balance with its heat production. The connection between a person's physical environment and the psychological state can be distinguished by specific levels of thermal comfort and the environment. To improve understanding about thermal comfort, researchers must not project only an ambient temperature, but consider thermal comfort from all specific variables in any such edificial environment such as humidity level, hominal activity, radiant temperature, air velocity, and clothing level (Clo thermal insulation values assigned to individual items of apparel, e.g., "0.09 Clo" for a short-sleeve shirt and "0.35 Clo" a thick sweater, etc.). What can be considered is skin temperature as a part of thermal comfort determination but the most central factor is internal body temperature. It has long been known that the human body stays constant at 37 degree Celsius. It may change by a fraction temporarily as a result of environmental factors and personal factors (sickness, or being within a hot or cold environment whether that be climatically permanent or peregrinatorially weather-temporary). Then the change in a person's internal temperature will affect how that person's brain reflects upon whether or not to dispose heat out from the body through the skin. ASHRAE (American society of heating, refrigerating and air conditioning engineers) has provided thermal comfort equations [2]. Using these equations is also a way of considering human thermal comfort. These equations were derived to predict human thermal comfort on various parameters. PMV has been the main standard test conducted on both a group of persons or on an individual person. The PMV comfort equation provided combinations of the variables which created copious data and more parameters to consider, and with the PMV values established, then it is possible to determine PPD (Predicted Percentage of Dissatisfied) values. In the end, we can observe whether PMV method would be comparable to this multimodal approach.

Since human beings are not alike, it is difficult to specify one particular temperature to satisfy human comfort in any given space. Specified data have been collected to define conditions with a percentage of occupants. Monitoring an optimal human level of comfort is an exhilarating process. In this study, we are not considering human thermal comfort by an ASHRAE equation. These experiments consist of a thermal imaging device, psychology test, and physiology sensors, all of which are introduced to the testing apparatus. The human body is suitable for a non-contact method measurement because of the various heat signature changes occurring in certain regions, particularly, for this study, the facial area. The advantage of a thermal camera is that it is the only one of the quantity of quantitative devices that employs a noncontact method. This means that in non-contact methods [18] participants do not have to know that they are being tested. A thermal camera is not a new technology; there are a lot of fields that utilize thermal cameras including for military and medical purposes [9, 24]. These cameras also have been around to monitor airports or industrial houses to provide security. For the thermal camera, the device can be placed at short-range distances and is fully equipped for these various purposes of medical, security, surveillance, and even other uses. There are, however, some disadvantages of using a thermal camera. For example, a signal that a thermal camera provides is insufficient in forming and is indecisive, owing to hominal movement. Relying on a thermal camera is very tedious work because the person has to remain still with minimal movement. Therefore, the techniques of numerical Fast Fourier transform and computational method [60] have been used in particular different cases.

This thesis work's analyses combine different signals from hominal physiological sensors, thermal camera, and a regular camera. Based on the obtained data, the analyses of breathing rate, blood volume pressure, skin conductance, respiration rate, periorbital region, and of the survey question test are accomplished separately and included in the final evaluation. The results will show, with some uncertainty, whether a person has been experiencing discomfort or comfort.

1.1 Motivation

The difficulty of handling an experiment with participants was to perform a real simulation of comfort analysis without creating any confusion on the signal data. Any tension that would progress, resulting from the nervous situation of being put into preparations (such as being hooked up to electronics) or additional discomfort would create uncertainty of the hominal response. The gadget sensors such as those for respiration rate, skin conductivity, blood volume pressure, and respiration rate are placed in personal contact. This means that the participant has to cooperate with such contact devices. And while collecting data, the process might create uncertainty from researcher error. The short range signature received by the thermal camera, on the other hand, would minimize researcher error of discrepancies and inequalities of the contact apparatus operating unevenly among participants. While participants feel discomfort or comfort at the experiment, the thermal camera would directly confirm the examination without any additional discomfort. The highly sensitive thermal camera comes with different ranges and sensitivities. In this study, the thermal camera is only arranged to detect hominal facial features, such as nasal nostril, periorbital region, and whole facial area.

1.2 Goal and Objective

The objective of this research is to characterize human comfort level to affective states by using a multimodal sensing method. In order to complete this characterization, the following criteria have been analyzed:

- Select participants with all gender, background, and different ages to perform the experiment.
- Record and analyze humidity, room temperature, and outside temperature to determine the conditions that influence human comfort the most.
- Analyze the signal obtained from the skin temperature, respiration, blood volume, and skin conduction (sweat rate) to get a better understanding of human behavior due to comfort levels.
- Extract physiological face features on specific regions of interest where the changes are more responsive.
- Characterize the different results of comfort level analysis from different participants identified from the collected data where occurred the participants' discomfort or comfort levels, symptoms of discomfort levels, and variables of a zero-energy environment.

1.3 Method Limitation

Each person who arrives to the lab is different from one another as regards physiology, genetics, diet, exercise habits, occupational physical-mental stresses, and even did this person just eat?, just wake up?, and so on. To characterize comfort, the research had limitations on moving toward precision. The research might acquire more subjects and parameters to analyze. This study is limited to having to use the physiological sensors which were not the internal body temperature sensors. Such internal instruments are very useful devices for determining the hominal core temperature level. All sensors used in this study were external. The analysis of thermal camera is also limited to hominal facial features instead of the entire skin of the whole body. The participants' conditions such as medical issues, physical condition, or how much activity each individual did before the experiment was not collected. Finally, blood samples might need to be obtained to illustrate more detailed information on human comfort level.

1.4 Literature Review

The literature on this topic highlights several evaluations. From the facial aspect, we can extract time versus temperature. And then, the environment provides parameters with relative humidity, room temperature, heat radiation, and conduction as well as convection. Thermal breathing rate and temperature variations are characterized as a non-contact measurement technique. Non-contact measurement methods have several advantages and limitations, compared to conventional methods (contact). However, there is an increase of research and popularity to extract human signatures and to analyze human behavior.

A number of studies suggested that there is a correlation between mammals' body temperatures and their affective states. In this paper, [17] described that human affective and deception can be detected by using thermal imaging. Another independent research was conducted by monitoring a rat's stress level while in terrified circumstances.

Human comfort level is associated with an emotional state and level of body temperature as well as blood volume pressure. The change in the volume of blood flow under the surface of the facial skin or bodily skin was a result of thermo-muscular activity. Vaso-dilation and vaso-constriction are enforced to maintain a constant 37 ℃ internal temperature. Vaso-dilation occurs when the internal temperature is above 37℃, and blood vessel's diameter enlarges due to heavy blood flow throughout the body. In this condition, sweat is released by sweat glands to cool down the process. Then the heat vaporized into the environment. On the other hand, when the blood vessel decreases in diameter, vaso-constriction, and the blood created friction to absorb more heat. This condition usually happens in below 37℃ body temperature (cold weather or environment).

1.4.1 Thermal Imaging

Thermal imaging reveals to us the thermal graph on the object without visible illumination. Thermography has a long history when it comes to industrial and medical applications. The modern thermal imaging camera is similar to a camcorder and it has been downsized to fit into all applicable industries. The application has become popular for research and security purposes, in addition to, previously, what was just medical purposes. The advantage of a thermal camera is to observe changes in the body such as breathing rate and average skin temperature. Thermal imaging technology can be applied without any uneasiness of physical contact. This means, humans can do their usual activities without being aware of any distractions or constrictions. The disadvantage of a thermal camera is that the boundaries of the parameter are unlimited; there might be unwanted heat signatures that interfere with the thermal camera, in the distance.

1.4.2 Thermal Imaging Theory

There are three ways to transfer thermal energy from one object to another: conduction, convection, and radiation [7, 18, 19]. Conduction is defined as the direct thermal energy transferred between two objects. In a molecular view, molecules transfer heat to the adjacent molecule heating up the adjacent area of the solid. On the other hand, convection can refer to transfer of heat with any medium fluid movement (liquid or gas). Finally, radiation is the most powerful way to transfer thermal energy. Radiation is the forming of waves or rays and it can be transferred through a vacuum and can move with the speed of light. Heat, light, and sound are examples of radiation. A thermal camera uses infrared radiation to measure the temperatures of the object/subject.

1.4.2 Infrared Radiation

Infrared radiation is not visible with the human eye because it occurs beyond visible light. Infrared has frequencies between visible light and radio waves. The infrared radiation band is generally between 0.78 and 1000 μm (microns).The energy transmitted to an object can be immersed, reflected, and re-emitted. This occurrence is called emissivity of an object. Infrared radiation (IR) shows the temperature of the objects because IR uses the emissivity of the material. Every object emits energy from its surface to the surroundings in form of electromagnetic waves. When those waves collide with another object, this second object absorbs the energy and converts it into heat. A hot body is an object that emits more energy than it absorbs. A cold body is defined as an object that absorbs more energy than it emits [10].

1.4.4 Fast Fourier Transport.

Using FFT, the data analysis can be more effective toward producing a cleaner signal than the raw signal FFT is a very useful mathematical technique for transforming the function of time to the function of frequency. They also called time domain or frequency of domain. The result data sometime acquire milliseconds time scale to reveal. This method is developed by Cooley and Tukey [3].

1.4.5 Survey Subject Test

Thermal comfort is difficult to determine, due to a range of environmental and personal factors. Those limitations must be considered when deciding what will make people feel comfortable. In many extensive studies, thermal comfort and sensation have been expressed with direct question and answer. An effective way to predict thermal comfort is to survey the participant. Over the years, more research has been dedicated by predicting thermal comfort. Thermal comfort is also defined as human expression. Human satisfaction with the place is specified by sensations where thermal comfort gets described by feeling “comfortable” or “uncomfortable.” Thermal sensation and comfort are not the same. However, they are influenced by one and another. Meanwhile, thermal sensation is defined as human feelings that are primarily related to thermal balance of his/her body. This sensation can be expressed by “hot,” “warm,” or “cold.” Most of the work in this area has been addressed to analyze the discomfort and comfort associated with participants’ sensations in a steady state.

1.4.6 Hominal Body Analysis

A human body has an internal temperature of a constant 37 degree Celsius. This internal temperature can be kept constant only if there is a balance between the heat which a human produces and heat lost to the environment. The heat balance is controlled by the hypothalamus. The hypothalamus is a part of the brain that receives information of the body condition from the receptors. In a cold environment, the nerve impulses from the cold receptors decrease the blood flow and thus heat flows to the skin. To maintain 37 degree Celsius at vital parts (internal body), ideally the blood flow is reduced at hand and foot regions where the cold sensation will be first experienced by a person. In a cold environment, the heat lost into the environment is greater than the heat produced; therefore, the core temperature will decrease frequently.

In a hot or warm environment, the body temperature of skin is elevated by the high blood flow. The blood stream increases due to Vaso-dilation (opening more blood vessels). Therefore, heat exchanges between the core body and skin surface are usually small. During the muscle work, the body temperature will increase to advanced levels, depending on the amount of work. If the humidity and ambient temperature are increased, then the heat would also build up against the body core temperature. According to our experience, discomfort affective is a spontaneous reaction. Meanwhile, an optimal comfort affective is difficult to persuade due to more factors or parameters to effort, to put effort into.

1.4.7 Skin Conduction

In order to measure how much sweat a person produces, skin conduction quantity was acquired from a finger where the physiology sensor was positioned. Skin conduction was often collected in number of electrons. Skin conductivity was considered significant to characterize human comfort level. A higher skin conductivity quantity means there was more sweat present on the skin. We observed that skin temperature declined when sweat production ascended, or vice versa. Although sweat production depends on the rise of internal temperature, skin surface temperature can be correlated with the sweat due to the vaporization process. Whenever sweat rate rises the skin will be cooled by the increase of sweat evaporation.

1.4.8 Hominal Skin

Since the hominal body mostly consists of water, a body absorbs heat robustly. Heat flows from high to low temperature levels. The flow of energy to and from the skin determines our sense of hot and cold. Skin consists of multiple ectodermic layers such as muscle, fat, internal organs, and bones. Because it acts as boundary to the environment, skin protects body from the loss of excessive water. The skin also insulates internal organs from disease and it also functions as a temperature regulator. When a person is experiencing hot or cold, a skin has been generally used to transport or absorb heat. Skin is also there to prevent crucial nutrition loss from the body to the surroundings.

