Ph.D. DISSERTATION

CoBi: Bio-Sensing Building Mechanical System Controls for Sustainably Enhancing Individual Thermal Comfort

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ABSTRACT

Current existing thermal control systems are operated based on thermal comfort models generated by regression formulas averaging the thermal responses over data collected during extensive experiments involving panels of human subjects. These models may not be appropriate for an individual whose physiological characteristics happen to be located outside of the main stream from the experimental sample of occupants. By necessity, existing automatic control systems disregard individual characteristics such as health, age, gender, body mass, etc., which may affect physiological responses. Thereby these systems have serious limitations in ensuring individual thermal satisfaction.

While there have been many efforts to overcome the limitations of current technology and to improve individualized control, most of the attempts to make smart controllers for buildings have dealt primarily with optimizing mechanical building components to deliver uniform conditions, largely ignoring whether a generated thermal environment by building systems meet actual users' comfort and satisfaction. Over-cooling and over-heating are common unnecessary results.

Thermal control innovations for building mechanical systems are critically needed to demonstrate that meeting the physiological needs of occupants can actually save energy and improve environmental quality while enhancing user satisfaction.

The thermoregulation of the human body has a biological mechanism, homeostasis, which enables it to maintain a stable and constant body temperature by changing physiological signals including skin temperatures and heart rate. These signal patterns have the potential to provide information about each individual's current thermal sensation.

The goal of this research is to establish an adaptive thermal comfort control driven by ongoing human physiological responses or bio-signals. Confirming the optimum driver of skin temperature, and location of sensors, the bio-sensing adaptive control logic is developed to support the optimum control of HVAC terminal units. The bio-sensing controllers offer major opportunities for office, healthcare and residential buildings, especially where environmental quality and control can be linked to productivity and health, and where energy savings are critical. The CoBi bio-sensing adaptive HVAC systems control research would substantially improve occupant comfort, health, and well-being while advancing environmental sustainability with energy savings, at a small first cost for existing or new buildings.

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1. INTRODUCTION

Today's growing emphasis on minimizing energy use in buildings while maximizing the occupants' environmental satisfactions can compromise indoor environmental quality (IEQ) and individual control of environmental conditions. Control innovations for building mechanical systems are critically needed to demonstrate that meeting the physiological needs of occupants can actually conserve energy and improve environmental quality. Most existing thermal comfort models for mechanical systems controls are commonly designed based on thermal comfort regression formulas averaging the thermal responses of extensive experimental human subjects. Since the generalized models based on statistical regression already contain deviations with error rates, the generated models may not meet the needs of a person who has different physiological requirements from the assumed occupants. By necessity, existing comfort models disregard individual physiological characteristics such as age, gender, health and body mass index, and thereby have serious limitations for ensuring individual thermal satisfaction. While there have been many efforts to overcome current technology and research limitations and to improve individualized control, they are still based on pre-set programmable parameters and/or require physical access to a controller.

The human body has a biological thermoregulation mechanism (homeostasis), which enables it to maintain a stable and constant body temperature via changing physiological signals such as skin temperatures and heart rate. These signal patterns have the potential to provide information about an individual's current thermal comfort conditions. This research is based on the potential of human physiological responses to establish an adaptive thermal comfort controller, which can be triggered by an individual's unique and changing bio-signals for automatic mechanical system controls.

The research outcomes will contribute to a wide range of building types, from offices and healthcare facilities focusing on the quality of individual environments and will substantially improve occupant comfort, health, and well-being while advancing environmental sustainability and energy savings, at a small first cost for existing and new buildings.

2. BACKGROUND

2.1. Current Building Energy Consumption and Thermal Condition

According to the U.S. Green Building Council (USGBC, 2010), buildings contribute to environmental impacts accounting for 72% of electricity consumption, 39% of energy use and 38% of all carbon dioxide emission in the U.S as summarized in Figure 1.

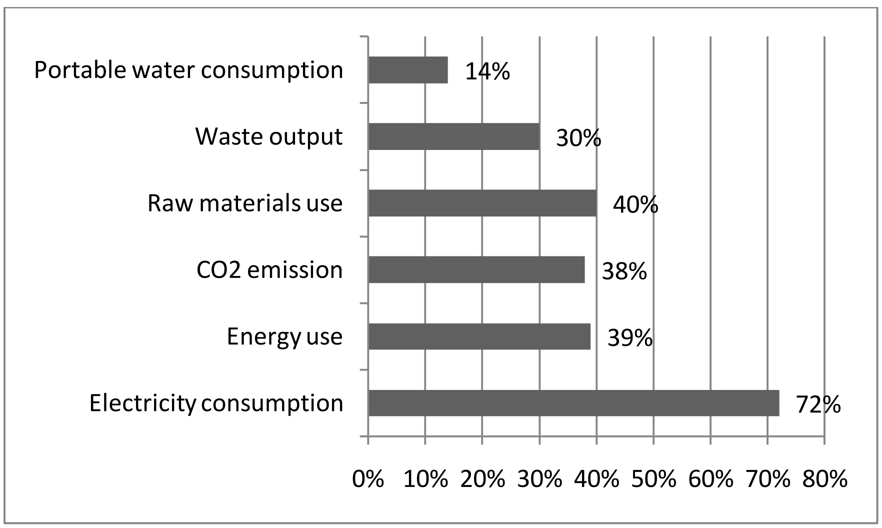


Fig. 1. Environmental impacts of the built environment in the U.S. (USGBC, 2010)

In the energy use of buildings, EIA (2003) estimates heating system contributes to 34% of the building energy consumption while 15% of the total energy used by buildings is consumed for cooling and 4% for ventilation (Figure 2). These statistics explain that 21% of all energy used in the U.S. is for building mechanical systems. This one fifth of total energy use in the U.S. can be compared with the total consumed energy in India (EIA, 2008).

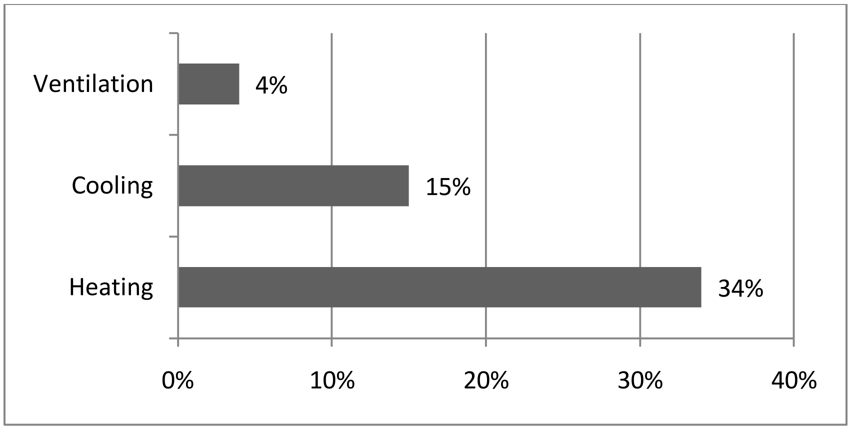


Fig. 2. Percentage of energy consumption by end-use equipment in buildings (EIA, 2003)

Despite the large amount of energy use for heating, cooling and ventilation, 60% of the sampled building occupants of 20 buildings from a recent research reported thermal discomfort in their workstations. (Loftness et al., 2009). The research also found that 23% of the surveyed occupants reported their discomfort at "very dissatisfied" while only 5% of them answered "very satisfied" as illustrated in Figure 3.

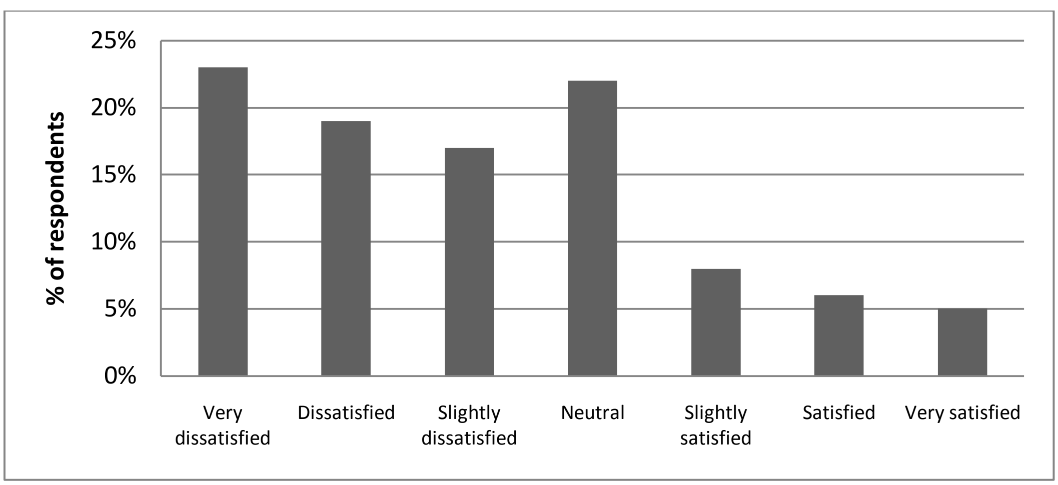


Fig. 3. Thermal comfort survey data (Loftness et al., 2009)

The finding of the research is well supported by the survey research performed by the International Facility Management Association (IFMA, 2003). The 2003 Corporate

Facility Monitor survey conducted by the IFMA reported that “too cold” and “too hot” sensations ranked first and second as complaints in office buildings while the order of the complaints were reversed in the 1991 survey (BUILDINGS, 2003).

As such, thermal discomfort has been a consistent problem in the built environment while the energy use for the thermal environmental conditions in buildings accounts for a large percentage of the total energy use. Therefore, the limitation of the built environment in energy use and thermal comfort indicates the significant role of energy effective building mechanical systems for environmental and physiological benefits.

2.2. Thermal Comfort and Its Significance

Thermal comfort is defined in ASHRAE-55 (2004) as the condition of mind which expresses satisfaction with the thermal environment. It is affected by heat transfer in the form of conduction, convection, and radiation, and is maintained when the generated body heat is in the equilibrium condition with the surrounding thermal environment. Thermal comfort is determined by six variables: air temperature, mean radiant temperature, air velocity, and relative humidity as environmental factors, as well as clothing (insulation) and activity level (metabolic rate) as human factors (ASHRAE-55, 2004). Heat transfer variations as a result of environmental and human factors lead to humans’ maintaining constant internal temperature of 37°C (Karakitsos et al., 2008). To sustain such heat balance, the human body uses thermoregulatory principles. When significant heat gain or heat loss occurs, individual thermoregulation may be insufficient to ensure equilibrium and causing thermal stress and thermal discomfort responses such as too warm or hot, and too cool or cold.

Thermal discomfort is significantly related to individual physiological and psychological mechanisms. Discomfort is linked to thermal stress, which can affect work performance and individual health (Wyon, 1996; Witterseh, 2001; Hannula, 2000; Row, 2002). Since work performance and individual health are directly linked to organizational success, including outcomes, maintaining thermal comfort is critical.

2.3. Current Thermal Control Technologies

There have been many efforts to quantify the environmental parameters affecting thermal comfort, and to identify the strategic sensor-controller mechanisms. Dry bulb temperature has been used as the dominant control parameter for thermal comfort. Other scientific efforts to increase the accuracy of comfort prediction, include the development of effective temperature which integrates air temperature and relative humidity, and the further development of operative temperature which includes air temperature, humidity air speed and mean radiant temperature as each critical to the delivery of thermal comfort (ASHRAE-55, 2004). Currently, operative temperature is used to estimate human thermal sensation in the ASHRAE thermal comfort model (ASHRAE-55, 2004). As the model is presently the most progressive tool, it is adopted to building automatic control systems in most types of buildings.

This section provides a summary of the thermal comfort theory and the current models, and discusses the limitations of these models and the latest research efforts for advanced control strategies.

2.3.1. Current thermal comfort models

There are many efforts to develop objective thermal comfort models to estimate or to predict thermal comfort condition and thermal sensation. The most prevalent thermal comfort models are Fanger's PMV (Predicted Mean Vote) adopted in ASHRAE-55 (2004), and the Pierce Two-Node Model.

The PMV thermal sensation scale (Figure 4) was developed to link the environmental and human factors defining thermal comfort with subjective thermal sensation votes. The PMV is captured in an empirical equation for predicting the mean thermal satisfaction vote on an ordinal rating scale for a population (ESRU, 2009). The equation uses a steady-state heat balance for the human body and postulates a link between the deviation from the minimum strain on heat balance mechanisms, e.g. sweating, vaso-constriction, vaso-dilation, and thermal comfort vote. The Pierce Two-Node Model was developed at Yale University to separate the indices of thermal sensation (TSENS) and thermal discomfort (DISC) as predictors of thermal comfort based on effective temperature, and concluded that the subjects would experience the same skin temperature, skin wetness and heat loss to the environment (DOE, 2009a). Therefore, the model is an approach to thermal comfort / discomfort prediction using bio-signals, i.e. core body temperature and skin temperature as thermoregulatory strains.

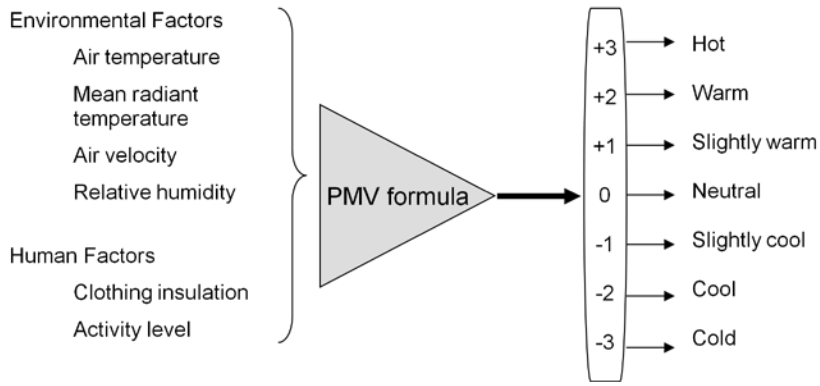


Fig. 4. Six major parameters and PMV scale (ASHRAE-55, 2004)

These two models were developed with the data collected from extensive controlled human subject experiments in uniform and steady state thermal conditions. Statistical regression is used to develop the correlation between measured environmental and subjects' thermal sensations. Since this regression uses an averaging process after mixing all the collected data, it cannot represent unique or individual physiological characteristics such as age, gender, and body mass index which are significant variable affecting thermal comfort (Charles et al., 2003). In addition, these models only apply to humans exposed to a constant condition at a constant metabolic rate for a long period of time (DOE, 2009a). These pre-assumed environmental and human conditions can be measurably different from real environments where conditions are dynamic, ill-defined and unpredictable.

2.3.2. Human physiological responses to thermal conditions

Heart rate and skin temperature fluctuate to maintain core body temperature, by increasing or decreasing heat exchange with the surrounding environment. Since thermal comfort is an integral response to air temperature, humidity, radiant temperature and air velocity, human skin temperature and heart rate play a significant role in the thermoregulation principle (Guyton & Hall 2006; Flesher et al., 1996). Shou's research also illustrates the links between thermoreception and thermoregulation. There are numerous thermo-receptors on our body surface which are responsible for communicating warm and cold sensations. The detected sensation is reported to the hypothalamus in the brain which is the temperature regulation center for the human body (Wang, 1992).

As shown in Figure 5, there are three thermo-regulatory mechanisms for maintaining a constant body core temperature in a changing thermal environment: changes in skin temperature, shivering and sweating (Wang, 1992). When humans are exposed to extreme conditions where the body gains or loses excessive heat, shivering and sweating are the primary modes in order to preserve the core body temperature (Wikipedia, 2009).

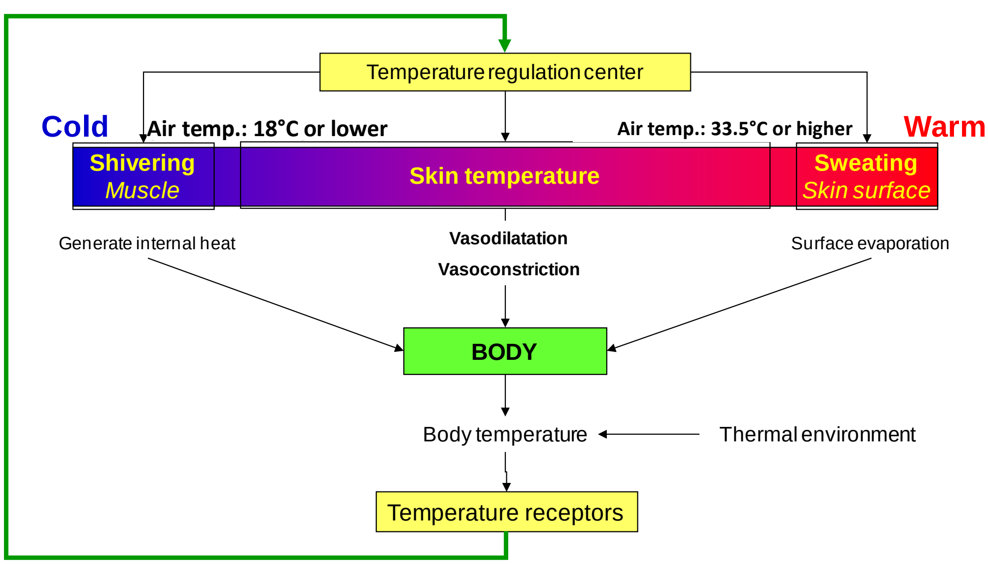


Fig. 5. A negative feedback mechanism for controlling body temperature (Wang, 1992)

One of the fundamental physiological features in humans is the ability of an organism to maintain its core body temperature, through thermoregulation mechanisms. When the body core is not able to keep a level temperature, and core temperatures are significantly higher or lower than normal, heat stroke or hypothermia may occur (Kirkes, 1907).

In the built environment, we rarely are faced with extremely low or high temperatures. Field measurement in the US office buildings consistently reveal ranges are between 20 and 27.8°C in the cooling season and 19.4 and 27.8°C in the heating season (CBPD, 2008). Hardy (1966) found that shivering occurs only when the air temperature is lower than 18°C, and sweating occurs only when the air temperature is higher than 33.5°C. As a result, the more prevalent regulatory mechanism in indoor environments is skin temperature.

Depending on body location, skin temperature variations are divergent. Each body location has a different surface exposure to air, different fat rate, and distance from the hearts and hypothalamus. Griefahn’s study (2001) shows that the rate of skin temperature change on an arm is slower than on the neck, and the rates of temperature change on forearm and neck may have opposite patterns when the rate of metabolism increases. The rate of skin temperature change on each body location could also be different depending on the subjects’ physiological conditions including the distribution and weight of fat and muscle (Griefahn, 2000). Indeed, age, gender and body mass index could be significant factors affecting skin temperature variations at different body locations. These diverse physiological characteristics will make it difficult to generalize about the expected skin temperatures at each body location in a given thermal environment.

Heart rate is another physiological variable significantly affected by metabolic rate (Berggren et al., 1950). Heart rate is related to oxygen consumption, which is related to genders, age, fitness, body mass and physical activity. It is also influenced by thermal sensation. LeBlanc (1976) investigated the negative correlation between the changing skin temperatures and heart rate in too cool condition, identifying that as temperatures drops, heart rate goes up but skin temperature goes down. His findings reveal heart rate can be an effective variable to estimate the cooling effect of the environment. However, because heart rate can also be affected by other factors such as stress and emotional status (Hughes, 2000), it may not be consistent even in the same thermal condition.

2.3.3. Thermal sensation prediction using bio-signals

Fanger (1970) quantified thermoregulation with the body heat balance formula that follows:

$$M - W = R + C + E + L + K + S$$

M: total rate of energy production, calculated from oxygen consumption

W: rate of external work

R: radiation (e.g. 60% heat loss from a nude body is via radiation)

C: convection (e.g. 10%)

E: evaporation of water through skin or from skin surface (e.g. 15% heat loss)

L: warming and wetting of air through inhalation / exhalation (e.g. 10%: 3%- inhaled, 7%- exhaled)

K: conduction through skin directly to surface, such as clothes, chair surface, floor, etc. (e.g. 3%)

S: heat storage in the body

Excretion of urine and feces: 3% of heat loss

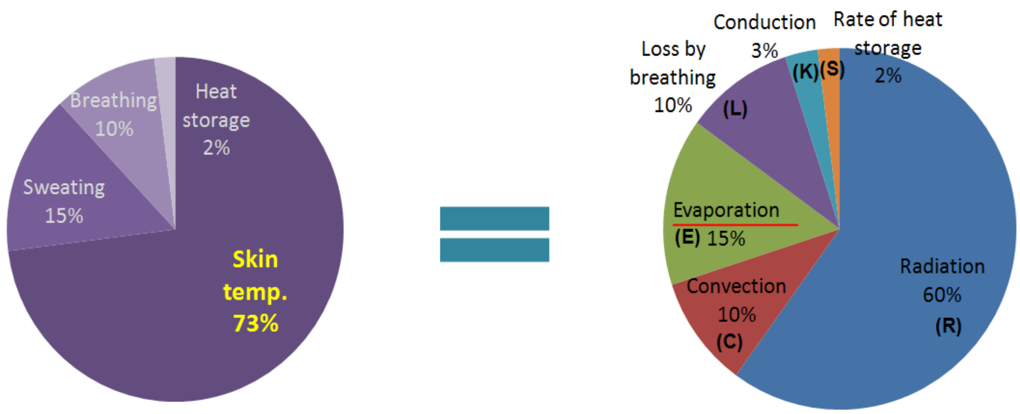


Fig. 6. Heat loss mechanism attributable to skin temperature controls (constructed based on Fanger's heat balance theory)

As the Fanger's formula shows, R (radiation), C (convection) and K (conduction) explain 73% of the body heat loss and are considerably related to skin temperature (Figure 6). Due to the significant role of skin temperature in heat balance, skin temperature has been widely researched as central to the development of thermoregulation and thermal sensation models. Evaporation is also a significant measure, with sweating explaining roughly 15% of our bodies heat loss and also influenced by skin temperature. However, sweat rates can be highly variable by individual and environmental condition. Thus, skin was chosen as the central bio-signal for this research.

To date, there are 16 major temperature models that estimate mean skin temperatures at different body locations in varying thermal environments as summarized in Table 1. These 16 models collectively identify 20 body locations that might significantly signal thermal sensation (Figure 7).

TABLE 1. Relative surface area of body regions and weighting factors used in the various formulas (Choi, 1997)

No.	Formula	Head		Trunk						Upper arm		Forearm		Hand	Thigh				Calf		Foot	Reference
	Location	A Fore-head	B Cheek	C Neck	D Chest	E Ab-domen	F Scapula	G Sub-scapula	H Lumbar	I Poste-rior	J Antero-lower	K Ante-rior	L Poste-rior	M Hand	N Anterior	O Antero-medial	P Postero-medial	Q Postero--lower	R Anterior	S Posterior	T Foot	
	Regional surface area[a]	0.072±0.005		0.355±0.019						0.154±0.005				0.049±0.002	0.187±0.019				0.116±0.005		0.067±0.003	
	Weighted type																					
1	Burton-3W				0.5								0.14						0.36			Burton (1935)
2	KSU-3W				0.5								0.14							0.36		Olesen (1984)
3	Ramanathan-4W				0.3					0.3					0.2				0.2			Ramanathan (1964)
4	Newburg/Spealman-4W				0.34								0.15		0.33				0.18			Houdas and Ring (1982)
5	Houdas-5W		0.07			0.175			0.175		0.19							0.39				Houdas and Ring (1982)
6	Palmes/Park-6W		0.14		0.19				0.19				0.11	0.05	0.32							Mitchell and Wyndham (1969)
7	Hardy/DuBois-7W	0.07			0.35								0.14	0.05	0.19				0.13		0.07	Hardy and DuBois (1938)
8	Gagge/Nishi-8W	0.07			0.175		0.175			0.07			0.07	0.05	0.19				0.2			Gagge and Nishi (1977)
9	Nadel-8W	0.21			0.1	0.17	0.11			0.12		0.06			0.15				0.08			Nadel et al. (1973)
10	Crawshaw-8W	0.19			0.08	0.12	0.09			0.13		0.12			0.12				0.15			Crawshaw et al. (1975)
11	Houdas/Colin-10W		0.2		0.05	0.125		0.2		0.05	0.05		0.05			0.125			0.075	0.075		Houdas and Ring (1982)
12	Colin/Houdas-10W	0.06			0.12	0.12		0.12		0.08			0.06	0.05	0.19				0.13		0.07	Houdas and Ring (1982)
13	QREC-10W		0.1		0.125				0.125	0.07			0.07	0.06	0.125	0.125			0.15		0.05	Mitchell and Wyndham (1969)
14	Hardy/DuBois-12W	0.07			0.0875	0.0875	0.0875		0.0875				0.14	0.05	0.095		0.095		0.065	0.065	0.07	Mitchell and Wyndham (1969)
	Unweighted type																					
15	Stolwijk/Hardy-10U	1/10			1/10	1/10	1/10			1/10				1/10	1/10		1/10			1/10	1/10	Stolwijk and Hardy (1966)
16	Mitchell/Wyndham-15U	1/15		1/15	1/15	1/15	1/15		1/15	1/15			1/15	1/15	1/15	1/15	1/15		1/15	1/15	1/15	Mitchell and Wyndham (1969)

[a] Regional surface area (mean±SD, n=10) is expressed as the fraction of the total body surface area

Many of these models have been developed to predict mean skin temperature for the purpose of medical diagnostics (Kubota, 2000). There are also efforts investigating the relationship between skin temperature and thermal sensation to more clearly establish thermal comfort in varying environmental and health conditions. Yao (2007) integrated eight of these thermoregulation models and conducted former controlled experiments to link skin temperature and thermal sensation, based on human subject experiments with 10 males and 10 females. Yao's regression formulas based on these experiments are shown in Table 2 and revealed the minimal number of body locations (: wrist, chest and anterior-calf) at three of the Burton's method showed similar results for mean skin temperature compared with the other methods adopting 10, 12 and 15 body points.

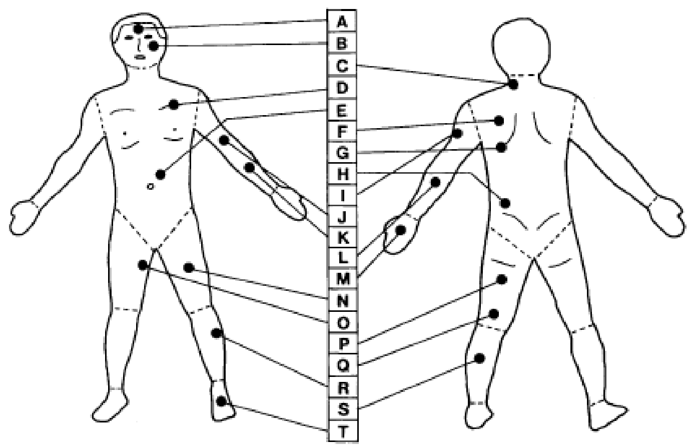


Fig. 7. Selected body locations (spots) for the calculation of mean skin temperature and seven major divisions (dashed lines) of the body surface for the calculation of regional average skin temperatures (Choi, 1997)

TABLE 2. Regression of local/ overall thermal sensation vs. skin temperature (Yao, 2007)

Overall/Local part	A	B	R^2
Overall	1.88	−61.96	0.95
Head	1.09	−36.94	0.94
Chest	1.65	−56.21	0.93
Abdomen	1.55	−53.25	0.92
Arm	0.91	−29.36	0.94
Hand	0.69	−22.78	0.90
Thigh	1.13	−37.98	0.92
Calf	0.98	−32.39	0.89
Foot	0.71	−21.30	0.93

$TS = A\ t_{Mean/local} + B$;

Where TS: Thermal sensation; $t_{Mean/local}$: Skin temperature of overall or local part

In addition to using skin temperature as an input variable in the thermal sensation formula, rates of skin temperature change were also utilized. Thermal sensation models developed by Wang et al. (1992) and Fiala (1998, 1999, and 2002) adopt skin temperatures and the rates of change at multiple body locations. Wang selected six body locations: head, trunk, arms, hands, legs and feet in core and skin areas. Fiala's model employed multiple body elements including the head, face, neck, shoulders, thorax, abdomen, arms, hands, legs and feet. These models were developed on regression processes between the subjectively measured human skin temperature data and the thermal sensations with the assumption of transient and uniform environment conditions for the applications (Zhang, 2003).

Beyond transient and uniform thermal environments in building environments, there are several efforts to develop bio-sensing controllers for heating and cooling of automobiles, which may have asymmetric thermal conditions. The common principle is to choose the most thermally responsive body locations and to use these physiological reactions to predict overall thermal sensations and even control environments. Toyota R&D labs investigated control systems for car air conditioning systems based on the driver's face skin temperature (Figure 8 and 9) (Taniguchi et al., 1992). They identified that skin temperature on the face could represent overall thermal sensation in a vehicle, and introduced a new method for controlling the air conditioning systems with multiple position of the driver's face skin temperature as the controlling index. They developed a multivariable regression equation to predict the thermal sensation based on the subjects' averaged face skin temperature and the rate of change per second as follows:

$$TSV = 0.81(\overline{t}sk - 33.9) + 39.1\overline{t}sk' \qquad (2)$$

where, TSV: Thermal sensation shown in Figure 6.
$\overline{t}sk$: Average face skin temperature (℃)
$\overline{t}sk'$: Rate of change of average face skin temperature (℃)

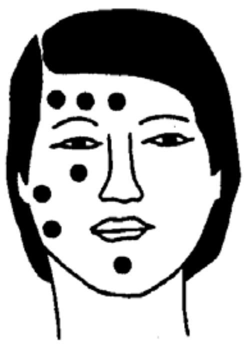


Fig. 8. Skin temperature measurement points (Taniguchi et al., 1992)

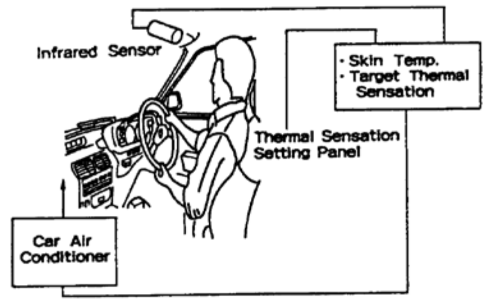


Fig. 9. Air conditioning system control process by skin temperature (Taniguchi et al., 1992)

Zhang (2003) developed local and whole-body thermal sensation and comfort prediction models for transient and asymmetrical thermal conditions for the HVAC system control of a car (Figure 10 and 11). She performed human subject experiments with 27 subjects to collect local skin temperatures and core temperature recorded thermal sensation and comfort levels while providing local heating and cooling to the subjects' body in asymmetric condition. Between the objective physiological changes and the subjective thermal satisfaction data, the research developed regression models for skin temperatures from the selected 22 body locations, as indicated in Figure 12, and perception to predict overall thermal comfort and sensation.

Fig. 10. Human subject tests in the Delphi Wind Tunnel (Zhang, 2003)

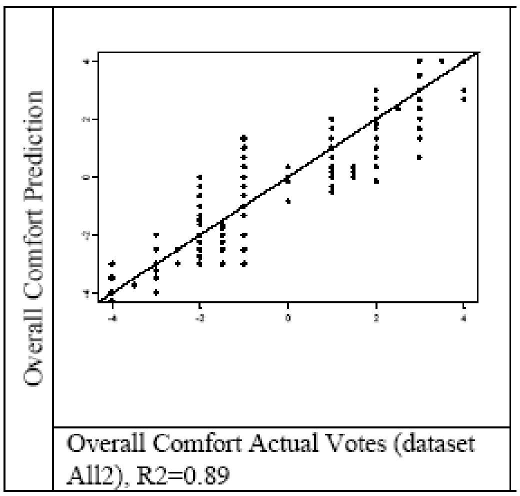


Fig. 11. Comparison between predicted overall comfort and actual condition (Zhang, 2003)

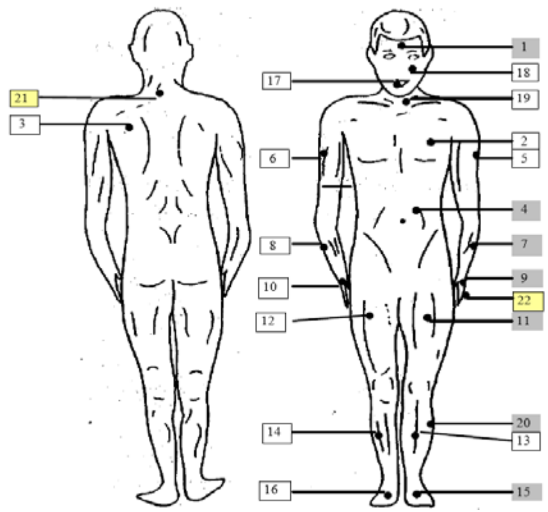


Fig. 12.Twenty-two skin temperature measurement locations (Zhang, 2003)

These advanced research findings reveal the potential for using physiological bio-signals to estimate overall thermal sensation for practical control application in the built environments. However, the quantitative thermoregulation formulas, based on statistical regression, were defined by an average of the human experimental subject data. Such statistical distillations disregard individual characteristics such as age, gender, health and body mass. However, those researchers do illustrate the value of skin temperature, the rate of change in symmetric and asymmetric conditions, and the body core temperature in extreme states, as effective variables to predict overall thermal sensation.

In additional to the average of human subject responses as control givens, another common limitation of the existing models is that each model has assumptions for activity level, relative humidity, clothing value and even the health and body mass of subjects. If the actual environmental and the human variables are not in the assumed scopes, i.e. dynamic conditions in clothing, activity level and thermal environment, the models may not work properly.

The third limitation of the precedent research in bio-sensing controls is the lack of practical applicability of the methods. Most of the discussed studies require ten or more sensors to be worn to measure local body skin temperature, especially in the models relating to building application. In particular, when collecting physiological information in real time for thermal sensation prediction, the intrusive sensors and their locations delimit practical implementation in buildings.

2.3.4. Current control strategies

A dry bulb thermostat is commonly used in each thermal zone of a building to sense and control room temperature. When an occupant has physical access to the thermostat, and the workgroup sharing that thermal zones have common requirements, using a thermostat is an effective way to maximize thermal comfort while preventing over-heating and over-cooling (Rose, 1997).

However, a conventional thermostat (Figure 13) still relies on a single environmental variable, dry bulb temperature in a zone, and does not have an ability to detect other environmental variables or local thermal conditions. Inappropriately located thermostats and environmental variability as well as variability in spatial / temporal occupancies can cause discomfort and energy waste by over-heating or over-cooling. These limitations may also cause thermal stress for occupants, especially those who are sensitive to their thermal environments due to their age or health, for example patients in healthcare and senior-care facilities.

Fig. 13. Prototypical conventional thermostat

Fig. 14. 7-Day programmable thermostat (Honeywell, 2010)

To make up the functional limitations of the conventional thermostat, a programmable thermostat was developed (Figure 14). It can be programmed on a weekly or daily basis. The principle is to allow the user to create two different temperature schedules – for example, one for weekdays and the other for the weekend, or a special for holidays. It is also possible to set two set points based on a daily plan considering occupancy conditions. Recently, an upgraded model of a programmable thermostat called the communicating thermostat was introduced in the market. This thermostat, “ecobee” can be programmed taking into account the daily pattern, occupancy conditions as well as activity levels of users (Figure 15). Based on the programmed setting and schedule by the user, the thermostat can actuate the cooling and heating system. It can also save the setting history so that the system can be controlled without programming anew each time.

Fig. 15. The ecobee Smart Thermostat and its control interface adopting iPod App. (ecobee, 2010)

Advances in thermostat design include local environmental control devices such as the Personal Environmental Module (Johnson Controls, 2007) shown in Figure 16, which enables the occupants to personalize their environments through controlling the speed of air supplied from the vents and the air temperature by controlling the ratio of supply to re-circulated air. The system is integrated with an occupancy sensor, which enable the system to be turned off when the workstation is unoccupied. Despite the automatic detection for controlling the operation mode, the system requires a physical access to the thermostatic controller to adjust the thermal condition to the occupant's thermal demands.

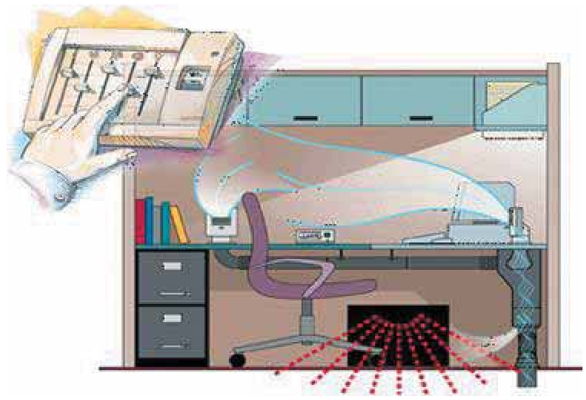


Fig. 16. Personal Environmental Module (Johnson Controls, 2007)

There have been efforts to develop an automatic control for a thermal zone or private room utilizing advanced control logics. Hamdi et al. (1999) developed an updated PMV model integrating fuzzy logic for simplifying the PMV calculation process. Through fuzzification and rule evaluations, the membership functions are calibrated based on the existing PMV function. However, this method was still dependent on the PMV formula and it mainly focused on only the calculation process. Liu et al. (2007) developed an advanced control logic using a neural network evaluation for individual thermal comfort. He indicated that the determination on the optimal combination of environmental parameters is most critical, and characterized the control logic to predict nonlinear thermal comfort depending on mean radiant temperature, air temperature, humidity, air velocity, clothing value, and metabolism rate, which have all been considered in the existing thermal comfort models. However, because there are diverse and hidden variables to affect thermal comfort perception, this control logic may carry the current PMV model's limitations. In addition, reporting the occupant's thermal sensation is still depending on the subject's feedback for training dataset. Thus, this control logic still has limitations in a fully automatic control.