1.4.9 Hominal Adaptation

It is believed that people can acclimatize themselves depending on the environment and outdoor climate. Humans and many other mammals have unusually efficient internal temperature regulating systems that automatically maintain stable core body temperatures in cold winters and warm summers. In addition, people have developed cultural patterns and traditions that help them adjust to extremes of temperature conditions. The clothing alteration has been a significant factor in how humans react to hot and cold environments.

1.4.10 Conduction and Convection

Heat flows from internal body to the skin surface and eventually to the environment, by conduction. Skin is a vital role to determine a thermal property. According to Cohen's paper, thermal conductivity of the skin is dependent on water content and temperature which means the less mass in the body the easier the system can discard the heat. Cohen also mentions that beef of muscle would conduct more heat than would fat.

The best way to describe convection on a body is to view convection from a transport of energy approach. The body interacts with surrounding matter. For instance, when there is a change in the temperature outside, the skin surface absorbs heat. The convection is highly dependent on mean heat radiant which comes from material or object transfer by fluid median to a body.

1.4.11 Discomfort vs. Comfort

When hominal body heat is not in balance, ideally the person would feel uncomfortable or experience discomfort. Usually, after a load of activity, a body would heat up. When the blood is pumped by the heart, it is transported to the veins, arteries, and vessels. The incoming blood generates a heat transfer from the inner surface of the veins to the outer surfaces and then skin surface. The change of temperature on the internal body would cause a person to feel discomfort emotionally, or psychologically. The hypothalamus in the brain of a person that sends its signal to alert human motivation to make a few body adjustments to level one’s self with the environment (e.g., putting a jacket on, adjusting air conditioner, etc.)When small areas of stimulation and a small temperature change are used, cold or warm receptors maybe excited without conscious sensations. The strong signals are only detected when a certain number of impulses per unit of time reach the central nervous system [34].

1.4.12 Air Movement

A vaporization process on skin depends on airspeed factor. When the humidity is high, the vaporization process may not occur rapidly due to a pressure dependent factor. Under the ASHRAE standard handbook of application, the required airspeed for light activity is approximately more than 0.8 m/s (without air movement discomfort may occur). The more air velocity flows, the more surface conductance is overcome (Figure 1.1.). When the amount of exposed skin increases, the effectiveness of air speed may decrease due to simple vaporization process.

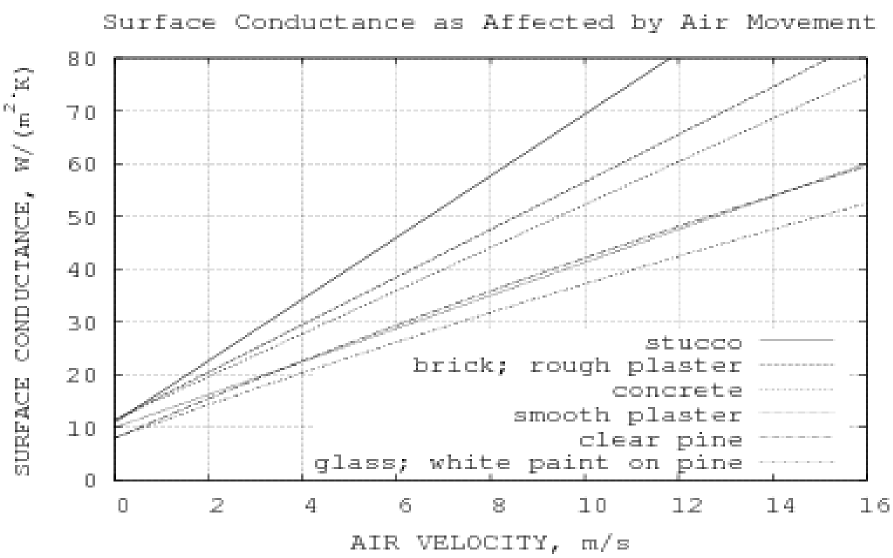

Figure1.1: ASHRAE air velocity vs. Surface conductance.

CHAPTER 2

DISCOMFORT AND COMFORT STATE PREDICTION

2.1 Method Used and Experimental Setup

The experiment was performed fall 2013 at the Zero Energy Building, University of North Texas, Denton, Texas. The participants, software, and system description are described below.

Figure 2.1: Zero Energy building (front)

Figure 2.2: Zero Energy building (above)

2.1.1 Participants

Initially twenty-four participants from all backgrounds including males and females have participated in the experiment program. Out of twenty-four participants, sixteen participants had suitable data analysis. All participants lived in the North Texas region and agreed to contribute to this study. Each participant spent between 45 to 50 minutes to complete the human comfort activity and two sessions of experiments. In order to control the experiment variables in the human comfort level study, the amount of clothing that a participant could wear while under the experiment was limited to not more than 0.8 Clo which is equivalent to light clothing consisting of, say, of an outfit of a short-sleeve shirt, any type of long pants, underwear, socks, and shoes.

2.1.2 Hardware and Software

2.1.2.1 Software

All activities are performed inside Zero Energy Building's living room. Thermal Images were collected using Thermal Flir research Pro 2.10 software (Figure 2.3) and Flir tool Software (Figure 2.4).For a few variables in Zero energy building, HOBO Sensors are deployed in the room. Using Hoboware software, the data successfully recorded each experiment session.

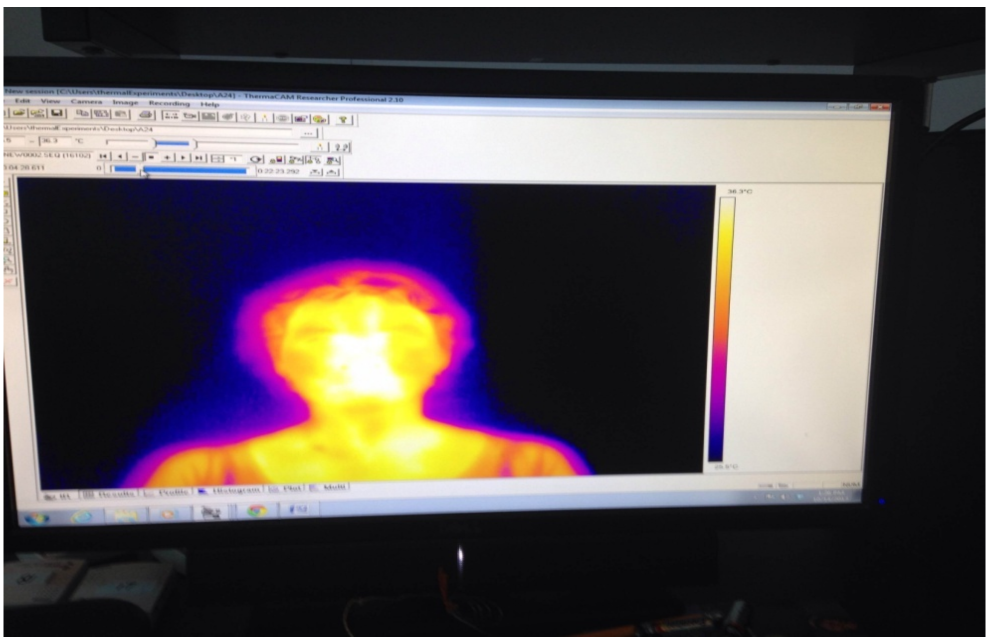

Figure2.3: Therma Cam Researcher Pro 2.10

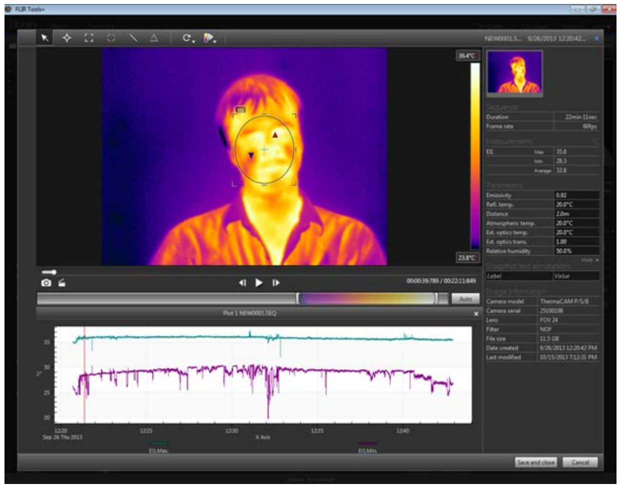

Figure 2.4: Flir Tool software

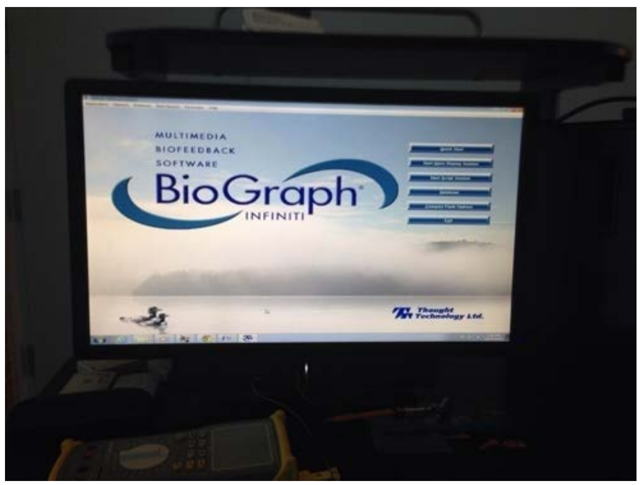

Figure 2.5: Biograph Infiniti software

Meanwhile, physiology sensors were recorded by Bioinfinity software (Figure 2.5). All four types of sensors, blood volume pressure (BVP), skin conduction (SC), skin temperature (ST), and respiration rate (R), were incorporated in one control box.

2.1.2.2 Hardware

The participants reactions were recorded by a thermal camera, four physiology sensors (respiration, blood volume sensor, skin conduction, temperature), and a webcam. A Flir thermal camera thermo vision A40 (high resolution infrared imaging, real time color video output, plug and play network configuration) with 60 frames per second of (320 by 240)resolution is established at the short range distance. To record environment data parameters, HOBO sensors (relative humidity, illumination, ambient temperature), and air velocity meter were used as well as zero energy lab ambient and outside temperature sensors. Wall surface temperature was recorded by using a super multimeter.

2.1.3 Description of System Setup

The experiment is designed to detect changes in physiological signals from participants by inducing thermal comfort/discomfort conditions through low-to-medium-level physical activity. Our side goal is to detect a range of temperature body, heart rate pulse, and respiration changes in participants, which are associated with the comfort/discomfort conditions. The experiment consists of a thirty minutes session during which participants' physiological, verbal, and non-verbal responses were recorded using the following devices:

a) Thermal camera
b) Web camera
c) Wearable physiological sensors, including: volume pulse, skin conductance, temperature, and respiration sensors
d) HOBO sensors

The experiment took place in the Zero Energy building living room area at University of North Texas Discovery Park.

2.1.4 Physiology Sensors

The system included four different sensors connected through a sensor box encoder from Thought Technology LTD.

Figure 2.6: Physiology sensors control box

In Figure 2.6, all sensors are inter-connected to one control box. A control box sends a signal to a nearby computer. The Multimedia Biofeedback signature on Biograph Infinity software was used to receive all the signals provided by the physiology sensors.

Figure 2.7: Skin Conductance (SC sensor)

Figure 2.8: Blood Volume Pulse (BVP sensor)

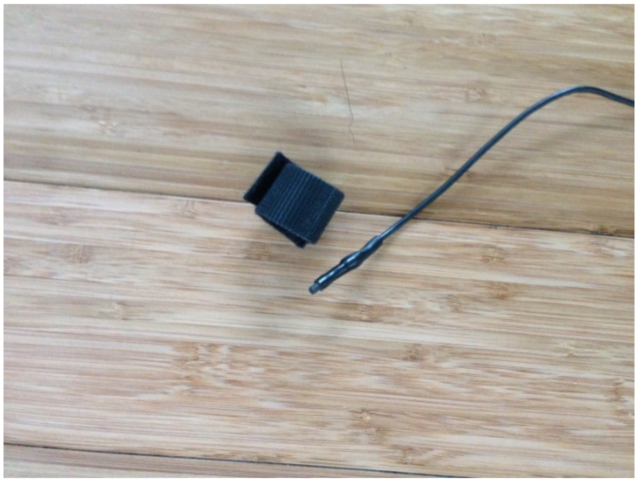

Figure 2.9:Skin Temperature (ST sensor)

Figure 2.10: Abdominal Respiration (AR sensor)

Figures 2.7 to 2.10 are the physiological sensors used to measures each participant's response to discomfort and comfort affective. These sensors were always placed on non-dominant participant hands.

2.1.5 Thermal Camera

Figure 2.11: Thermal camera device

A thermal camera is used to detect sensible heat. It is a small and reliable infrared camera to be used in networked multi camera house installations. The set parameters of the thermal camera are described in the following:

Emissivity	0.92
Reflective Temp.	20.0 C
Distance	2 m
Atmospheric Temp.	20
Ext. Temperature.	20
Ext. Transition	1
Relative Humidity	50%

Table 2.1: Parameter of thermal camera

Camera Model	Thermacam P/S/B
Camera Serial No.	25100298
Lens	FOV 24
Filter	NOF
Frame Rate	60 fps
Company	Flir System
Series	Thermovision A40

Table 2.2: Thermal camera information

2.1.6 HOBO and Various Sensors

HOBO sensors (Figure 2.12) were positioned in various areas of Zero Energy lab living room, in order to record relative humidity, lightning illuminate, and ambient temperature..

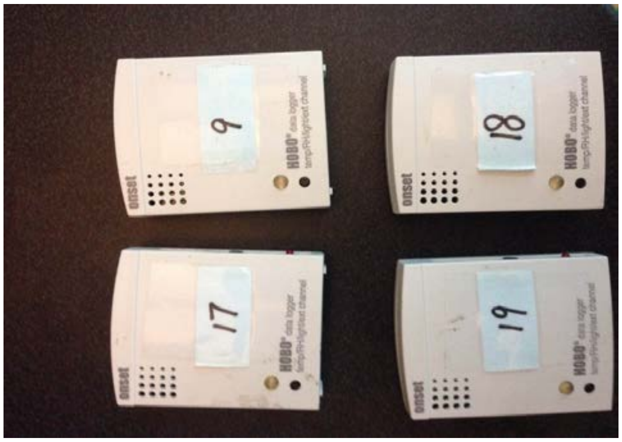

Figure 2.12: HOBO sensors

Newport True RMS super meter is a thermocouple device to measure room temperature and wall temperature at instance time. This multimeter (Figure 2.13) has a lot of options including omega scope laser emitted for distance analysis.

Figure 2.13: Super Meter Newport.

Figure 2.14: Omega HHF air speed meter

In order to measure air flow speed at instance time, Omega HHF1000 series is positioned in this study. Omega HHF measures air speed in Celsius, Fahrenheit, or Kelvin. To assure the accuracy of air speed device, the calibration was performed and also the probe wind meter was placed on one specific place (close to facial area) by participant's chair.

2.2 Experiment Setup

2.2.1 Surveys

In this experiment, we provided subjects with a few psychology questions. The participants experienced real time survey questions. The inquire time has been recorded on each question presented at the session or level activity. The subject reported their thermal sensation, discomfort, and whether or not the environment was thermally acceptable while the temperature rose or fell.. For example, while participants waited for a 10-minute break to acclimate their body to the Zero Energy building environment, a first set of survey questions was presented to them. Because of the clothing level significantly influencing human comfort, on the survey, participants also had to describe the clothing level they were wearing. The survey scale and sensation are described below (2.3.2).

2.2.2 Thermal scale and Thermal sensation

To observe human level of comfort further, in this study thermal scales and sensation should be taken as correlation to thermal camera data and physiology sensors. The data obtained from survey question regarded thermal scales and sensation. Thermal scales were (+3) hot, (+2) warm, (+1) slightly warm, (0) neutral, (-1) slightly cool, (-2) cool, and (-3) cold. In this following scale, sensation surveys are also present including “very comfortable", "comfortable", "slightly comfortable", "neutral", "slightly uncomfortable", "uncomfortable", and "very uncomfortable." The participants’ responses might have had a few different scales of variations due to experiences and emotional dissimilarities in our experiment condition.

2.2.3 Clothing

According to ASHRAE handbook [4], clothing can be predicted by operative correlation with humidity ratio and dew point temperature. The clothing variable was limited to $\pm$0.57 Clo;this permitted the subjects to apparel themselves during testing by selecting/donning an ensemble of garments that could allowably include either one t-shirt or short sleeve shirt; shoes; socks; and khaki pants, trousers pants, jeans, or long pants.

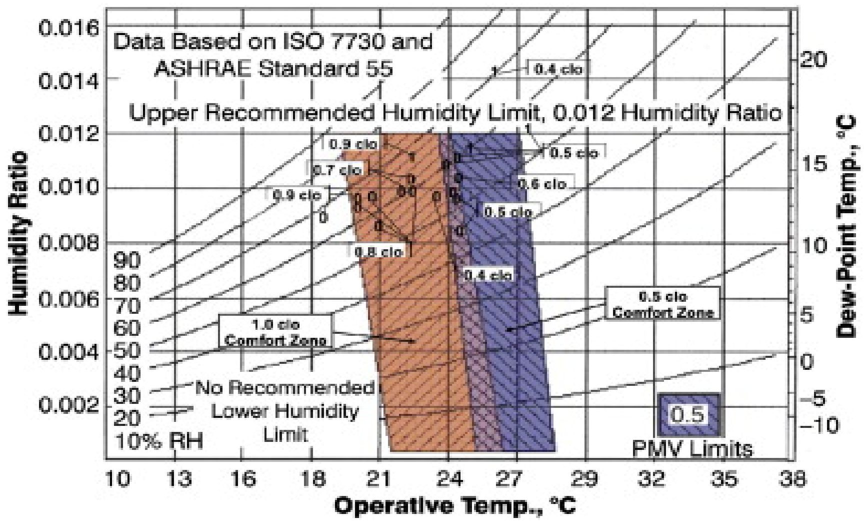

Figure 2.15: Clothing graph. Source: ASHRAE 55 [1, 2, 4]

2.3 First Stage of Experiment.

2.3.1 Acclimation

In order to regulate the participants' condition and their body adaptation, participants were asked to repose for 10 minutes in Zero Energy building. To control the atmosphere and temperature in zero energy building, the air conditioner was turned on according to default automatic sensor, and ambient temperature was recorded.

Figure 2.16: Experiment room and setup

2.3.2 Exercise Activity

The objective of the exercise activity was to simulate the increasing amount of heat and temperature of the body. This activity was performed to obtain a better understanding of hominal impression in thermal comfort level. Subjects were asked to perform a 10 minutes workout on the air resistance elliptical machine inside the Zero Energy building. A metronome was provided to harmonize all participants' exercise techniques. Although, the exercise is difficult to evaluate due to anyone's individual background and intensity of performance level, an approximately 2.8 Met rate was performed during exercising. This data was obtained according to ASHRAE metabolic rate table on the handbook application. The inside and outside temperatures were recorded by using temperature sensors at Zero Energy building during the process.

Figure 2.17: Air resistance elliptical

Figure 2.18: Test subject

2.3.3 Recording and Surveys Question

After the 10 minutes workout activity, subjects were asked to sit on a fixed comfortable chair facing the camera apparatus. The subjects were connected to 4 different sensory systems. These included respiration, blood volume pressure, skin conductance, and temperature. The participants were recorded by using audio and video motion and a thermal camera. Then the participant was asked to avoid any sudden or excessive movement to prevent error data because of the sensitive motion of the camera apparatus. Then a computer was used to control and record signals (audio and video). In this 10 minutes period of recording, the participants were asked to answer specific survey questions. These survey questions were given continually during the beginning, middle, and end of the recording sessions.

Figure 2.19: Subject's view from the test chair

Figure 2.20: Test chair with wind velocity meter

2.4 Second Stage of Experiments

A participant's condition adapted (relaxed back to normal temperature) to the surroundings of the Zero Energy Building environment after the first stage of the 10-minutes recording session. The next stage was commenced under the wind blower (fan) to create air movement. In order to perform a different level of discomfort, the participant's body was directly exposed to the wind of 0.5m/s to 3m/s range. The participant was then recorded once more with sensors (Respiration, Blood volume pressure, skin conductance, and Temperature). The thermal camera and video imaging were also put in place to record the reaction. A computer on the second stage of the experiment was used to accommodate the result and signals data. A set of questions was also answered by the participant in the beginning of the recording, as well as in the middle and end of the session.

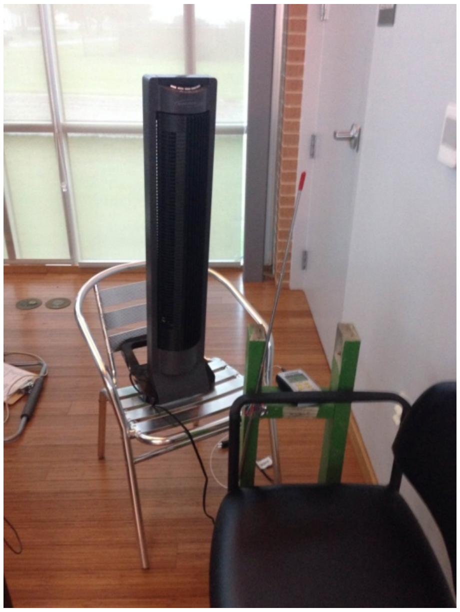

Figure 2.21: Fan for second stage

Other than workout activity, air movement provided by a fan was set according to ASHRAE standard 55. Air speed velocity level between 3 m/s to 0.8 m/s was performed during the second stage of experiment. On this order, a distance of the fan was changed from 1 to 8 feet without an adjustment to speed (mode) of a fan.

2.5 Data Collection Detail

2.5.1 Surveys Question

Out of 24 participants, 18 people were successfully included in the data. According to the data, the result of the exercise activity was either hot or warm sensation. There are three set sofa main surveys (for thermal sensation and thermal comfort levels) in the experiment; a set of questions presented on the first stage after the workout activity; second, scale questions presented again 10 minutes after the data collection of stage 1 test; and finally, the third questions, a survey, was performed while the fan was on and aimed to the test subject. In further analysis, while the fan distance is calibrated and shifted around by the researcher, an additional two questions were presented to analyze a better understanding within comfort level investigation. The three sets of main questions were performed significantly in dissimilar times (Table 2.3).

Question survey scale sensation	Time Presented
Thermal Survey 1	10 minutes after work out activity
Thermal Survey 2	The first 10 minutes after stage one data collection
Thermal Survey 3	5 minutes after second stage data collection

Table 2.3: Survey timeline

Sensation scale	Description
3	Hot
2	Warm
1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Table 2.4: Scale from 3 to -3 on sensation survey

Along with thermal sensation affective, we also recorded several of thermal comfort survey, “very comfortable (3) to very uncomfortable (-3)”, at the similar time as thermal sensation has been presented (Table 2.4).In addition, the result includes one more question, in Stage 2with a fan on. From the analysis we have a graph (Fig. 2.23) relationship.

Thermal comfort scales are described below (Table 2.5):

Sensation scale	Description
3	Very Comfortable
2	Comfortable
1	Slightly Comfortable
0	Neutral
-1	Slightly Uncomfortable
-2	Uncomfortable
-3	Very Uncomfortable

Table 2.5: Thermal comfort scale

For figure 2.22, the result associated with the human sensation scale graph is attached a result associated among the human sensation scale and subject's reaction.