3. STATEMENT OF THE PROBLEM

3.1. Limitations of Current PMV Thermal Comfort Formula and Advanced Thermal Sensation Models

As discussed in the background section, the most popular thermal comfort formula, Predicted Mean Vote (PMV), assumes environmental and human factor conditions to generate an optimal thermal condition. However, only one environmental condition is measured real time, air temperature, in a location adjacent to a group of occupants ranging from 1 to 200 in a thermal zone (CBPD, 2008). Air velocity, mean radiant temperature, relatively humidity, clothing value, and the dynamically changing activity level (i.e. metabolic rate) are not factored at all.

As a result, many researchers have found that there is a significant difference between the actual mean vote and predicted mean vote. This is partially due to the PMV model's use of average subjects' responses and on the model's assumptions of environmental and physiological conditions. In addition, the current PMV model does not consider individual physiological characteristics including age, gender, health and body mass, which have been shown to be significant variables for thermal sensations (Cena et al, 2001). Doherty and Arens (1998) identified that actual thermal sensations have a 1.3 scale difference compared to the PMV on a scale of -3 to 3. Humpreys (1994) also identified that the PMV model is more accurate with sedentary activity and light clothing, but the discrepancy would increase with higher activity levels and heavier clothing.

These limitations in statistical regression principles were also evident in advanced research related to skin temperature as a measure of actual thermal sensation. This research developed thermal perception models using human physiological reactions as input variables. However, with variations in physiological characteristics including gender, age, health, body mass, muscle, skin surface area, and composite layers of viscera, the skin temperatures of each body location vary individually (Griefahn, 20001; 2000). In addition, no specific sites have been defined for skin temperature measurement in most existing formulas (Choi, 1997). As a result, each existing model generates some deviations and error rates in predicting thermal perception.

3.2. Limitations of Current Thermostatic Control Strategies

The background research identified numerous weaknesses in current thermostatic control strategies:

- Single environmental variable- dry bulb air temperature than dry bulb temperature, relative humidity, air velocity and mean radiant temperature.
- Larger zone sizes, integrating needs of 1-200 individuals with widely varying individual conditions.
- Individual thermal sensation diversely related to gender, age, health, body mass, etc.
- Dynamic variations such as activity and clothing values.

These weaknesses cause some limitations of the current control strategies based on the predicted mean vote (PMV), thermal sensation model and manual thermostatic control in their application to the built environment as summarized in Table 3. The PMV based control is applicable for automatic control, but has no capability to reflect dynamic environmental and human factors, and individual thermal preference. Thermal sensation prediction model-based control does not consider individual physiological conditions, and the data collection and sensor locations for the model are inappropriate for pragmatic application. Manual thermostatic control could generate better performance than other control strategies, but still have a limitation in an automatic control.

TABLE 3. Limitations of current control strategies

	PMV-based control	**Thermal sensation prediction-model based control**	**Manual (thermostatic) control**
Automatic control	X	X	
Dynamic environmental factors		X	X
Dynamic human factors		X	X
Individual physiological conditions			X
Non-intrusive / convenient sensor numbers and locations			X

Thus, based on the limitations of current control technologies and research results, this dissertation is focused on bio-sensing based control for individual thermal comfort, relying on the human subject as an integrated sensor, which is able to overcome the limitations of the current control strategies. The objective and hypotheses are discussed in the following section.

4. RESEARCH OBJECTIVES

As discussed in the previous section, there have been several efforts to develop human physiological reactions- and responses-based thermal sensation models and mechanical system controls for the built environment. These control techniques, however, fail to fully consider individual physiological characteristics including age, gender and body mass. The purpose of this research is to develop a bio-sensing driven controller for mechanical systems and to demonstrate the advantages of the controller for individual thermal comfort, task performance, as well as energy savings. For the purpose of practical applications in buildings, the research also considers functionality and convenience for the users.

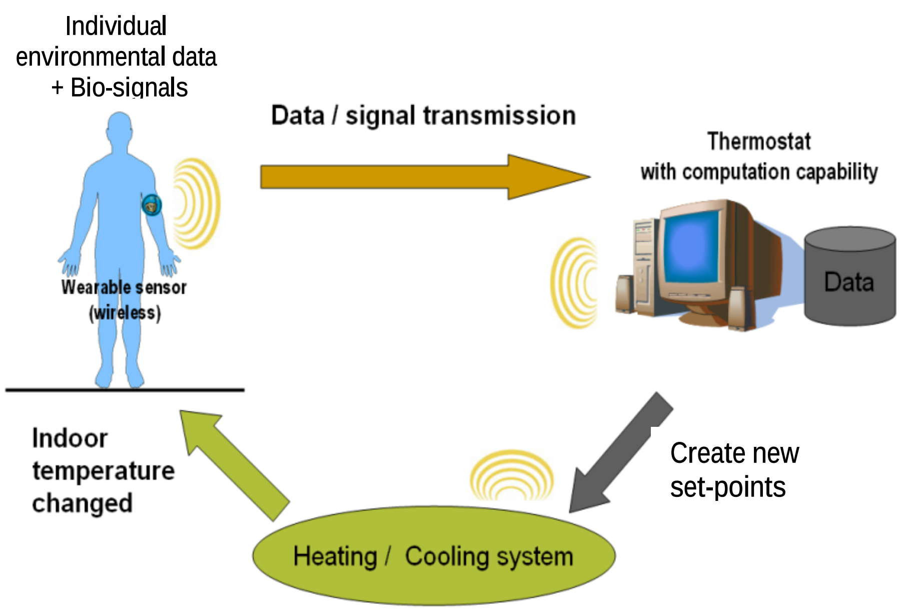


Fig. 17. Conceptual flow diagram of the proposed control system

To investigate the potentials of bio-signals and to develop a bio-sensing driven controller for individual thermal comfort (CoBi) to be applicable to any individual, the following research objectives are developed.

4.1. Research Objective 1

To investigate the correlation between bio-signals (skin temperature and heart rate), thermal conditions, and user satisfaction with thermal conditions.

- *Hypothesis 1: Certain bio-signals may respond to the thermal environment more clearly and robustly than other signals.*

There are several types of bio-signals that could be considered for this research including skin temperature and heart rate. Skin temperature and heart rate have been well proved as variables reflecting thermal sensation. Heart rate is not commonly used in thermal comfort models. Even though it is significantly affected by activity level, which is one of variables for the PMV formula, most physiological signal-based thermal sensation models depend mainly on skin temperature. This research investigated both heart rate and skin temperature responses to thermal conditions, and estimated which bio-signal type has more potential to characterize thermal sensation.

4.2. Research Objective 2

To identify the most responsive body location for skin temperature measurement to accurately indicate a subject's thermal comfort condition once skin temperature was determined to be the better bio-signal for control.

- *Hypothesis 2: Skin temperature at specific body locations reflects most accurately a subject's thermal sensation.*

- *Hypothesis 3: The most responsive body location is consistent for both heating and cooling response.*

Since this research is focused on practical application in real building environments, selecting the most responsive body locations that are non-intrusive is very important. Skin temperatures and the rates of change in dynamic thermal conditions vary widely depending on body locations. Bio-signals were measured from 10 body locations while the chamber generates different thermal conditions, reflecting cooling and heating variations in buildings.

4.3. Research Objective 3

To develop a bio-signal sensing based control system for forced-air (e.g. under-floor air distribution) HVAC systems.

- *Hypothesis 4: Depending on the parameters including time-interval for data calculation and sizes of physiological and environmental data, the accuracy of thermal sensation prediction and setpoint air temperature generation could be influenced.*

Since the control logic of the CoBi system adopts multiple statistical processes, estimating thermal sensation and correct setpoint temperature would be significantly affected by system parameters such as time-interval for calculating skin temperature gradients and data sizes for analysis. Any functional error of the CoBi bio-sensing controller may cause thermal stress to the occupants with the system over-shooting and overloading. The data analyses include the parameter decision to enhance the system performance. The system parameters are discussed in Section 7.1.

4.4. Research Objective 4

To quantify the physiological benefits and energy savings of the CoBi bio-sensing controller.

- *Hypothesis 5: The adaptive performance of the CoBi controller can contribute to maintaining the subject's thermal comfort, task performance and conserving energy use while preventing over-cooling and over-heating.*

The generated CoBi setpoint temperatures were compared with the setpoint calculated by the PMV formula for thermal comfort. Then, the thermal sensation data reported in the controlled experiment with the CoBi system were compared with the estimated sensation by the PMV formula using the experimental conditions as input variables. Parallel comparisons of the subjective sensations and the objective environmental benefits illustrate the gains of the CoBi system performance over the existing PMV formula-based control. In addition, task performances of the subjects were reviewed to investigate the contribution of the CoBi controller to their thermal sensation, which could affect the work productivity.

5. METHODS AND PROCEDURES

In this research, bio-signals and environmental data were measured through human subject experiments, and the data were analyzed to investigate relationships between the overall thermal sensation, and bio-signal(s).

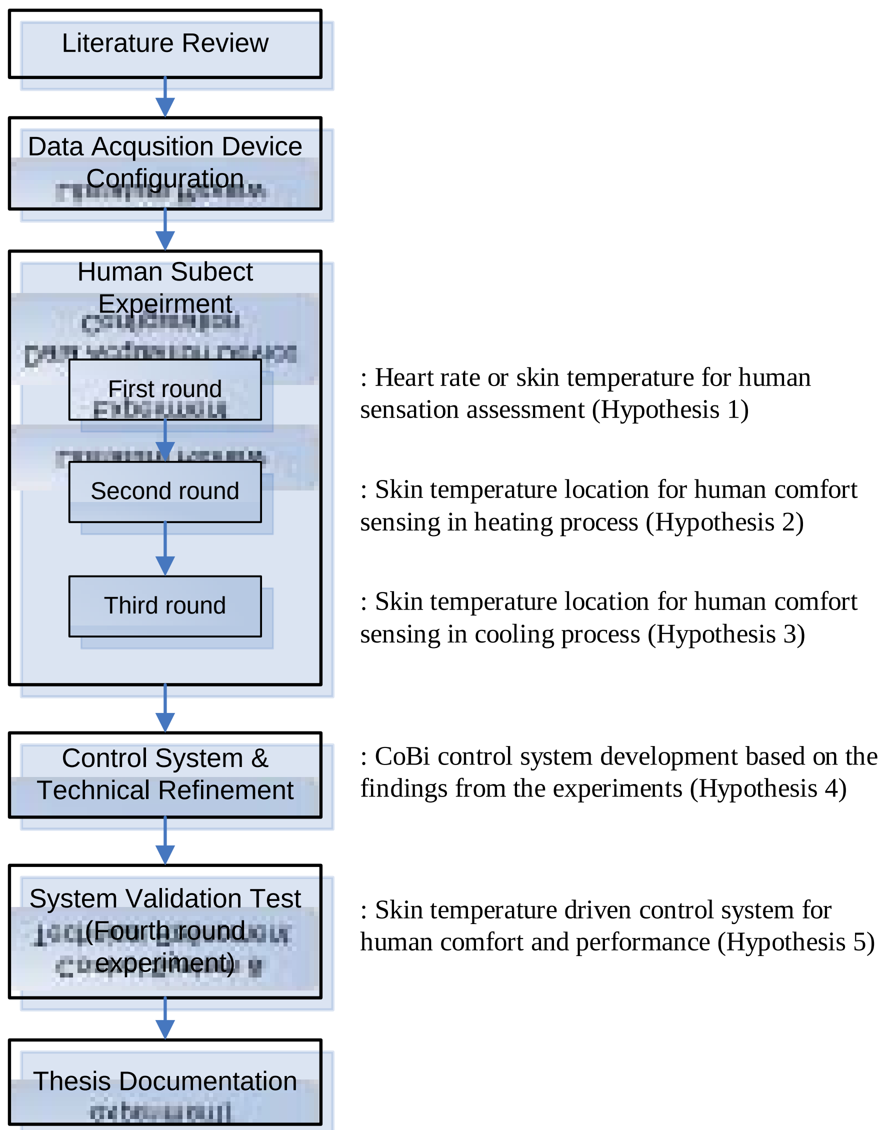


Fig. 18. Research flow diagram

The first round of human subject experiments was to find the most responsive bio-signal type between skin temperature and heart rate. Based on the findings, the second and third rounds of experiments were designed to investigate the most responsive body location to generate an interpretable signal for estimating thermal sensation. Based on the findings from the first three human subject experiments, the fourth round of experiments related to testing the bio-sensing controller in the environmental chamber for validation tests of the control system. Figure 18 summarizes the research methods and steps. The experimental resources and approaches are described in the following section.

5.1. Experimental Resources

5.1.1. Environmental chambers

For the first-round human subject experiment comparing the viability of two different bio-signals, three studio units in a residential building in Seoul, Korea were used. The dimension of the chamber is as follows (Figure 19):

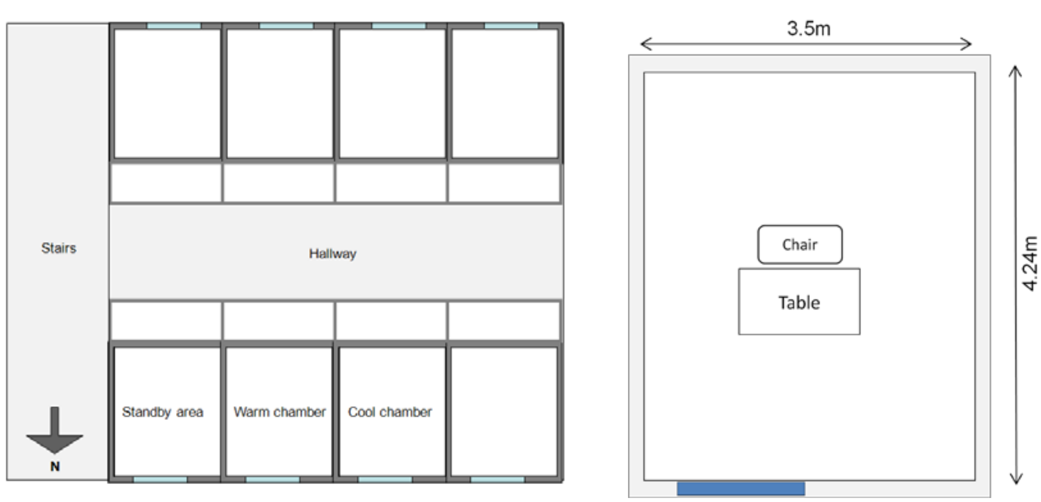


Fig. 19. Floor plans of the selected building facility (left) and the environmental chambers

Since the purpose of the experiment was to investigate whether there are significant differences in heart rate and skin temperature between cool and warm thermal conditions, the first chamber is maintained at 25 to 27°C, and the second chamber is maintained at 18 to 20°C. A third unit was used for standby, set at neutral temperature of 22 to 23°C. Each chamber maintains the targeted temperature conditions by employing the radiant floor heating system. The thermal condition of these chambers is discussed in Section of 6.1.

Fig. 20. Interior and exterior views of the Intelligent Workplace

The second, third and fourth rounds of experiments were conducted in the Intelligent Workplace (IW), a "living laboratory" at Carnegie Mellon University (Figure 20, 21 and 22). The chamber of the IW was reconfigured for the second and third-round human subject experiments and control system implementation. The size of the cubic chamber is a 2.7m by 2.7m with 2.7m (height). The floor consists of nine pieces of grid panel (0.9m by 0.9m). One floor panel has four air diffusers, two of them for supplying warm air and the other two for cool air. The warm air diffusers are connected to two units of heaters at 1000Watts/each. Through flexible ducts, the cool air diffusers were linked to an air conditioner with the capacity of 6,000 BTU (Figure 23 and 24).

Fig. 21. Exterior (left) and Interior views of the chamber

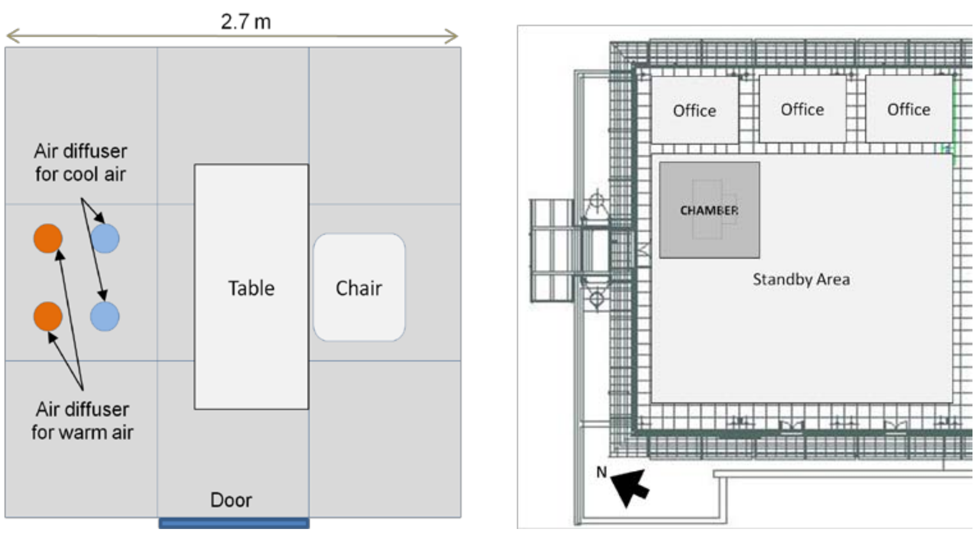


Fig. 22. Floor plan and the location of the environmental chamber

Fig. 23. Air conditioner (left) and portable heater connected to the floor of the chamber

Fig. 24. Air conditioner and two portable heaters are connected through flexible ducts to the floor diffusers of the chamber

5.1.2. Data acquisition tools

5.1.2.1. Objective data acquisition

For data acquisition for bio-signals and environmental conditions, several types of sensors and data acquisition boards were used. 10 units of skin temperatures were connected to two data acquisition (DAQ) boards for the measurement of 10 body locations discussed in Section 5.2. Each DAQ board was put into a waist bag in order for a subject to carry it easily while wearing the sensors (Figure 25).

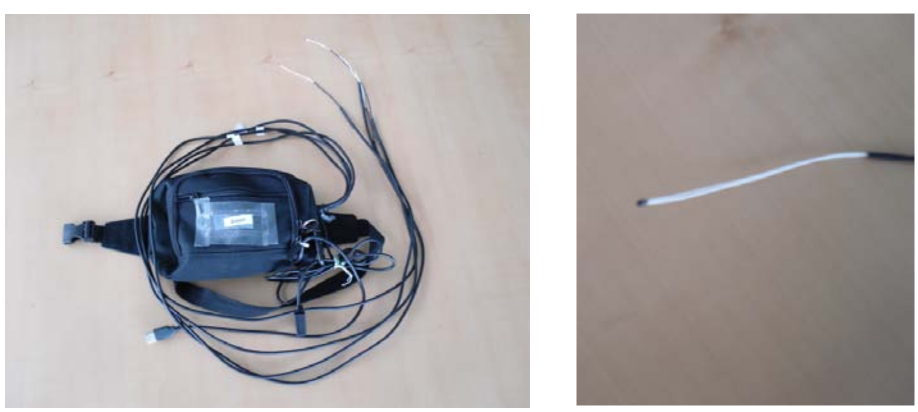


Fig. 25. Skin temperature sensors in the wearable waist bag (left) and the sensor head contacting skin surface

Fig. 26. Tripod set for sensor installations at the spot adjacent to the subject's seat

All of the environmental sensors including air temperature, mean radiant temperature, CO2 and relatively humidity sensors were installed on a tripod as shown in Figure 26, with the sensors placed at the level of breathing zone recommended by ASHRAE-55 and -62 (2004). The air temperature sensors were placed on the heights of 1.6m, 1.1m, 0.6m and 0.1 m to monitor the air temperature stratifications. The CO2 and relative humidity sensors were placed on the level at 1.1m recommended by ASHRAE-62 (2004). The mean radiant globe temperature sensor was installed at 0.6m from the floor as directed by ASHRAE-55 (2004) considering the sedentary activity level (1.2 Met) required in the experiments.

The surface temperature sensors to measure the wall surfaces of the chamber were placed at the center of each surface on the 1.1m level from the floor. The surface temperature sensors (Figure 27) were also placed on the ceiling and floor at a point adjacent to the subject's seat so that the accurate environmental conditions for each experimental subject's location were captured.

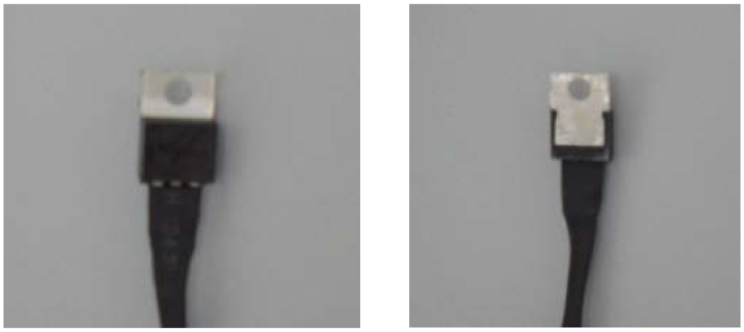


Fig. 27. Surface temperature sensors (front and rear sides)

All of the data acquisition devices are summarized in Table 4.

TABLE 4. List of data acquisition devices

Data collection device for bio-signal measurement			
Resources / Tools	**Purpose**	**Figure**	**Specification**
Surface temperature sensor (Thermistor) (Model: STS-BTA)	Skin temperature measurement		Range: -25 °C to 125°C Resolution: 0.03°C Accuracy: ±0.2°C
Heart rate sensor (Model: EHR-BTA)	Heart rate measurement		Operating temperature: 0°C to 60°C
Body fat monitor with scale (Model: Omron HBH-400)	Body weight, body fat percentage measurement and body mass index estimation		Measurement: body mass index, weight, skeletal muscle %. Range: 0 to 330 lbs Resolution: 0.2 Lb
Data acquisition board (Model: Sensor DAQ)	Data acquisition from bio-signal sensors		Three 13 bit, single-ended analog channels. One digital sensor channel. Two general-purpose analog input channels: three 13 bits single ended, 14 bits differential

Data collection device for environmental condition measurement

Resources / Tools	Purpose	Figure	Specification
Temperature sensor (Model: LM35DT)	Air, chamber surface and mean radiant temperature measurements		Range: -55°C to 150°C Resolution: 0.01°C Accuracy: ±0.5°C
CO_2 sensor (Model: Telarire6004)	CO_2 density measurement in the chamber		Range: 0 to 2000 ppm Accuracy: ±40ppm
Air velocity sensor (Model: Testo 405-V2)	Air velocity measurement		Range: 0 to 2000fpm (10m/s) Resolution:0.1fpm (0.01m/s) Accuracy: ±5%
Humidity sensor (Model: HIH-4000-003)	Relative humidity measurement		Range: 0 to 100% Resolution:0.5% Accuracy:±3.5%
Black globe (reconfigured with LM35DT)	Mean radiant temperature measurement		Range: -55°C to 150°C Accuracy: ±0.5°C
Data acquisition board (Model: NI DAQ USB-6008 & 6009)	Data acquisition from environmental sensors		8 analog inputs (12-bit, 10kS/s) 2 analog output (12-bit, 150 S/s) 12 digital I/O, 32-bit counter

Heating and cooling device

Resources / Tools	Purpose	Figure	Specification
Portable heater (Model:3LY40-8440)	Heating for the chamber		Two units used (1,000 watt each)
Air conditioner (Model: Firgidaire FAA062P7A)	Cooling for the chamber		Capacity: 6,000 BTU

Software for sensing, control and data analysis

Resources / Tools	Purpose	Figure	Specification
LabVIEW 8.5	Data acquisition from sensors and control logic design		
Minitab 5.0	Data analysis		

To display all of the collected data from the chamber and a human subject, a data acquisition interface was developed using LabVIEW 8.5 software as shown in Figure 28. Based on a sensing interval of 10 seconds, the interface continuously shows all collected data including heart rate, skin temperatures from 10 body locations, as well as air temperature, humidity, carbon dioxide and surface temperatures of the chamber.

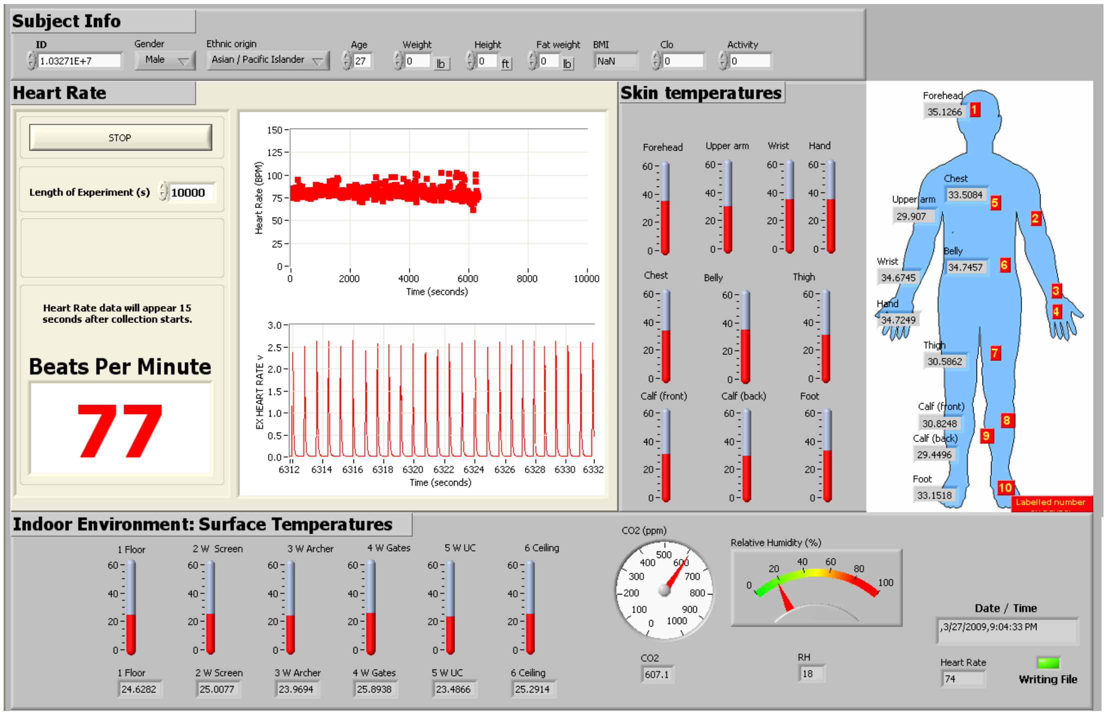


Fig. 28. CoBi data collection interface (designed with LabVIEW)

5.1.2.2. Subjective data acquisition

- Human subject recruitment

For the first-round human subject experiment, voluntary subjects were randomly recruited from Shingu College in Seoul, South Korea with the help of the Department of Interior Design. For the second, third and fourth rounds of experiments, subjects were recruited from the Carnegie Mellon campus through advertising on the campus bulletin boards, and compensated at $10 per hour.

- Questionnaire for thermal sensation and comfort

To determine thermal sensations from subjects as environmental conditions change, the seven-point scale survey developed for the PMV model (ASHRAE-55, 2004) was adopted as shown in Table 5.

TABLE 5. Examples of thermal perception questionnaires

1. What is your overall level of thermal comfort?

Very unsatisfied	Unsatisfied	Slightly unsatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
□	□	□	□	□	□	□

2. What is your overall thermal sensation?

Very cool	Cool	Slightly cool	Neutral	Slightly warm	Warm	Very warm
□	□	□	□	□	□	□

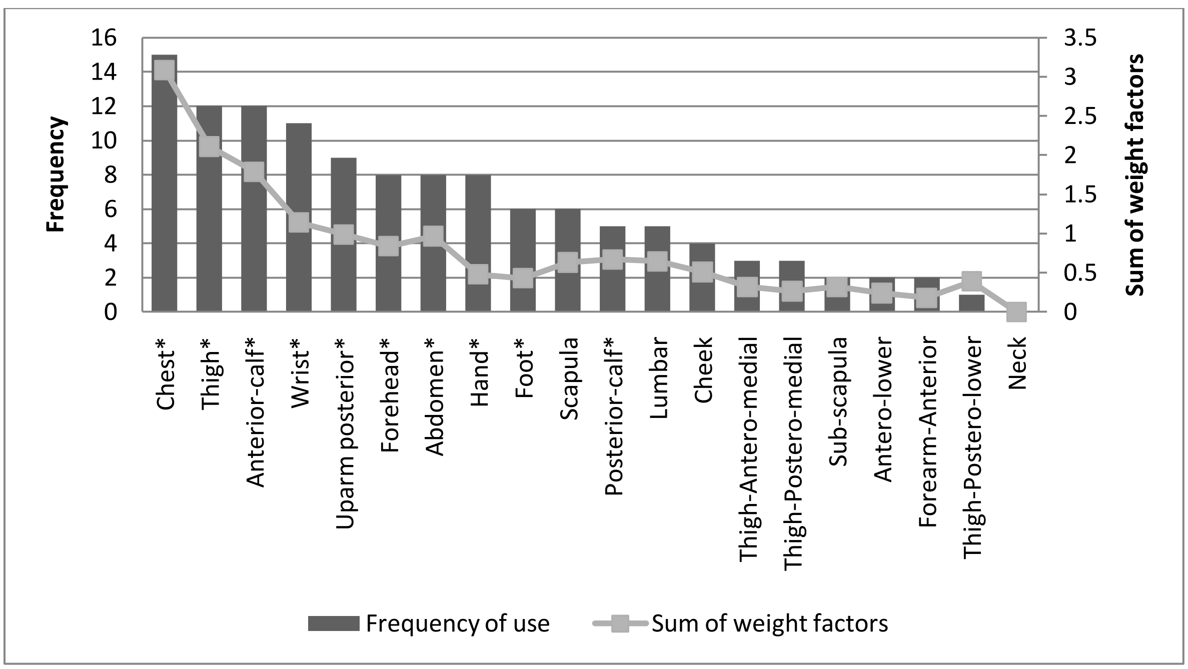


Fig. 29. Most frequently used body areas in 16 existing thermoregulation models (Choi, 1997)

The 10 body locations selected for skin temperature measurements were decided based on the findings of the 16 thermoregulation models completed over the 60 years as shown in Figure 29. Subjects were asked to report their thermal sensations on the forehead, upper arm, wrist, hand, belly, thigh, calf, foot, the overall body, and their overall thermal satisfaction through the survey interface developed in LabVIEW (Figure 30). Each subject can simply report their thermal sensation, and overall comfort through the interface using a moving button, and the selected answers are automatically recorded in the data acquisition computer. The research mainly focuses on the overall thermal sensation which is the most important measure for a thermal comfort condition in ASHRAE-55 (2004) while minimizing the dissatisfaction rate or possibility (Figure 31). Since all the experimental conditions are thermally symmetric environments defined by ASHRAE-55 (2004), the reported local body sensations were used only for monitoring any partial discomfort, which can be expected as a rare condition in a symmetric thermal condition. The overall comfort data is also used as a reference to support the data of the overall thermal sensation.

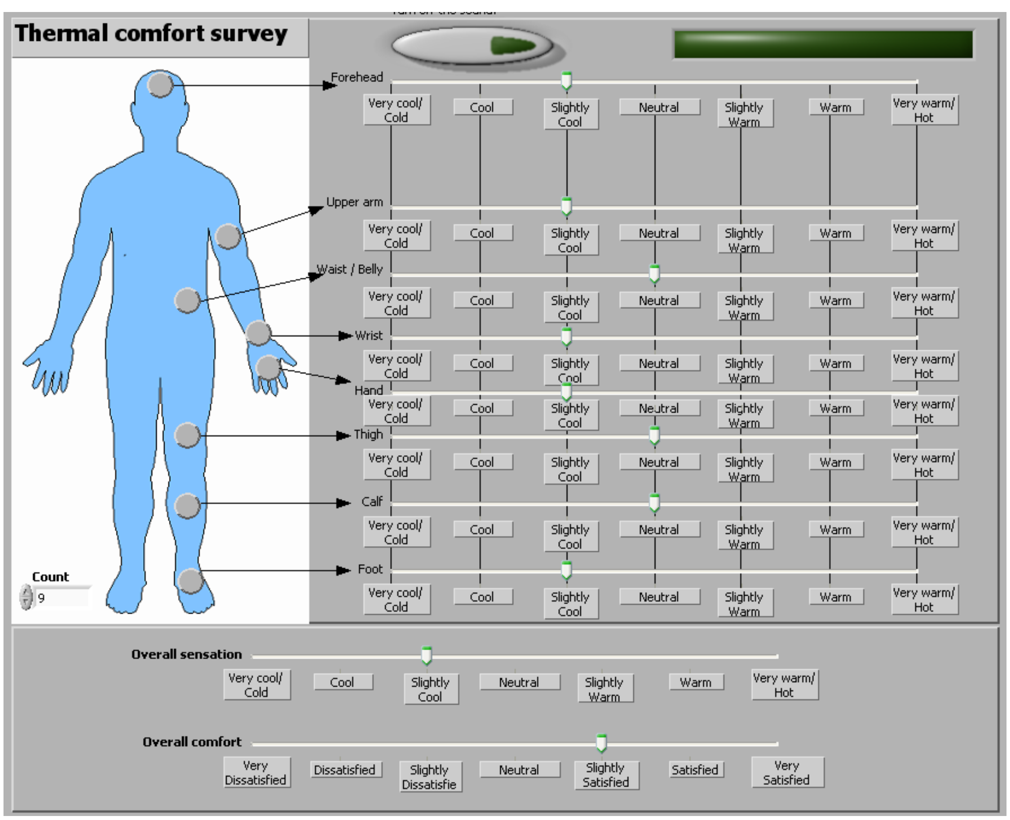


Fig. 30. CoBi thermal perception survey interface (design with LabVIEW)

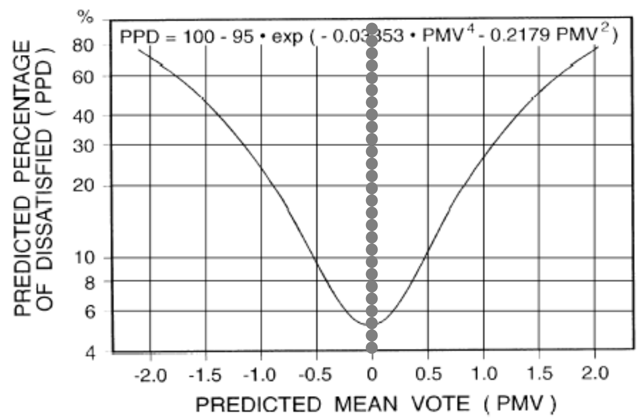


Fig. 31. Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV) (-2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm) (ASHRAE-55, 2004)

5.1.2.3. Experimental conditions of human factors

For a consistent and stable experimental condition, the subjects were asked to not have any food and water at least 30 minutes before the experiment, and asked to stay in a moderate temperature environment for 30 minutes or an hour prior to the experiment.

5.2. Human Subject Experiments

The research performed four different rounds of human subject experiments. The number of subjects participated in each round of experiments ranges from 11 to 27, and the total number of subjects participated in the research is 71. Table 6 summarizes the sample size by experiment round and their demographics. Each subject's bio-signal and environmental data were acquired with the sensing interval at 10 seconds, and the number of the bio-signal data generated from each subject is between 900 and 1080. The collected bio-signal and environmental datasets were paired with each thermal sensation survey dataset for data analyses.

Each round of the human subject experiments performed in this research was reviewed and approved by the Carnegie Mellon University Institutional Review Board (IRB).

TABLE 6. Summary of experimental subject information

	First round	Second round	Third round	Fourth round
Subject size (male: female)	15 (6 : 9)	27 (15 : 12)	11 (6 : 5)	18 (8: 10)
Number of thermal sensation survey	120 (8 / subject)	270 (10 / subject)	110 (10 / subject)	216 (12 / subject)
Experimental time	180 minutes	130 minutes	130 minutes	210 minutes
Average age (St.Dev.*)	23.20 (4.78)	27.33 (6.46)	27.09 (6.32)	25.72 (4.21)
Average BMI (St.Dev.)	21.401 (3.347)	22.746 (3.239)	21.953 (2.646)	23.014 (3.042)

* St. Dev: standard deviation.

5.2.1. Measurements of physiological information

5.2.1.1. Physiological information

One of the human variables affecting thermal comfort is body mass index (BMI), which estimates body fat percentage (Wang, 1992). Since physical movement may generate different metabolism rates affected by the subject's BMI, the generated heat from the human body can be different individually despite the same activity level defined by the PMV model. At the beginning of each experiment, the body mass index of each subject was calculated by measuring the subjects' weight and height.

5.2.1.2. Skin temperature measurement

Existing thermoregulation models have selected three to fifteen body segments for skin temperature measurement to estimate mean skin temperature (Yao, 2007). As illustrated in Figure 29, the most frequently used body locations for assessing skin temperature in the 16 existing thermoregulation models are the chest, thigh, anterior-calf, wrist, posterior upper arm, forehead, abdomen, hand, foot and scapula. The body areas are ordered by the selection frequency in the existing models alongside the sum of the weight factors assigned in each model's formula.

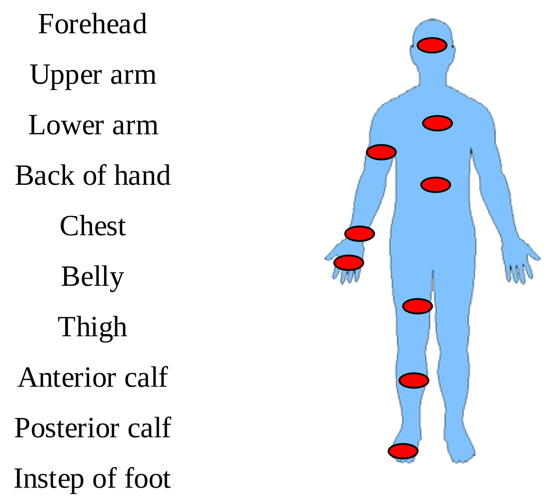


Fig. 32. CoBi selected body locations for bio-signal collection

These body locations for skin temperature sensors are important for both control effectiveness and for practical system application of wearable sensors. In this research, ten body locations were selected from those most frequently used in the existing models to measure skin temperatures: forehead, posterior upper arm, wrist, back of the hand, chest, belly, thigh, anterior calf, posterior calf, and instep of a foot (Figure 32). The sensing interval was 10 seconds for all the measurements. As the posterior-calf has a larger weight factor than the scapula, and is a more convenient sensor location, the research selected the posterior-calf as the 10^{th} skin area for the experiment.

5.2.1.3. Heart rate measurement

To investigate the relations between heart rate and thermal sensation, heart rate was also measured with a 10 second sensing interval, using a heart rate sensor worn on the chest.

5.2.1.4. Survey for thermal perception

During the experiment, subjects were asked to report their thermal sensation on each skin temperature measurement location, and overall thermal sensation and comfort every 10 to 15 minutes. In the pilot study for the research, it was found that the highly frequent thermal perception survey hindered the subjects' awareness to discriminate the thermal sensation from the prior perception. Based on this finding, the research selected 10 to 15 minutes for the thermal perception survey interval depending on the taken time for answering the survey.

5.2.2. Measurements of work productivity

Thermal comfort has been researched as a significant variable affecting work productivity. Three performance task-sets were given to subjects in the second and third rounds of experiments, and six performance task-sets were completed by subjects in the fourth-round experiment. Each-task set consists of 40 three-digit by two-digit multiplication problems. A subject was asked to do each task-set for eight minutes. The answers were scored in terms of correctness, speed, and the combined score based on the number of accurate answers and the number of responses. Since all the subjects have individually different performance skills, an individual's performance was only compared to the highest score among the performed task-sets by the same individual and was converted into percentage. Correctness, speed and the combined score were used for evaluating work performance of subjects in different thermal comfort conditions.

5.2.3. Measurements of environmental information

For the CoBi experimentation to be robust, all environmental conditions other than air temperature must be held constant. This included: mean radiant temperature, surface temperature, carbon dioxide (CO2) concentration, and relative humidity as well as air velocity.

5.2.3.1. Air temperatures, Mean radiant temperature, and Surface temperatures

Symmetric thermal conditions are critical to thermal sensation, as defined by ASHRAE-55 standards, so the test chamber was controlled to ensure whether the different between two extreme surface temperatures was maintained within 5.4 °C.

To monitor the thermal conditions in the experimental chamber, both air temperature and mean radiant temperature were continuously measured. Air temperature stratification was also monitored at 1.6m, 1.1m, 0.6m and 0.1m above the floor finish. All the surface temperatures on the four sidewalls, ceiling and floor were monitored to maintain the horizontal symmetric condition. Since the environmental conditions were measured using the same LabVIEW interface with bio-signal data acquisition, the sensing interval of 10 seconds were shared between the data acquisitions for bio-signals and environmental conditions.

5.2.3.2. CO2, Relative humidity, and Air velocity

To maintain a consistent thermal condition in each experiment and to estimate the operative temperature, relative humidity and air velocity were also measured. CO2 density was also measured to monitor the air quality in the chamber, with a goal of ventilation consistency, but not to exceed the upper limit, 1000ppm, suggested by ASHRAE-62 considering the outdoor CO2 concentration at an average of 400 ppm.

6. BIO-SIGNAL TYPES AND BODY LOCATIONS

6.1. First-Round Experiment: Identifying the Most Robust Bio-signal for Thermal Sensation

The objective of the first-round experiment was to investigate if heart rate or skin temperature is more significantly related to thermal sensation. Several researchers report that thermal environments measurably affect the heart rate (Liu et al., 2008; LeBlanc et al, 1976; Kamon et al, 1971). However, these studies are typically focused on extreme thermal environments. Because this research is focused on indoor environments where the thermal variations will be relatively moderate, the effect of thermal condition on heart rate may be different to that of the extreme thermal environment.

6.1.1. Experimental procedure

The human subject experiments were undertaken with 14 volunteers from a college in Korea, aged between 19 and 33 years, in twin chambers. One chamber was for the cool condition and the other for the warm condition. Each experiment lasted for three hours including changing clothes, waiting in a standby condition, conducting the experimental measurement, and answering the thermal sensation survey.

Each chamber used an independent radiant floor heating system controlled by an individual heat pump. To generate different thermal conditions, one room was conditioned with a warm floor and the other with a cool floor. The air temperature of the warm room ranged from 25 to 27 ºC, and that of cool room was from 18 to 20 ºC. Mean radiant temperature, CO2, air velocity and relative humidity were maintained at a constant level. Table 7 summarizes the thermal conditions of each chamber.

TABLE 7. Thermal conditions of the chambers

		Cool chamber	**Warm chamber**
Air temp on 1.1m height		18-20°C	25-27 °C
Surface temperature	Northern wall	16±0.5°C	21±0.5°C
	Southern wall	17±0.5°C	23±0.5°C
	Eastern wall	17±0.5°C	23±0.5°C
	Western wall	17±0.5°C	23±0.5°C
	Ceiling	17±0.3°C	24±0.3°C
	Floor	16-18°C	32-34°C
Relative humidity		30±5%	27±5%
CO2		600-900 PPM	600-900 PPM
Air velocity		0 m/s	0 m/s

To maintain the same clothing value, all the subjects were asked to change to a uniform at 0.8 Clo: long-sleeve running shirts and pants assembled for the experiment. A subject was asked to change their activity levels in four phases: lying down on a floor (0.8 Met), sitting on a floor (1.0 Met), sitting on a chair (1.2 Met), and cycling (2.5 Met) (to mimic active work) (Figure 33). Subjects were also asked to report their thermal sensation at the end of each activity. To ensure the same starting thermal condition for a subject, they remained in a waiting room for 30 minutes prior to and between the experiments, to stabilize their metabolism rates and to prevent any differences in experimental conditions among the subjects. The air temperature of the standby room was 23±0.5°C with 27.5±2.5 % relative humidity.

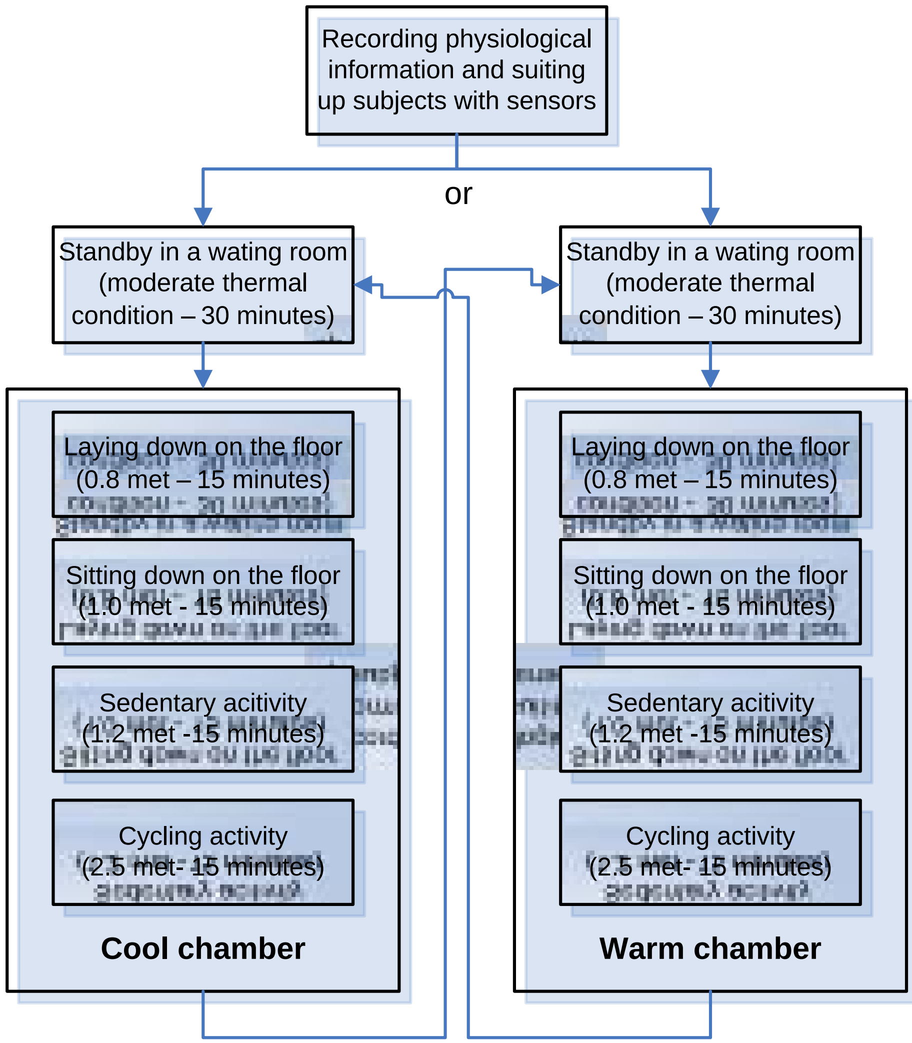


Fig. 33. First-round experiment procedure diagram

During the experiment, skin temperatures at 10 body locations, heart rate, and environmental conditions including air temperature, relative humidity, mean radiant temperature, radiant surface temperatures on walls, ceiling and floor, carbon dioxide concentration and air velocity, were continuously recorded with a 10 second sensing interval. The environmental component measurements were to ensure consistent control conditions across all tests. A subject remained in each activity level for 15 minutes from 0.8 to 2.5 Met. The experiment was repeated in the cool and warm chambers (Figure 34).

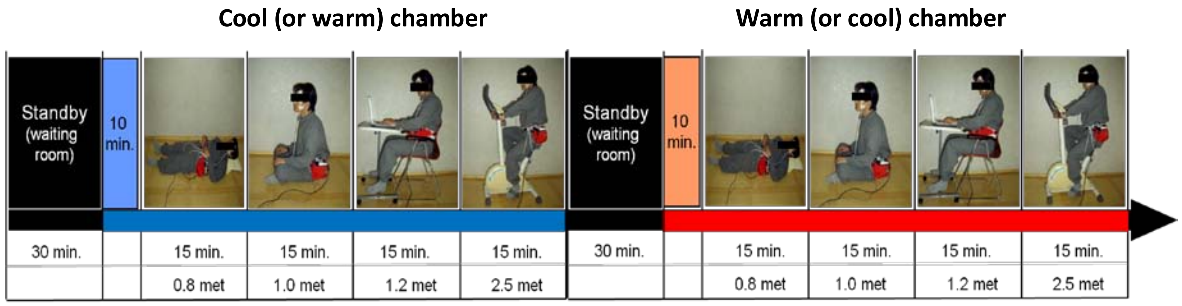


Fig. 34. Figurative procedure of the first-round experiment

6.1.2. Correlation between heart rate and thermal condition

6.1.2.1. Comparison of heart rate between cool and warm conditions

The lack of statistical significance in the experimental results reveal that measured heart rates may not adequately reflect thermal comfort at low activity levels.

Figure 35 and 36 illustrate the average heart rate of each subject in each activity level. As expected, heart rates vary depending on subjects. In low activities (0.8, 1.0 and 1.2 Met) the heart rates ranges from 55 to 85, but the levels are increased up to 130 in 2.5 Met. The measured heart rates show very similar patterns between the cool and warm chambers across the subjects, although heart rates are consistently higher in the worm chamber. Heart rates at 0.8, 1.0 and 1.2 Met have averages between 70 and 73 beats per minute (BPM) in the cool chamber, while the average heart rate at 2.5 Met is increased to an average at 86.6 BPM with a large standard deviation. In the warm chamber, the patterns of heart rate are similar with those in the cool chamber, though the averages are higher with a 98.41 BPM at 2.5 Met.

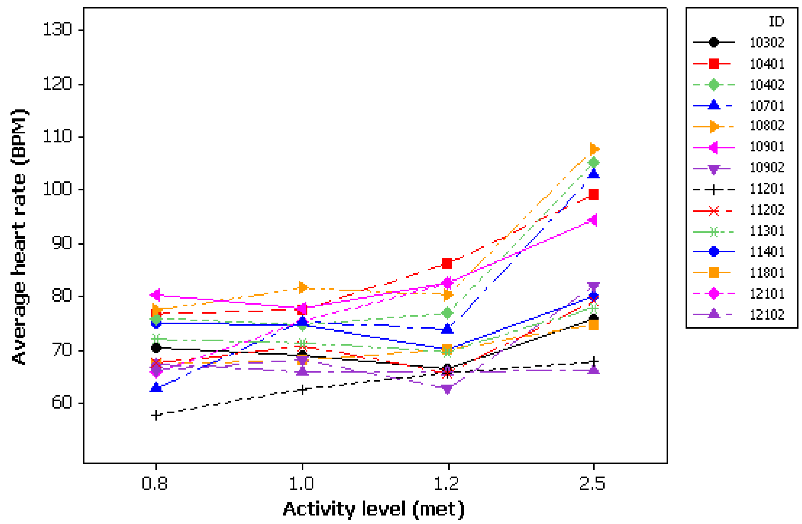


Fig. 35. Heart rates of subjects in each activity level in cool chamber

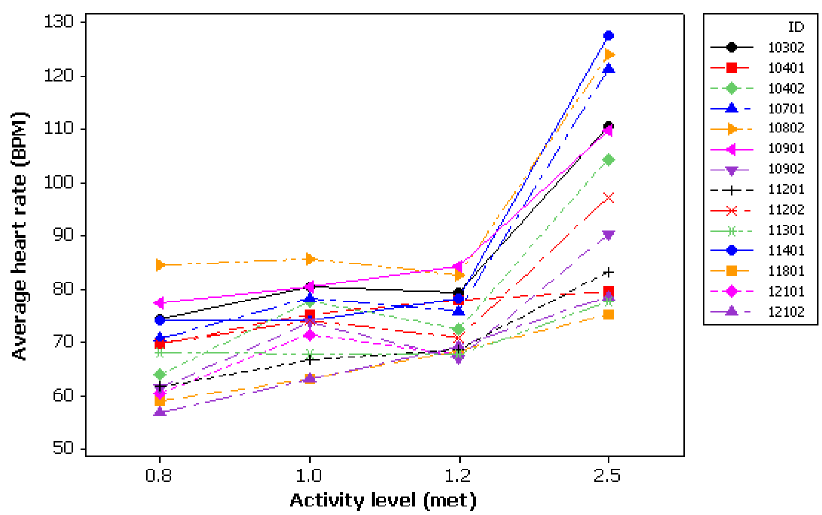


Fig. 36. Heart rate of subjects in each activity level in warm chamber

The ANOVA test in the heart rate data measured from all the subjects is shown in Table 8 and 9. The heart rate at 2.5 Met is significantly different compared to other activity levels, with p-values at around 0.000 in both the cool and warm conditions. However, the heart rate at the low activity levels, 0.8, 1.0 and 1.2 does not reveal statistically significant differences in the cool and warm chambers.

TABLE 8. ANOVA test with all data set in the cool chamber

Activity (Met)	Average	St. Dev.	p-value	p-value
0.8	70.13	6.37	0.536	*0.000**
1.0	72.28	5.25		
1.2	72.70	7.65		
2.5	86.59	14.43		

*: Statistically significant

TABLE 9. ANOVA test with all data set in the warm chamber

Activity (Met)	Average	St. Dev.	P-value	p-value
0.8	67.99	7.93	0.056	*0.000**
1.0	73.69	6.73		
1.2	73.59	5.99		
2.5	98.41	19.06		

*: Statistically significant

The measure of hearts rates from a subject in each chamber is compared through a paired t-test to investigate the effects of thermal sensation on heart rate (Table 10).

TABLE 10. Paired t-test of heart rates of subjects between cool and warm conditions

Activity level (Met)	Average heart rate (BPM)		p-value
	Cool chamber	Warm chamber	
0.8	70.13	67.99	0.235
1	72.28	73.69	0.266
1.2	72.7	73.59	0.636
2.5	85.55	98.41	***0.017****

*: Statistically significant

The paired t-test between the two chambers explains that no significant differences are found in all activities except at 2.5 Met. Only at 2.5 Met is the average heart rate in the warm chamber higher than that of the cool chamber with a statistical significance.

During the experiment, subjects were asked to maintain 2.5 Met by cycling on an indoor bike for 15 minutes. However, it was challenging for subjects to keep a constant pedaling speed to maintain the constant 2.5 Met. This experimental limitation may cause the wide range of deviation in heart rate at 2.5 Met compared with other activity levels, and may generate a significant difference in the heart rate between the two thermal conditions. Due to the limitation of the experimental condition, the research mainly consider the activity levels between 0.8 and 1.2 Met, which are more prevalent in general built environments. Based on the statistical analyses, it is concluded that the heart rate is more affected by a subject's activity level with a large difference in metabolism rates, rather than by the variations in thermal conditions expected in typical indoor environments.

6.1.2.2. Comparison of heart rate by gender

At low Met, no significant differences of heart rate patterns between genders were found.

The paired t-test in Table 11 illustrates no significant comparison sets between the two thermal conditions in each gender group except for male subjects at 2.5 Met. The average heart rate at 2.5 Met in the warm condition is higher than that under the cool condition by an average of 10 beats per minute (BPM). Due to the experimental limitation discussed in the previous section, this finding may need further investigation with a larger sample sizes.

TABLE. 11. Paired t-test of heart rate by gender group

	Male (N=6) Average heart rate (BPM)			Female (N=8) Average heart rate (BPM)		
Activity level (Met)	Cool chamber	Warm chamber	P-value	Cool chamber	Warm chamber	P-value
0.8	68.25	64.75	0.127	72	71.24	0.799
1	70.19	69.5	0.656	74.38	77.88	0.081
1.2	71.67	70.97	0.792	73.73	76.21	0.389
2.5	76.61	86.92	***0.026****	93.21	108.27	0.124

*: Statistically significant

6.1.2.3. Comparison of heart rate by BMI group

No significant differences of heart rate patterns between low and high body mass index groups.

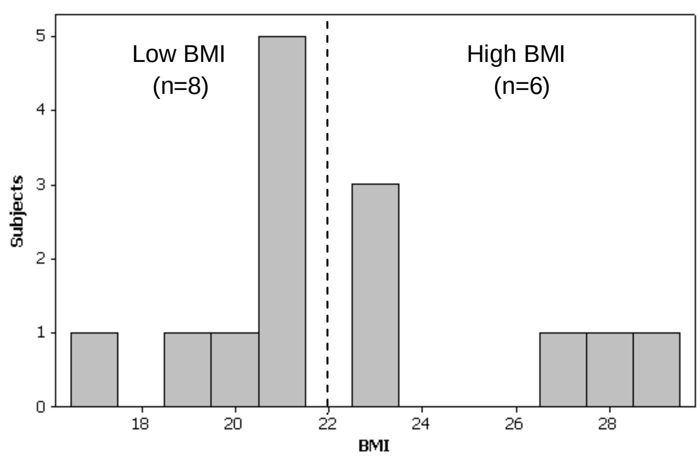


Fig. 37. Distribution of subjects' BMI

Conventionally, the body mass index is grouped in four categories: under weight (≤ 18.5), normal weight (18.5-24.9), over weight (25-29.9), and obese (≥30) (World Health Organization, 2010). Since the BMI distribution of the recruited subjects was all between 17 and 29 (Figure 37), 22 was selected as a threshold to define a low-BMI and a high-

BMI group to balance the number of subjects for the comparison analysis. No BMI group shows significant differences in heart rates between the two thermal conditions. All of the calculated p-values are significantly higher than 0.05 (Table 12).

In summary, the heart rate may not be significantly affected by thermal conditions. This finding holds true irrespective of gender and body mass index. Therefore, heart rate may not be a good indicator to estimate the thermal sensation of a subject.

TABLE. 12. Paired t-test of heart rate by BMI group

	Low BMI (N=8) Average heart rate (bpm)			High BMI (N=6) Average heart rate (bpm)		
Activity level (Met)	**Cool chamber**	**Warm chamber**	**p-value**	**Cool chamber**	**Warm chamber**	**p-value**
0.8	68.97	68	0.630	71.67	67.99	0.296
1	72.07	74.25	0.273	72.57	72.95	0.810
1.2	73.65	73.53	0.968	71.43	73.67	0.281
2.5	85.64	96.08	0.157	85.45	101.14	0.079

6.1.3. Correlation between skin temperature and thermal condition

There are many research and experiments indicating the significant relationship between skin temperatures and thermal conditions (Wang et al., 1992; Hardy et al., 1966; LeBlanc et al., 1976; Yao et al., 2007). Given the existing research, this research seeks instead to identify body locations of significance. Since the main purpose of the first-round experiment is to find the relationship of heart rate and thermal sensation, the skin temperature analysis deals with only major distinctions in skin temperature at different metabolism rates in the cool and warm conditions.

6.1.3.1. Comparison of overall skin temperature between cool and warm conditions

Skin temperatures are significantly affected by thermal conditions.

To calculate an average body skin temperature of individuals, the 10 collected skin temperatures from the head to foot are simply averaged for an arithmetic mean level. In the cool chamber, the average skin temperature normally shows the highest level at 0.8 Met and the lowest at 2.5 Met as illustrated in Figure 38. Since the temperature of the cool chamber is significantly lower than the standby room, the skin temperature decreases as the subjects stays longer because they lose their body heat to the environment and the performed activity levels are not high enough to compensate for the body heat loss. The average skin temperature also varies depending on individual physiology in similar thermal conditions. The range of skin temperatures across the subjects is between 24ºC and 32ºC depending on individual physiological characteristics and activity levels.

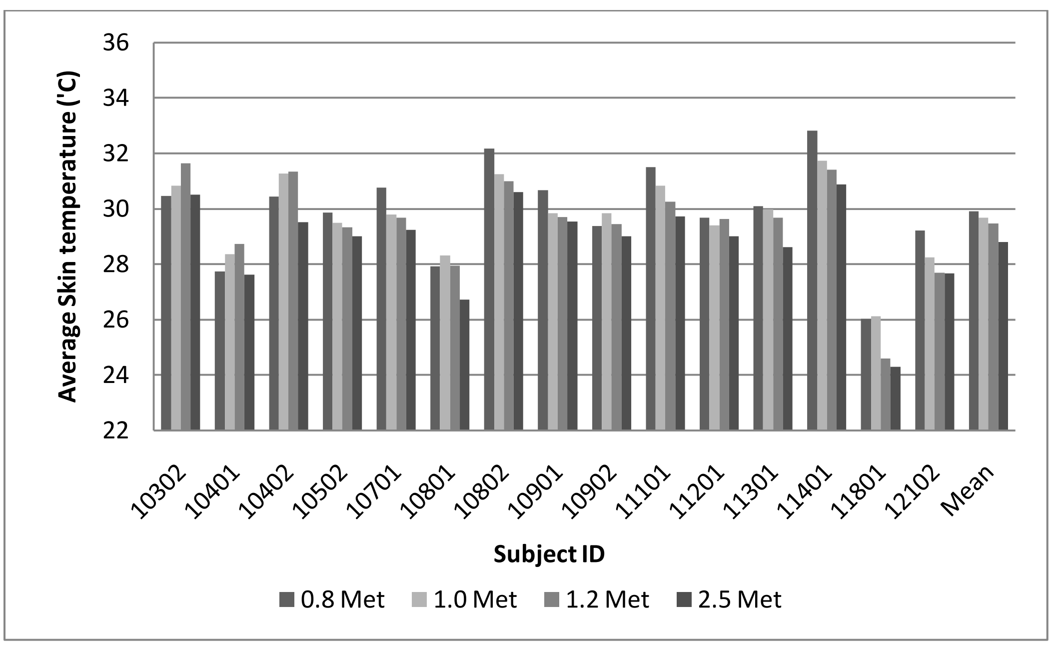


Fig. 38. Skin temperatures with different activities in the cool chamber

The warm chamber shows the opposite outcome (Figure 39). Typically, the average skin temperature increases slightly as the activity level increase. However, the pattern is not as consistent compared to the case of the cool chamber. The range of skin temperature across the subjects is between 28.5ºC and 34ºC depending on individual physiological characteristics and activity levels.

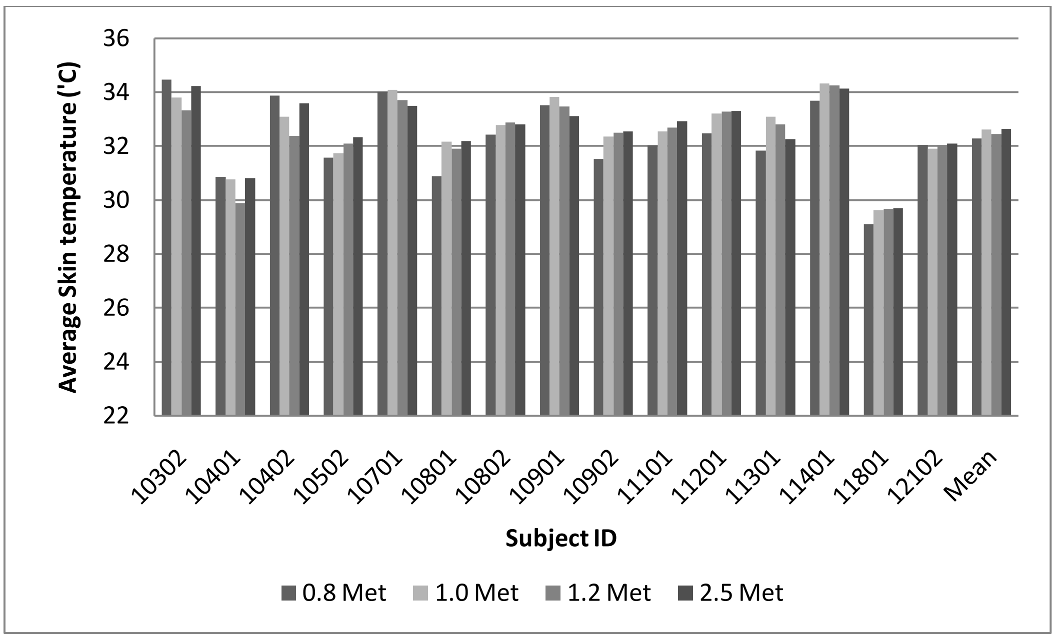


Fig. 39. Skin temperatures with different activities in the warm chamber

The overlap between the average ranges of 24°C to 32°C in the cool chamber and 28.5°C to 34°C in the warm chamber make absolute skin temperature a poor indicator for the thermal sensation. The paired t-test supports the distinction of the average skin temperature between the two different chamber conditions. The test results show that all comparisons of skin temperatures between the two thermal conditions of each activity level are statistically significant with a p-value at 0.000 (Figure 40 and Table 13).

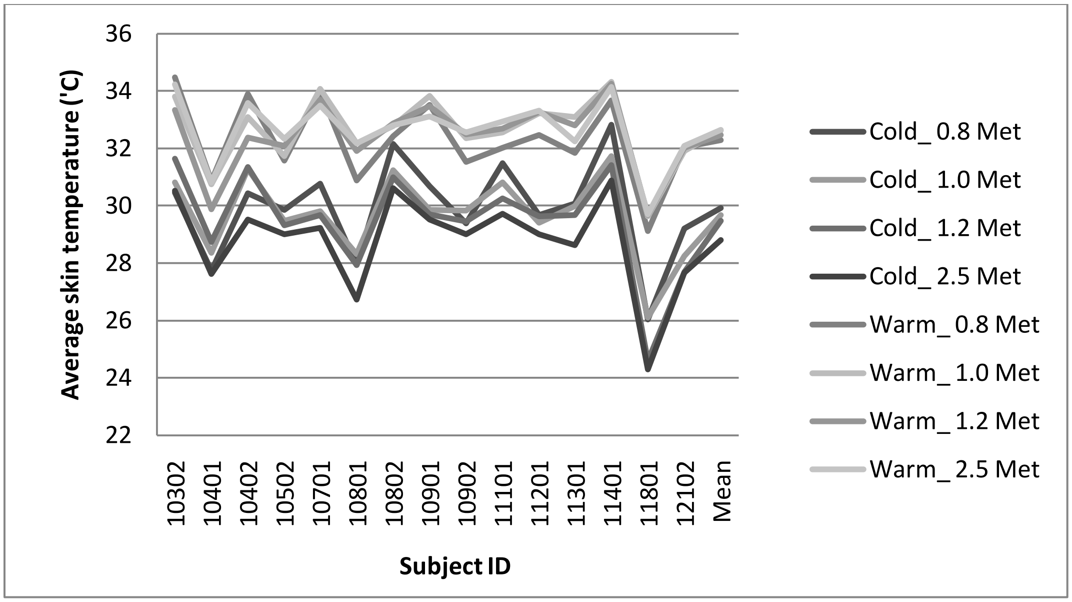


Fig. 40. The comparison of skin temperatures between the cool and warm chambers

TABLE 13. Paired t-test of heart rates of subjects between cool and warm conditions

Activity level (Met)	**Average skin temperature (°C)**		**p-value**
	Cool chamber	**Warm chamber**	
0.8	29.92	32.29	***0.000****
1	29.69	32.62	***0.000****
1.2	29.47	32.46	***0.000****
2.5	28.79	32.64	***0.000****

Since the comparison tests in Figure 40 and Table 13 illustrate that all of the average skin temperatures are significantly different depending on the thermal conditions, further analyses based on the gender and body mass index were not performed.

6.2. Body Location Selection for Thermal Sensation Estimation

The number of sensors and their locations are critical to the practical application of the proposed model. In the second and third-round human subject experiments, the skin temperatures from each sampled body location were analyzed to investigate the body location where skin temperature has the most potential to mirror a subject's overall thermal sensation. The experimental conditions and procedures were the same for the two rounds except for air temperature. The second-round experiment was a study of response during a temperature rise from 20°C and to 30°C and the third-round was for a temperature drop from 30°C to 20°C. These two sets of experiments help to define the best sensor location for the heating-up environment and for the cool-down environment.

6.2.1. Experimental methods and procedures

Each round of the experiment was performed for 100 minutes in the environmental chamber at Carnegie Mellon University. Each subject started the experiment in a standby room between 23°C and 24°C for 30 minutes to stabilize his/her physiological condition after being fitted with 10 skin temperature sensors. This standby setting can contribute to a consistent level of metabolism rate at the starting point in each experiment.

Air temperature was increased from 20°C to 30°C at the rate of one degree per 10 minutes for the second-round experiment, and decreased from 30°C to 20°C for the third-round experiment. Figure 41 shows a typical condition of the environmental chamber during the second-round experiment. In the chamber, the CO2 concentration ranged between 500 and 800 ppm. Considering the average outdoor CO2 concentration at 400 ppm, the indoor density was within the range recommended by ASHRAE-62 (2004): less than 700 ppm above the outdoor concentration. The relative humidity was normally around 25% ±5%.

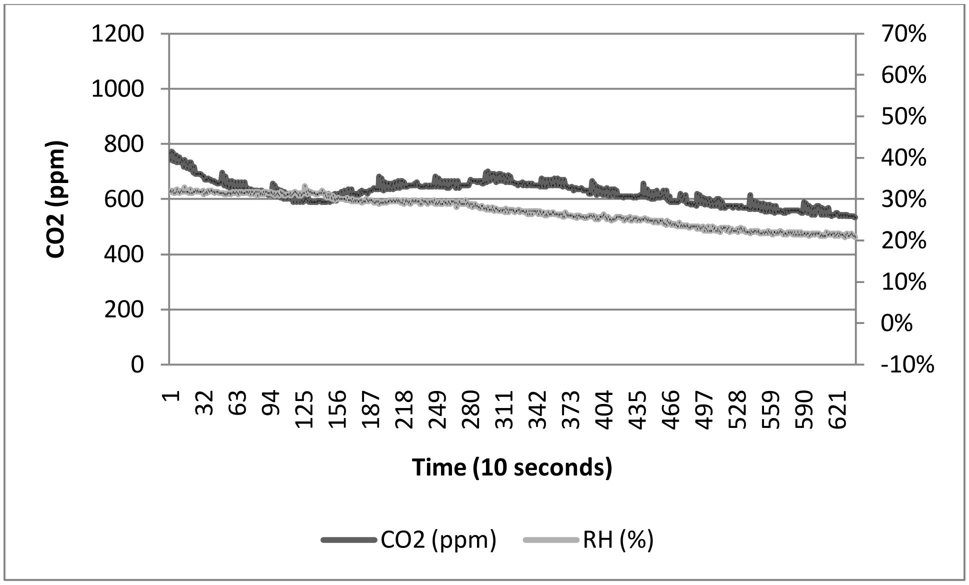


Fig. 41. Relatively constant CO_2 and relative humidity conditions during the second-round experiment (air temperature rising from 20-30°C)

The radiant thermal condition in the chamber is symmetric without any significant differences between wall surface temperatures, the ceiling, and the floor surface. The chamber environment has a moderate difference between the horizontal and vertical variation, well within ASHRAE-55 (2004) standards that limit temperature difference to less than 10ºC, and vertical temperature difference between the ceiling and the floor to less than 5 ºC. As shown in Figure 42, the differences between wall surface temperatures were lower than 1 ºC and between ceiling and floor surface were less than 2.0°C.

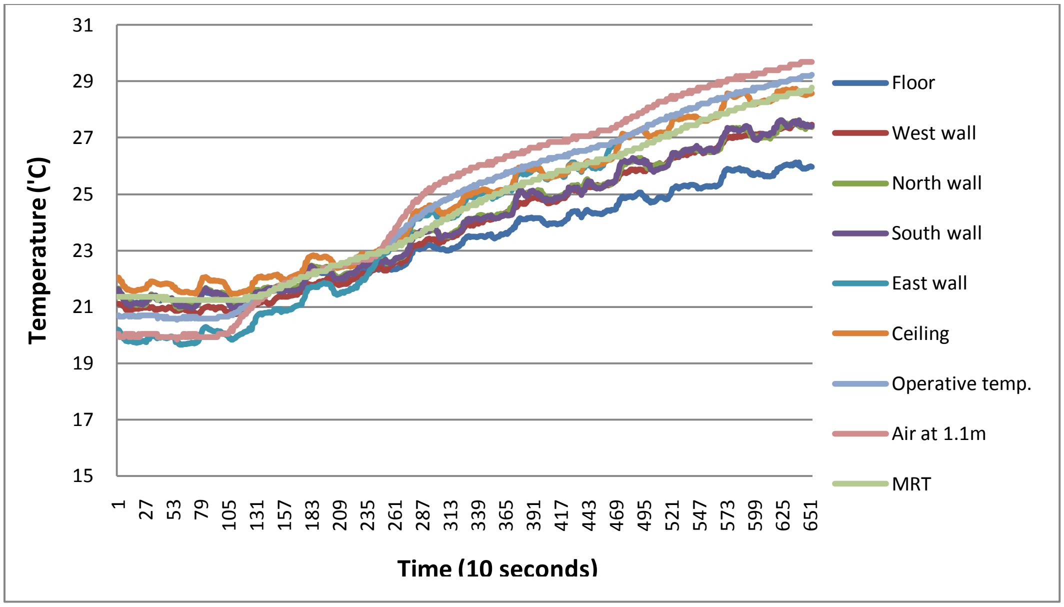


Fig. 42. Surface thermal conditions in the chamber during the second-round experiment

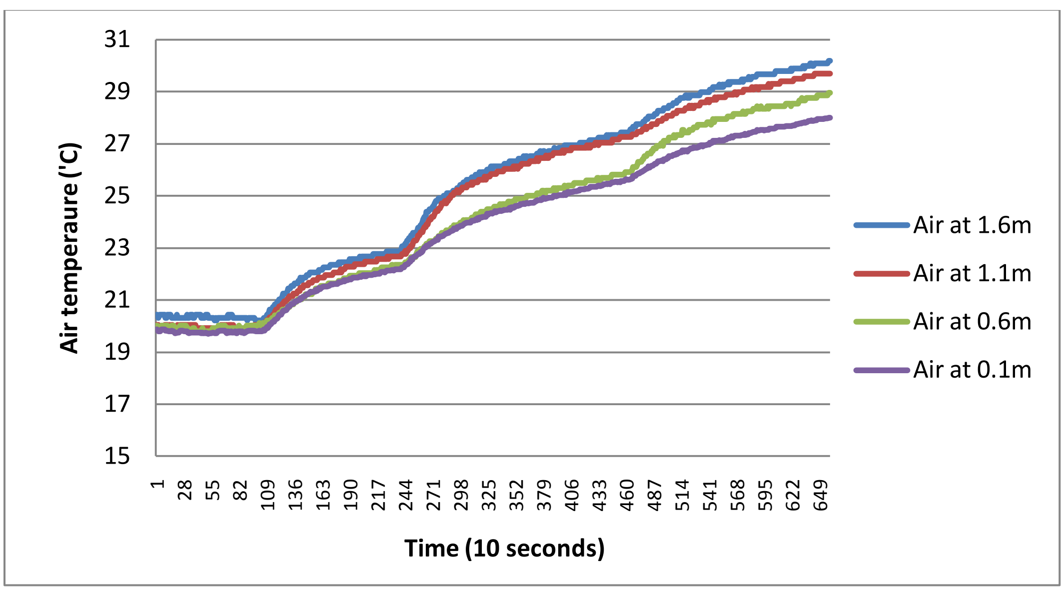


Fig. 43. Air temperature stratification

The test environment also had no significant air temperature differences or stratification at: 1.6m, 1.1m, 0.6m and 0.1m, below ASHRAE-55 (2004) recommendations for vertical air temperature difference of 3ºC or lower (Figure 43).