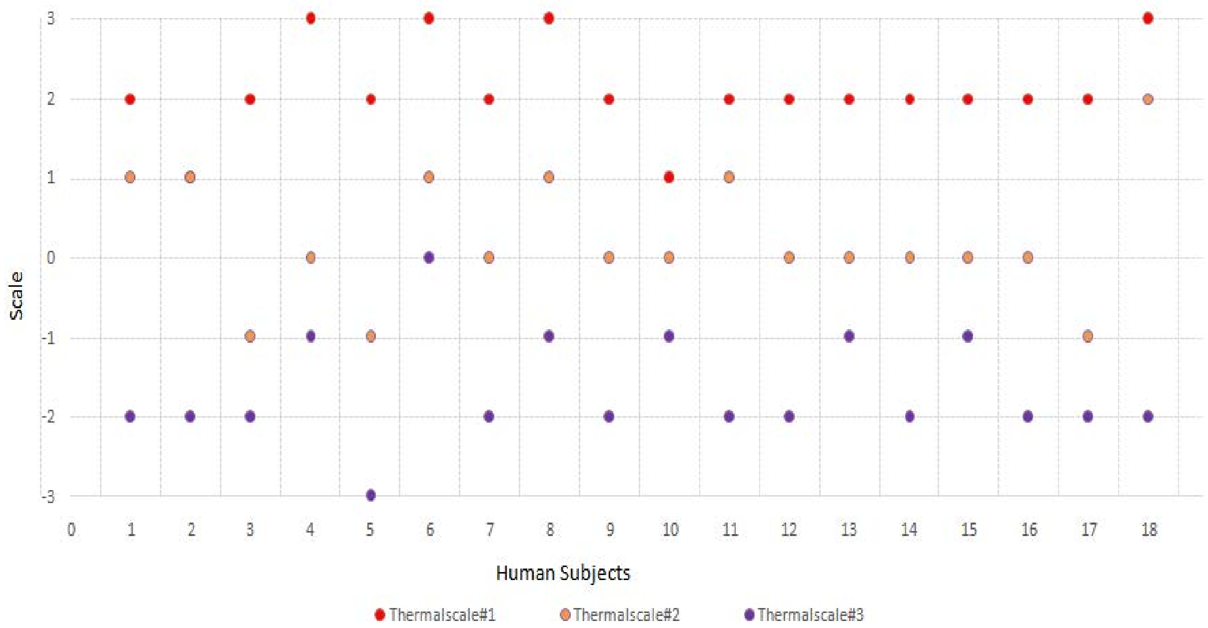

Figure 2.22: Thermal Sensation from 18 human subjects.

Four person answer +3 (hot) and one person show -3 (cold). These are the maximum and the minimum of the scale sensation data test result (Figure 2.22). Our sensation analysis are based from PMV method scale from ASHRAE handbook scale.

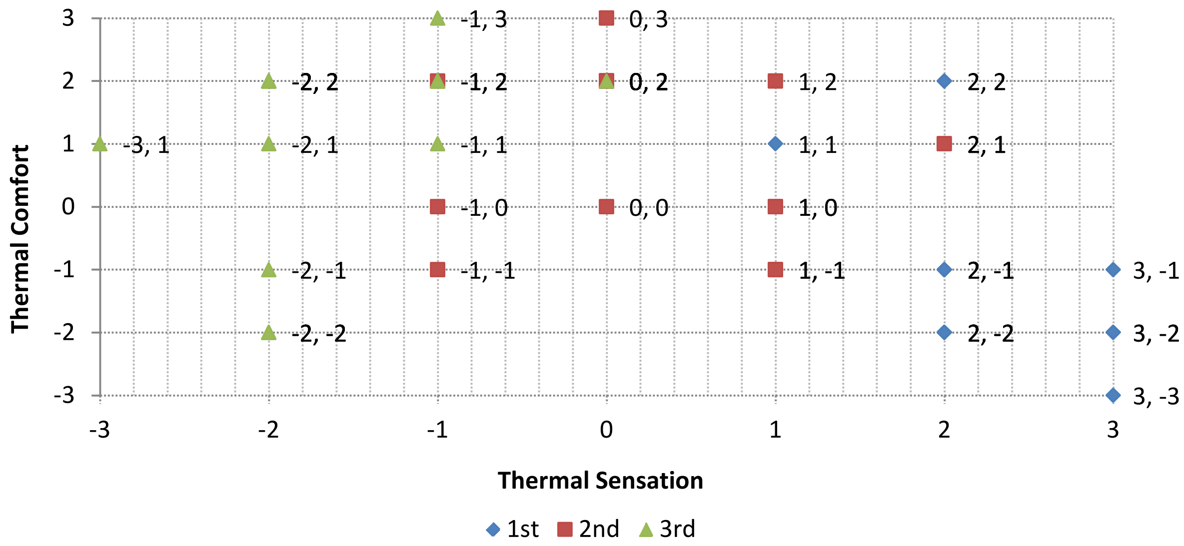

Figure 2.23: Thermal sensation vs. thermal Comfort

2.5.2 Body Mass

In order to confirm the human analysis explicitly, height and weight of the participants were recorded to obtain body mass. The body mass is incorporated in the following levels (Table 2.6): underweight, normal, overweight, and obese.

Underweight (U)	Normal(N)	Overweight(O)	Obese(Ob)
<18.5	18.5-24.9	25-29.9	30 or greater

Table 2.6: Body mass range

The body mass analysis was calculated by using Excel software. The height and weight information are recorded in feet, inches, and pounds. Then the results are converted into metric system. The formula is provided in equation (1):

$$\frac{M}{H^2} = \text{BMI} \qquad (1)$$

The mass (M) is recorded in kilograms (kg) and height (H) is described by meters (m), and then Table 2.7 was achieved:

Subject	BMI	Desc.
a6	29.531	O
a7	22.455	N
a9	25.822	O
a10	25.893	N
a11	25.100	O
a12	24.002	N
a13	26.001	N
a14	24.271	N
a15	22.460	N
a16	22.953	N
a17	19.786	N
a18	20.450	N
a19	26.211	O
a20	38.645	Ob
a21	24.403	N
a22	20.670	N
a23	30.412	Ob
a24	21.258	N

Table 2.7: Record of body mass

Most of the participants (male and female) are in normal body mass description (Table 2.7). The data obtained by requesting their height and body were included on the survey.

2.5.3 Thermal Mapping and Recordings

Using the temperature on the facial region, average temperature, overall maximum frame temperature, and overall minimum frame temperature were calculated. The data expanded which enabled the viewing of additional terms of calculation including specific areas of facial (frame per seconds), standard deviation, temperature differences in each frame, and finally, whole entire frame from the top of the head to below shoulder as an input (Figure 2.24 and 2.25). These figures are raw examples of the timeline at Stage 1of our experiment presented on the Thermal cam Researcher Pro 2.10 (10 minutes timeline).

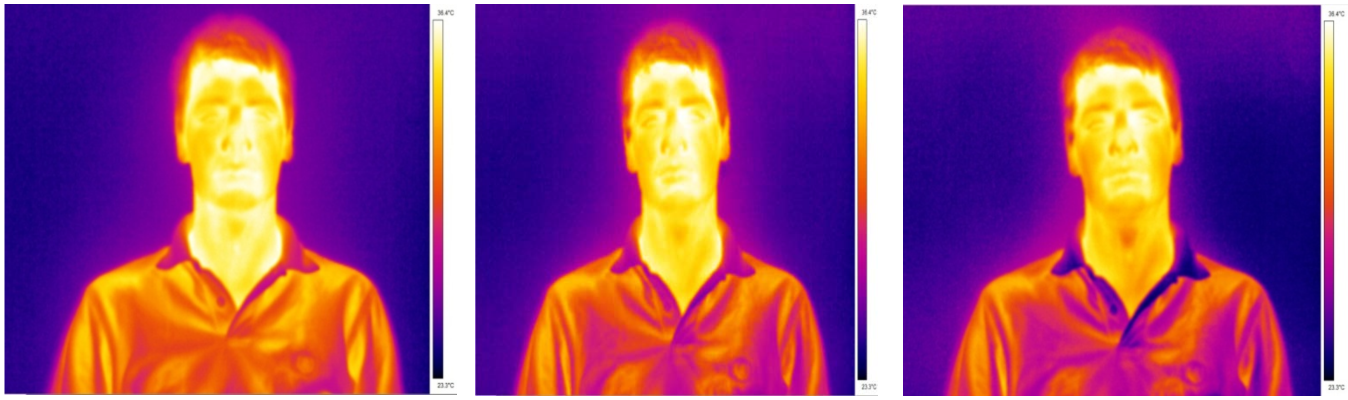

Figure 2.24: Male participant

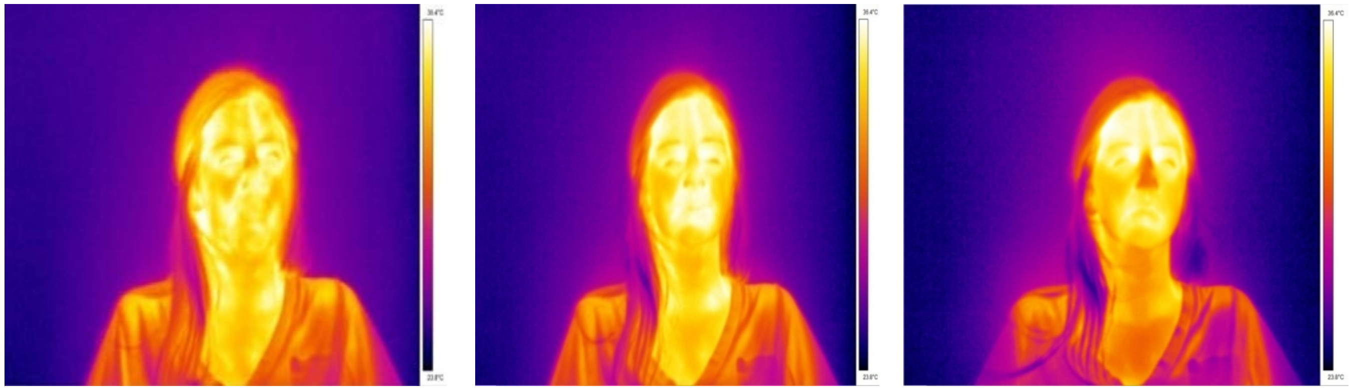

Figure 2.25: Female participant

The points of interest on this mapping region are nasal nostril (nose) area, face region, and periorbital region. Nostril is a significant area to compute breathing rate analysis. The thermal camera recognized the warm temperature in the breathing system which experiences significant temperature differences. Periorbital region is taken as an essential area. The periorbital featured a higher thermal signature than did the face region. It is located between our optical area beside the nose region (Figure 2.26) which is responsible for elevated temperature with respect to the facial area.

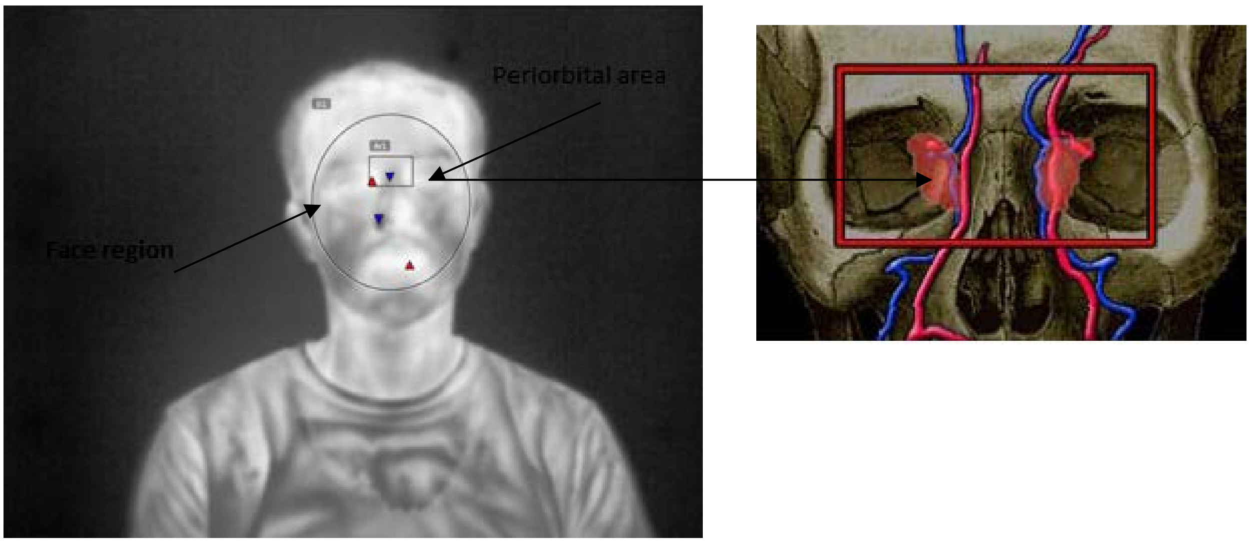

Figure 2.26: Face and periorbital region of interest.

2.5.4 Breathing Rate

There are several techniques to consider in breathing rate analysis. In previous research [17], a FFT (fast fourier transform) was performed to obtain a clearer analysis. The region of interest is under the nasal nostril by the nose (Figure 2.27). Because the exhaled air contains CO2, that means exhalations are warmer than inhalations. Breathing rate illustrates participants under stress or physical activity. Average breathing rate are ranged from 12-20 breaths/min at rest and 30-40 breaths/min after physical activity in a healthy individual's condition [9, 45, 30].

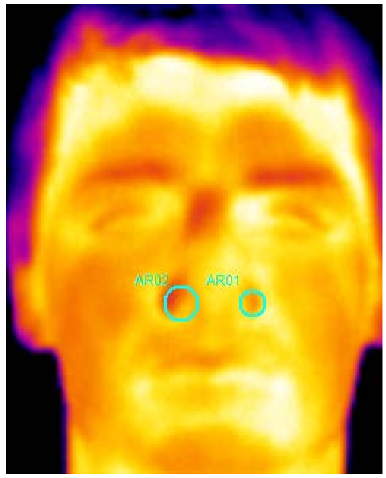

Figure 2.27: Nasal nostril Area

2.5.5 Environmental Data

According to HOBO sensors, the average of the ambient temperatures on each experiment day was 74.6 Fahrenheit or 23.7℃. These statistics were used to compare the discomfort and comfort affection. On the different day and time, the humidity at the Zero Energy lab ranged from 60 to 70%. There were no indications of extreme humidity or ambient temperature on the experiment days.

2.5.6 Physiological Sensors

Data were exported into text file with more than hundred thousand data for each participant. Then the data were converted to different save files of Excel to prevent the software from crashing. The time of correlation was measured in minutes, not seconds, because seconds were mostly redundant for the availability of equipment.

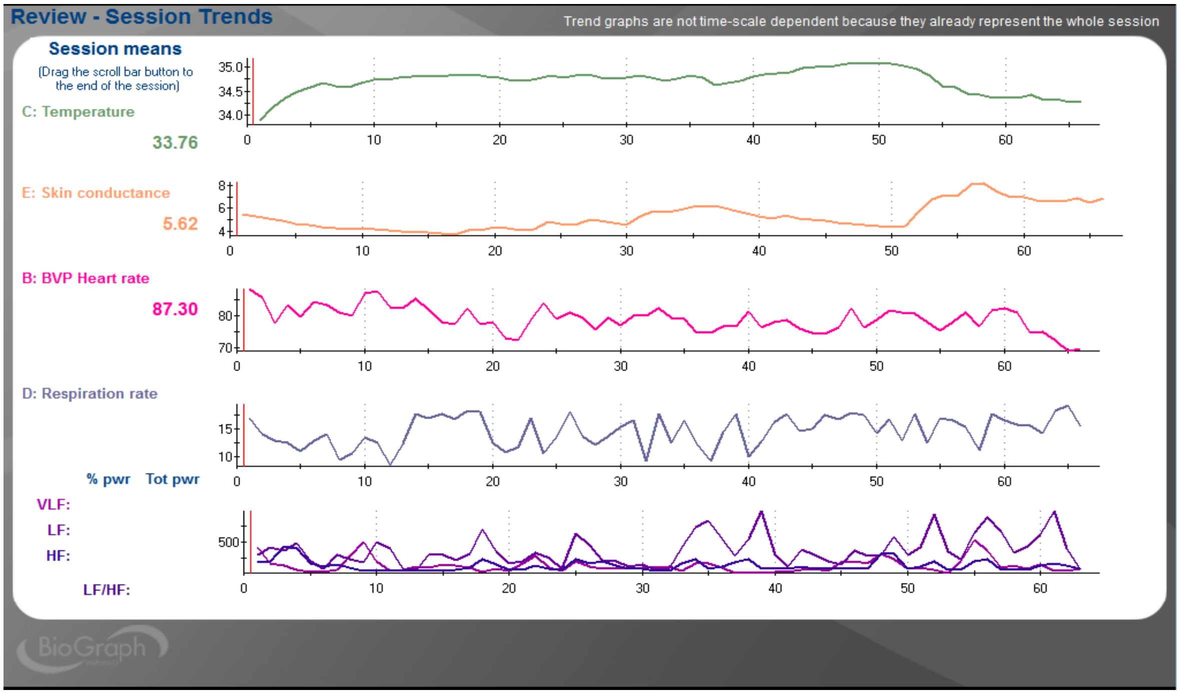

Figure2.28: Overall data signal from Biograph

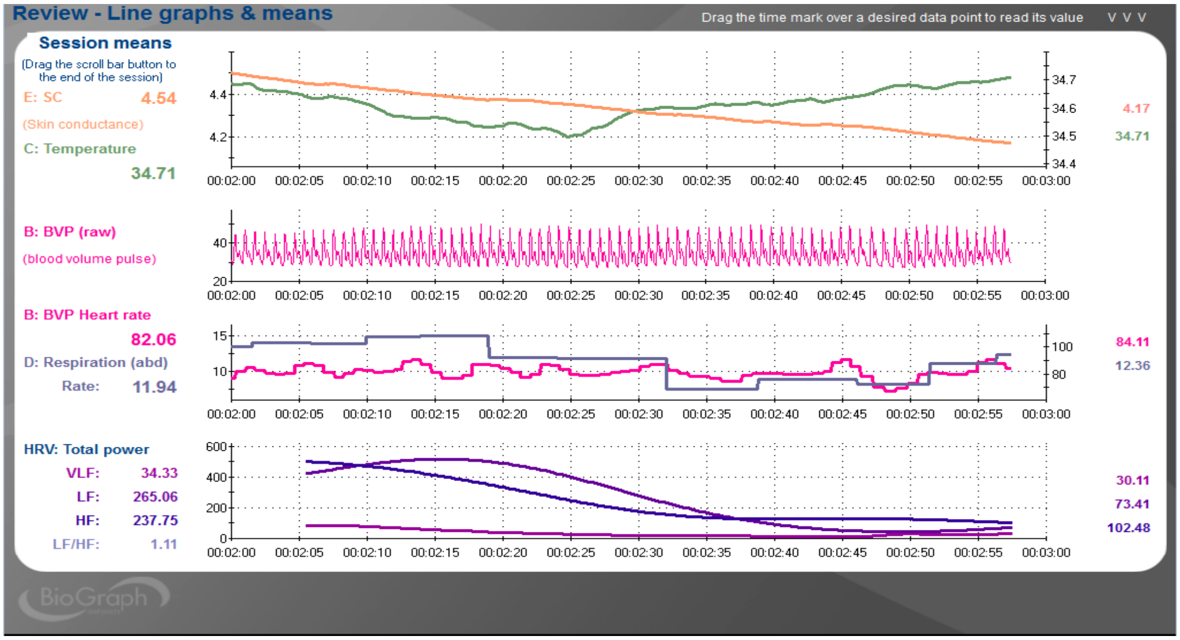

Figure2.29: Live data signal from physiology sensors

The correlation between skin conduction and skin surface temperature had been computed into two tables. The data were obtained from first stage session of the experiment, then the results were calculated by using Excel. Seven subjects have positive correlation and nine subjects have negative correlation. The averages of both correlations are 0.589 and -0.636.

No.	Subject	Co. coef
1	a10	0.613035
2	a12	0.059985
3	a14	0.526419
4	a19	0.538995
5	a20	0.932819
6	a21	0.563882
7	a22	0.891012
	average	0.589449

Table2.8: Positive correlation

No.	Subject	Co.coef
1	a9	-0.84117
2	a11	-0.79143
3	a13	-0.87566
4	a15	-0.37284
5	a16	-0.86298
6	a17	-0.63224
7	a18	-0.42645
8	a23	-0.95428
9	a24	-0.03601
	average	-0.64367

Table 2.9: Negative correlation

Negative correlation means, as the skin conduction increases, the skin temperature decreases or vice versa. Meanwhile, positive correlation means the skin conduction increases, then the skin temperature also increases, or vice versa. The negative correlation certainly has stronger relationship compared to positive correlation.

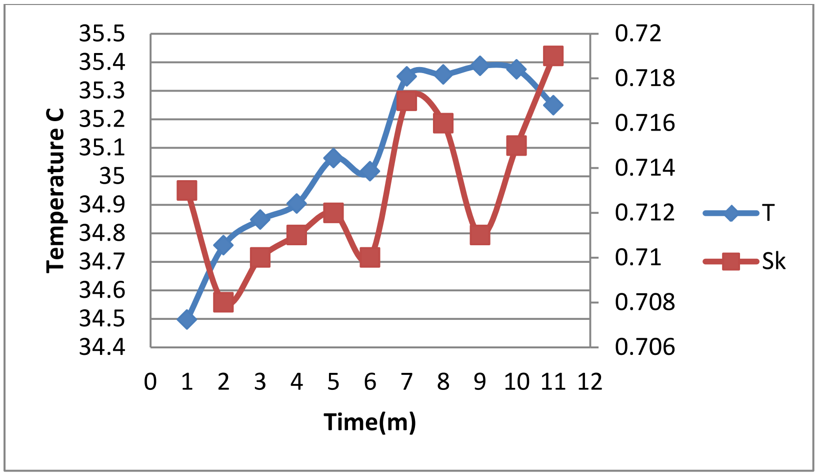

Figure 2.30: Underweight or normal body mass has random signal skin conduction

The less body mass, the more efficient a person in cooling their body. The sweat rate generally occurs spontaneously as body temperature increases. The sweat rate also appears to be plentiful due to the applied customization of the research condition.

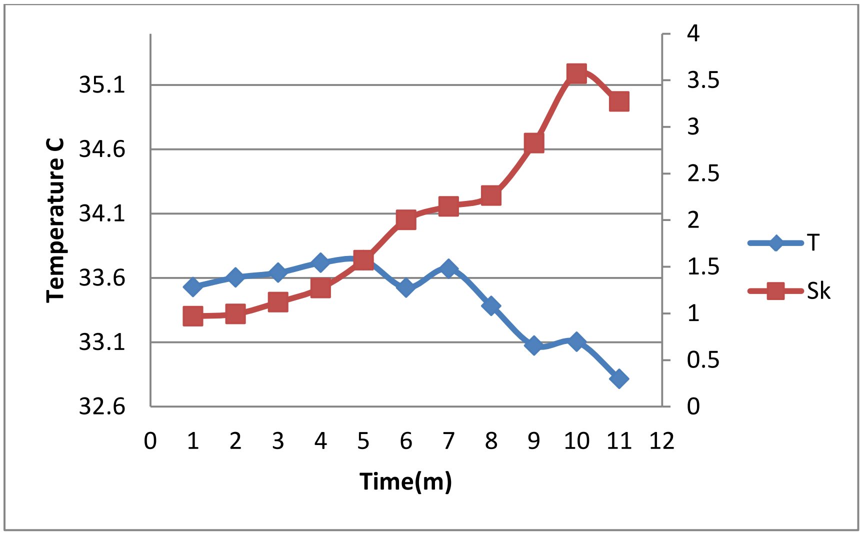

Figure 2.31: Overweight or obese body mass display a relative increase in skin conduction

Meanwhile, more body mass in the cooling period (Figure 2.31) specifies that sweat rate gradually increases relative to skin temperature. This indicates that the more body mass, the more the work for the cooling process, due to greater mass needing to be cooled down.

CHAPTER 3

PROCESSING AND ANALYSIS

3.1 Data Processing and Analysis

The hominal heat features appeared ubiquitously for any possible different outcome. A summary of clean data signal would be the first approach to determine aspects of comfort. To overcome a challenge on the complexity of the data, each participant's signal is set into a group plan simultaneously. The boundary has been selected and uniform analysis has been performed. The objective is to combine both each variable from the data as well as the correlation output.