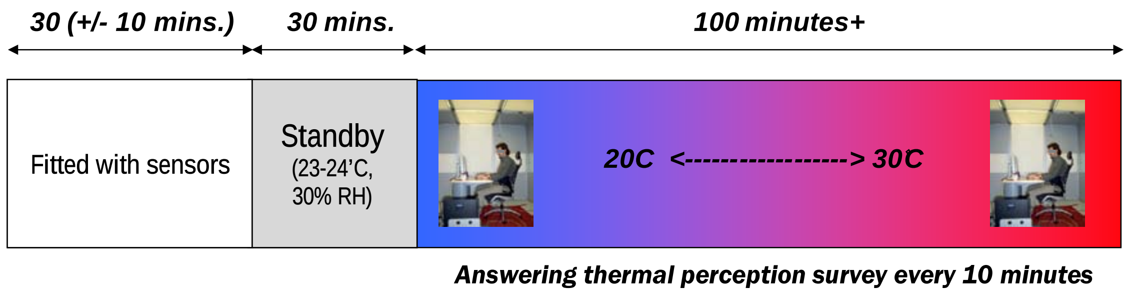
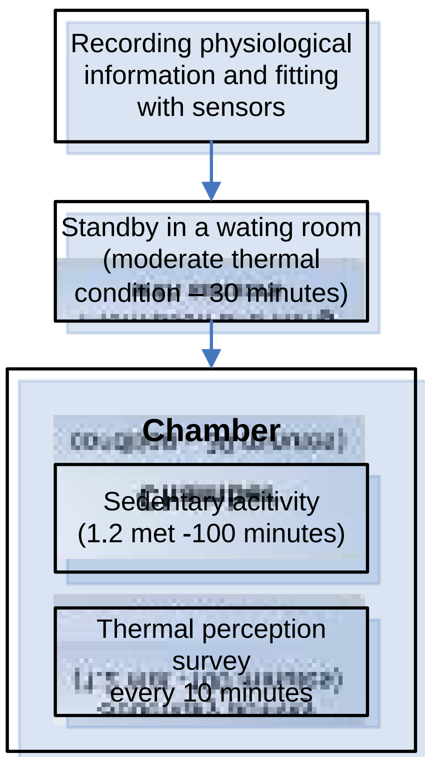


Fig. 44. Figurative procedure of the second-round experiment



: 2nd round : temperatures rising 20°C to 30°C at 1°C per 10 minutes.

: 3rd round: temperatures falling 30°C to 20°C at 1°C per 10 minutes.

Fig. 45. The procedure of the second and third human subject experiments

As shown in Figure 44 and 45, subjects were asked to maintain sedentary posture (1.2 Met) for computer-based work during the experiment, and were also asked to report their thermal sensation every 10 minutes. All collected data were grouped based on the surveyed sensation for a correlational analysis between the thermal sensation and skin temperature.

6.2.2. Signal patterns in the heating process (Second-round experiment)

In the second-round experiment, 27 human subjects participated and generated 270 datasets by reporting their overall thermal sensations 10 times throughout the 100 minutes of the experiment. The data analysis was performed based on three parameters of skin temperature: the absolute level, the gradient (i.e. rate of change), and the mean of square of gradient.

6.2.2.1. Absolute level of skin temperature in the heating process

The experimental results reveal that absolute levels of skin temperatures of selected body locations do not clearly indicate a subject's thermal sensation.

Skin temperatures were measured at 10 selected body locations for comparison to report thermal sensation as room temperature changed. As illustrated in Figure 46, skin temperatures on most of the selected body locations only increased as the air temperature rose from 20 to 30ºC. The similar patterns between these skin temperatures and the air temperature illustrate that the selected skin areas except the foot, posterior calf and anterior calf seem to be sensitively affected by their ambient conditions.

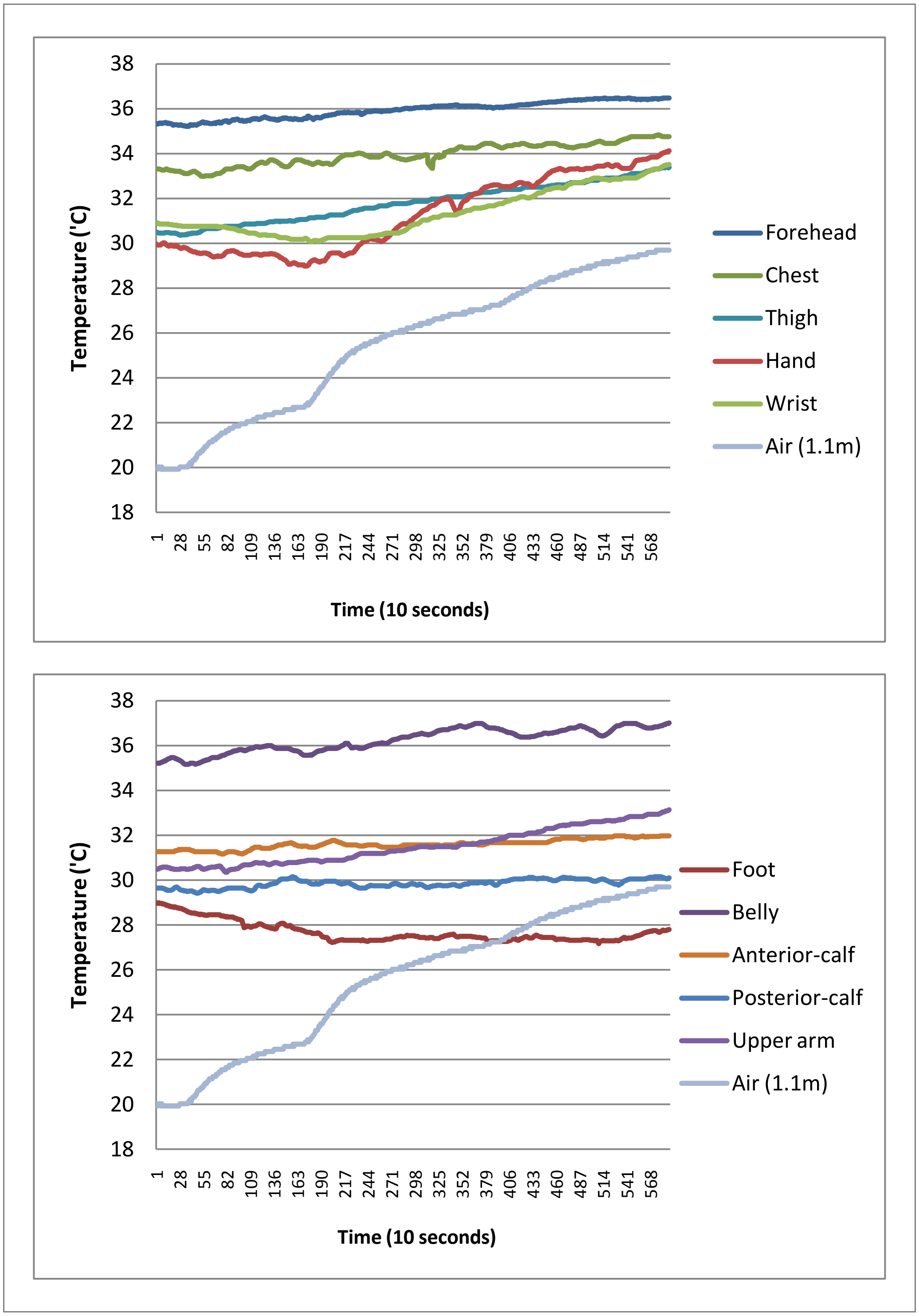


Fig. 46. Patterns of skin temperatures at 10 selected body location as air temperature rises from 20°C to 30°C (ID: 2128082)

These patterns are consistently across all subjects. However, the absolute levels of the skin temperatures vary depending on individual physiological characteristics. For example, Figure 47 describes the absolute levels of skin temperature on the forehead, foot and wrist collected from two subjects in a similar thermal condition. Even though each body location of the two subjects generates a similar pattern of skin temperatures, the delta between the subjects are significantly different and ranging from 0.1 ºC to 2.2ºC depending on the body locations. In addition, each subject generates different levels and patterns of a selected body area depending on the thermal sensation.

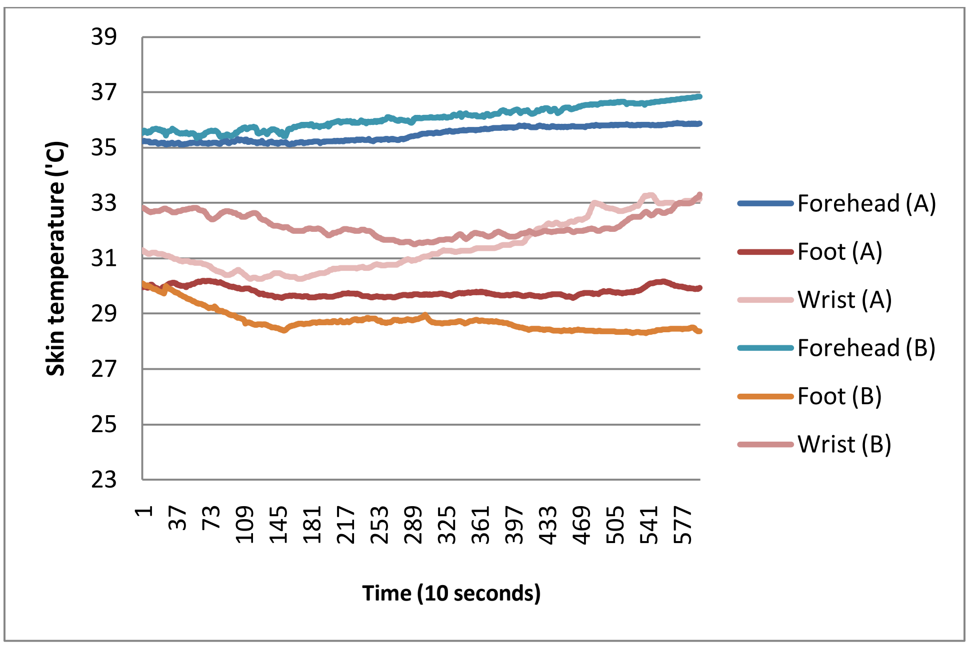


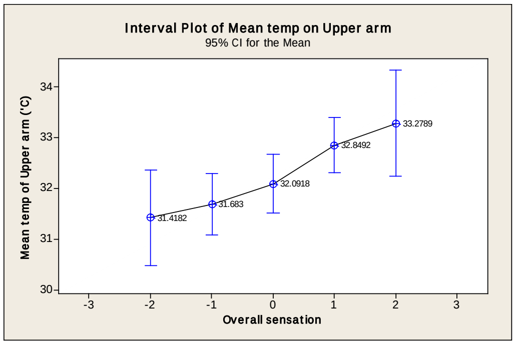
Fig. 47. Comparisons of skin temperatures between two subjects in a similar thermal environment ((A): Subject A, (B): Subject B)

Indeed, different those subjects generate different skin temperatures at the same body location in their neutral sensations. Since skin temperatures are controlled based on the physiological thermoregulation principle, individual physiological characteristics such as body mass index, gender, age, health, etc. generate temperature differences between subjects (Griefahn, 2000). These diversities in skin temperature levels across the subjects imply that the absolute level of skin temperature measured on a body point may not provide appropriate information to estimate thermal sensation. As discussed in the background section, the wide ranges of differences among subjects cannot provide any generalized solution to estimate the thermal sensation.

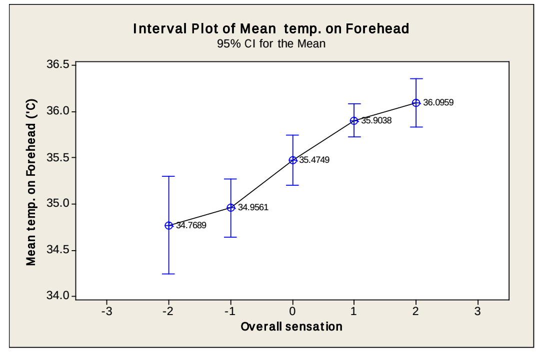
Table 14 summarizes the skin temperature levels of all subjects at each of the 10 body locations. This statistical analysis uses confidence intervals of mean skin temperature to find a general pattern of skin temperature across all subjects. The height of the line at each sensation on the charts illustrates the confidence interval of all subjects' data. The 95% confidence interval suggests the span of possible mean values at each sensation. Overall, the skin temperatures on the forehead, chest, belly, posterior calf, thigh and upper arm increases as the thermal sensations are changed from cool to warm sensations. Even though the ranges of skin temperatures are increasing, there is no significant division between neutral (0) and slightly cool (-1), and between neutral (0) and slightly warm (+1) sensation. It points out that the ranges are widely different depending on individual characteristics as discussed previously. Since maintaining the neutral sensation is critical for individual thermal comfort, it is essential for any control system to accurately detect each subject's neutral thermal sensation as conditions vary from slightly warm to slightly cool.

TABLE 14. Confidence intervals of mean skin temperatures collected from subjects

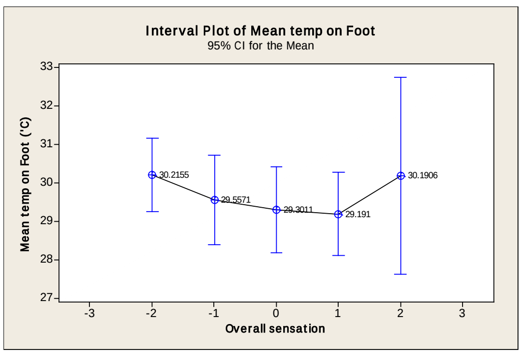
Upper arm



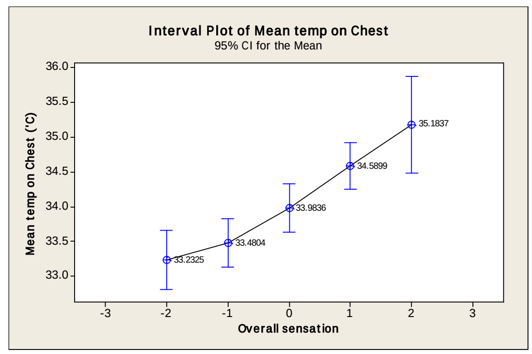
Forehead



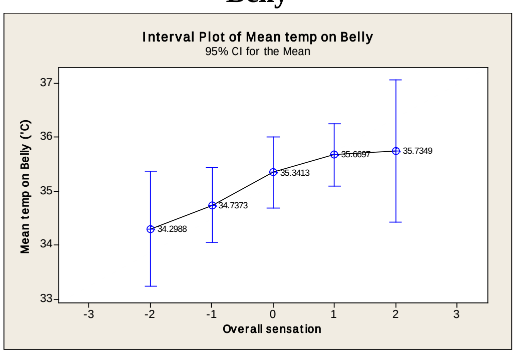
Foot



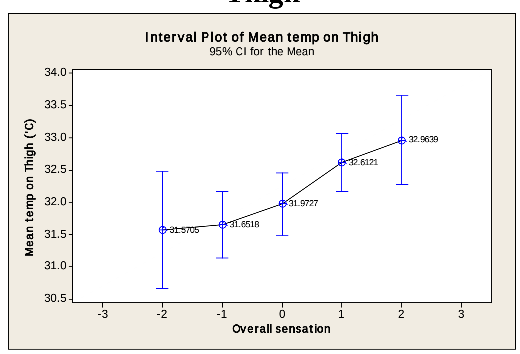
Chest



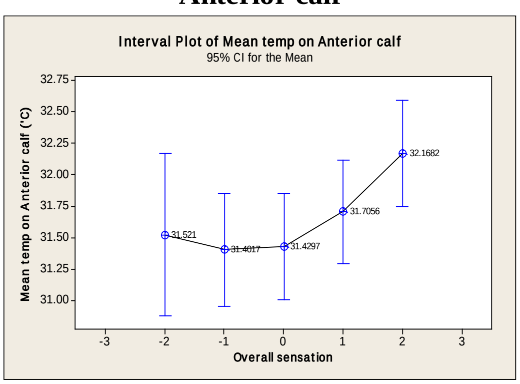
Belly



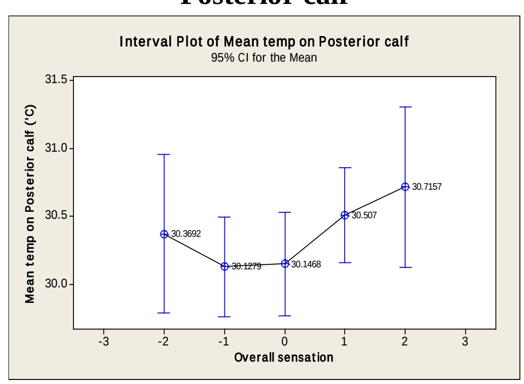
Thigh

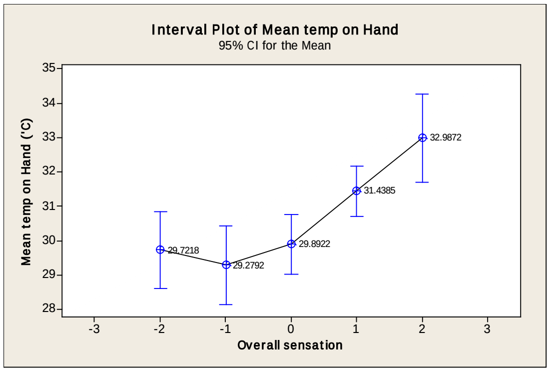
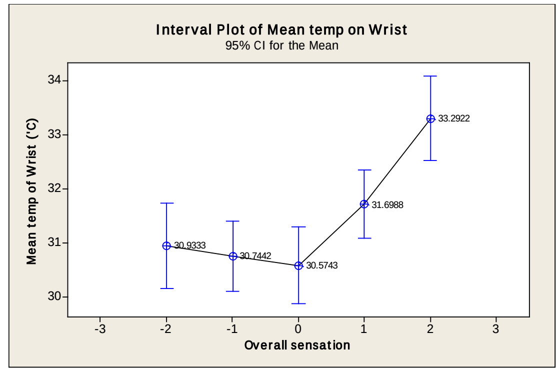


Anterior calf



Posterior calf



Hand	Wrist
	

In the two sample t-test (Table 15), the forehead and chest show statistical significances in skin temperatures between the two sensations, i.e. neutral vs. slightly cool, and neutral vs. slightly warm sensations. Considering the patterns of the skin temperatures and the generated air temperature, the forehead and chest are sensitively affected by the ambient temperature and their skin temperatures fluctuate accordingly. It may be not due to thermal sensations but to the relatively thinner fat layers in these locations that result in sensitive responses to fluctuations in the ambient temperature (Hori et al., 1983).

The hand and wrist show statistical significance variations in skin temperatures only between the neutral and slightly warm sensations. Since the mean skin temperatures in these locations increase quickly in the slightly warm sensation, the patterns generate significant p- values (Table 15). Overall, all body locations except the forehead and chest, have wide confidence intervals at each sensation. This finding reveals that the generated skin temperatures of each location vary depending on subjects even in a same thermal sensation. This limitation implies that the absolute level of skin temperature may not be adequate to be used for the subject's thermal sensation estimation.

TABLE 15. Two sample t-test of skin temperatures between neutral and slightly cool or slightly warm conditions

	Average skin temperature (°C)			Two sample t-test	
	Slightly cool (n=26)	**Neutral (n=26)**	**Slightly warm (n=26)**	**P-value (neutral vs. slightly cool)**	**P-value (neutral vs. slightly warm)**
Forehead	34.956	35.475	35.904	***0.013****	***0.009****
Foot	29.56	29.30	29.19	0.747	0.886
Chest	33.48	33.984	34.590	***0.040****	***0.013****
Belly	34.74	35.34	35.67	0.198	0.442
Thigh	31.65	31.97	32.61	0.355	0.051
Anterior calf	31.40	31.43	31.71	0.926	0.343
Posterior calf	30.13	30.15	30.51	0.941	0.155
Hand	29.28	29.89	31.44	0.382	***0.007****
Wrist	30.74	30.57	31.70	0.715	***0.018****
Upper arm	31.68	32.09	32.85	0.320	0.056

6.2.2.2. Gradient (i.e. rate of change) of skin temperature in the heating process

The experimental result reveals that the gradients of skin temperature on the hand, wrist and upper arm can be used to estimate thermal sensation at neutral, slightly cool and slightly warm conditions.

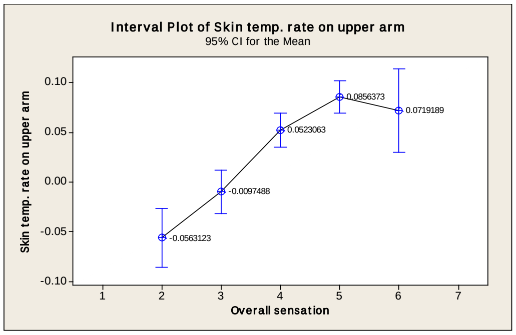
For a more detailed analysis, the gradient (i.e. rate of change) of the skin temperature is calculated as a parameter of the bio-signal. As shown in Table 14, overall, the skin temperatures show an incremental pattern from cool to warm sensation, or lowest levels around neutral, slightly warm or cool sensation depending on body locations. This feature makes the gradient larger when the rate of change is calculated with a larger time interval. This research selects three minutes as a time-interval to calculate the gradient of the skin temperature and the time-interval decision process is discussed in Section 7.1.1.

As shown in Table 16, the gradient of the forehead peaks at the neutral sensation and is always positive even at the cool sensation. The gradients of the belly and posterior calf are inconsistent with the thermal sensations. However, the foot, chest, thigh, anterior calf, hand, wrist and upper arm generate gradients with increasing patterns as the sensation is warmer. The gradient of foot increases from negative to zero while the sensations are changing from cool to slightly warm. The highest gradients occur at the slightly warm sensation on hand and wrist.

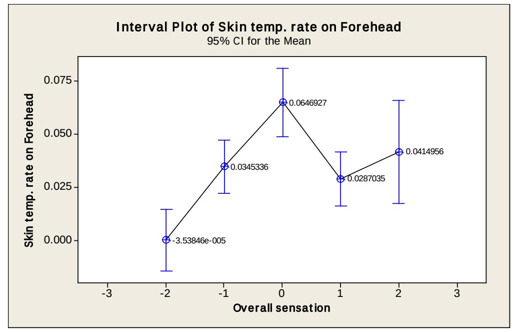
In particular, the gradient of the wrist is around zero at the neutral sensation across the subjects while other skins areas generate positive or negative gradients, or gradients that range considerably around zero. The thigh and hand also show zero or near-zero gradients distinctively from other neighbor sensations at the slightly cool sensation. However, in the case of the hand, the gradient changes noticeably when it is in the warm sensation. This tells us that the gradients around zero may mean slightly cool or slightly warm depending on the subject. The thigh also shows clear differences in the gradient by thermal sensation, but its gradient in the neutral sensation, which is a target to be maintained for thermal comfort, does not provide a unique estimation of sensation because the gradients are almost the same or identical across the neutral, slightly warm and warm sensations.

TABLE 16. Confidence intervals of skin temperature gradient (i.e. rate of change) of all the collected data (Unit of y-axis: °C / 3 minutes)

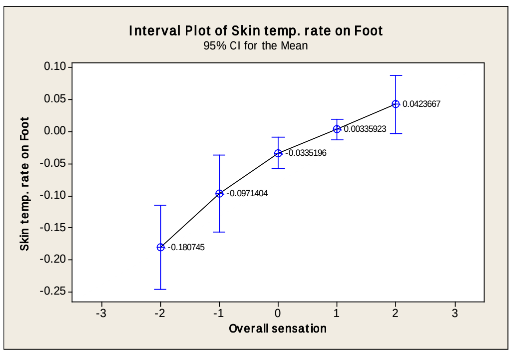
Upper arm



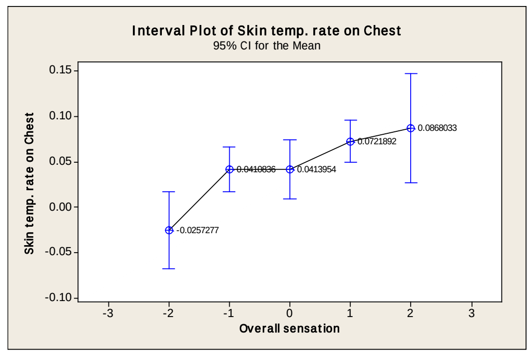
Forehead



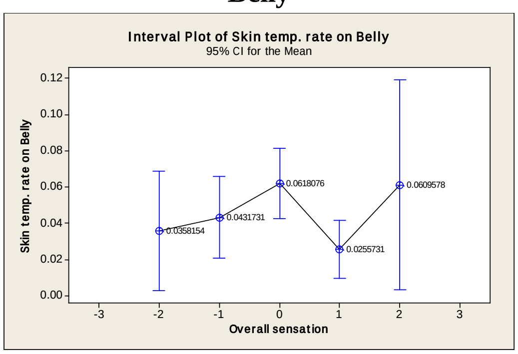
Foot



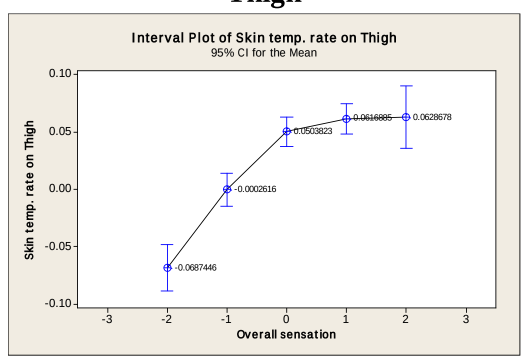
Chest



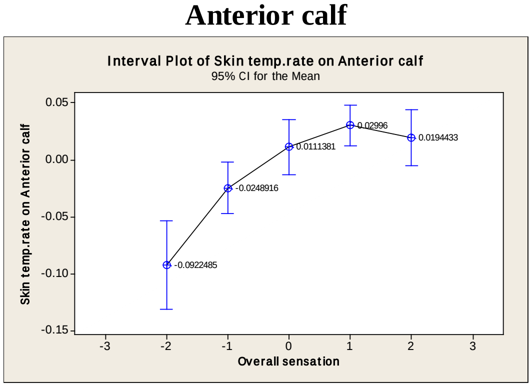
Belly



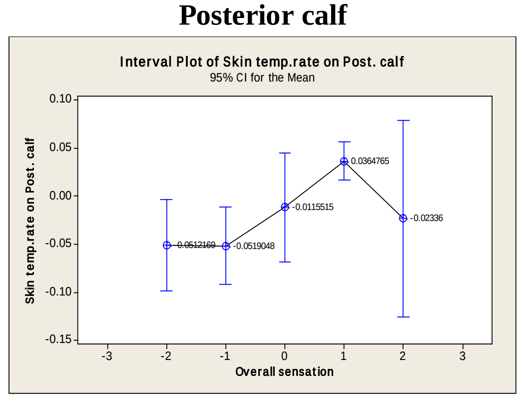
Thigh

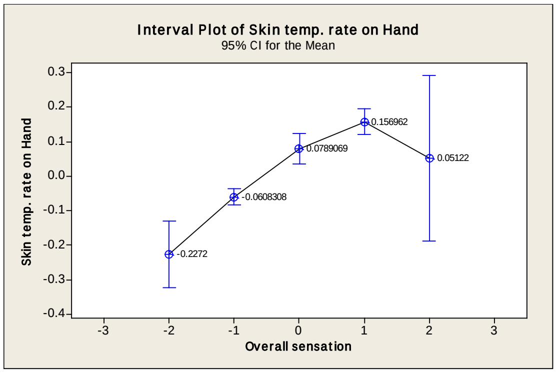
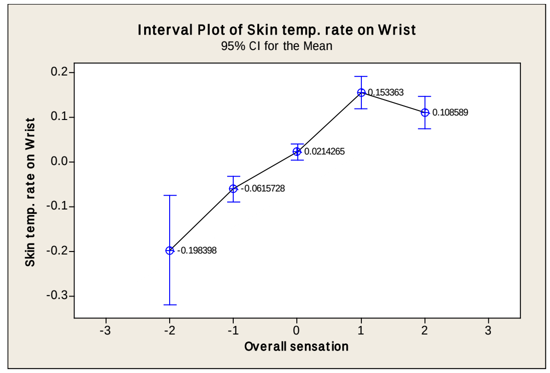


Anterior calf



Posterior calf



Hand	Wrist
	

As a result, the gradient of the wrist shows the clearest pattern in the neutral sensation. This gradient is statistically distinct when compared with the neighbor sensations, i.e. slightly warm and slightly cool sensations. This attribute implies that the gradient of skin temperature at the wrist could be well used to estimate a subject's thermal sensation.

The results of two-sample t-test also support the findings discussed above. As shown in Table 17, the forehead, hand, wrist and upper arm have significant p-values in the comparisons of gradients between the neutral and slightly cool sensations, and between the neutral and slightly warm sensations. However, the gradient of the forehead is always a positive value at all sensations. This feature makes it impossible to estimate a subject's thermal sensation based on the gradient information.

The gradients of the hand, wrist and upper arm increase from the negative to the positive values as the thermal sensations change from slightly cool to slightly warm. The gradients show the closest value to zero on these skin areas. Therefore, the hand, wrist and upper arm may be feasible locations to be used for estimating the thermal sensation based on their gradients.

TABLE 17. Two sample t-test of skin temperature gradient at between neutral and slightly cool or slightly warm conditions

	Slightly cool (n=26)	Neutral (n=26)	Slightly warm (n=26)	P-value (neutral vs. slightly cool)	P-value (neutral vs. slightly warm)
Forehead	0.0345	0.0647	0.0287	***0.004****	***0.001****
Foot	-0.097	-0.0335	0.0034	0.051	***0.014****
Chest	0.012	0.016	0.0722	0.987	0.115
Belly	0.0432	0.0618	0.0256	0.202	0.004
Thigh	-0.0003	0.0504	0.0617	***0.000****	0.216
Anterior calf	-0.0249	0.0111	0.0300	***0.029****	0.205
Posterior calf	-0.0519	-0.012	0.0365	0.239	0.110
Hand	-0.0608	0.079	0.1570	***0.000****	***0.009****
Wrist	-0.0616	0.0214	0.1534	***0.000****	***0.000****
Upper arm	-0.0097	0.0523	0.0856	***0.000****	***0.005****

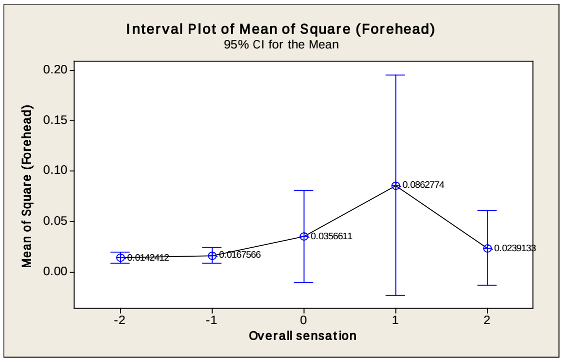
6.2.2.3. Mean of Square of Gradient (MSG) in the heating process

The analysis of MSG confirms that the gradient of the wrist in the neutral sensation is around zero or the smallest compared with that of slightly warm and cool sensations.

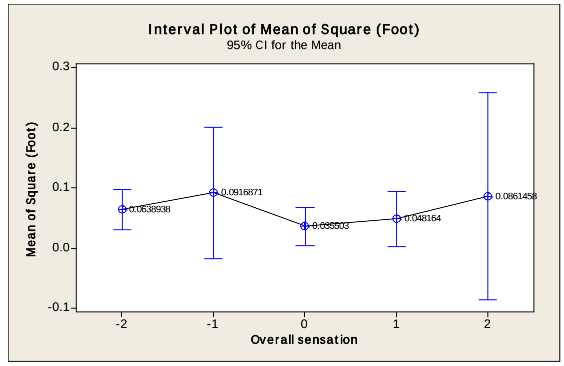
The data analysis of the gradient alone may cause errors when the skin temperature of a body location contains an inflection point in the period of neural sensation. In this case, the average gradient would be near zero in the thermal sensation period while the absolute value of the gradient could be larger than zero. Therefore, the mean of square of the gradient for each thermal sensation has been calculated.

TABLE 18. Confidence intervals of mean of square of skin temperature gradient (MSG) in each body location

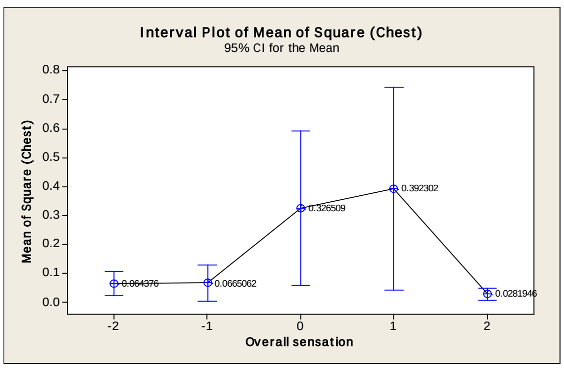
Forehead



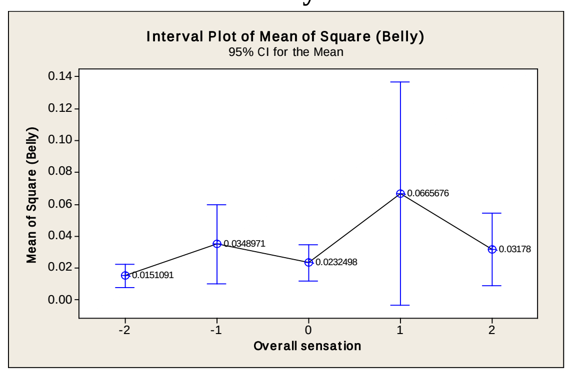
Foot



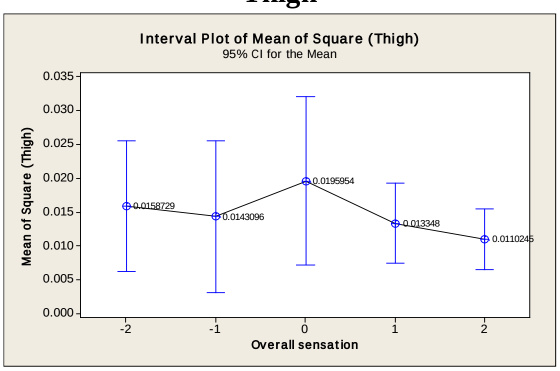
Chest



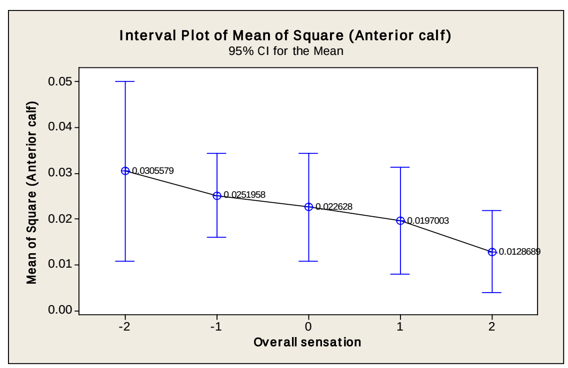
Belly



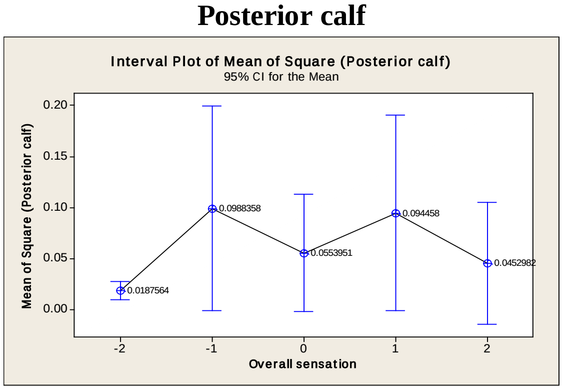
Thigh



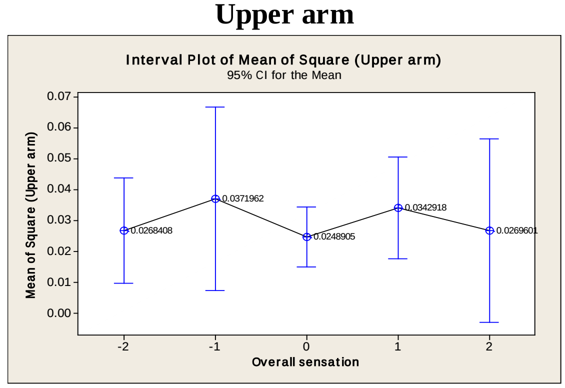
Anterior Calf

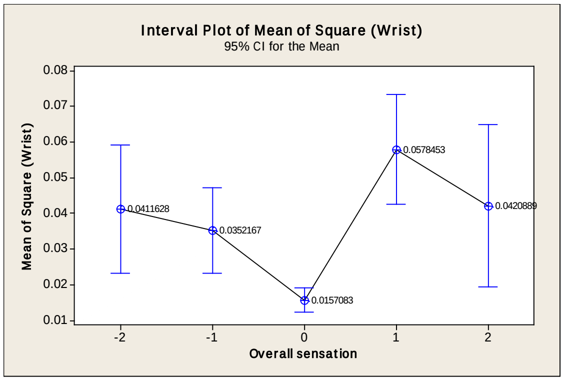
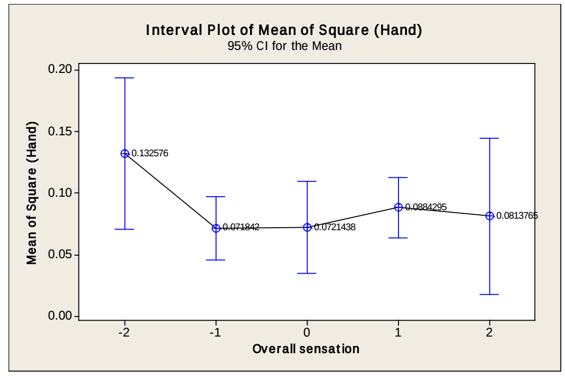


Posterior calf



Upper arm



Wrist	Hand
	

As shown in Table 18, the gradient of skin temperature at each body location for each individual subject is squared and the summation is divided by the total number of data samples in each period of thermal sensation, and grouped by thermal sensation. The ANOVA result illustrates that only the wrist has a very significant p-value at around 0.000 while other body areas have statistically insignificant p-values. This implies that the gradient of the wrist is very close to zero in the neutral sensation, and that the skin temperature is constant without any significant fluctuation. As shown in Figure 48, the skin temperature on the wrist shows a flat or lower slope than that of hand and upper arm.