3.2 Thermal Features

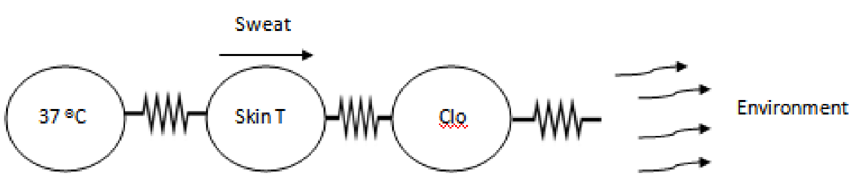

Figure 3.1: Thermal conduction diagram

The human body produces heat energy from core (internal) temperature. The normal body temperature usually is approximately at 37 degree Celsius. When the core temperature increases then the body would propel some of the heat to the environment. Conduction occurrence in boundary condition is described by a system in figure 3.1. Heat is conducted through skin membranes and then clothing garments and eventually transferred to the environment through vaporization process. Body mass results compared with the signals data show that a person with less body mass has an efficient heat conduction process. A skinny person's body heats up quicker and produces more sweat and also propels more heat energy away quicker than a person with more bodily mass.

If the garments clothing are thicker (more than 1.0 Clo), while temperature increases (warm area), the body takes some of the heat and returns it to the body's core, and then the core temperature rise seven further. In cold weather or a cold area, a person's body loses his/her heat generations to the environment due to the second thermodynamics law. For example, people are wearing their coat in the winter to prevent a significant heat loss to the environment. Heat naturally flows from an object at higher temperature to lower temperature. In the experiment, the participants were wearing approximately a 0.57 Clo garment level. In exercise activity, their metabolism increased to 3.0 Met/180 w/$m^2$from seatedposition (acclimation session) to 1.0 Met or 60 w/m^2.Therefore on a graph (Figure 3.2), their heat generation increased by 1 degree.

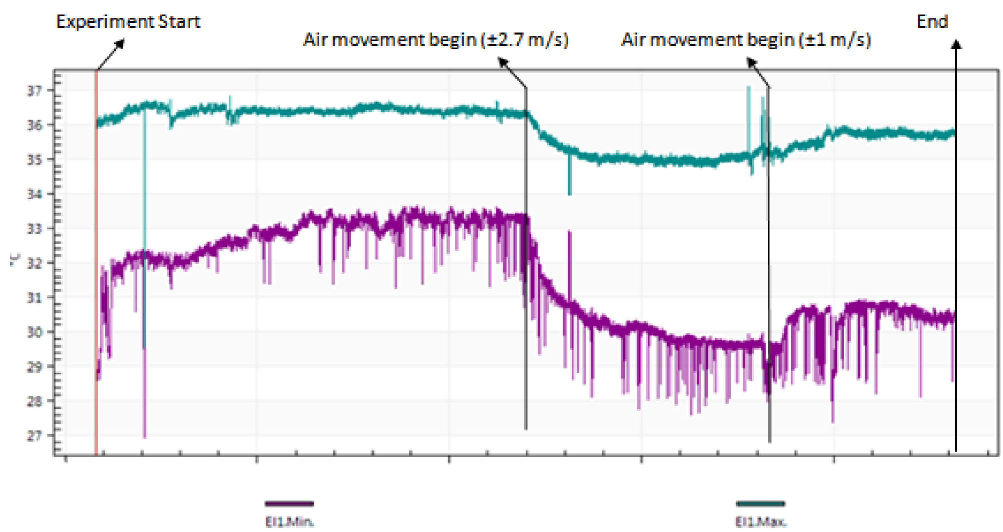

Figure 3.2: Whole session timeline setup on thermal imaging signal

Finally, when the air moved, the skin temperature went down. This phenomenon causes more sweat from the exercise activity. When the sweat and air movement were present, the heat vaporized rapidly to the environment. When the air decreased to $\pm 1\ m/s$, each participant showed (Figure 3.2) the amount of heat increased.

3.3 Thermal Comfort Condition

3.3.1 Warmth Discomfort

According to the data obtained, most of the participants sensed hot or warm after the exercise activity. Their blood was pumping faster, and their breathing rate rose (Figure 3.3). In this case, skin temperature also rose along with skin conduction level (Figure 3.5). In the process of increasing temperature, most participants were feeling hot and uncomfortable or slightly uncomfortable. The increase of the temperature and instantaneous sweat production can factor into human sense of discomfort. However, if humidity and temperature are lower in levels, then it will take a while to conduct and produce heat conduction across the skin surface.

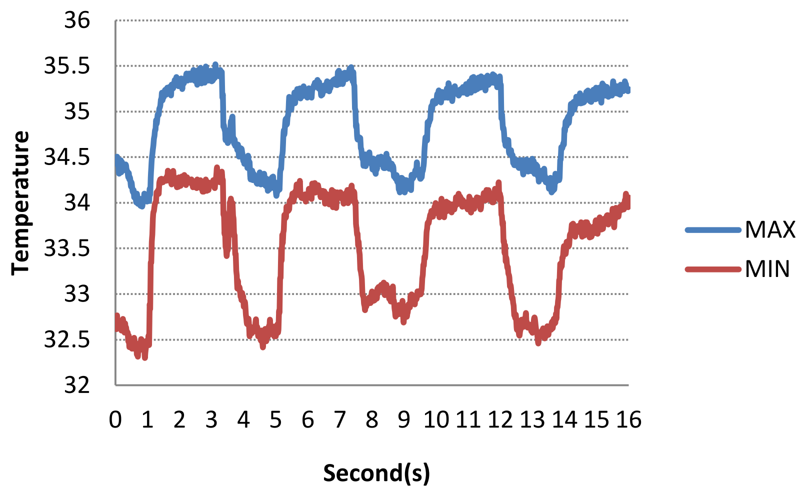

Figure 3.3: Breathing rate after participant's activity.

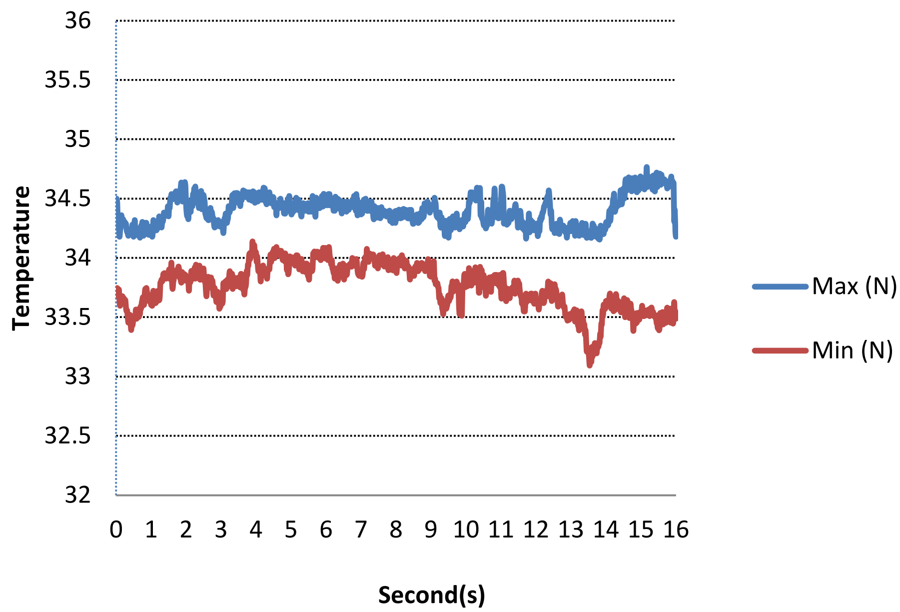

Figure 3.4: Breathing rate after 10 minutes session

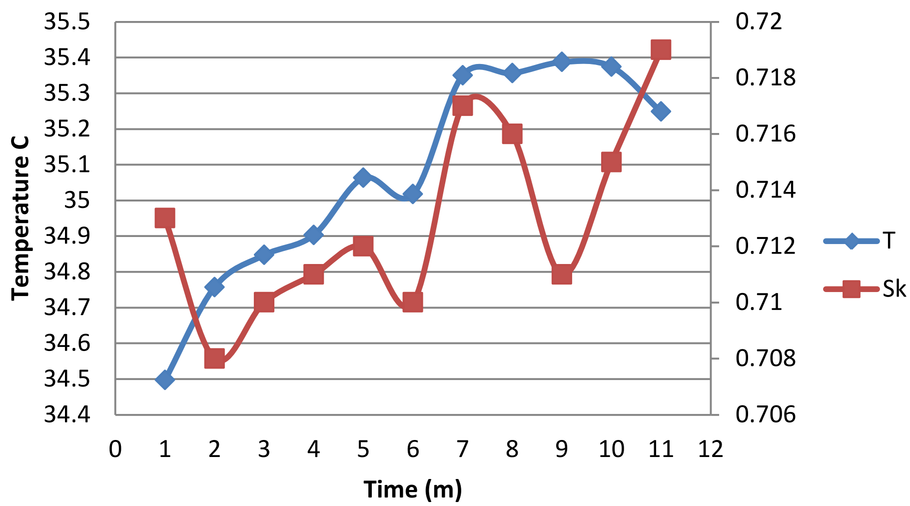

Figure 3.5: Skin conduction and temperature correlation

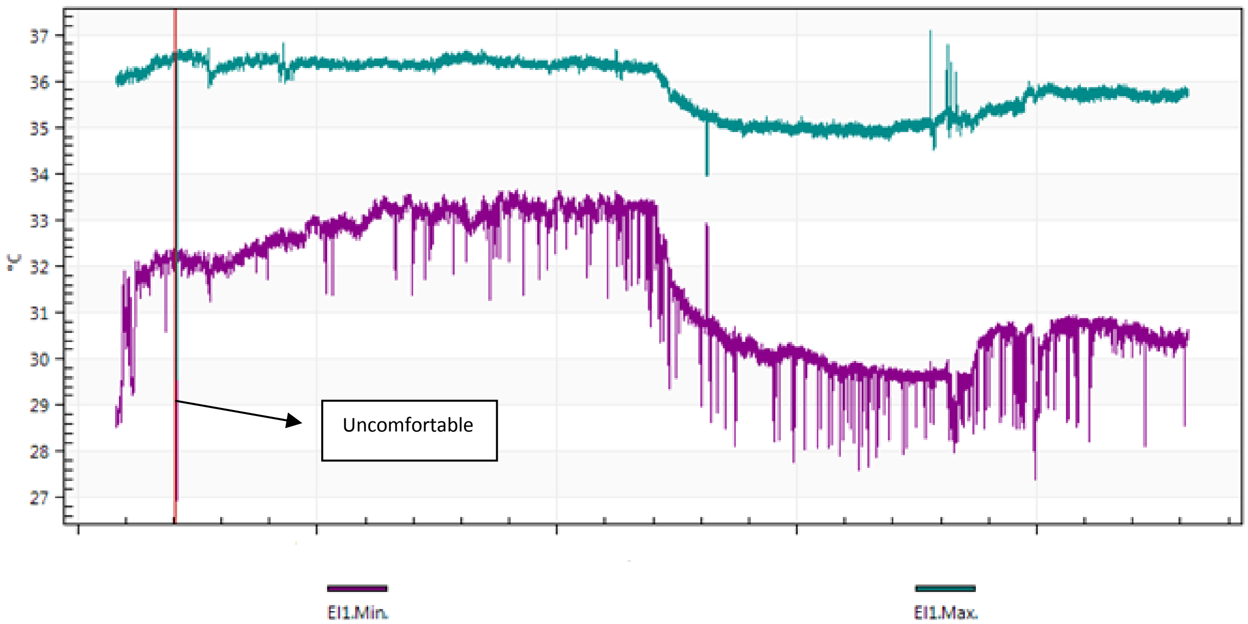

Figure 3.6: A signal from thermal imaging in facial region. Uncomfortable state according to comfort surveys