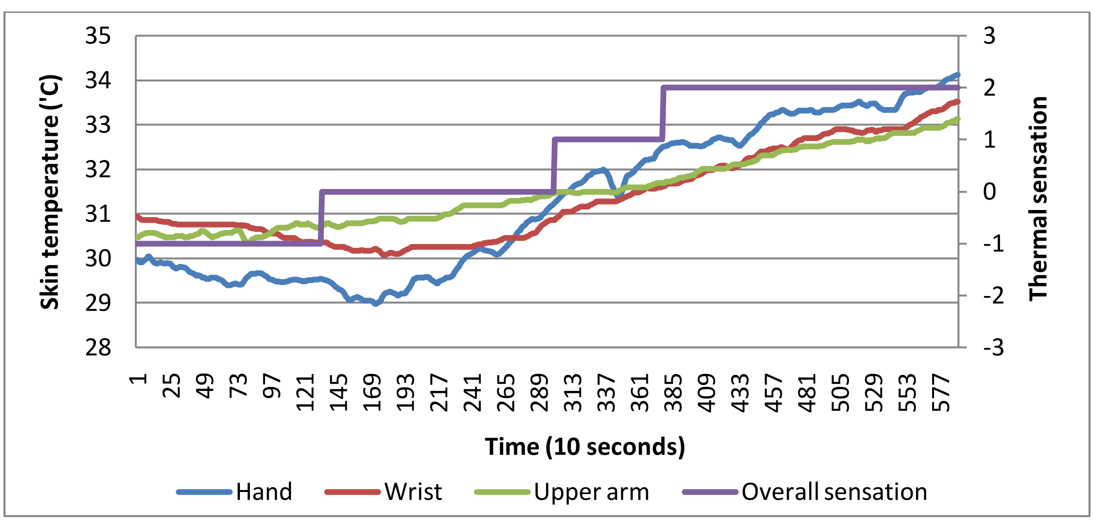


Fig. 48. Patterns of skin temperatures on hand, wrist and upper arm and thermal sensations

(ID:21208082)

TABLE 19. Two sample t-test of mean of square of gradient at between neutral and slightly cool or slightly warm conditions

	Slightly cool (n=26)	**Neutral (n=26)**	**Slightly warm (n=26)**	**P-value (neutral vs. slightly cool)**	**P-value (neutral vs. slightly warm)**
Forehead	0.0168	0.036	0.086	0.409	0.382
Foot	0.092	0.0355	0.048	0.318	0.641
Chest	0.067	0.619	0.773	0.062	0.758
Belly	0.0349	0.0232	0.067	0.386	0.218
Thigh	0.0143	0.0196	0.0133	0.516	0.354
Anterior calf	0.0252	0.0226	0.0197	0.723	0.715
Posterior calf	0.099	0.055	0.094	0.442	0.474
Hand	0.0718	0.0721	0.0884	0.989	0.456
Wrist	0.0352	0.01571	0.0578	***0.003****	***0.000****
Upper arm	0.0372	0.0249	0.0343	0.425	0.317

The two-sample t-test also supports this finding related to the pattern of the skin temperature on the wrist (Table 19). The mean of square of the gradient is 0.01571 at the neutral sensation, which is smaller than that of other neighbor sensations with statistical significances with p-values of 0.003 and 0.000. Compared with the wrist, other skin areas including the hand and upper arm do not show any significant p-values in the t-test.

6.2.2.4. Body location selection for estimating thermal sensation in the heating process

A series of statistical analyses concludes that the wrist is the most responsive area to generate an interpretable signal in estimating the subject's thermal sensation.

This research adopted a filtration strategy for statistical analysis to find the most responsive body location. First, the absolute level of skin temperature was investigated across all the selected body locations. The two sample t-test results explained that each skin area generates different levels of skin temperature and those levels vary depending on the individual. Their inconsistent levels across subjects and selected skin areas indicate absolute skin temperature levels may not be an interpretable parameter for estimating thermal sensations. However, both the gradient and the mean of square of gradient show statistical significance.

The analysis of the gradients explains why some skin areas- including the hand, wrist and upper arm- generate the lowest absolute gradients around zero at the neutral sensation. The mean of square of gradient (MSG) provides evidence that the hand and upper arm contain an inflection point in the period of the neutral sensation. Such an infection point causes an average gradient at around zero for the neutral sensation, but the actual gradients include negative and positive values that together become an average value around zero. The MSG calculation supports that the gradient of the wrist is most stable at the neutral sensation without fluctuations from negative to positive values. The filtration strategy for statistical analyses reveals that the wrist is the most responsive area to generate an interpretable signal in estimating the subject's thermal sensation.

To ensure a clearly distinctive pattern of skin temperature for each skin area, the calculation adopts intervals of three minutes, further discussed in Section 7.1.1.

6.2.3. Signal patterns in the cooling process (Third-round experiment)

The wrist was found to be the most responsive skin area in the heating process (the second-round human-subject experiment). The wrist generates a consistent skin temperature in the neutral thermal sensation. Even though the level of skin temperature on the wrist varies depending on the subject, the pattern is consistent across the subjects, showing zero or the minimum gradient in the neutral sensation, a positive gradient under (slightly) warm sensations, and a negative gradient in (slightly) cool sensation. Since the second-round experimental condition was based on warming conditions, a third-round experiment was initiated to investigate whether the variations in skin temperature at the wrist were consistent in the cooling process as well.

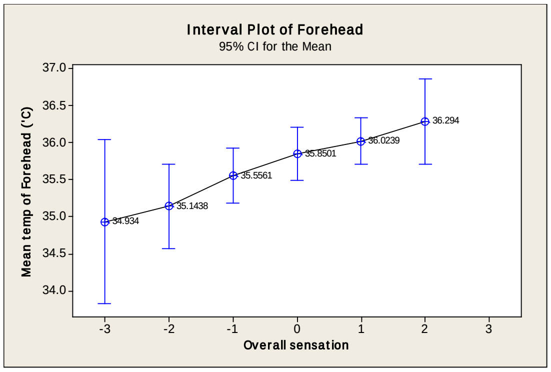
6.2.3.1. Absolute level of skin temperature in the cooling process

> ***The experimental results reveal that the absolute level of skin temperature may not adequately indicate the thermal sensation due to a wide variation depending on individual in the cooling process.***

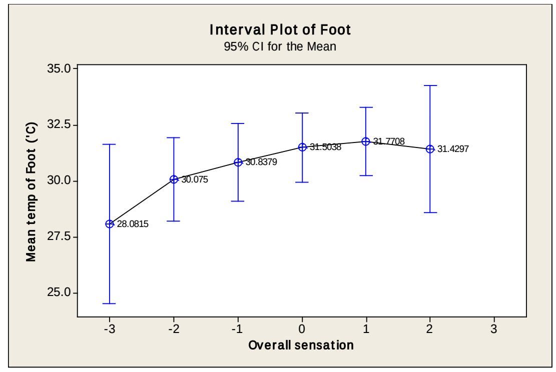
All of the skin temperatures measured at the 10 body locations shows similar patterns with certain decreasing rate from the (slightly) warm sensation to the cold sensation across the subjects. All body locations reveal higher temperatures in warm conditions and lower temperatures in cool or cold conditions, except for the belly as shown in Table 20.

TABLE 20. Absolute levels of skin temperature in each thermal sensation score

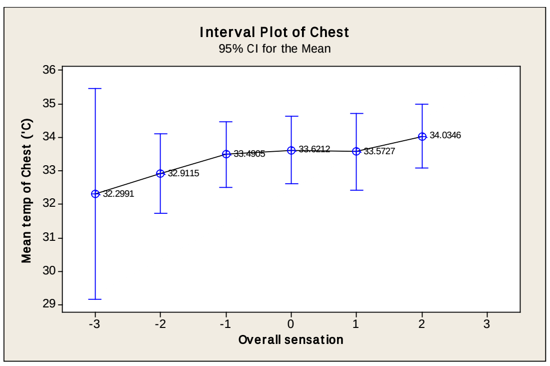
Forehead



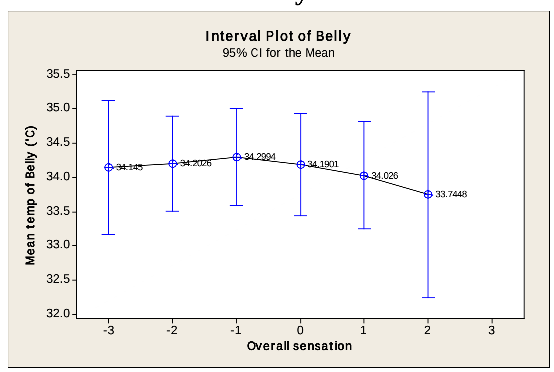
Foot



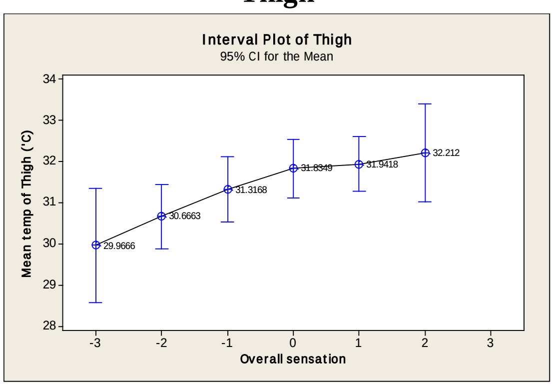
Chest



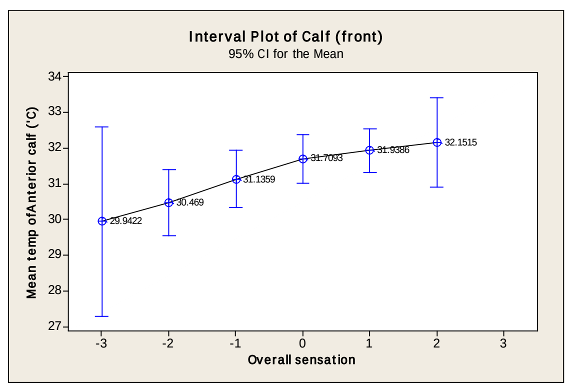
Belly



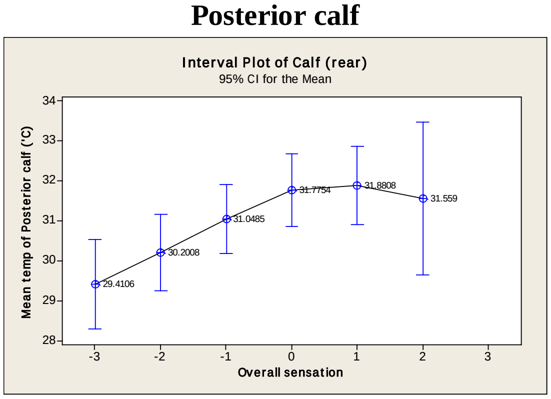
Thigh



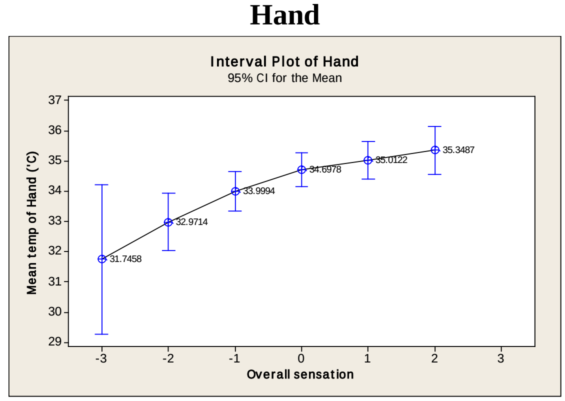
Anterior calf

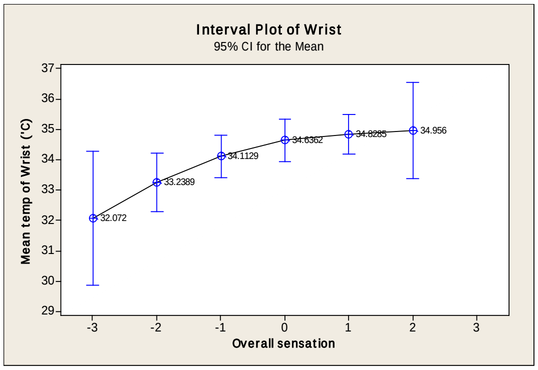
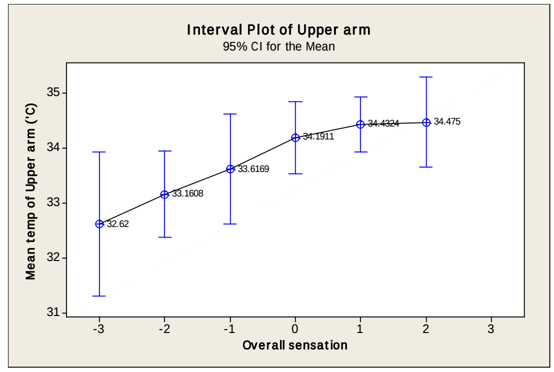


Posterior calf



Hand



Wrist	Upper arm
	

The belly generates almost constant levels of skin temperature regardless of the overall thermal sensation. Overall, since the generated skin temperatures vary depending on the subjects, the confidence interval of mean skin temperature at each sensation is too wide to be overlapped with the intervals of other sensations.

Table 21 summarizes the two sample t-test results of skin temperatures between the neutral and slightly warm (or slightly cool) sensation. Since the confidence intervals of the skin temperature in each sensation is too wide, the t-test results do not show any statistical significance. The outcome implies that the absolute level of skin temperature in each sensation varies depending on the individuals. Therefore, the absolute level of skin temperature may not be appropriate for estimating a subject's thermal sensation.

TABLE 21. Two-sample t-test of skin temperatures in between neutral and slightly cool or slightly warm sensations

	Slightly cool (n=10)	Neutral (n=10)	Slightly warm (n=10)	P-value (neutral vs. slightly cool)	P-value (neutral vs. slightly warm)
Forehead	35.556	35.850	36.024	0.217	0.423
Upper arm	33.62	34.191	34.432	0.294	0.519
Wrist	34.113	34.636	34.829	0.245	0.650
Hand	33.999	34.698	35.012	0.860	0.409
Chest	33.49	33.62	33.57	0.830	0.942
Belly	34.299	34.19	34.03	0.813	0.735
Thigh	31.32	31.835	31.942	0.278	0.804
Anterior calf	31.136	31.709	31.939	0.218	0.564
Posterior calf	31.05	31.78	31.88	0.206	0.860
Foot	30.84	31.50	31.77	0.507	0.776

6.2.3.2. Gradient (i.e. Rate of change) of skin temperature in the cooling process

The analysis of skin temperature gradients reveals that the wrist and posterior calf show significant differences between neutral and slightly warm or slightly cool sensations.

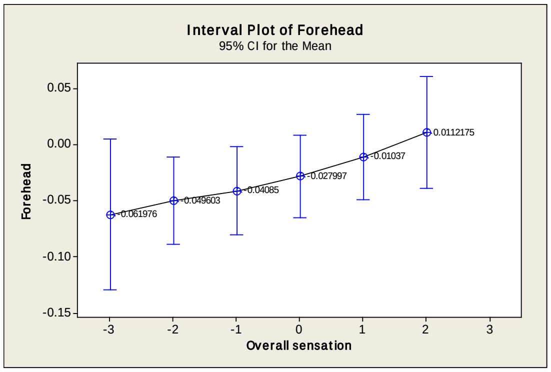
For more detailed analysis, the gradient (i.e. rate of change) of skin temperature is calculated as a possible index for bio-sensing controls. As shown in Table 22, the overall patterns of all the skin temperature gradients are similar to the results of the second-round experiment except for the forehead and belly. The forehead, wrist, foot, belly and thigh generate larger gradients at the warm sensation, and smaller or negative gradients at the cool or cold sensations. On the other hand, the anterior calf and the upper arm show irregular patterns regardless of the thermal sensation.

The gradient of the wrist is most adjacent to zero under the neutral sensation. Even though the confidence interval of the gradient at slightly cool is consistently narrow with an average of -0.8°C per three minutes across the subjects, this finding does not provide any additional information to be connected with the other sensations. The confidence interval of the gradient under the neutral sensation slightly overlaps with that of the slightly warm sensation. The forehead is easily affected by the ambient temperature due to its shallow skin depth with its thin fat layer. The decreasing air temperature from 30°C to 20°C significantly affects the forehead gradient, which start generating negative gradients from the beginning.

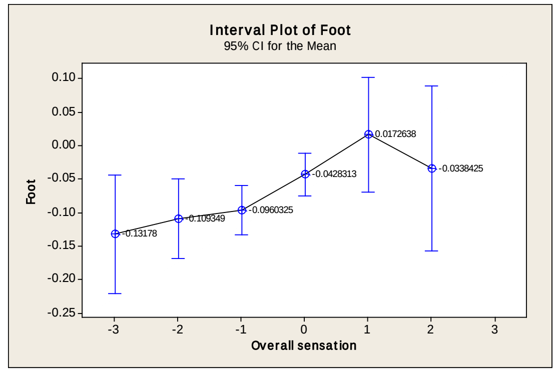
The foot generates wide ranges of gradients across the subjects. It causes a wide confidence interval in each sensation and does not show any distinction at the neutral sensation. The confidence interval of the neutral sensation fully overlaps that of the slightly warm condition. In the gradient ranges of the chest and the belly, zero is placed across several thermal sensations: slightly cool, neutral and slightly warm sensations. This feature makes it difficult to estimate the thermal sensation based on the gradients of the body locations.

TABLE 22. Confidence Intervals of mean skin temperature gradient in each thermal sensation (Unit of y-axis: °C/ 3 minutes)

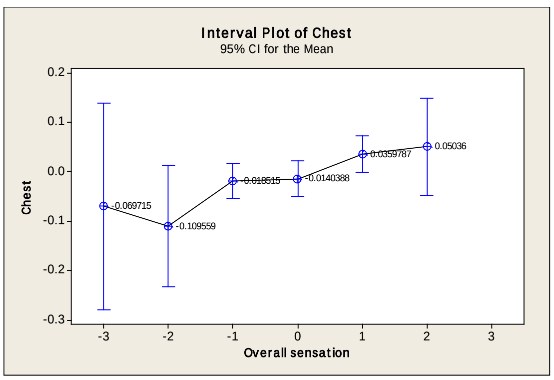
Forehead



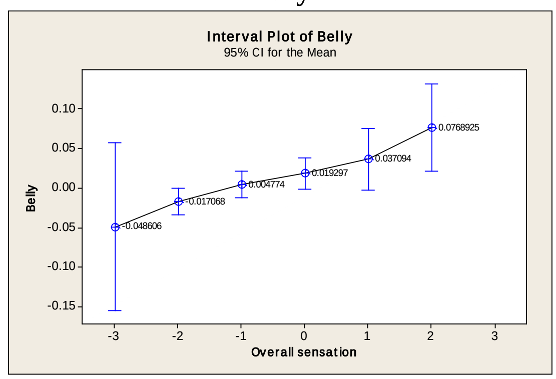
Foot



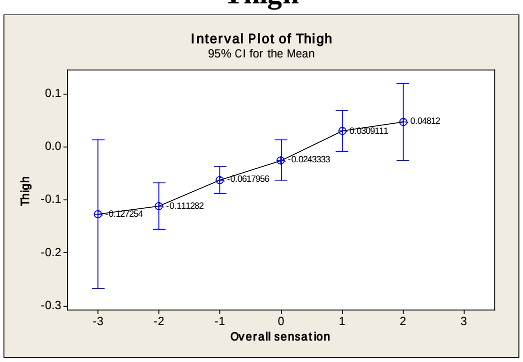
Chest



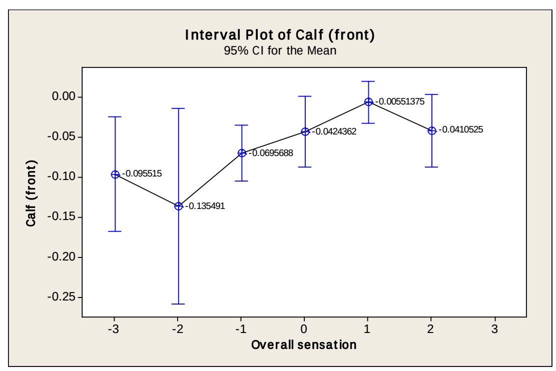
Belly



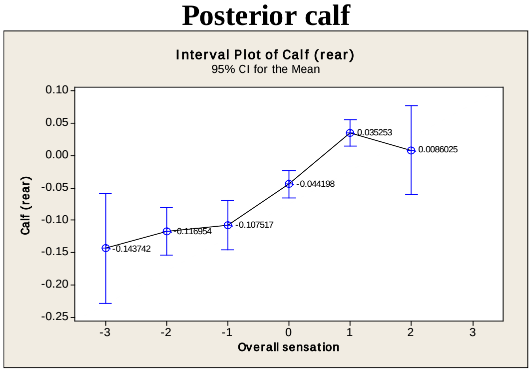
Thigh



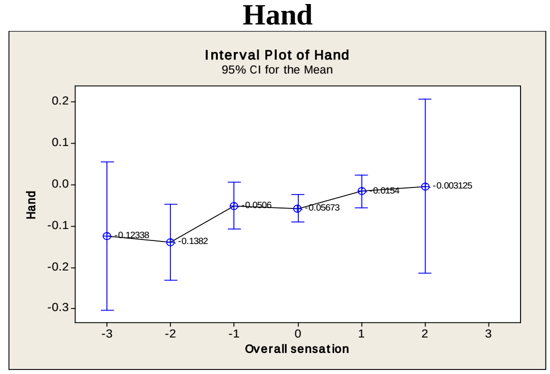
Anterior calf

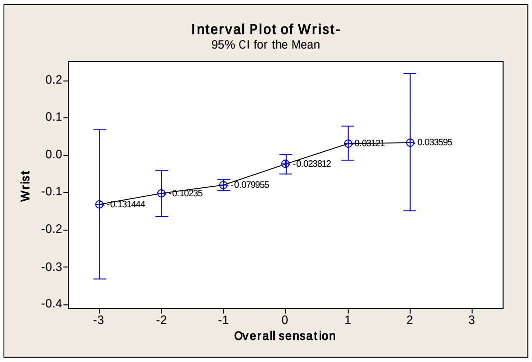
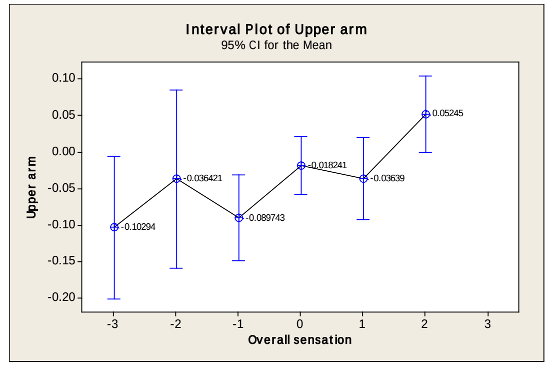


Posterior calf



Hand



Wrist	Upper arm
	

The anterior calf, hand and upper arm almost show negative gradients across all the sensations. This implies that those skin temperatures decrease as the ambient temperatures fall from 30°C to 20°C. The thigh, posterior calf and wrist generate zero or minimum gradients in the neutral sensation. The posterior calf shows a clear division between the neutral and slightly cool sensations and between the neutral and slightly warm sensations, but the gradient in the neutral sensation is negative, which implies reduction in the skin temperature. Also, the gradient in the neutral sensation at the thigh is slightly lower than zero, and the confidence interval of the slightly warm sensation cover zero at the body location.

In the experiment, the survey is performed every 10 minutes and attempts to measure skin temperatures with ten-second intervals. The measured temperatures are grouped by the reported sensation. This resolution limits the ability to catch the moment when a subject is in the neutral sensation. Therefore, the thigh, posterior calf and wrist may have gradients at zero when the subjects are in the neutral thermal sensation.

Table 23 summarizes the significant difference of gradients between the neutral sensation and slightly warm or slightly cool sensation. Since the neutral sensation reflects thermal comfort (ASHRAE-55, 2004), it is critical to find any difference in gradients between the two discrete sensations.

TABLE 23. Two-sample t-test of skin temperature gradients in between neutral and slightly cool or slightly warm sensations

	Slightly cool (n=10)	Neutral (n=10)	Slightly warm (n=10)	P-value (neutral vs. slightly cool)	P-value (neutral vs. slightly warm)
Forehead	-0.0409	-0.0280	-0.0104	0.597	0.463
Upper arm	-0.0897	-0.0182	-0.0364	***0.038****	0.559
Wrist	-0.0800	-0.0238	0.0312	***0.001****	***0.032****
Hand	-0.0506	-0.0567	-0.0154	0.836	0.089
Chest	-0.0185	-0.0140	0.0360	0.837	***0.040****
Belly	0.0048	0.0193	0.0371	0.221	0.373
Thigh	-0.0618	-0.0243	0.0309	0.081	***0.034***
Anterior calf	-0.0696	-0.0424	-0.0055	0.277	0.117
Posterior calf	-0.1075	-0.0442	0.0353	***0.006****	***0.000****
Foot	-0.0960	-0.0428	0.017	***0.025****	0.160

The thigh shows a statistically significant difference between the slightly warm and neutral sensations across the subjects. The foot also generates a significance distinction between the slightly cool and neutral sensation. The wrist and posterior calf show significant differences between the neutral and slightly warm or slightly cool sensations with p-values lower than 0.05. Therefore, based on the analysis results of skin temperature gradients, the wrist and posterior calf would be the most responsive skin area to estimate the thermal sensation of a subject.

6.2.3.3. Mean of Square of Gradient in the cooling process

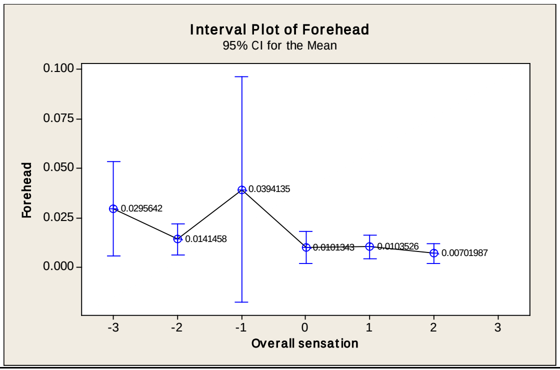
The skin temperatures at the wrist and belly generate the most stable and minimum mean of square of gradient during the neutral sensation compared with other sensations across the subjects.

The data analysis of the gradient may cause errors when the skin temperature of a body location contains an inflection point at neutral sensation. In this case, the average gradient would be near zero in the thermal sensation period while the absolute value of the gradient could be larger than zero. Therefore, the mean of square of gradient (MSG) in each thermal sensation was calculated.

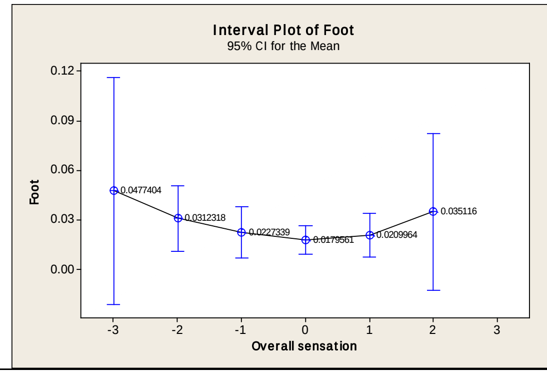
The gradient of skin temperature at each body location for individual subject data was squared and the summation was divided by the total number of data samples in each period of thermal sensation. The mean of square of gradients for all subjects were grouped by thermal sensation as calculated in the second-round human subject experiment as shown in Table 24.

TABLE 24. Confidence interval of mean of square of skin temperature gradient in each thermal sensation

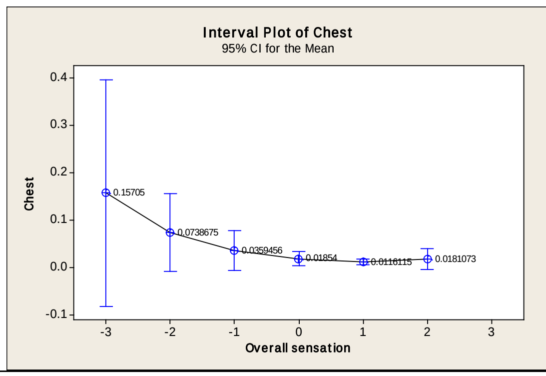
Forehead



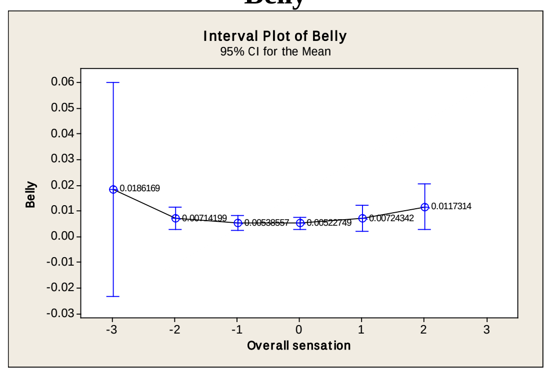
Foot



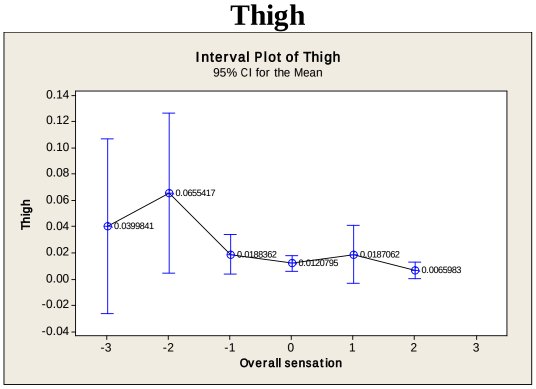
Chest



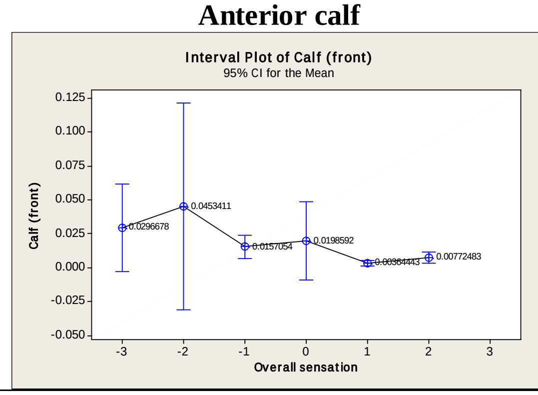
Belly



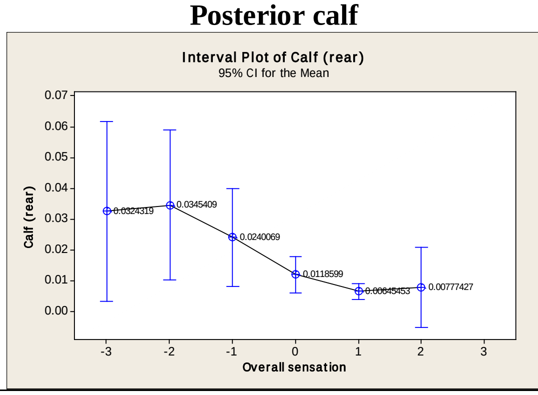
Thigh



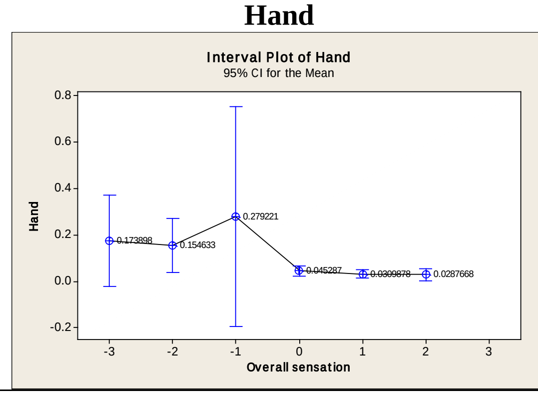
Anterior calf



Posterior calf



Hand



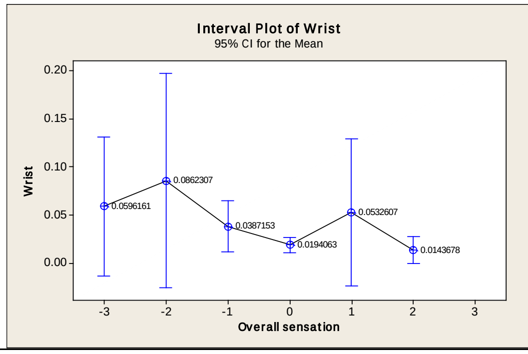
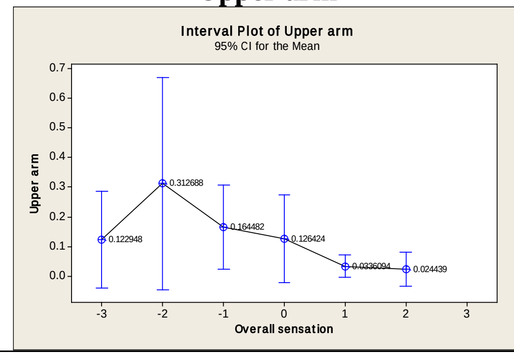
Wrist	Upper arm
	

Table 25 summarizes the two-sample t-test of mean of square of gradient. Since the confidence intervals in each sensation of a selected body location is wide enough to overlapped with confidence intervals of other sensations, all the p-values are larger than 0.05 and have no statistically significant result.

TABLE 25. Two-sample t-test of mean of square of gradient between neutral and slightly cool or slightly warm sensations

	Slightly cool (n=10)	Neutral (n=10)	Slightly warm (n=10)	P-value (neutral vs. slightly cool)	P-value (neutral vs. slightly warm)
Forehead	0.0394	0.0101	0.01035	0.279	0.962
Upper arm	0.164	0.126	0.0336	0.681	0.201
Wrist	0.0387	0.0194	0.053	0.144	0.345
Hand	0.279	0.0453	0.0310	0.293	0.261
Chest	0.0359	0.0185	0.01161	0.382	0.352
Belly	0.00539	0.00523	0.00724	0.921	0.438
Thigh	0.0188	0.01208	0.0187	0.354	0.522
Anterior calf	0.0157	0.0199	0.00364	0.752	0.226
Posterior calf	0.0240	0.01186	0.00645	0.133	0.81
Foot	0.0180	0.0180	0.0210	0.534	0.655

A small size of the confidence interval in the MSG calculation indicates that the generated skin temperatures in the period of a thermal sensation have no large variation with a constant or minimal deviation. It can support the significance of minimal gradients found in Section 6.2.2.

In Table 24, for the posterior calf, the minimum MSG occurs during the slightly cool sensation rather than the neutral sensation, which implies that the changing pattern of the gradient during the cool sensation is more consistent. For the wrist, the minimum mean of square of gradient occurs during the neutral sensation. The warm sensation induces smaller MSG with a large confidence interval across the subjects, but the size of samples is only four while the neutral sensation contains 10 as the sample size. The cold condition does not have a sufficient sample size with only five cases for the t-test. Thus, the confidence intervals in warm and cool sensations are not statistically meaningful.

It may be hard to clarify which MSG generated at each body location is the most meaningful to the thermal sensation. Since the purpose of the experiment was to find if any unique pattern occurs across the subjects with a certain level of consistency, minimum deviation in the mean of square of gradient are most important to designing a bio-sensing control system. Based on the principle, the wrist, chest, belly, thigh and hand seem to show a significant pattern in terms of minimum deviations of the MSG (Table 24) and stability across the subjects. Therefore, this research regards the stable pattern of the deviations as meaningful outcomes which support the most responsive body location selection.

6.2.3.4. Skin area selection for estimating thermal sensation

Table 26 summarizes all of the experimental results in the second and third experiments. As indicated, the wrist consistently shows statistical significance across the series of analyses except in the mean of square of gradient (MSG) analysis of the cooling process. However, the wrist generates a stable trend and the smallest MSG. Therefore, based on the investigation of the experiments in the heating and cooling process, the wrist is selected as the most responsive body location for estimating individual's thermal sensation.

TABLE 26. Summary of statistical significance of the second (heating process) and third-round (cooling process) experiment data analysis

	Heating process (Second-round experiment)			Cooling process (Third-round experiment)		
Body location	**Absolute level**	**Gradient**	**Mean of square of gradient**	**Absolute level**	**Gradient**	**Mean of square of gradient**
Forehead	Significant	Significant				
Upper arm		Significant				
Wrist		***Significant***	***Significant***		***Significant***	***Insignificant, but stable***
Hand		Significant				Insignificant, but stable
Chest	Significant					Insignificant, but stable
Belly						Insignificant, but stable
Thigh						Insignificant, but stable
Anterior calf						
Posterior calf					Significant	
Foot						

7. BIO-SENSING CONTROL SYSTEM DEVELOPMENT

7.1. Parameters for Thermal Control Systems

The human subject experiments provide evidence that the gradient of skin temperatures on the wrist supply the necessary information to differentiate neutral sensation from slightly cool and slightly warm sensations.

To develop a CoBi control system for building HVAC system, the research considered several parameters for the correct estimation of thermal sensations based on skin temperatures on the wrist:

- Time interval for calculating gradients
- Array size of skin temperature gradient data
- Control interval decision
- Rate of setpoint air temperature change for the HVAC systems control
- Parameters of PI control logic
- Array size of air temperature

7.1.1. Time interval for calculating a gradient

To calculate the gradient of skin temperature on the wrist, a time interval of three minutes was used in the experiments.

As discussed in the second-round experiment, the three-minute interval generates larger gradients than those of intervals at 30 seconds, one minute, and two minutes. The most appropriate time interval is selected by means of human subject experiments. Figure 49 illustrates how significant information can be extracted depending on time interval. The data collected from the sampled subject experiment is used to investigate the p-values of two sample t-test between slightly cool and neutral sensations, and between slightly warm and neutral sensations focusing on each subject case during the second-round experiments. When the time interval of 30 seconds is used for differentiating neutral sensation from slightly warm and slightly cool sensations, the generated p-values are small enough for statistical significance, comparing gradients between the two thermal sensations. However, 22% of the comparison sets failed to detect the difference of skin temperature gradients between the two sensations. The time interval of one minute is better than that of 30 seconds with lower percentage of detection failures.