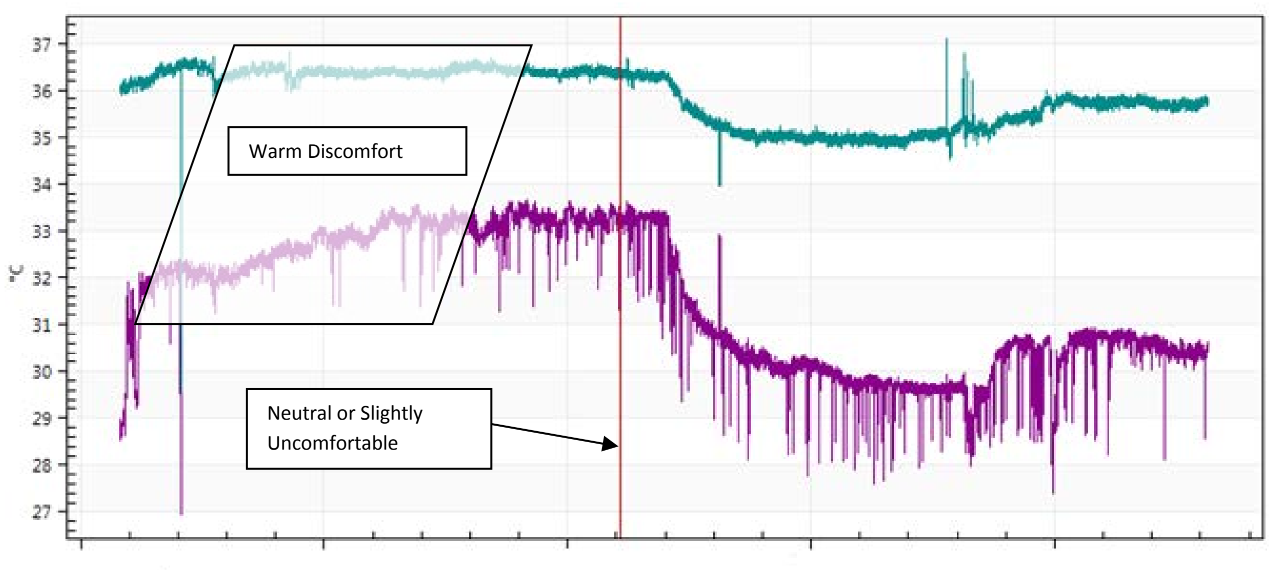

Figure 3.7: Area of discomfort and a neutral state according to the surveys

According to the data collected, most people experienced an increased in their temperature while in hot or warm condition. The skin conduction or sweat also increased with respect to temperature and body mass. The flexibility of sweat either fluctuated up or down, dependent on the body mass. The participants group analyzed with Flir Tools software. In the thermal camera result (Figure 3.6 & 3.7), a person's facial skin temperature increases between "uncomfortable" and "Neutral". At this state of uncomfortable, the person also produces sweat (Figure 3.5), therefore he/she gets uncomfortable. From the analysis, a process of temperature rising followed by amount of sweat productions is a factor of discomfort affection. The discomfort is an actual area of skin temperature rise driven by core temperature while the sweat is working on the cooling process. A slight temperature rise accompanied by sweat, in this case one degree Celsius, at the humidity existence period of time will affect the hominal behavior. On the other hand, if a skin temperature is constant with only a little sweat, then the participant would consider his/her affective neutral. Figure 3. 8 shows a hominal adaptation includes the body temperature which proven that their skin, heart rate, blood flow, respiration reduced by time.

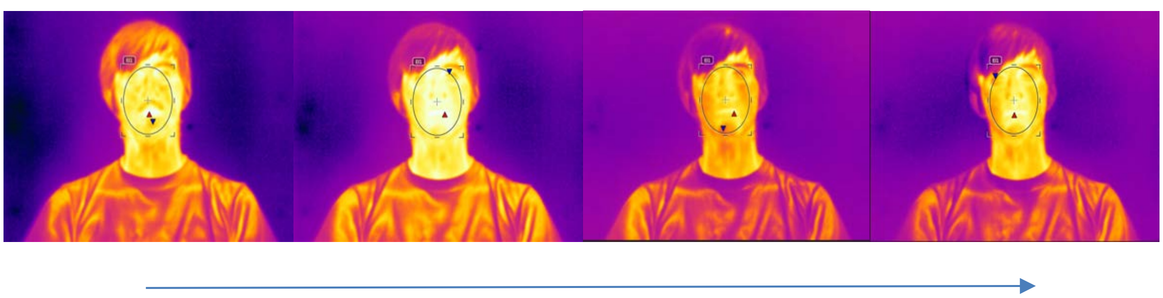

Figure 3.8: 22 minutes timeline hot to cool down

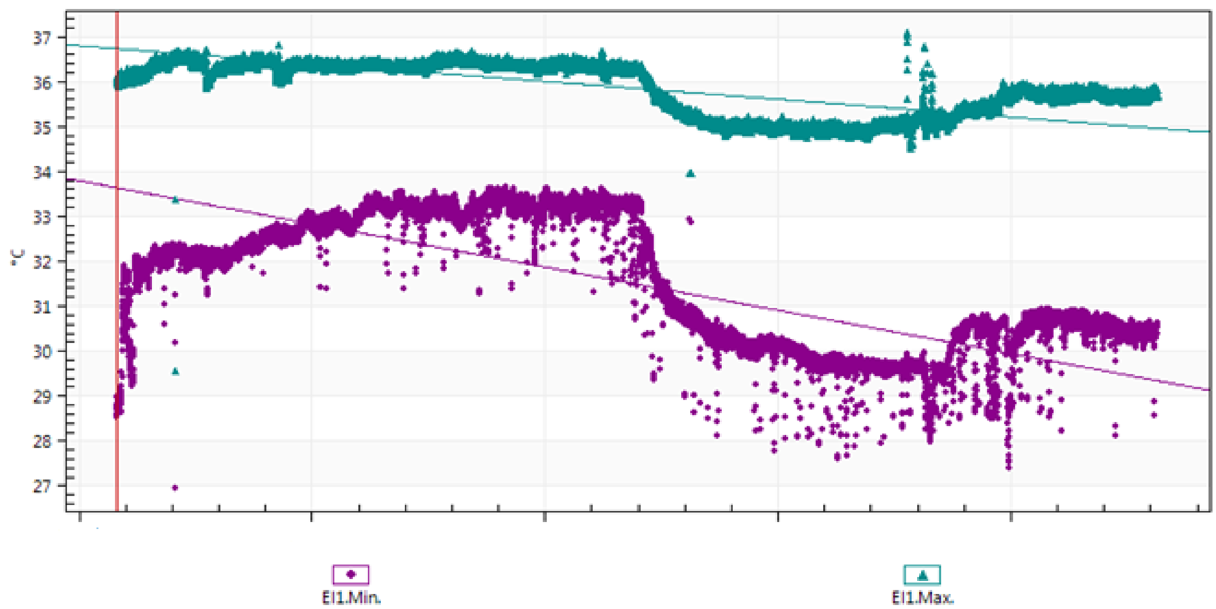

Figure 3.9: Best fit lines shows the correlation between temperature and time

3.3.2 Cold Discomfort

When cold, the temperature of internal body needs to have to stay at 37℃. Sometimes, blood vessels decrease to retain more heat within the core body. A decrease of heat follow by less body mass reduces the vessel's diameter rapidly. As a result of this, the blood pressure increases as does the body temperature. Blood stream will create more friction, which raises heat over the body. That’s why, our hands and feet get the first chill sensation faster than anything else body-wise. In the second stage experiment, the participant was already cooling down from the first activity, depending on their amount of sweat in the body. When people with less body mass cool down, their sweat is still abundantly present. Air movement is a factor of how much the heat will depart from the body. The more sweat they have, the more heat is being released into the environment. If the heat is still declining, then the rest of the body will take some of the heat from the core body. As a result of this process, the discomfort sensation has occurred with participants as shown in Figure 3.10. The process of decreasing the temperature would more greatly affect the lesser body massed person. Since the person with less mass is efficient on heat transfer process, then the skin temperature would begin to decrease swiftly. In this case, a person with “normal” body mass will feel cold faster than will an overweight or obese person. The participant with more mass would keep their body warm because of less fat to cool down. This is the reason why the overweight or obese body type feels better without extra wears of clothing in a cold environment.

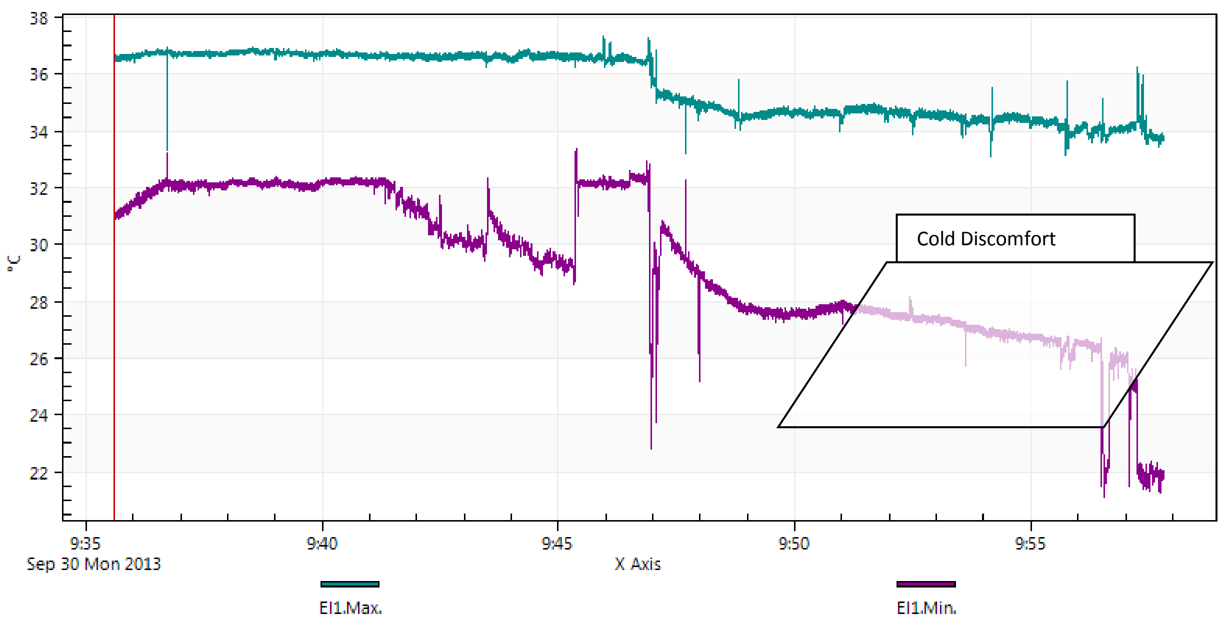

Figure 3.10: Cold discomfort region, temperature is decreasing (Facial)

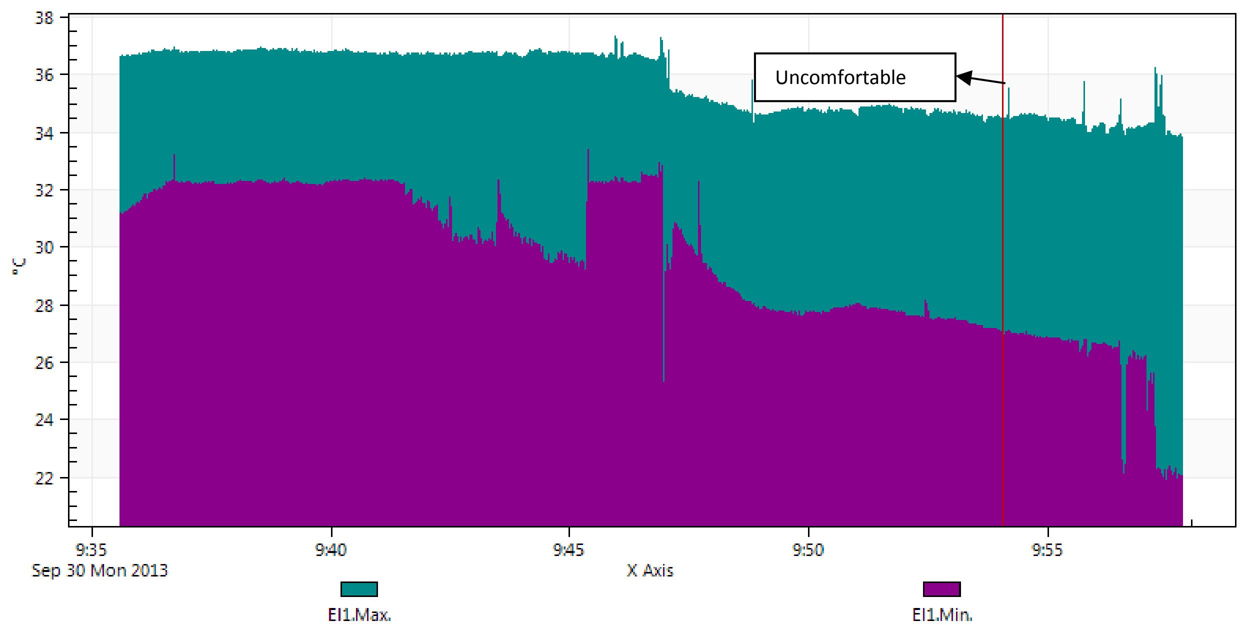

Figure 3.11: Area between max and min temperature at periorbital region

Figure 3.11 also shows that periorbital temperature region will always higher than the facial temperature region. Figure 3.10 shows a person feeling cold because of an abundance of body sweat and air movement between 3 to 2 m/s. A body's temperature condition less than one degree ambient temperature at this condition usually will bring a chill sensation to the person. In the cold case condition, it is difficult to determine sensation from one lone point of view. For example, when the cold exists, hands and feet will experience faster reaction due to vasoconstriction. So, it would be useful to further study, from the point in time of after a person's core temperature has decreased, in the region of the hands and feet for heat loss phenomena.

3.3.3 Comfort Zone

A person deliberately adapts to a "comfortable" ambient temperature. When pleasant surroundings and milieu are sensed by a person, then that person's affective controls his/her opinion. Most participants felt comfortable instantaneously when the air movement was generated into the area initially, which held them in comfort durationally for some time. A condition of a constant temperature in the core body and skin temperature are accepted by the participants, and is a person's affective in neutral condition, for this thesis. This result is based on a thermal camera (Figure 3.12). If a participant can maintain his/her average temperature, maximum temperature, and minimum temperature in a constant condition, then a comfort zone or region will be achieved by his/her affective state.

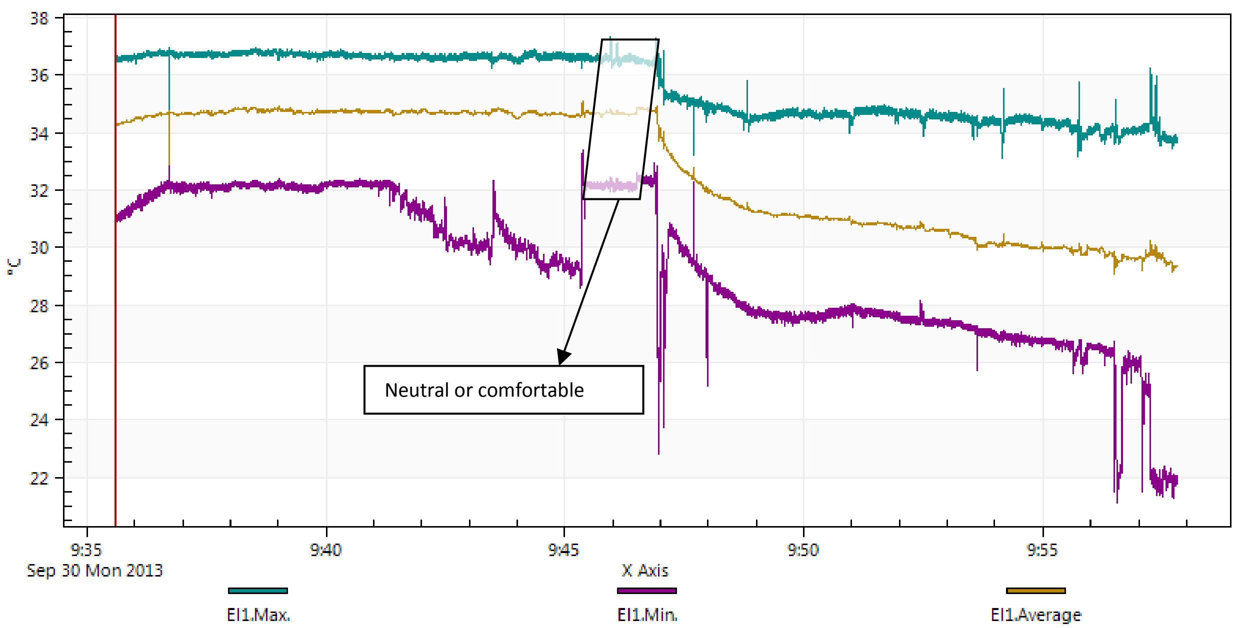

Figure 3:12.Neutral constant state

3.4 Result and Discussion

After the work out activity	Thermal Comfort 1
10 minutes after first stage of data collection	Thermal Comfort 2
5 minutes after the fan turned on	Thermal Comfort 3

Table 3.1: Description of human comfort survey

Table 3.1 describes when the question surveys were presented by the researcher. In Figure 3.2 the comfort levels stage are being described by each participant on the exact time. The blood volume pressure, temperature, respiration and skin conductance at the specific time were also collected and organized at the end of the experiment.

Survey 1	a6	a7	a9	a10	a11	a12	a13	a14	a15	a16	a17	a18	a19	a20	a21	a22	a23	a24
Thermal comfort#1	1	1	-2	-3	-2	-2	1	-2	-1	-1	-1	-2	-1	2	-2	2	-1	-1
BVP#1	33.014	28.896	33.163	32.531	35.743	37.002	35.262	34.266	33.251	35.709	34.626	38.69	27.154	35.089	33.403	35.132	36.703	38.424
T.skin#1	32.645	34.566	33.531	33.423	34.727	33.493	32.414	34.48	33.936	32.202	33.524	34.433	33.703	33.429	34.497	35.08	34.87	35.025
Respiration#1	11.847	13.748	9.065	9.144	9.044	13.268	9.15	10.44	10.394	9.261	8.835	8.902	12.291	14.433	9.136	8.452	13.209	8.748
Skin conductance#1	1.353	4.367	0.969	0.716	3.285	1.438	1.256	1.374	1.071	1.034	2.261	5.007	0.916	0.608	0.713	2.586	1.489	1.306
Survey 2	a6	a7	a9	a10	a11	a12	a13	a14	a15	a16	a17	a18	a19	a20	a21	a22	a23	a24
Thermal comfort#2	0	0	-1	0	0	-1	2	2	2	2	-1	2	2	2	3	2	2	1
BVP#2	35.56	34.816	33.218	35.358	38.265	42.265	33.623	34.66	33.828	30.265	33.311	47.807	36.785	28.639	39.244	32.332	36.381	37.315
T.skin#2	33.596	33.045	33.104	34.089	35.048	34.881	33.763	35.491	34.27	33.283	35.178	34.797	34.082	34.18	35.374	35.582	35.664	35.491
Respiration#2	12.663	14.718	10.162	9.682	9.447	13.347	9.943	10.96	10.912	10.058	10.092	9.106	13.065	14.358	9.793	8.747	13.018	9.456
Skin conductance#2	2.276	7.811	3.571	1.049	1.76	1.282	0.834	1.471	0.986	0.737	1.969	4.512	1.285	0.657	0.715	4.188	1.067	1.641
Survey 3	a6	a7	a9	a10	a11	a12	a13	a14	a15	a16	a17	a18	a19	a20	a21	a22	a23	a24
Thermalcomfort#3	2	-2	1	1	1	2	2	2	-2	2	-2	2	2	2	3	-1	2	2
BVP#3	32.964	33.404	38.891	33.122	38.171	38.569	33.113	33.689	33.588	37.904	35.866	32.951	33.303	31.808	31.039	31.638	35.146	35.363
T.skin#3	33.905	29.287	31.967	33.007	34.314	33.378	31.151	34.208	30.748	30.843	34.652	35.074	32.887	33.595	34.589	35.236	35.258	34.391
Respiration#3	12.376	14.242	9.813	9.223	9.531	14.075	9.201	10.536	10.811	8.663	10.381	8.522	12.963	14.963	10.324	8.372	13.522	9.482
Skin conductance#3	2.453	8.741	6.251	1.593	5.614	1.624	1.175	1.44	2.09	0.72	3.029	4.607	1.835	0.681	0.688	3.48	1.024	1.945

Table 3.2: Data result of thermal comfort

When a participant sensed a "comfortable" or an “uncomfortable” experience in the experiment session (from the surveys), then the exact data were recorded in real precise time. The results from eighteen participants (Table 3.2) were obtained directly from physiological sensors and then combined with thermal comfort level responses from the surveys. And then we properly correlated each group of thermal comfort information and various physiological data.

Survey question	Signals	Correlation coefficient
Thermal comfort 1	Blood Volume Press.1	-0.129
	Temperature 1	-0.122
	Respiration 1	0.343
	Skin conductance 1	0.069
Thermal comfort 2	Blood Volume Press.2	-0.047
	Temperature2	0.265
	Respiration 2	-0.119
	Skin conductance 2	-0.280
Thermal comfort 3	Blood Volume Press.3	0.008
	Temperature 3	0.330
	Respiration3	0.016
	Skin conductance3	-0.524

Table 3.3: Correlations coefficient result between thermal comfort survey and sensors

Each survey question period is correlated with thermal comfort values (-3 to 3). (Table 3.3) Respiration 1 has a weak positive correlation of 0.343. It means, if the thermal comfort 1 decreases, the respiration rates will decrease. Temperature 2 indicates that when skin temperature increases, then the thermal comfort increases. But this result is not always exact due to negative correlation for temperature 1. According to the thermal camera, the condition of the participant's skin temperature should be visually in constant contour. A particular result may appear differently depending on the environmental circumstance or factor. Since most of the participants are experiencing "neutral or balance" response at survey 2, then an additional heat loss or heat gain on a person's body may create an uncomfortable status due to environment change factor.

On the other hand, we can also observe that skin conductance 3 has a moderate correlation of -0.524, which means that when the thermal comfort 3 decreases, the skin conductance rate will increase. This correlation is expected as the more sweat exists, the lower thermal comfort experience (uncomfortable region) due to air movement. Each correlation number shows a potential result. Therefore, using these correlation approaches, we can validate that participants’ responses on the comfort survey and the sensors have an effective relationship to differentiate each other, even though they show a weak relationship in their coefficient numbers. When the experiment would be able to have more participants, in the future, then the correlation coefficient numbers expectation would increase intentionally.

CHAPTER 4

CONCLUSION

4.1 Conclusion

In this research two stages of data collection were performed in one experiment. This experiment was included in two different stimulation activities: exercise work out and air movement action. The specific sensors are also supported with actual real time and real comfort survey questions.

The sensors indicated that there are variations in thermal comfort in skin, respiration, blood volume pressure, and skin conduction. Core body temperature and body mass play a significant role introducing various different sensations. A “normal” body mass is more efficient in generating its heat and cooling down its body temperature. The sweat that a person produces is also abundantly present compare to a person with "overweight" and "obese" mass. “Normal” skin conductivity fluctuated randomly as the body used muscle or mass cooling. However, people overweight and obese are quicker in providing their sweat as well as constantly amplifying their skin conduction. For all body masses, when temperatures increase and heat-gaining processes physically are developing, this leads to a condition of discomfort, which is thus followed by sweat production on the skin surface. When temperature is decreasing due to rapid sweat evaporation, discomfort also occurs, that of heat loss. Finally, the result patterns of all sensors are visually expected and the human comfort sensations can be predicted by these approaches. According to the result, at this time, the correlation between comfort survey questions and sensors are going in the right direction, although, weak relationships occur due to the small number of participants. Our experiment shows that these modalities complement each other in detecting human comfort. Particularly, our initial finding seems to suggest that the more data we collected, the stronger was the thermal comfort correlation coefficient number.

4.2 Future Work

An additional internal temperature sensor can be considered in our further investigations. We could input core temperature sensors directly to corporeal internal areas rather than just relying upon the skin surface temperature. Since we consider the skin conduction data after the exercise activity, we do not know how much rate will be generated. To obtain how quick overweight and obese subjects generate their sweat, i.e., skin conduction, we should consider putting sensors on their skin during the exercise session. Blood volume pressure, respiration, and skin conduction can be considered in more detail by recording their background activity, age, medical history, and living areas. Finally, we require more participants to generate a strong relationship in our results correlation. One thing we may also consider is possibly adding to and/or disregarding the exercise activity, for the future, to better simulate real-life and its more sedentary realities. The experiment should involve a real house situation activity, for example, a commonplace light engagement (e.g., reading, watching TV, card playing, etc.) in a “climate control room” in which the researcher can control the temperature, humidity, and air movement.

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