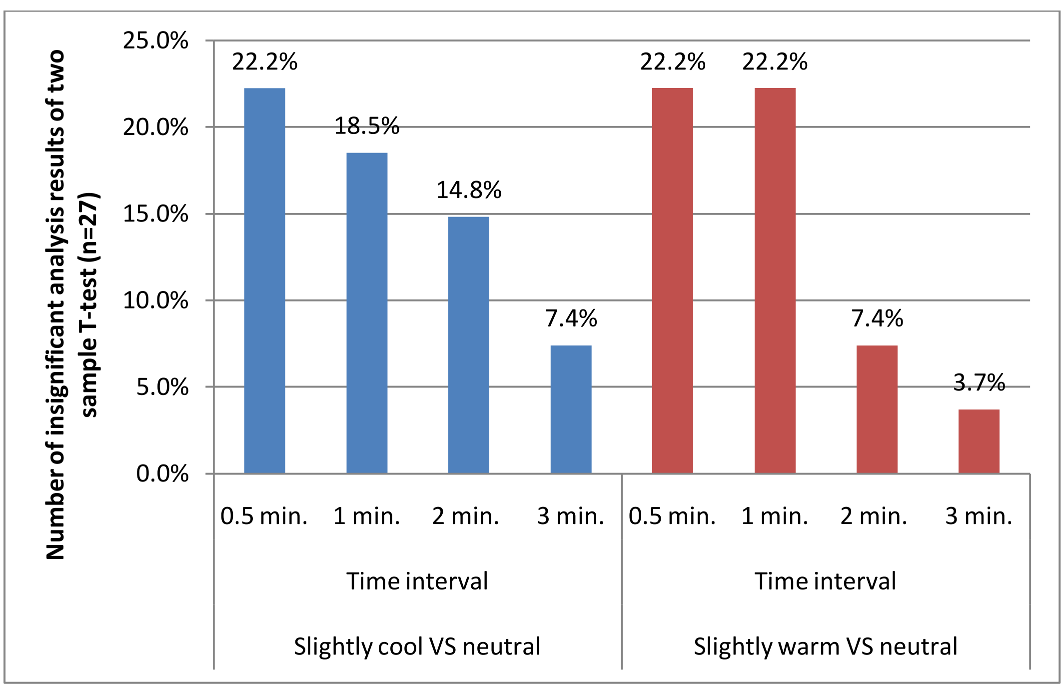


Fig. 49. Percentage of failure to differentiate neutral sensation from slightly warm and slightly cool sensations in different time-interval settings

Among the four time-interval settings, the three minute time-interval provides the lowest failure percentage at 7.4% and 3.7% in differentiating neutral sensation from slightly cool and from slightly warm sensations respectively. This outcome implies that the t-test generates much smaller p-values with the three minutes time-interval than other settings. Based on this finding, the three minute time-interval is selected for calculating the gradient of skin temperature on the wrist.

7.1.2. Array size of skin temperature gradient data

The array size of skin temperature gradient data is critical to assess a subject's thermal sensation based on the collected skin temperatures. Array sizes of 6, 12 and 18 are tested for an optimal size selection. As the sensing interval is set to 10 seconds, the array size of six ensures that the skin temperature data is collected for one minute. Similarly, array sizes of 12 and 18 indicate that the data was collected for two and three minutes respectively. The array size determines the number of data points in the t-test for calculating confidence intervals for corresponding time periods. Since a confidence interval implies the range of mean value of the processed dataset, an appropriate array size is crucial to provide a statistically meaningful outcome.

The appropriate array size was selected based on experimentation. The developed CoBi control system was tested with the three array size options (6, 12, and 18). The test followed the procedure of the fourth-round human subject experiment (discussed in Section 8) except that the clothing value was kept constant at 0.8 Clo (pants and long sleeve t-shirts). Each test was performed for three hours and each array size option was sustained for one hour. Each subject's thermal sensation was reported every 15 minutes through the data acquisition interface.

Figure 50 illustrates the fluctuation of thermal sensation reported during the time period created with each array size setting. During for the first full hour, the CoBi system is operated with array sizes of 18. The 12 and 6 array size options are employed during the second and third full hours respectively. The thermal sensations fluctuate between the neutral and cool sensations during the 18 array size option run. The sensation ranges between neutral and slightly cool sensations under the 6 array size option. The 12 array size option provides the most comfortable condition as the neutral sensation is reported three out of four times of the thermal sensation survey.

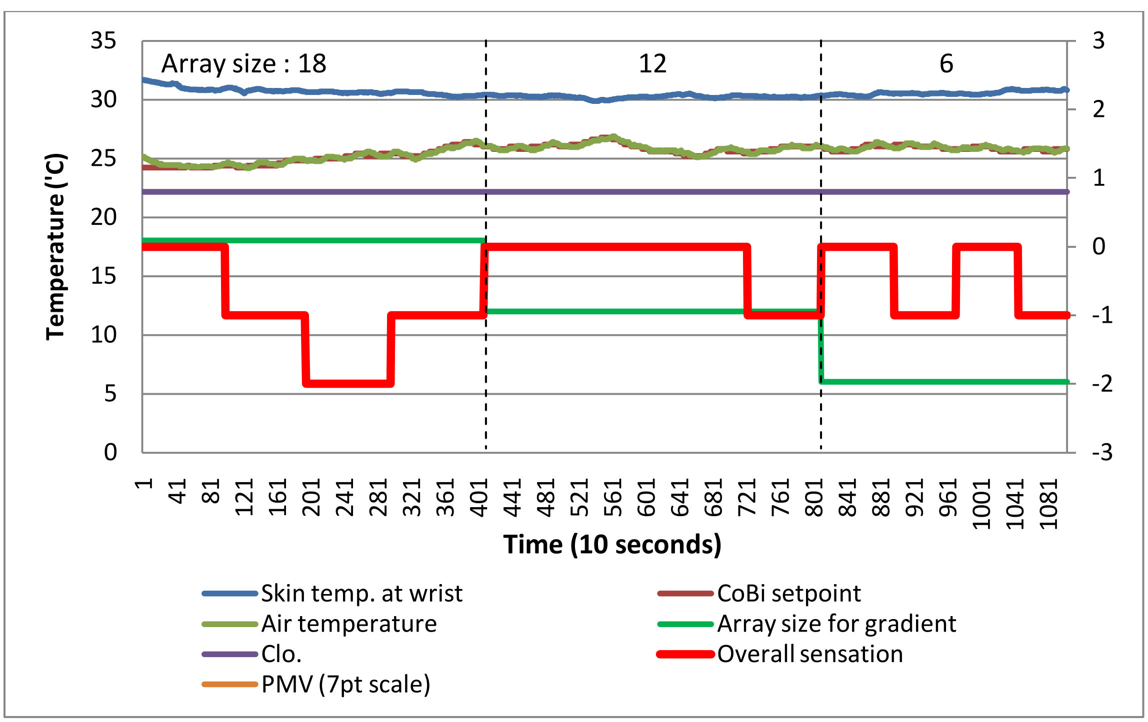


Fig. 50. Thermal sensation depending on the array size of gradient (ID: 201091001)

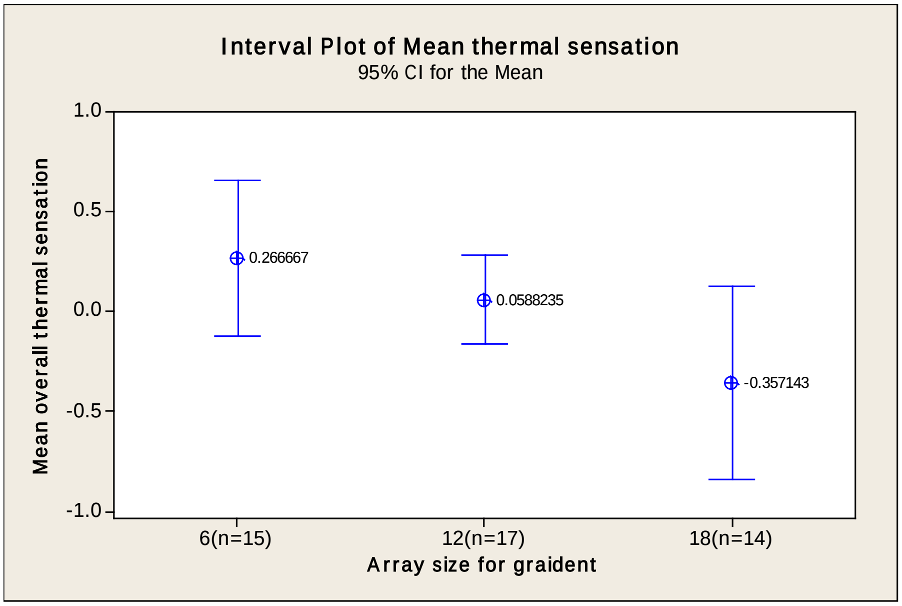


Fig. 51. Confidence interval of thermal sensation in each array size option (p=0.047)

As illustrated Figure 51, the confidence intervals of the mean thermal sensation in each array size option show the narrowest and most adjacent value at the neutral sensation with the 12 array size option. The ANOVA test generates a statistically significant p-value at 0.047. Overall, the array size of six reveals relatively warmer sensations while the 18 array size reveals cooler sensations. Since the array size at 6 is of a relatively small number of data points for the statistical test, it causes a large confidence interval and fails to estimate a correct thermal sensation of the subject. The 18 array size seems to contain already-outdated information about skin temperature.

As discussed in the previous section, the gradient is calculated in three-minute intervals every 10 seconds. This implies that the data in the 18-array size includes the skin temperature data which was obtained six minutes before the current condition. This data may be inadequate for representing up-to-date thermal sensations, and may trigger incorrect estimations of a subject's thermal sensation. Therefore, the array size of 12 seems to be the most effective for analyzing the thermal sensation using a confidence interval to be compared with a gradient at zero, i.e. the neutral sensation at any given moment.

7.1.3. Control interval decision

Since the research mainly considers the potential use of skin temperature for a building's mechanical systems control, it does not set up the mechanical system for a single operational mode, i.e. cooling only or heating only. The environmental chamber is thermally affected by the outdoor condition, which in this case is the indoor condition of the Intelligent Workplace office space. If the HVAC system was limited to a single operational mode (i.e. heating or cooling), the human subject experiment would need to delay for the chamber temperature to be cool when the system determines the subject to be in too warm in the heating-only mode, and vice versa. Also, to investigate the control system performance during the limited time, the system cannot adopt a fixed control interval. The control interval could vary depending on the type of mechanical system and indoor environmental condition. Therefore, the research adopts an event-based control instead of a fixed control interval. The event-based control indicates that the mechanical system could be actuated depending on the t-test outcomes of the gradient data in the 12 size-array estimating a subject's thermal sensation. This array size can be a default setting for any type of system and environmental condition.

7.1.4. Rate of setpoint air temperature change per unit decrease or increase

Depending on the estimated thermal sensation, the setpoint air temperature is updated +0.2ºC or -0.2ºC per event; the definition of event is discussed in the previous section.

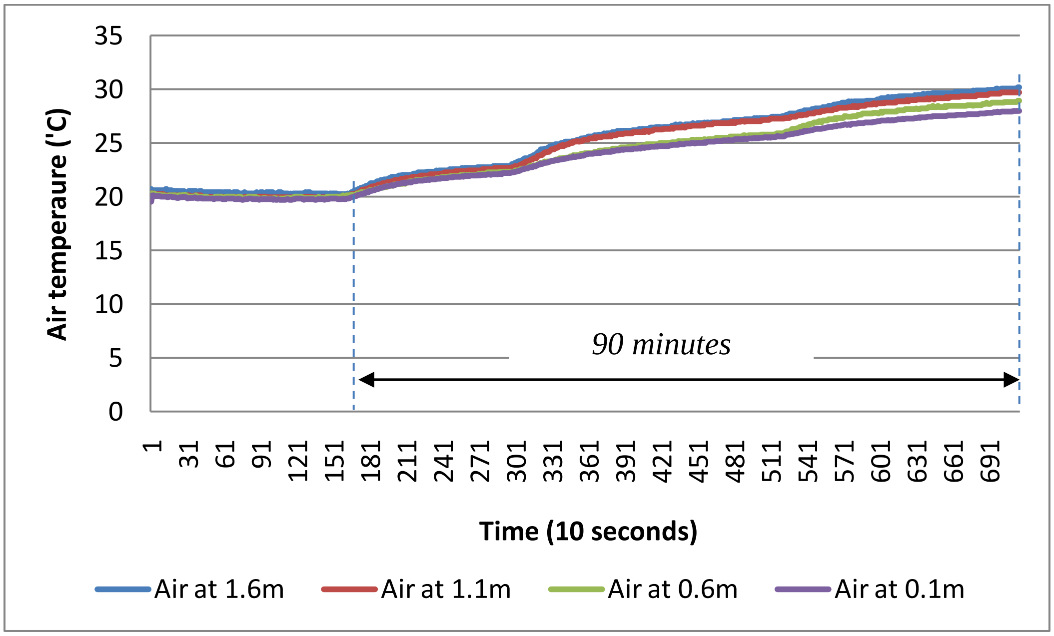


Fig. 52. Air temperature increasing rate in heating mode

As illustrated in Figure 52, it takes an average of 90 minutes to research to 30ºC from 20 ºC with the current heating capacity of the mechanical systems. The functional limitation indicates that it takes 9 minutes to increase the air temperature by 1 ºC, and takes 1.8 minutes to 2 minutes to increase the air temperature by 0.2ºC. This estimated time could be different depending on the embodied thermal energy in the experimental equipment and surface materials in the chamber.

The other factor to be considered is the array size of the skin temperature gradient to estimate a subject's thermal sensation. As discussed in the previous section regarding the array size of skin temperature gradient data, the array size of 12 is selected for the optimal size for the estimation of thermal sensation. The array size indicates the amount of data collected for two minutes. Since the array is continuously updated every 10 seconds, which is the sensing interval, the selected rate of air temperature change - 0.2ºC provides critical information to explain skin temperature patterns while the air temperature is changing. Since the operation frequency of the chamber's mechanical system relies on specific timing to reach the setpoint temperature given a 0.2 ºC temperature climb, the control interval is averaged at two minutes. This time variable is used for deciding one parameter in the PI control, a component in the CoBi control system.

7.1.5. Parameters of PI control logic

A proportional-integral-derivate controller (PID controller) is the basic and most popular control loop feedback controller employed broadly in industrial control systems (UMICH, 2010).

PID controller : $$u = K_p e + K_i \int edt + K_d \frac{de}{dt}$$

PI controller : $$u = K_p e + K_i \int edt$$

Where the tuning parameters are:
Proportional gain (Kp), Integral gain (Ki), Derivative gain (Kd)

The proportional gain contributes to removing the error between a setpoint and the generated output (UMICH, 2010). The integral gain involves eliminating steady-state error for a unit step input, and the derivative gain plays a role in reducing overshooting and oscillation.

The embedded PID algorithm in the LabVIEW 8.5 adopts Ziegler and Nichols for auto-tuning the parameters of a PID controller. The package contains the following three types of loop performance: fast (1.4 damping ratio), normal (some overshooting), and slow (little overshooting) (Figure 53 and Table 27).

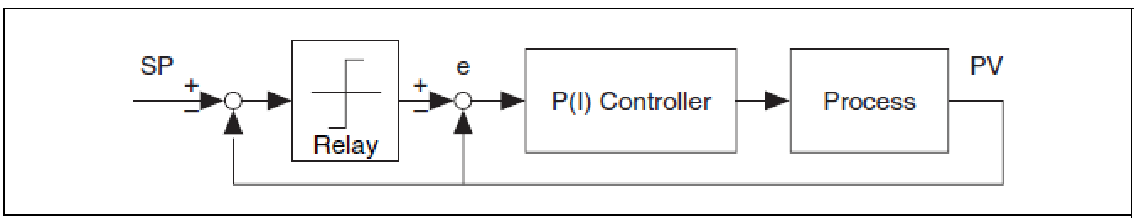


Fig. 53. Process under PID control with setpoint relay (National Instruments, 2009)

TABLE 27. Tuning formula under PI control (slow) (National Instruments, 2009)

Controller	K_c	T_i	T_d
P	$0.26T_p/\tau$	—	—
PI	$0.24T_p/\tau$	5.33τ	—
PID	$0.32T_p/\tau$	4.0τ	0.8τ

* Where Tp is the time constant, and the gamma (ד) is the dead time (interval of time between initiation of an input change or stimulus and the start of the resulting observable response.

Since the CoBi system's sensing interval is 10 seconds and the control interval is approximately two minutes, it employs a PI control logic without the derivative gain (D). The time constant, Tp is 120 seconds (i.e. 2 minutes), and the gamma is 10 seconds. The parameters of Kc (proportional gain) and Ti (integral time) are calculated at 2.88 and 0.8883, respectively, using the formula given in the LabVIEW 8.5 (Table 27).

7.1.6. Array size of air temperature

The CoBi control system developed uses the PI outcome for the mechanical system operation control. When the PI logic generates a negative (or positive) outcome, the cooling (or heating) system would be actuated. Since the system may generates an overheating or overcooling condition despite the PI parameters, an array of air temperature is implanted before the step of the PI control logic. The data array is processed through t-test and it has a role of filtering the fluctuation of air temperature signal, and the array size is set at five to maintain an air temperature around a given setpoint temperature while minimizing the effect of overshooting by the mechanical system. When the confidence interval (CI) range of air temperature calculated by the t-test covers the setpoint, the mechanical system does not operate. When the maximum (or minimum) of CI is less (or larger) than the setpoint, the heating (or cooling) system is actuated.

Figure 54 illustrates the CoBi setpoint temperature and the actual air temperature generated by the mechanical system in the three array size options to estimate the error between the setpoint temperature and air temperature. When the array size of 1 was used, the error reaches up to +0.3°C and -0.3°C to -0.4°C from the setpoint at 27.7°C. The array size of 10 generates almost same size errors as the array size of one. The array size of five provides the minimum error, -0.1°C and +0.2°C between the setpoint temperature and the air temperature, which is more stable than other array size option. Based on this finding, the array size of five is used for the filtration process to maintain air temperature with the smallest error in relation to the setpoint temperature.

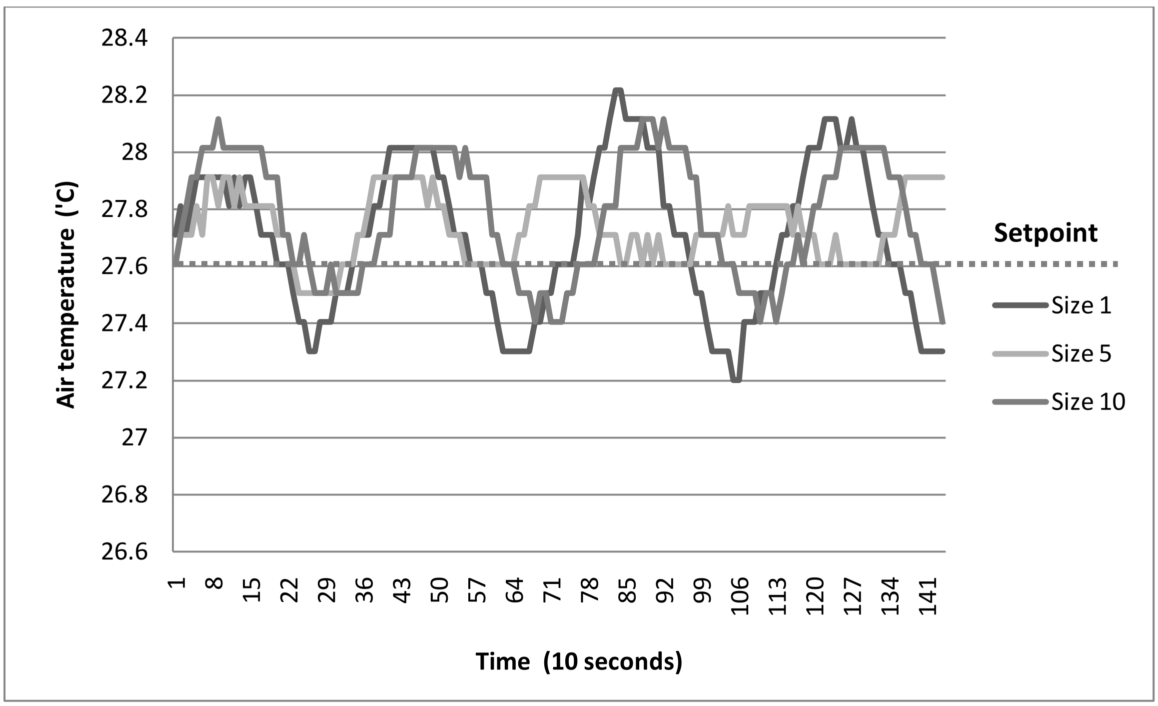


Fig. 54. Generated air temperature in three different array size settings at 27.7°C setpoint temperature in the CoBi control system

7.2. CoBi Control System Development

Based on the findings of the series of human subject experiments and the parameters discussed in Section 7.1, the CoBi bio-sensing mechanical control system is developed as shown in Figure 55. The control flow chart is divided into three segments for a process description.

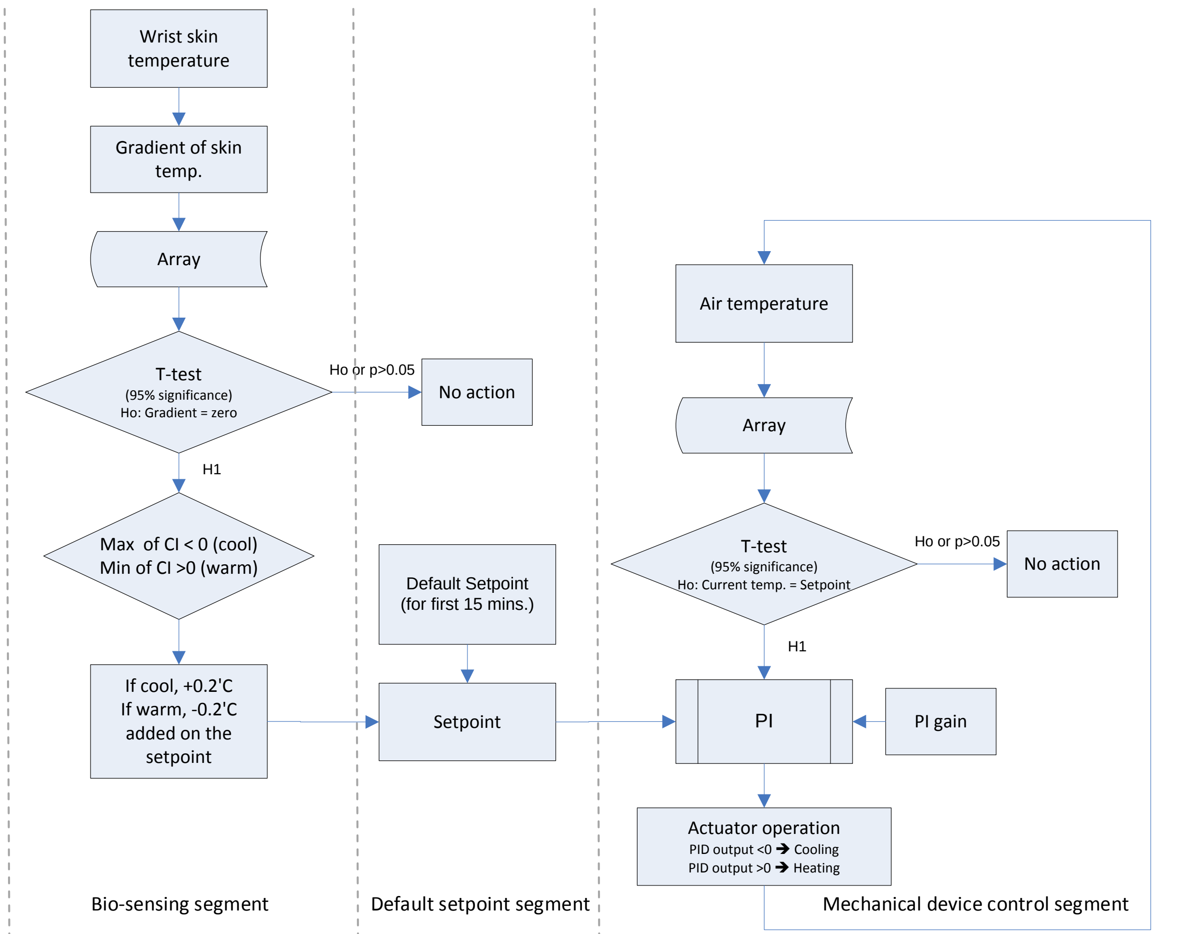


Fig. 55. The developed bio-sensing mechanical device control system

7.2.1. Bio-sensing segment

The wrist skin temperature is collected every 10 seconds. Based on the three minute time-interval, the gradient is calculated using the formula: T(wrist, i) – T(wrist, i-18). The gradient is recorded in the array until the array size of 12 is achieved. The collected 12 dataset is processed for statistical analysis, i.e. t-test with 95% significance level. The null hypothesis is that the mean gradient is zero, which is when the thermal sensation is estimated as neutral. When the t-test outcome has a p-value larger than 0.05, the system suspends any action for control. Also, if the confidence interval of the mean gradient calculated by the t-test contains zero, it implies that the null hypothesis is accepted and that there is no action to be processed.

If the t-test generates a statistically significant result rejecting the null hypothesis, the calculated confidence interval of the mean gradient is compared with zero. When the maximum of the interval is smaller than zero, the system estimates the subject's sensation as slightly cool. If the minimum of the interval is larger than zero, the subject's sensation is estimated as slightly warm. Depending on the estimation, 0.2ºC is added to the setpoint in the slightly cool condition, or subtracted from the existing setpoint air temperature at the slightly warm condition.

The developed CoBi system is for a real-time control system. Based on the data collected every 10 seconds, the bio-sensing segment estimates the subject's sensation using three options: slightly cool, neutral and slightly warm sensation. The process of estimating thermal sensation and updating setpoint temperature is continued in a frequency of less than 2 minutes. This real-time control process does not require the system to estimate the subject's sensation at other temperatures: cool, cold, warm or hot levels.

7.2.2. Default setpoint segment

The default setpoint temperature is crucial for the CoBi system because it is used as a basis for the initial process and will be updated based on the estimated thermal sensation. Since the preferred comfort condition is different depending on individuals (Charles et al., 2003), a customized default setpoint is very important for providing thermal comfort for a subject. The validation test (discussed in Section 8) found a default setting where the slightly warm or cool sensation is felt to be acceptable, resulting in an update to generate the neutral sensation. Thus, in the validation test, the default setpoint is decided using the current PMV formula or a subject's historical data in the neutral sensation, gathered from the pilot study completed prior to the test.

7.2.3. Mechanical device control segment

The updated setpoint information is given to the PI control logic in the mechanical device control segment. This control section adopts an array as a filter for air temperature data. The t-test generates a confidence interval of the mean air temperature based on the five recorded datasets for each 50 second-data window every 10 seconds. This filtration strategy and the t-test minimize overshooting conditions in the mechanical system operation. The calculated mean temperature from by the t-test is transferred to the PI logic as an input variable, and the control logic generates the output depending on the delta between the setpoint and the mean air temperature.

This research is aimed at generating sensing, actuating and control strategies for occupant comfort with constant air volume systems that support variable temperature control. These could include fan-coil systems, constant volume with terminal reheat/re-cool, under-floor air with variable supply air temperature, mixing boxes, etc. Thus, the CoBi control system uses the PI output as a binary variable to shift the operating modes between cooling and heating. When the PI output is negative, the cooling mode will be operated and when the output is positive, the heating mode will be operated.

8. VALIDATION OF A BIO-SENSING CONTROL SYSTEM TO ACHIEVE NEUTRAL THERMAL RESPONSES (Fourth-round experiment)

8.1. Methods and Procedures

In the CoBi bio-sensing driven controller test, a total 18 human subjects participated in the experiment. 10 subjects were used to test the CoBi control system, and 8 subjects were participated in the test to confirm the limitations of the system.

The CoBi bio-sensing driven controller test took three hours and subjects were asked to add or remove clothing layers in three steps, affecting the Clo value: 1.1 Clo was comprised of a jacket, moderately warm pants and long sleeve t-shirts; 0.8 Clo with only moderately warm pants and long sleeve t-shirts; and 0.5 Clo combining moderately warm pants with short sleeve t-shirts varying the order by subject. The clothing value properties adopted in the experiment are summarized in Table 28.

The Clo value was changed every hour while maintaining their activity levels at 1.2 Met, reflecting office work, such as typing on the computer. The thermal sensation survey was also completed by the subjects every 10 to 15 minutes and the collected subjective information was compared with the estimated thermal sensation using the current PMV formula.

TABLE 28. Clo-value variations for the CoBi bio-sensing control test (Engineering Tool Box, 2008)

Garment description		Clo	Summer	Winter	Swing
	Panties	0.03	0.03	0.03	0.03
Underwear	Bra	0.01	0.01	0.01	0.01
	Short sleeve	0.06	0.06	0.06	0.06
Shirts	Short sleeve	0.09	0.09	0.09	0.09
	Normal, long sleeve	0.25		0.25	0.25
Trousers	Overall	0.28	0.28	0.25	0.25
Jacket	Light jacket	0.35		0.35	
Socks	Socks	0.02	0.02	0.02	0.02
Shoes	Thin shoes	0.02			
	Thick shoes	0.04	0.04	0.04	0.04
		TOTAL	**0.53**	**1.1**	**0.75**

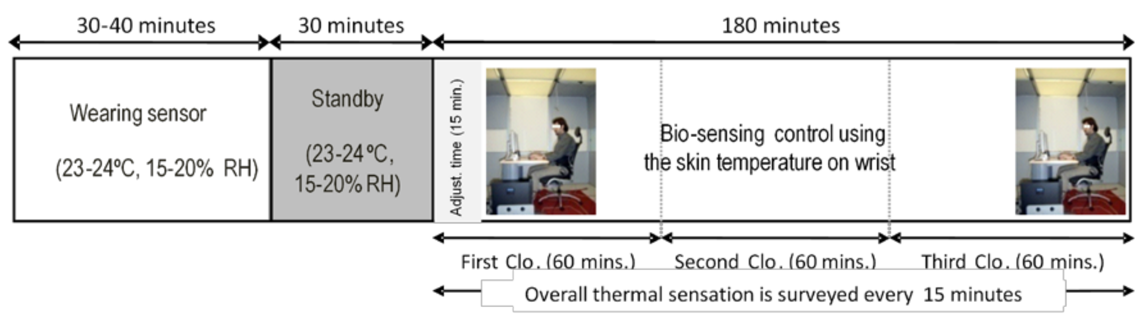


Fig. 56. Figurative procedure for the validation test

As described in Figure 56, each subject changed their Clo value from 0.5 to 1.1 in three steps. The first 15 minutes was an adjusting time at the default setpoint temperature. The default setpoint temperature was determined using the PMV formula or a subject's pre-defined comfort temperature. While the skin temperature at the wrist was measured with a sensing interval of 10 seconds, the CoBi control system estimated continuously the individual thermal sensation and automatically generated a new setpoint temperature. For three hours, the subject's thermal sensation was surveyed every 15 minutes.

8.2. Surveyed Thermal Sensation

8.2.1. Thermal sensation reported in test

Figure 57 illustrates the thermal sensations reported by one subject during the validation test. The subject changed clothing layers from 1.1 Clo to 0.8 and 0.5 Clo with the CoBi controller automatically generating temperature increases corresponding to the wrist skin temperature gradients. During the experiment, the subject reported their thermal sensations as continuously neutral, and overall thermal satisfaction was very satisfied or satisfied.

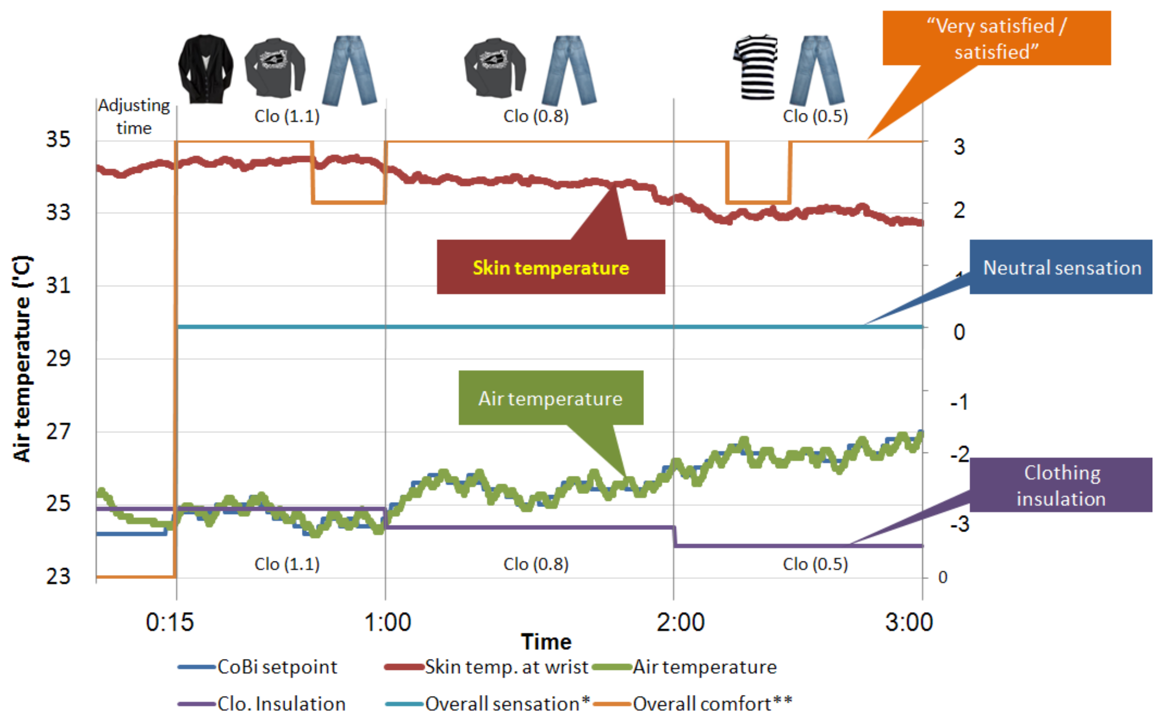


Fig. 57. Skin temperature and generated air temperature pattern resulting from changing clothing values (Clo) (ID: 201101001)

As such, the CoBi control system ensured thermal comfort by incrementally changing air temperature to correspond to the variation of each subject's wrist skin temperature, such that the neutral sensation can be maintained constantly. In the experiment, each subject reported his/her thermal sensation 12 times and Figure 58 shows all the collected thermal sensation data from all the subjects. Except eight cases, the remaining 112 surveys were reported at thermally neutral sensation, which indicates the successful delivery of thermal comfort at 93% beyond the goal of 80% satisfied in the PMV formula, and far beyond the field reality of 40% satisfied or very satisfied (CBPD, 2008).

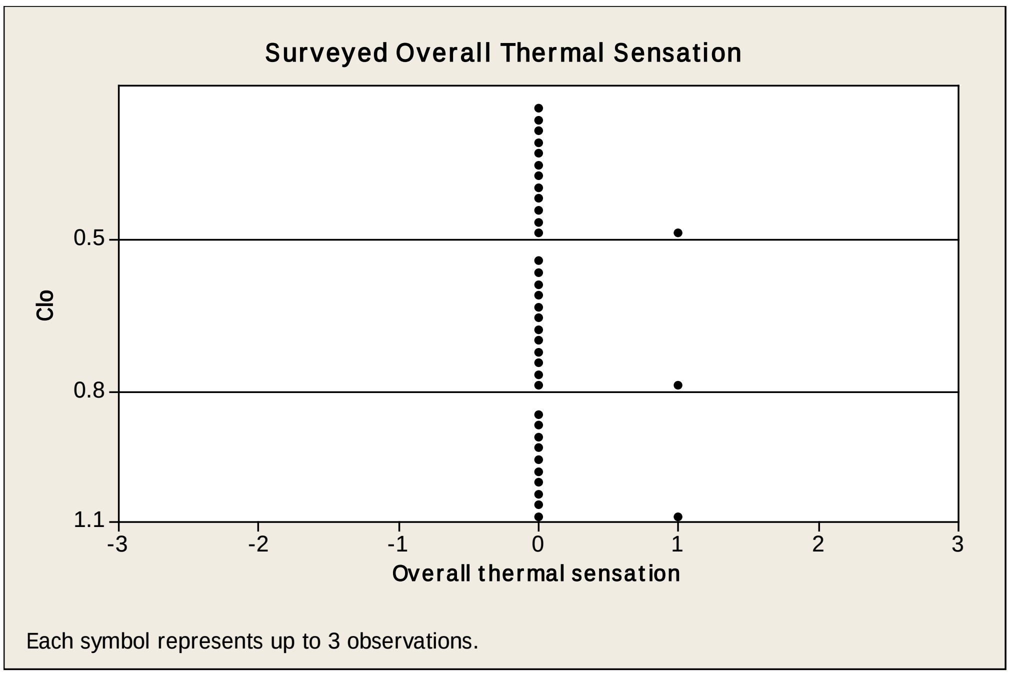


Fig. 58. Surveyed thermal sensation in the CoBi validation tests

8.2.2. Calculated thermal sensation using the PMV formula

Figure 59 shows the estimated thermal sensation that would have been expected given the CoBi setpoints using the PMV formula. In most cases, the PMV estimation of thermal sensation would have been deemed warmer than the actual surveyed sensation data. On average, the PMV estimation is 0.55 warmers than neutral at 0.5 Clo, 1 warmer at 0.8 Clo and 1.5 warmer at 1.1 Clo conditions as compared to the actual surveyed sensation.

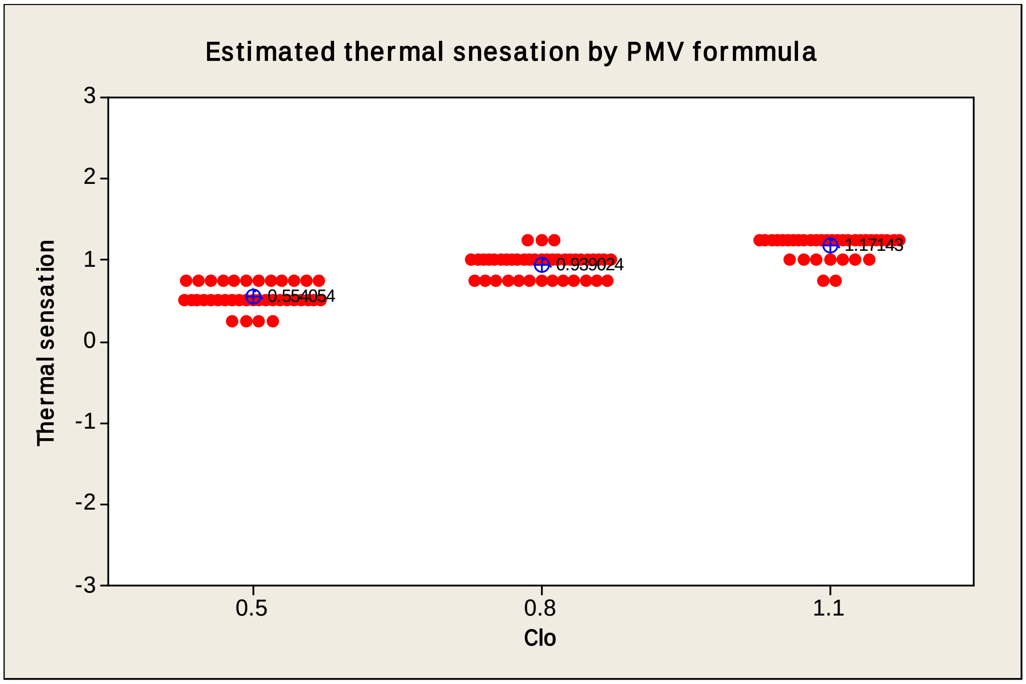


Fig. 59. Calculated thermal sensation by PMV (-3: cool…0: neutral….3: hot)

8.3. CoBi - Generated Thermal Conditions

Figure 60 illustrates the setpoint temperatures generated by the CoBi system to maintain each subject's neutral thermal sensation and each Clo value. Given 0.5 Clo, the average setpoint is 26.4°C, ranging from 25.2°C to 28°C, falling to 26°C at 0.8 Clo, and then 25.8 °C at 1.1 Clo. The range of temperatures automatically set by the bio-signals supports the claim that even under the same or similar Clo value and activity level, the preferred thermal environmental conditions vary depending on each subject's physiological conditions and preferences.

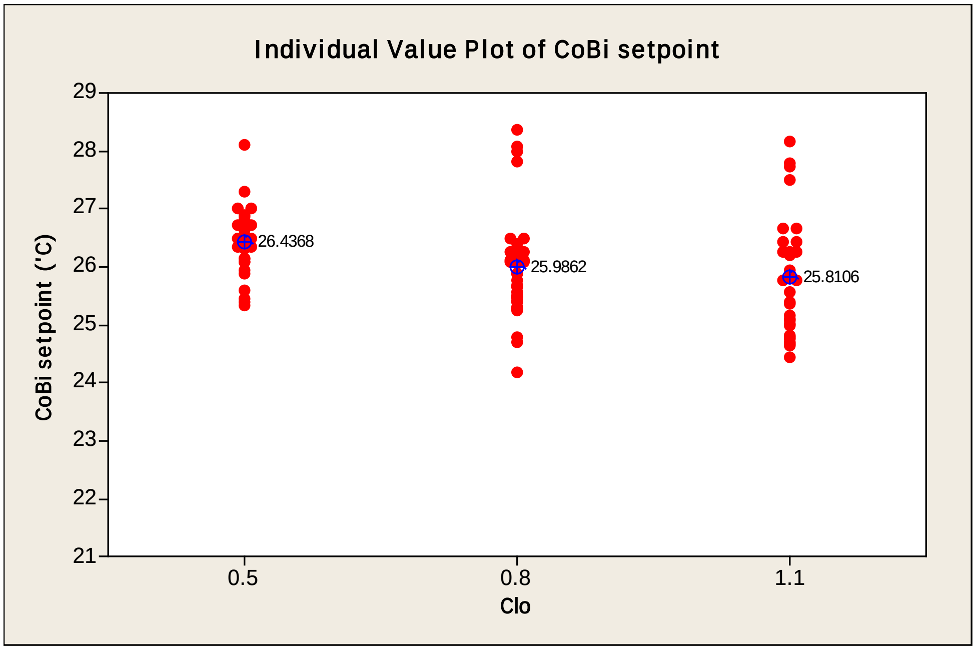


Fig. 60. Setpoint temperature generated by the CoBi bio-sensing control system to maintain neutral sensations

Comparisons of thermal setpoints generated by the CoBi control system to the setpoint air temperature calculated using the current PMV formula are shown in Table 29. The deltas are always cooler with PMV setpoints measuring 0.9°C. 2.5°C and 3.8°Cat 0.5, 0.8 and 1.1 Clo respectively. It is critical to note that both physiological signals and satisfaction suggest measurably higher air temperatures than the PMV formula would generate.

TABLE 29. Estimated setpoint temperatures by the current PMV formula

Clo value	Estimated setpoint air temperature by the PMV	Assumed relative humidity range	Average CoBi setpoints
0.5 Clo	25.5ºC		26.44 ºC
0.8 Clo	23.5ºC	15% to 25%	25.98 ºC
1.1 Clo	22.0ºC		25.81 ºC

The setpoint temperatures proposed by both the PMV formula and the CoBi bio-signal control system given the experimental conditions are displayed in Figure 61. Depending on Clo values, the differences between the CoBi and the PMV setpoints range from 1.5 ºC to 3.8ºC. This may be a result of PMV not considering individual parameters such as age, gender, body mass index, etc. and the lower PMV setpoints have resulted in measurable (60%) thermal discomfort complaints by occupants in buildings adopting PMV control systems (CBPD, 2008).

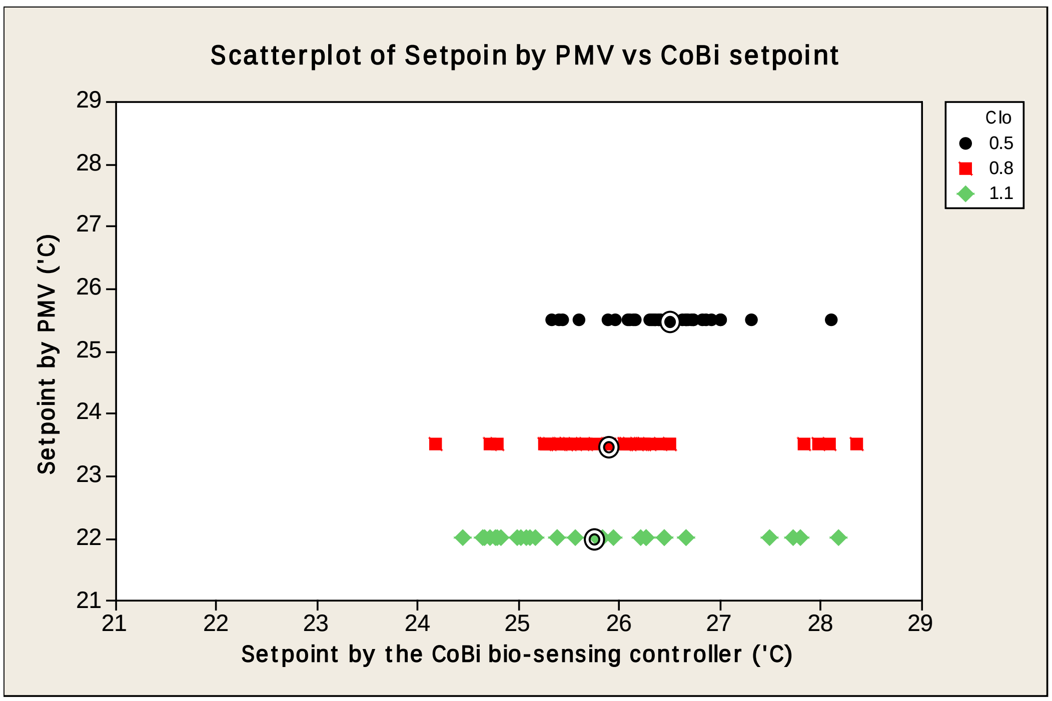


Fig. 61. Comparison of setpoints generated by CoBi bio-sensing control and PMV methods

Table 30 summarizes the average setpoints and sensations of both the PMV and CoBi control methods with standard deviations. As illustrated, in a low Clo condition (summer months), the difference of the setpoint is 1 ºC, but the difference increases to 3.8ºC in the higher Clo condition (winter months).

TABLE 30. Summary of average setpoint air temperature and thermal sensation of the CoBi controller and PMV control systems

Clo	Average CoBi setpoint (Std.Dev.)	Average PMV setpoint	Average reported sensation (Std.Dev.)	Average estimated sensation by PMV (Std.Dev.)
0.5 (n=37)	26.437 (0.532)	25.5	0.0811 (0.2767)	0.5512 (0.1074)
0.8(n=38)	25.986(0.888)	23.5	0.0526 (0.2263)	0.9418 (0.1439)
1.1(n=31)	25.811 (1.017)	22	0.0968 (0.3005)	1.1598 (0.1566)

8.4. Significant Findings from the CoBi Bio-Sensing Controller Test

During the CoBi bio-sensing controller test, two significant results were found: a negative correlation between the body mass index and the CoBi setpoint temperature, and a significant difference of the CoBi setpoint between genders. Since body mass index and gender are not considered in the current PMV thermal comfort model (Fanger, 1970), these findings are meaningful arguments for the amendment of the current model and for developing a new thermal sensation prediction formula.

8.4.1. The effect of individual human body mass index on the CoBi setpoint temperature

In the CoBi controller test, a negative correlation occurred between the subjects' body mass index and CoBi setpoint temperatures. As illustrated in Figure 62, the higher CoBi setpoint temperatures were generated in the subjects with lower body mass index (BMI). With a BMI over 31, setpoints are between 24.7 ℃ and 25.5 ℃ , while lower BMI of 20 resulted in the CoBi generated setpoints of 25.5 ℃ to 28.5 ℃ . Based on the correlation between the two variables, a regression formula is generated with a statistical significance (p=0.000). The coefficient of the formula is -2.318, which shows the negative correlation between the two variables.

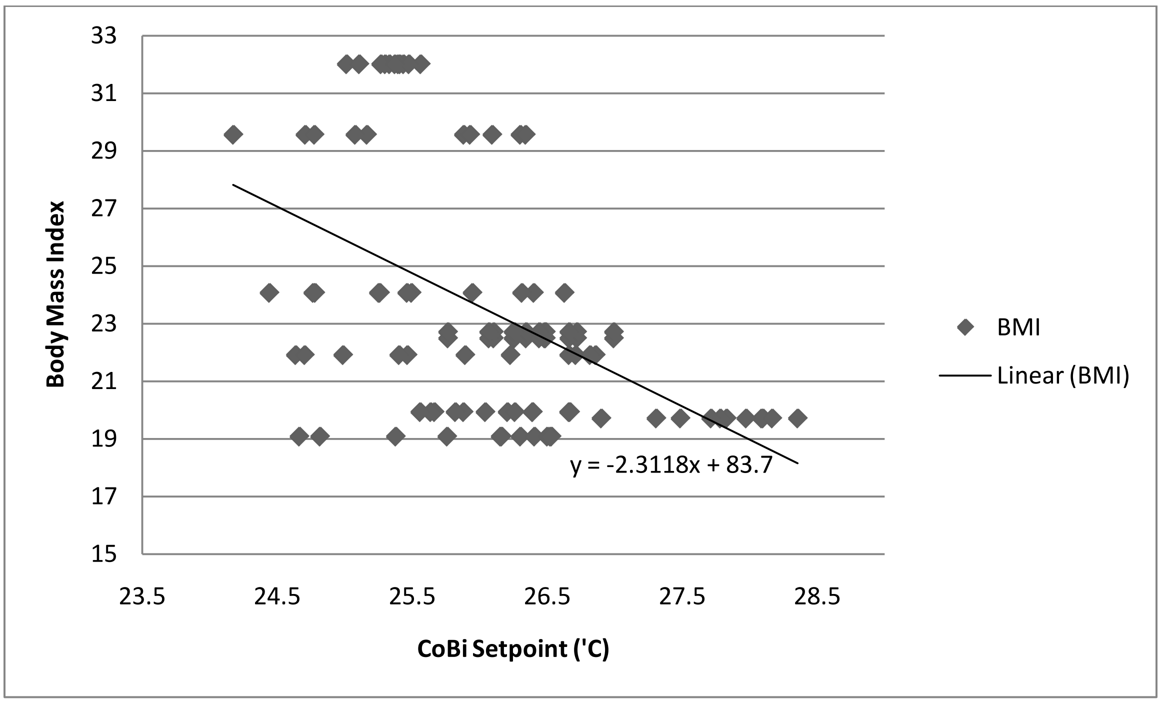


Fig. 62. Negative correlation between body mass index and CoBi setpoint (p=0.000)

8.4.2. The effect of gender on the CoBi setpoint temperature

The CoBi bio-sensing controller also generates higher setpoint temperature for female subjects to ensure their neutral sensation. As shown in Figure 63, the average CoBi setpoint temperature was 26.3°C across the three Clo-insulation conditions for the female subjects, while it was 25.9°C for the male subjects. The comparison also has a statistical significance, with a p-value at 0.034. In addition, the CoBi generated setpoint temperatures are more widely distributed for female subjects than for male subjects. This finding illustrates that females may need a wilder variation in temperature than males to secure their neutral sensation.

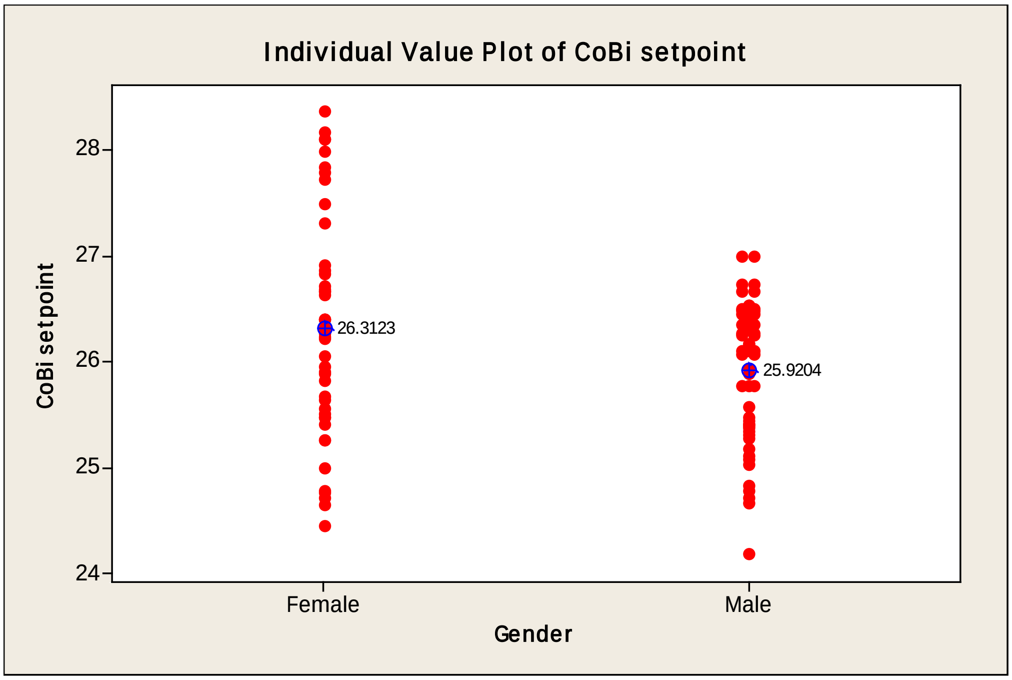


Fig. 63. Individually controlled temperatures resulting in neutral sensations (p=0.034)

Human factors such as body mass and gender are very significant variables for estimating thermal sensation, and these variables should be considered in the development of PMV models.

9. TASK PERFORMANCE AND ENERGY SAVING POTENTIALS

9.1. Performance Impacts

9.1.1. Task performance test procedures

In the second and third-round human subject experiments, task performance tests were conducted with all the experiment subjects. Each subject was asked to undertake three sets of multiplication questions. Each task-set consists of 40 questions, and 8 minutes is given for answering. Each question is a three-digit by two-digit multiplication problem. The first task was given 20 minutes after the start of the experiment, the second task is given 50 minutes after the start of experiment when slightly cool, slightly warm or neutral sensation was typically reported, and the third task was administered 80 minutes into the experiment, before and after the task period subjects are asked to report thermal sensation.

Since individual subjects have different levels of computation skills, the scores of each subject are standardized based on his/her maximum score in the task-set. The correctness and speed of each task is scored separately depending on the number of correct answers and number of answered questions. Each subject began in a standby area which had a moderate temperature at 23ºC to 24ºC with 30% relative humidity. The standby time was also used for a warm-up practice for the task performance test. The subject was asked to practice 20 questions which are similar to the ultimate task.

9.1.2. Performance impacts in the heating process (Second-round experiment)

As shown in Figure 64, the surveyed overall sensations during the performance tests are distributed from the cold to warm sensations. Depending on the sensation points, the frequency size varies and some sensation levels such as cold, cool, and hot do not contain the meaningful sample size for a statistical analysis.

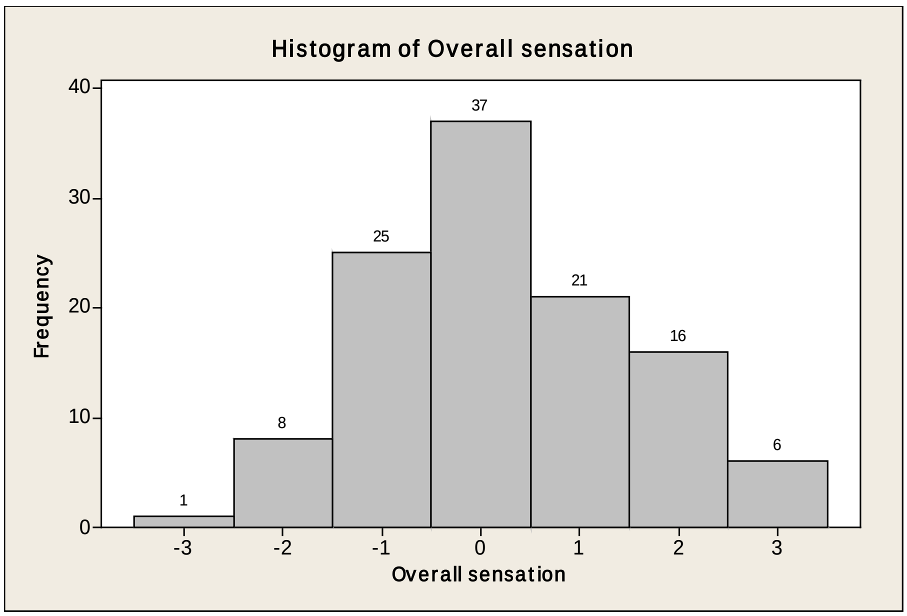


Fig. 64. Distribution of surveyed thermal sensation data in the second experiment

Considering the small sample size in the sensations other than neutral, the reported overall sensations are grouped by their similarity to generate a relatively larger sample size in each sensation group for the ANOVA test. Cold (-3), cool (-2) and slightly cool (-1) sensations are merged into one single cool sensation group, and hot (+3), warm (+2), and slightly warm (+1) sensations are also clustered into a warm sensation group. The neutral sensation is not merged with other sensations due to its sufficient sample size.

The ANOVA test in Figure 65 clearly shows the correctness score of 97.8% in the neutral sensation, and scores of 91.5% and 91.8% in the cool and warm conditions, respectively. The p-value of the test is 0.002, which is statistically significant.

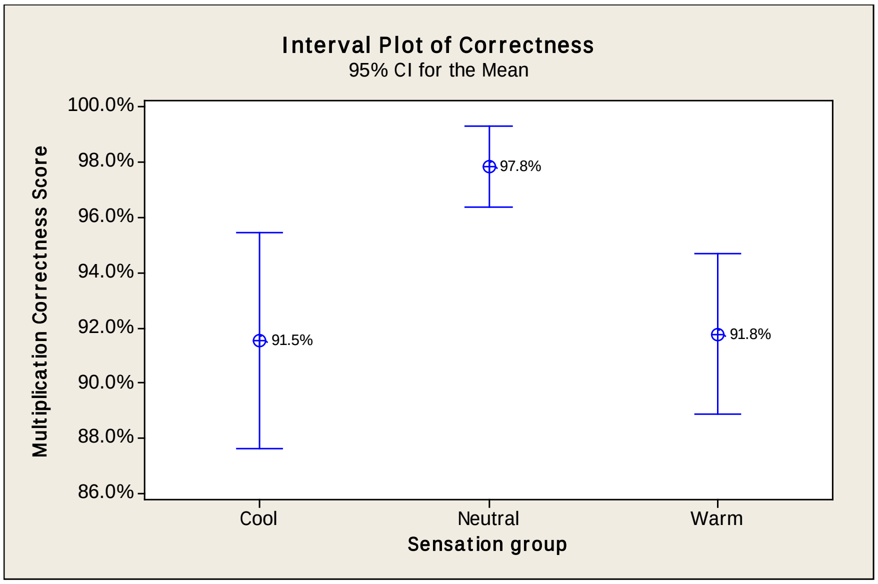


Fig. 65. ANOVA test of performance correctness score with sensation groups (p=0.002)

Applying the same analysis strategy to speed evaluation, the subject responds were grouped in to three major sensations: cool, neutral and warm. In Figure 66, the ANOVA test reveals a large significance with a p-value at 0.006, and the highest speed score at 94.4% is reported in the neutral sensation. The cool and warm conditions correlate with lower speed scores than the neutral sensation group with 85.6% and 91.2% as their average scores, respectively. The speed score when subjects report cool sensations is 9% lower on average than when reporting neutral sensation with a statistical significance of a p-value at 0.001. The difference in the scores between the warm and neutral sensations is not statistically significant in the two-sample t-test (p=0.208). Therefore, one might conclude that subjects' speed is more affected by their reported cool sensations rather than warm sensations.

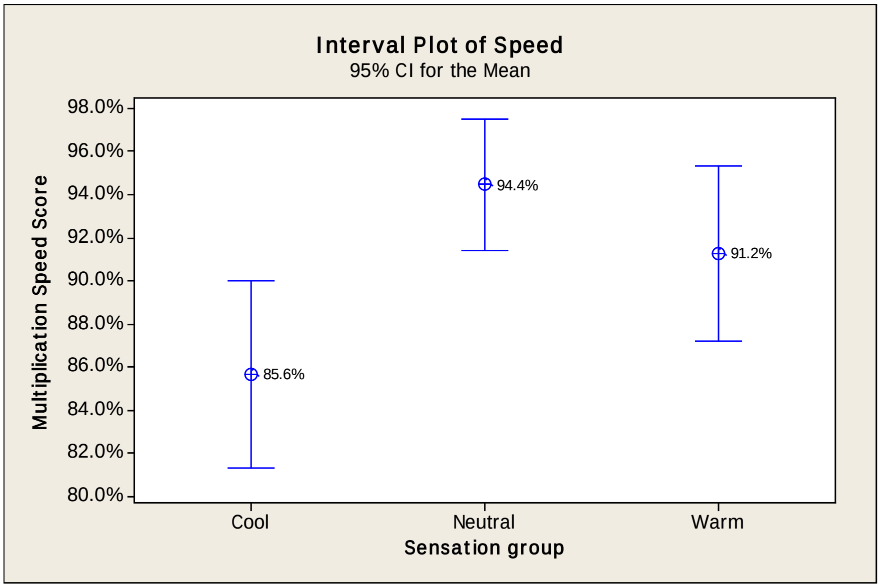


Fig. 66. ANOVA test of performance speed score with sensation groups (p=0.006)

The ANOVA test of a combined speed and correctness score reveals a statistically significant relationship with neutral sensations (p=0.000), with average high scores of 95.3% in the neutral sensation (Figure 67). The cool and warm conditions have lower average scores than the neutral sensation group at 81.5% and 86.5% respectively.

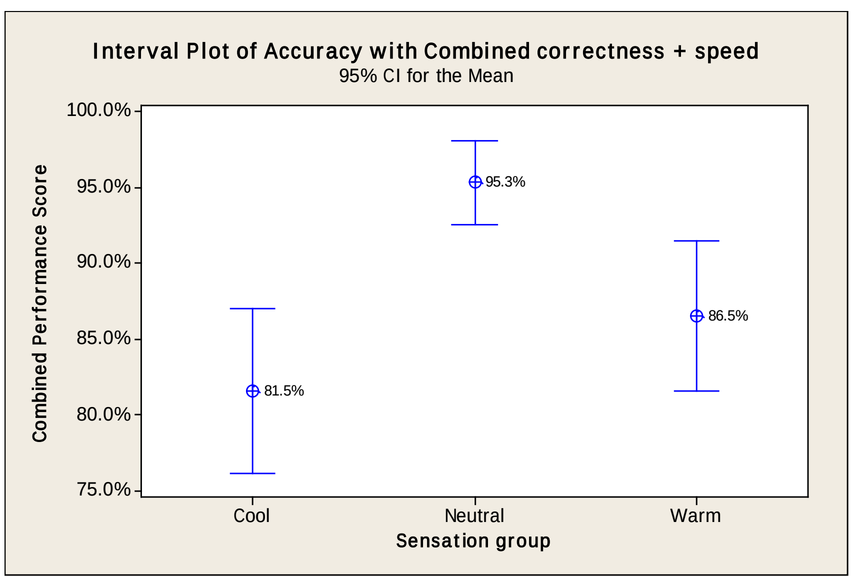


Fig. 67. ANOVA test of combined speed and correctness by thermal sensation groups (p=0.000)

9.1.3. Performance impacts in the cooling process (Third-round experiment)

All the sensation response data from the experiment participants paired with their task performance. To avoid sample sizes that were too small as shown in Figure 68, subjects were grouped in sensation groups of cool (-3, -2, -1), neutral (0) and warm (+1, +2, +3). The ANOVA test in Figure 69 illustrates that the subjects' correctness score is highest at the neutral sensation. The average score at neutral sensation was 95.8%, which is higher than 93.4% at cool sensations and 94.9% at warm sensations. Even though the p-value of the ANOVA test is not statistically significant, the test reveals meaningful highest scores in the neutral sensation group.

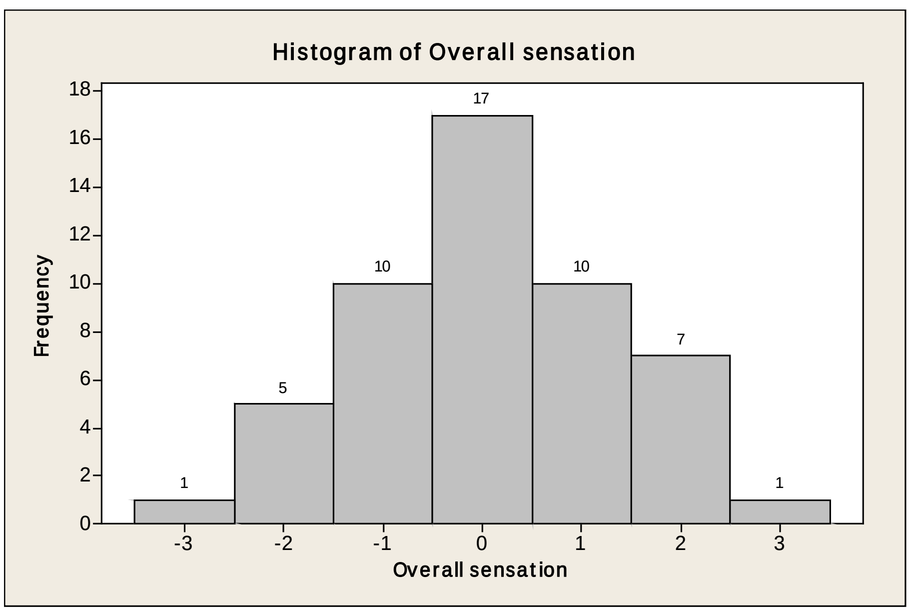


Fig. 68. Distribution of surveyed thermal sensation data in the third-round experiment

Unlike multiplication correctness which is highest at the neutral sensation, the ANOVA test of multiplication speed reveals the highest scores under cool conditions. The scores then decrease as the reported sensation becomes warmer (Figure 70). However, the result is not statistical significant with a large p-value at 0.583.

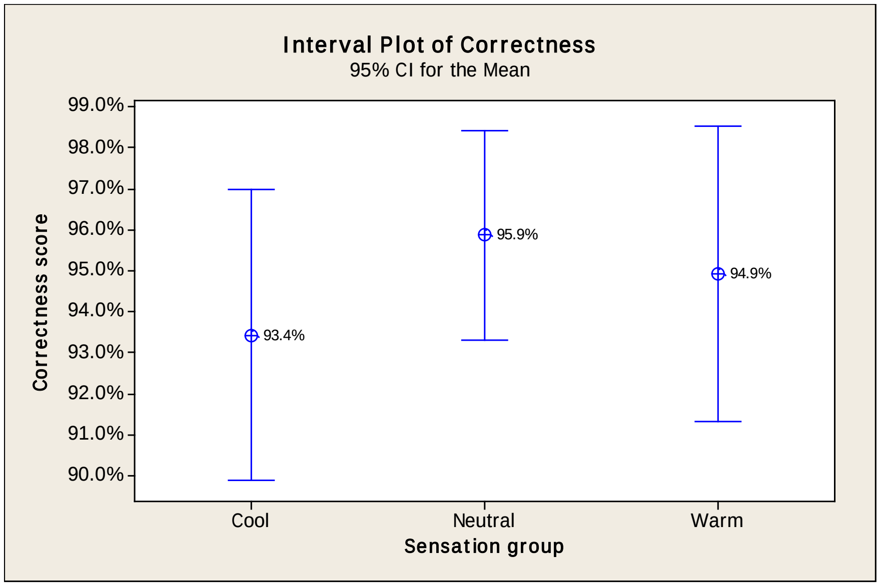


Fig. 69. ANOVA test of performance correctness score with overall sensations (p=0.546)

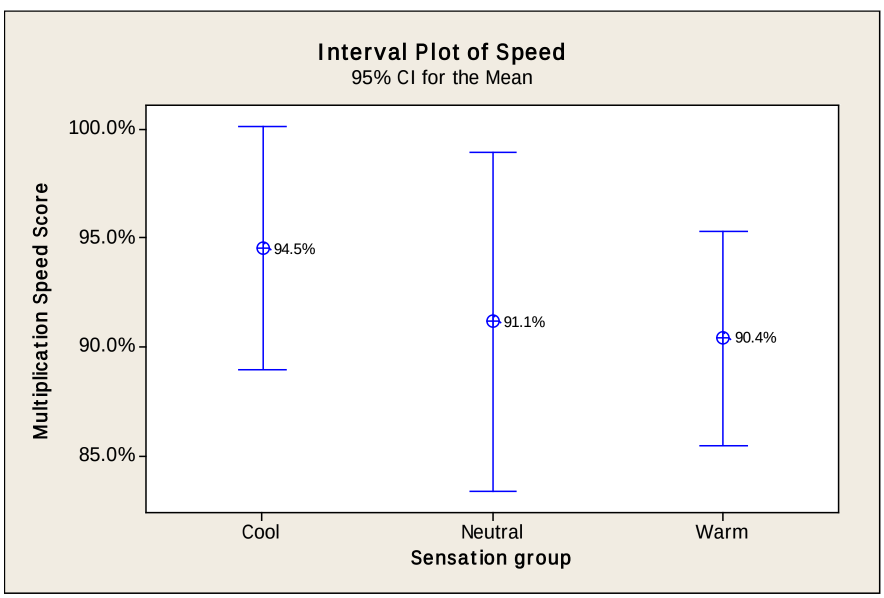


Fig. 70. ANOVA test of performance speed score with overall sensation groups (p=0.583)

As illustrated in Figure 71, combining speed and correctness into a multiplication "productivity" score also revealed no statistical significance. This may be due to the confounding effect of greater speed at cool sensations and greater correctness at neutral sensations. The ANOVA test of the performance correctness scores with speed shows no statistical significance. The score pattern is similar with that of the correctness score with the highest mean score in the neutral sensation, but the results do not show statistical significance.

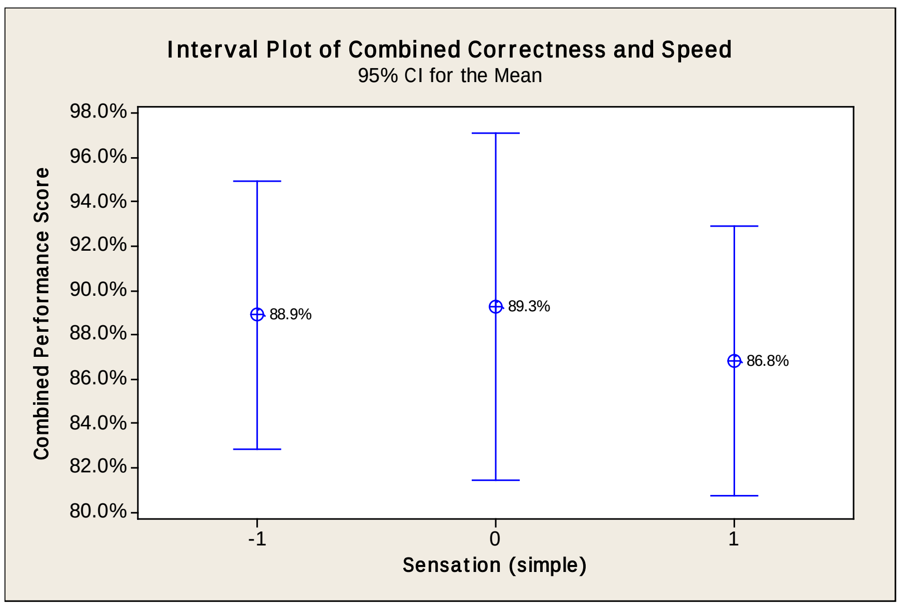


Fig. 71. ANOVA test of combined speed and correctness score by sensation groups (p=0.838)

In summary, compared with the task performance results of the second round experiment in a warming temperature trend, the ANOVA test of the task performance in a cooling temperature trend does not reveal any statistical significance. This may be because the human body compensates for thermal stress as temperatures drop from warm to cool with self-regulation. This research is not focused on the comparison of multiplication performance or productivity change related to cool and warm sensations. However, it can be summarized from the second and third round human subject experiments that the highest multiplication performance scores were reported in the neutral sensation with statistical significance when room temperatures were rising, but no statistical significance when temperatures were falling. This data set should be adequate to suggest that maintaining a neutral sensation for the subject enhances task performance.

9.1.4. Performance impacts in self-adjusting thermal environment (Fourth-round experiment)

9.1.4.1. Performance correctness and overall sensation

In the fourth experiment, when the CoBi control system is operated for self-adjusting temperature control, subjects reported continuous neutral sensations (Figure 72) with only 8% reporting slightly warm sensations during the task performance tests.

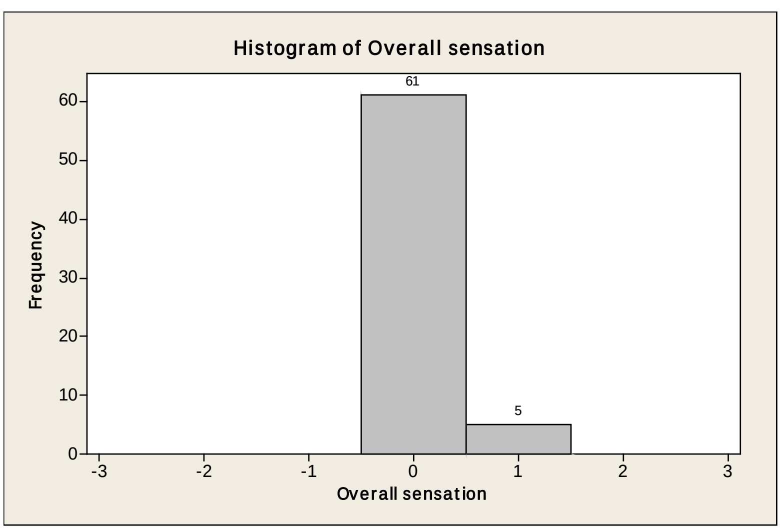


Fig. 72. Distribution of surveyed thermal sensation data in the fourth-round experiment

The purpose of this analysis of task performance was to ensure that performance outcomes did not vary across the series of tasks given continuous neutral sensations (thermal conditions were controlled by the CoBi control system driven by individual skin temperature at the wrist).

As shown in Figure 73, the average multiplication correctness score fluctuates from 88.3% to 96.1% depending on time, but with significant overlaps. The highest average score is in the sixth task at 96.1%, and the lowest one is in the third task at 88.87%. The ANOVA analysis yielded an insignificant p-value at 0.194 illustrating that the tasks performed under the thermal conditions managed by the CoBi control system provide a consistent level of correctness score across the subjects.

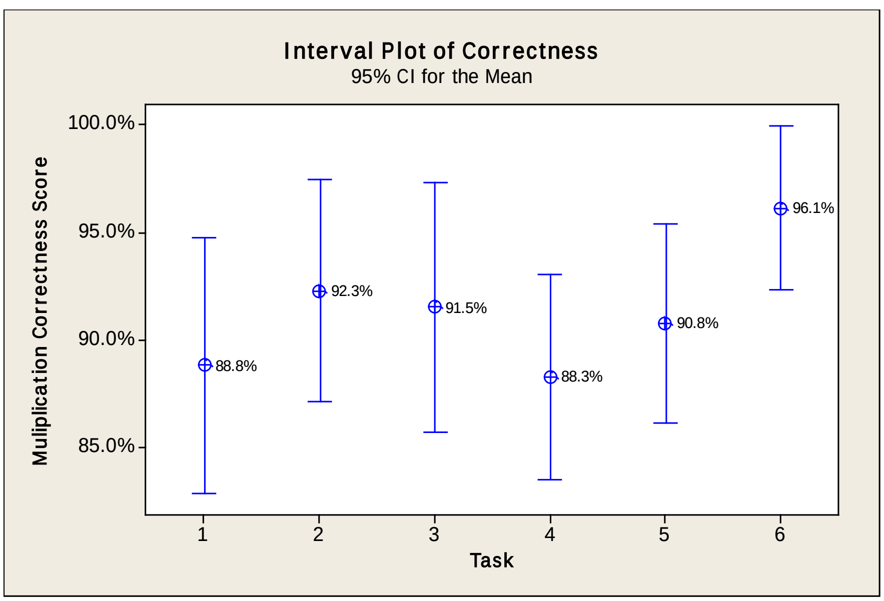


Fig. 73. ANOVA test of performance correctness score with overall sensations (p=0.194)

9.1.4.2. Performance speed and overall sensation

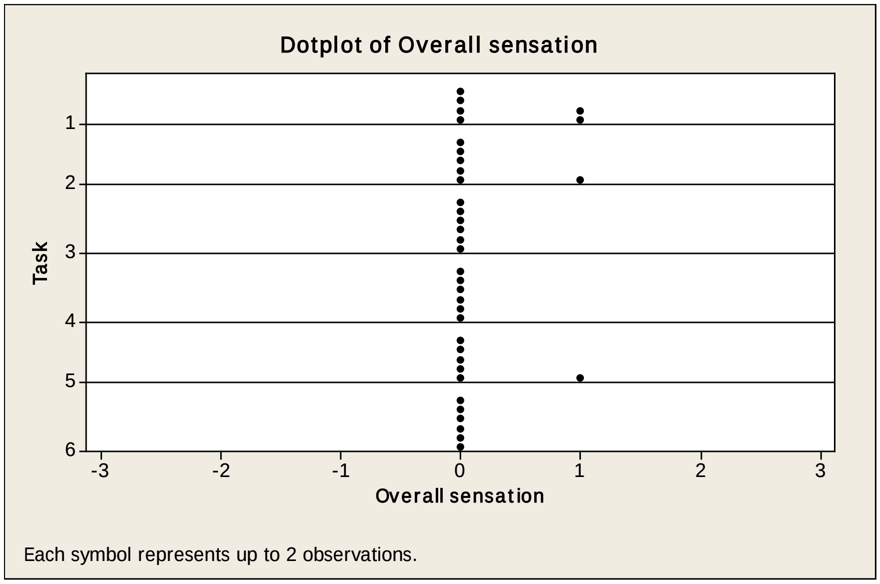


Fig. 74. Distribution of thermal sensation in each task

The multiplication task speed is inconsistent across the subjects. Even though neutral thermal sensations were typically reported during each test as illustrated in Figure 74, the speed score of the performance shows statistically significant differences over time with a p-value at 0.000 across the tasks in the ANOVA test (Figure 75). The average score has shown an increasing trend from the first to the third and from the fourth to the sixth test. Considering the almost constant condition at the neutral sensation, this result may be caused by other factors such as tiredness.

The experiment took three hours without a break, and the performance test was given every 30 minutes. During the experiment, some subjects reported that it was long and that they felt a bit bored. Therefore, the subjects' fatigue might affect the results, and a further study may be required to identify specific reasons for variability.

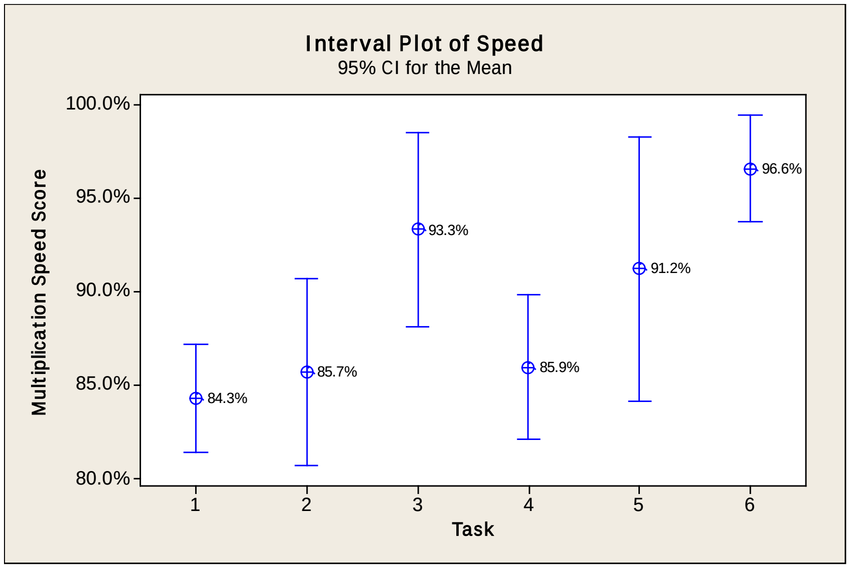


Fig. 75. ANOVA test of performance speed score with overall sensation groups (p=0.000)

When a combined score of speed and correctness is considered, the outcome still reveals a statistically significant link between time of test and performance (p=0.001) (Figure 76).

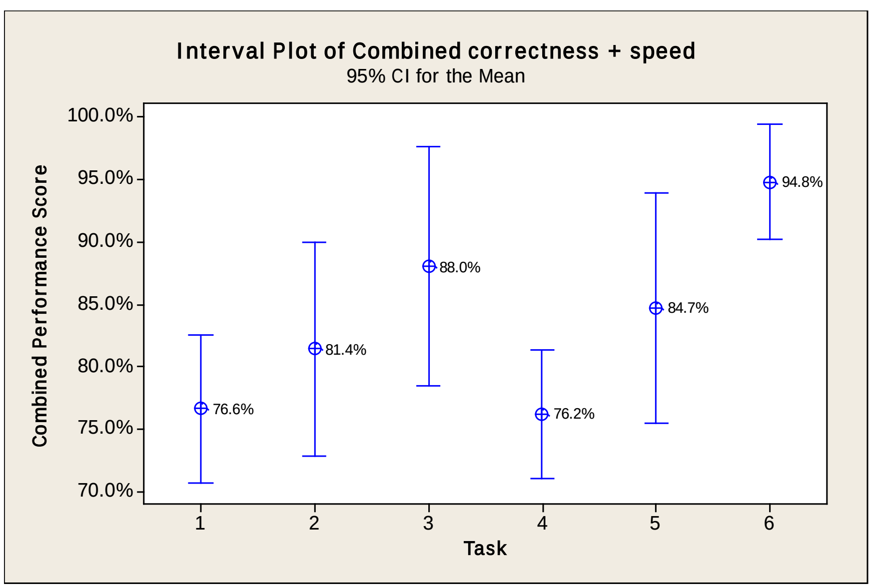


Fig. 76. ANOVA test of combined speed and correctness score with overall sensation groups (p=0.001)

Considering task performance six of multiplication in correctness, speed, and the combination of correctness and speed, the fourth-round experiment concludes that the correctness is most consistent with neutral sensation over time. The outcome highlights the crucial role of the neutral thermal condition for human performance where one's correctness is critical. Multiplication speed shows significant variation over time that may be attributable to the subjects' tiredness over three hours repeated problem sets.

9.1.5. Task performance conclusion

The relationship between thermal sensation and task productivity has significant precedent research (Wyon, 1996; Kroner et al., 1992; Bauman et al, 1992). These researchers reveal that maintaining thermally comfortable conditions using an individual temperature controller such as the Personal Environmental Module (Johnson Controls, 2007) contributes to occupants' work productivity. Since productivity has a significant portion in organizational success, it is critical to maintain thermally comfortable conditions for building occupants.

As found in the human subject experiments in this research, the greatest number of multiplication correctness scores was accomplished by subjects in the neutral sensation in both experimental conditions of the cooling and warming process. In addition, the greatest multiplication in speed occurred in the neutral sensation during the second-round experiment (warming room temperature) with a statistical significance. Even though the third-round experiment (cooling room temperatures) did not show statistical significance, the performance correctness consistently shows the highest score in the neutral sensation.

Given continuous individually neutral thermal conditions assured by the CoBi control system, multiplication correctness score did not reveal significant variations over time and six sets of multiplication tasks. Multiplication speed, however, did reveal variability with the highest score reported in the third and sixth tests. Considering the constant thermal sensation and the consistent correctness score of the subjects, the speed score outcome in the performance test might be affected by other factors including tiredness with repetitive tests.

In summary, maintaining neutral thermal sensations contributes to the correctness of multiplication performance, one of many tasks that are critical to workplace productivity.

9.2. Energy Saving Potential of the CoBi Bio-Sensing Control System

Depending on the season, the CoBi system can contribute to energy savings potential. Average CoBi individual setpoint temperatures are higher than PMV setpoint temperatures in all of the Clo (clothing value) conditions. Moreover, the CoBi system consistently resulted in neutral sensations, which the PMV model classifies as lowest dissatisfaction level. Figure 77 and 78 summarize the comparisons of setpoint temperature and the reported sensation in between the CoBi system and the PMV formula. 0.5 Clo is the level of clothing worn in the summer, 0.8 Clo in the swing season, and 1.1 Clo in the winter season.

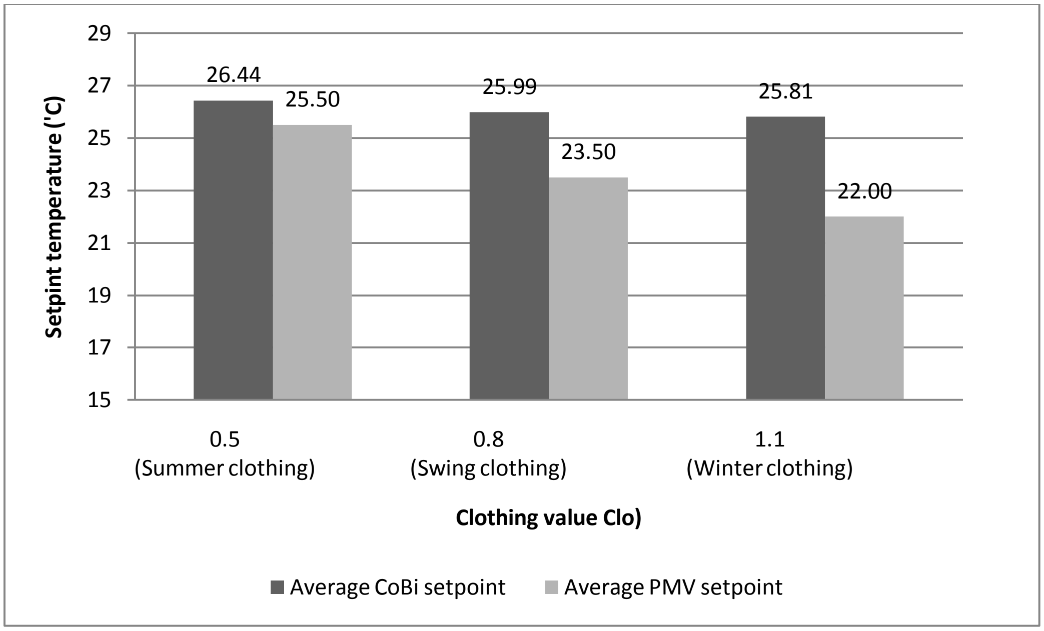


Fig. 77. Differences in average setpoint temperatures between the CoBi system and the PMV formula

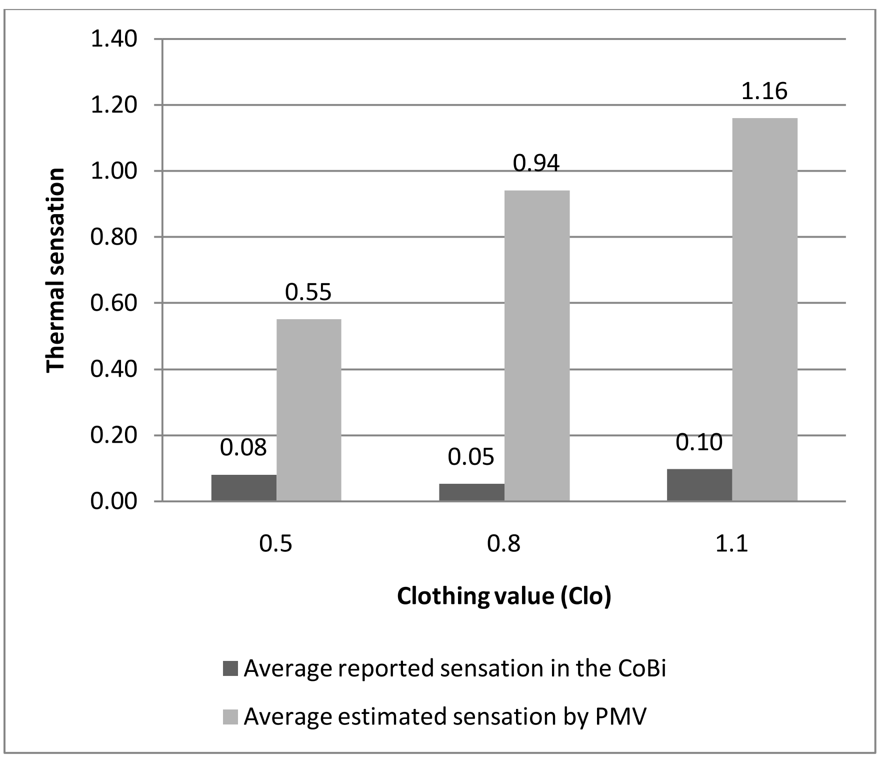


Fig. 78. Comparison of average sensations reported (estimated) with the CoBi control system and the PMV estimation (0: neutral sensation, +1: slightly warm)

In the summer season, introducing higher setpoint temperatures as indicated by the CoBi bio-sensing control system would increase comfort and provide energy savings. The average setpoint temperature generated by the CoBi system is 26.44°C while the PMV driven system recommends 25.5°C for neutral sensations. The delta between the two setpoint temperatures is almost 1°C, which can result in 3.6% energy savings (North Carolina State Energy Office, 2009). In the winter, the CoBi system would also generate a higher setpoint temperature at 25.81°C than the PMV system at 22°C, a difference of 3.81°C, which would increase energy use in perimeter spaces for the winter months. This additional energy demand may be a necessary increase in even in the PMV controlled buildings to achieve 80% comfort mandated by law. The CoBi controller results in more than 93% of the occupants in the neutral sensation – thermally comfortable. Subjects would report cool or cold sensations in the conditions generated by the PMV formula.

Since thermal comfort affects building occupants' health and productivity significantly, it cannot be an object to negotiate for energy savings. Even though the PMV formula suggests a lower temperature of 22°C for neutral sensation, occupants would complain their cool and cold sensations and performance would be compromised. Moreover, the PMV setpoints may not be accurate for humidity conditions lower than 30% typically in heating periods and the condition for these experiments.

Table 31 illustrates the extent of energy savings for cooling, totally as high as 5.3% of annual energy saving in office buildings. The calculation is based on EIA (2003) assumption of 40% of floor area in the building zone that would be cooling year round. Heating loads would be 30% of the area in the swing season and 60% in the heating season and a total energy increase would be 1.1% and 2.7% respectively with measurably increased user comfort. Given CBECS (2006) heating and cooling energy averages for office buildings, the net energy savings for the years would be 0.062 quadrillion BTU with 93% thermal satisfaction rate, resulting from the CoBi bio-sensing individual control system.

TABLE 31. Estimated energy savings by the CoBi system compared with the PMV-based control

		Cooling season	Swing season	Heating season
Assumption	Building system	Conventional HVAC system (No economizer)		
	Cooling (heating) area of a building (EIA, 2003)	100% (0%)	70% (30%)	40% (60%)
	Seasonal length (EIA, 2003)	3.5 months	4.5 months	4 months
Expected energy saving for cooling*		1.1%	2.4%	1.8%
Expected increase in energy for heating*		0%	1.1%	2.7%
Annual Energy Savings		**1.1 % of energy use in office building**		

* 3.6% of energy saving effect by 1°C setpoint increase for cooling or decrease for heating assumed (DOE, 2009b)

In addition to these setpoint energy savings that significantly increase user comfort, the CoBi controller can act as occupancy sensor to further enhance energy conservation. Using the signal strength from bio-sensors, the CoBi system can detect the occupancy condition. During the unoccupied condition, the setpoint temperature can reset to a broadband of acceptable temperatures, from 5°C to 8°C of setback for winter or setup for summer temperatures for additional 10% of energy savings based on measured home energy savings (DOE, 2009b).

The CoBi bio-sensing individual controller will contribute to 1.1% energy savings by preventing over-cooling and over-heating conditions as compared to the current PMV-based control system and increase user satisfaction from 80% to 93%. The CoBi system can further extend these energy savings by acting as occupancy sensors.

10. CONCLUSION

10.1. Research Contributions

The purpose of this research is to develop an individual sensing, actuating and control system using bio-signals such as the skin temperature to manage building mechanical systems to provide occupants with thermally comfortable conditions. This control system entitled CoBi bio-sensing individual controller uses a human body as an integrated sensor for thermal comfort evaluation. The system interprets the measured skin temperature that reflects the thermal sensation to modify heating or cooling systems operation.

The CoBi system developed employs a real-time data collection and control. Since the control system uses physiological patterns of thermoregulation, i.e. skin temperature gradient rather than the absolute level of skin temperature, it is adaptive and adjustable to individuals' thermal preferences for mechanical system operations with automatic controls. This research contributes both control theory and industry application, and offers significant physiological and environmental benefit, as described the in the following sections.

10.1.1. Characterization of bio-signals related to individual thermal sensation

The CoBi research included a series of human subject experiments and identified significant linkage between skin temperature patterns and diverse thermal conditions.

After careful evaluation of 10 body locations for thermal responses to changing temperatures, the wrist was identified as one of the most sensitive and robust bio-signal locations. While existing thermal sensation models have popularly used skin temperature, less attention has been paid to the skin temperature change patterns as a significant parameter for the models. This research demonstrates that gradients in skin temperature at a selected body location can be used to develop a simplified, but adaptive and adjustable model for individual thermal preferences to eliminate thermal discomfort. The findings and principles investigated in the this research contribute to building systems integration of individual and automatic controllers without a high cost of implementation, and contribute to the area of building science linking occupants comfort and system performance with the help of advanced technology.

10.1.2. Human well-being and productivity through increased thermal comfort

The CoBi research proposes a new-generation thermostatic controllers to significantly increase individual comfort in new and existing buildings. Compared to existing PMV driven controllers with limited adjustability for occupant's thermal preference or physiological characteristics, the CoBi control system can fully satisfy the occupant and be implemented via wireless communication between users and building systems. Human subject experiments revealed that the CoBi controller results in more than 93% of the subjects in the neutral sensation-thermally comfortable condition. Since the CoBi controller is dependent on individual bio-signals, it can prevent any excessive overshooting and let unoccupied spaces float to a broader temperature band. These features contribute to environmental and physiological benefits.

10.1.3. Environmental sustainability through energy savings

In existing buildings, many occupants complain of overly cooling conditions in the summer and less frequents of over-heating in the winter, in spite of the temperatures falling within the ASHRAE comfort guidelines. Even though there are occasionally accessible thermostats, people often need to compensate with more clothing, or adding fans and heaters. Moreover, the continued use of HVAC systems in unoccupied periods wastes energy. The CoBi bio-sensing controller will prevent excessive conditioning and allow unoccupied spaces to float to a broader comfort band, to ensure measurable energy savings. The estimated annual energy saving in human subject experiments is 1.1% in total with 5.4% savings only for cooling.

10.1.4. Integration with existing and advanced mechanical systems

The CoBi controller is designed to provide individual input into mechanical system set points. Bio-signal data from the occupant is wirelessly transferred to a thermostat which has the computational capability to estimate thermal sensations, and incrementally correct temperatures to ensure individual comfort. Smart thermostats also ensure broader applicability of the CoBi system, integrating bio-signal sensors with both existing and advanced locally controllable HVAC systems. These systems include radiant ceiling / floor systems, distributed heat pump and fan coils, under-floor air and local mixing boxes, with bio-signal input for on-off control, thermostat, valve, and damper settings, etc. A four-pipe system is the most common perimeter system in the U.S. and is easily controlled by interfacing bio-signals with the hot water and chilled water valve settings. With a VAV system, local dampers, mixing boxes and terminal re-heat coils would interface with the CoBi controller. Also, distributed systems such as a heat pump loop would be simply controlled when a CoBi controller was introduced as a replacement or addition to the thermostatic control circuit. Beyond temperature control in an individual workstation or a private room, a variable volume and temperature system (VVT) also offers significant potential for integration with the CoBi system. A CoBi integrator would scan the numerous individual bio-signals to make a decision to heat or cool based on ongoing analysis of the scanned setpoint temperature information. Frequent scanning would ensure that the best temperature conditions was selected for the greatest number of thermally satisfied occupants, and could prompt individuals to add or remove clothing layers, or turn on task systems when available.

Beyond existing technology, the CoBi controller could be used to integrate with emerging task HVAC systems. Similar to task lighting systems, task thermal systems assume that ambient temperatures will be kept at a much broader band of comfort for energy savings. Then individuals will determine whether they want conditions locally to be cooler or warmer, using a task conditioning system such as Personal Environmental Module (PEM) created by Johnson Controls (Figure 79). This system puts a mixing box at every desk, allowing the user to manually mix more primary cool air with filtered room air to establish workstation temperatures through two desktop air diffusers. CoBi bio-signal controllers could contribute to automating the task condition system for maximum user satisfaction and minimum energy waste when the occupant is away from the desk, while supporting a broadband ambient environment for enhanced energy effectiveness.

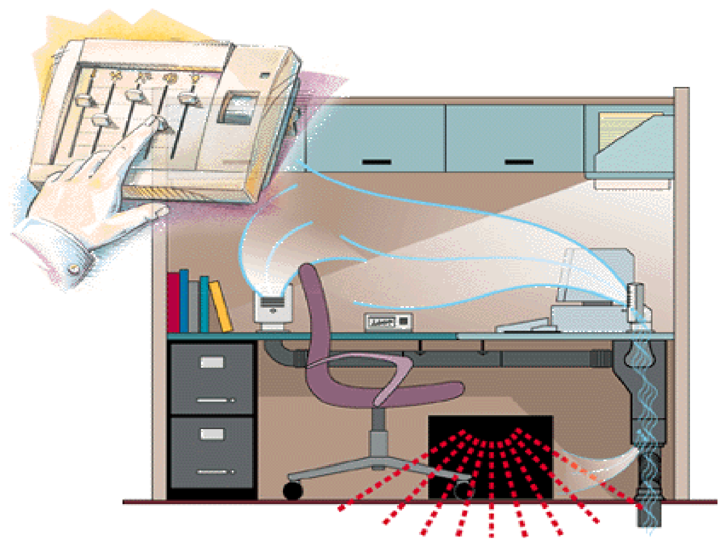


Fig. 79. Personal Environmental Module (Johnson Controls, 2007)

10.1.5. Business potential as green technology

Green building technologies to enhance energy savings and improve indoor environmental quality (IEQ) are emerging as a trend in the real estate industry, although the current solutions still do not satisfy the sustainability goals. Occupants in buildings such as offices and healthcare facilities are very sensitive to indoor temperature and indoor environmental quality, with advances in performance linked to profits in terms of work productivity, human health and energy savings. The potential to control indoor temperature based on individual characteristics-age, health, activity, clothing, radiant setting, etc. has human comfort, energy and market potentials.

In the current market of health-related appliances, there are many devices that measure blood pressure, skin temperature, calories burned, sweat, and even stress and heart rate. Some of these devices are in the form of a wrist watch and an arm bracelet, and could be modified to serve as CoBi environmental controllers. Integrating bio-signals with computational analysis and the wireless communication to a smart thermostat will allow the building mechanical system to be optimally operated. When the wearable device is integrated with other functional sensors or services such as occupancy sensors, health monitors, and portable PCs, the performance of the controller could be expanded to support human-health, building security, and manage energy.

10.2. Limitations

While this research effort was structured to ensure robust data sets, data analysis and conclusions, there were several limitations of the research that would merit further investigation.

10.2.1. Sample size in human subject experimentation

The total number of subjects who participated in the study was 72 xxx for the four rounds of experiments – most responsive body location, warming temperatures, cooling temperatures, and CoBi controlled neutral temperatures. The subject group size varied from 14 to 27 depending on the round of the experiment, and limited by financial and time constraints. Each of these subject however, completed 2 to 3 hours of experimentation and multiple responses to user satisfaction questionnaires and multiplication performance tests. This resulted in a response data set of 658, adequate and robust for drawing the conclusions presented in this dissertation. Because of the absolute number of subjects, the research did not group the collected data by gender, body mass index or age to confirm if the finding were consistent across the physiological groups. This limitation should be considered in future research.

10.2.2. Default starting set-point temperatures

In the CoBi control system tests, default temperatures set at the beginning of each test session may create conditions that are too cool or too warm for the subject, and limit the performance of the subject until the default conditions are corrected to suit the individual. Ideally, the test period would include time for a thermal readjustment of room conditions before the first human responses and performance testing occurs. It is also important to note that all of the CoBi testing was undertaken in rooms between 20°C and 30°C, a typical range for indoor conditioned spaces. The viability of this bio-signal controller in conditions below or above these temperatures would have to be considered in future research.

10.2.3. Rapid changes in Clo value and polyester clothing

Subjects were asked to change clothing during the three hour test period to simulate comfort in different seasons. The speed with which this clothing was removed or added by different subjects could have rapidly increased or decreased the subject's skin temperature due to Clo changes. This may occur in such a short period of time that the control system could not update the setpoint quickly enough due to the 0.2°C limitation on the rate of setpoint air temperature change. This causes a functional limitation in the control performance that needed to be checked in future research.

There was also an issue related to one subject who brought clothing layers made of polyester. This fabric did not breathe and caused wet skin and sweating, effectively changing skin temperature conditions unrelated to thermal sensation. This caused the CoBi system to detect "cool" sensations and increase air temperature, the opposite of what would be desired. The testing was modified to avoid polyester clothing, but a programming solution to this limitation could be developed in future research.

10.2.4. Individual controllers vs. shared controllers

The CoBi research effort was focused on individual sensor-controllers linked to single actuators on a local HVAC system. This would be the case for a single occupancy room with local fan-coils or VAV dampers, including hotels, individual offices, hospitals and even homes. In commercial offices, however, typically 15-20 people share a single thermostat (CBPD, 2008), and negotiated set-point temperatures would be necessary, selecting a single setpoint that minimized thermal stress between occupants. Bio-sensing control in multi-occupancy conditions has the potential to improve occupant thermal comfort and reduce energy use, and would be a meaningful topic for future work.

10.2.5. Applicable HVAC System types

The CoBi experimentation was configured with an all air HVAC system. The configuration was carefully set up to ensure a constant flow of air (for acoustic and air quality reasons), with only a variation in supply air temperature through a local air conditioner or terminal reheat unit. The location of air delivery was constant and ventilation rates were constant. Future research should test the robustness of the findings with water based systems, with variable air flow systems, and with radiant systems to ensure that variations in speed of HVAC response, air flow rates and/or HVAC noise do not compromise the positive benefits of a bio-sensing control system.

10.3. Future Work

The research limitations discussed would be good themes for future research, as well as the potential of bio-sensing controllers to achieve even greater levels of impact.

10.3.1. Control for double or multi-occupancy conditions

As discussed previously, the current CoBi system is designed for single occupancy spaces. Each user interacts with a local HVAC system to control optimal temperature. Even though there are many instances of single occupancy rooms, double or multiple occupancy conditions are a dominant condition in certain types of buildings, such as offices and homes. For multi-occupancy conditions, advanced learning algorithms would need to be developed, incorporating machine-learning algorithms using historical data of user thermal sensations and thermal environment data.

Individual thermal comfort bands vary depending on physiological characteristics. A subject having a high body mass index (BMI) may have relatively wider comfort bands in the heating season and narrower bands in the cooling season (Aggelakoudis and Athanasiou, 2005). Advanced learning algorithms would generate an optimal setpoint temperature through negotiation between occupant thermal comfort bands, clothing choices, as well as seasonal factors. This research effort is important to the practical applications of the CoBi bio-sensing control system.

10.3.2. Human-centered environmental system controlling all IEQ components

Human beings generate several types of physiological signals including heart rate, skin moisture, and pupil movement, in addition to skin temperature. As illustrated in Figure 80, each indoor environmental quality component (temperature, relative humidity, light, air quality, etc.) can be linked with single or multiple bio-signals that may correspond to the IEQ conditions. Since most people prefer to have personalized environments, with control as to their preferences, buildings should be able to provide environmental conditions which can satisfy individual occupants' needs. By translating each occupant's physiological signals, building environmental quality including thermal, visual, acoustic and air quality would be controlled to enhance user satisfactions while minimizing energy use. This research effort would expand the potential of the current dissertation research to effectively control building environments for human comfort, health and for energy efficiency.

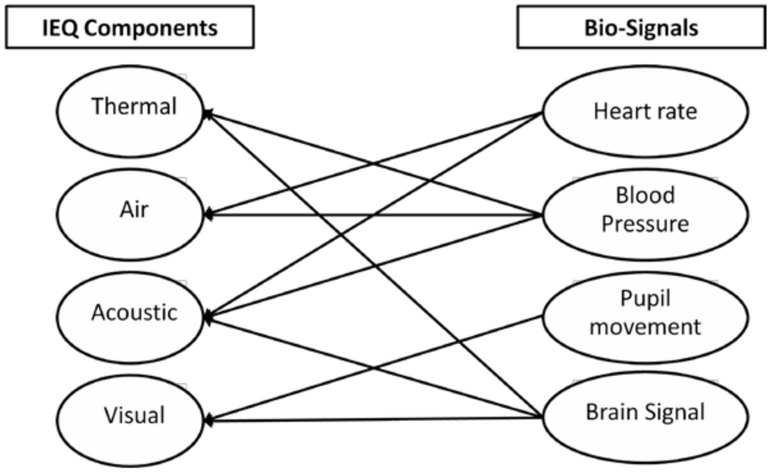


Fig. 80. Multiple bio-signal potentials for controlling indoor environmental quality components

10.3.3. Integration with passive strategies

Finally, the CoBi systems should be tested with passive conditioning systems as well as active HVAC. Since thermal comfort can be affected by air temperature, relative humidity, radiant temperature and air velocity, passive strategies such as natural ventilation and passive solar heating could be utilized to maintain a defined level of thermal condition while minimizing energy use. The CoBi system can acquire the data on outside temperature, humidity, wind conditions and solar conditions, and can estimate the most effective passive-active conditioning strategy through an energy optimization process. This passive strategy-based system operation would contribute to energy saving and environmental benefits beyond the building occupants' thermal comfort.

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APPENDIX

Human Subject Information

1. First-Round of Human Subject Experiments

No.	Gender	Ethnic origin	Age	Height (inch)	Weight	BMI
1	Female	Asian	23	65.4	101.2	16.66
2	Female	Asian	21	65.0	112.2	18.69
3	Female	Asian	20	64.6	165.0	27.82
4	Female	Asian	22	63.8	103.4	17.87
5	Female	Asian	20	64.6	125.4	21.15
6	Male	Asian	27	66.1	136.4	21.92
7	Female	Asian	20	63.0	127.6	22.61
8	Male	Asian	20	68.1	132.0	20.00
9	Female	Asian	21	63.0	116.6	20.66
10	Female	Asian	22	62.6	99.0	17.76
11	Male	Asian	22	66.9	136.4	21.41
12	Male	Asian	34	66.9	132.0	20.72
13	Female	Asian	19	62.6	125.4	22.50
14	Male	Asian	34	66.9	182.6	28.66
15	Male	Asian	23	67.7	147.4	22.60

2. Second-Round of Human Subject experiments

No.	Gender	Ethnic origin	Age	Height (inch)	Weight	BMI
1	Male	Caucasian	29	73	170.4	22.48
2	Male	Asian	24	68	173.4	26.36
3	Male	Asian	35	72	163	22.10
4	Male	Caucasian	45	73	234	30.87
5	Female	Caucasian	23	62	130.8	23.92
6	Female	Caucasian	31	67	127.2	19.92
7	Female	Asian	25	64	123	21.11
8	Male	Asian	26	70	149.8	21.49
9	Male	Asian	40	69	153.4	22.65
10	Male	Caucasian	23	70	175.2	25.14
11	Male	Asian	34	68	159.6	24.26
12	Male	Asian	22	70	206	29.55
13	Female	Caucasian	22	62	114	20.85
14	Female	Caucasian	23	64	155.2	26.64
15	Male	Asian	24	69	145.8	21.53
16	Male	Asian	22	67	121.8	19.07
17	Female	Caucasian	32	70	141	20.23
18	Male	Asian	31	67	112.8	17.67
19	Female	Caucasian	22	66	109.4	17.66
20	Female	Caucasian	20	65	144.6	24.06
21	Male	Asian	28	71	149.6	20.86
22	Female	Asian	25	62	111.4	20.37
23	Female	Caucasian	18	64	114.8	19.70
24	Female	Asian	20	62	129.8	23.74
25	Female	Asian	30	65	130.4	21.70
26	Male	Asian	30	71	180.8	25.21
27	Male	Asian	34	71	179.2	24.99

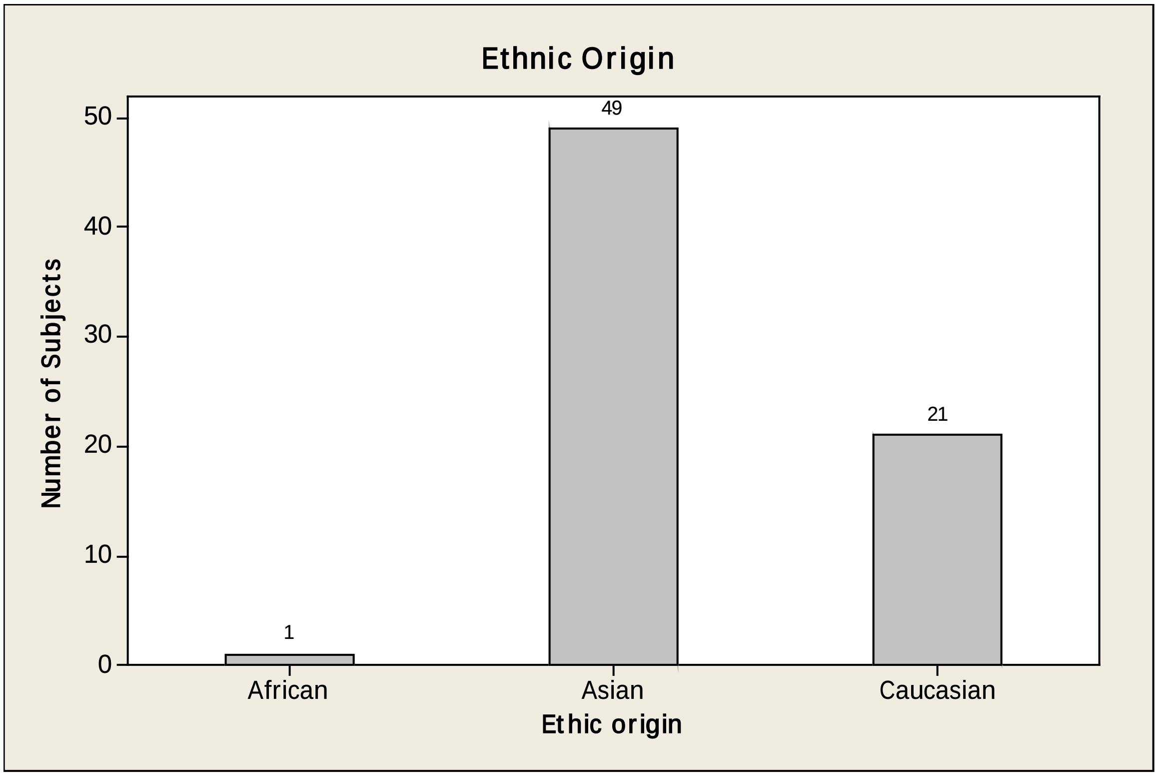
3. Third-Round of Human Subject experiments

No.	Gender	Ethnic origin	Age	Height (inch)	Weight	BMI
1	Male	Caucasian	30	73	171	22.56
2	Male	Asian	26	70	149.8	21.49
3	Male	Asian	40	69	153.4	22.65
4	Male	Asian	28	71	149.6	20.86
5	Male	Asian	22	67	121.8	19.07
6	Male	Asian	23	71	206.4	28.78
7	Female	Caucasian	33	70	140.6	20.17
8	Female	Caucasian	20	65	144	23.96
9	Female	Caucasian	19	63	115	20.37
10	Female	Asian	25	64	123.5	21.20
11	Female	Caucasian	32	67	130	20.36

4. Fourth-Round of Human Subject experiments

No.	Gender	Ethnic origin	Age	Height (inch)	Weight	BMI
1	Male	Asian	22	67	121.8	19.07
2	Female	Caucasian	33	70	141	20.23
3	Male	Asian	23	71	207	28.87
4	Female	Asian	22	65	163.6	27.22
5	Female	Asian	25	64	123	21.11
6	Male	Asian	24	69	146.2	21.59
7	Female	Asian	22	65	163.6	27.22
8	Male	Caucasian	31	72	160	21.70
9	Female	African	31	64	124	21.28
10	Female	Caucasian	20	65	145	24.13
11	Female	Asian	27	63	123.6	21.89
12	Female	Asian	26	60	100.9	19.70
13	Male	Asian	23	70	158.2	22.70
14	Female	Asian	24	64	131.6	22.59
15	Male	Asian	23	71	207.2	28.90
16	Male	Asian	23	70	158.2	22.70
17	Female	Caucasian	33	67	132	20.67
18	Male	Caucasian	31	73	172	22.69

5. Histogram of All Subject Ethnic Origin Data



6. Histogram of All Subject Gender Data

7. Histogram of All Subject Body Mass Index Data