SAKARYA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ DERGİSİ

Sakarya University Journal of Science
SAUJS

e-ISSN 2147-835X Period Bimonthly Founded 1997 Publisher Sakarya University
http://www.saujs.sakarya.edu.tr/

Title: Determination of Metabolic Rate from Physical Measurements of Heart Rate, Mean Skin Temperature and Carbon Dioxide Variation

Authors: Mehmet Furkan ÖZBEY, Aydın Ege ÇETER, Cihan TURHAN

Recieved: 2021-08-13 00:00:00

Accepted: 2021-12-17 00:00:00

Article Type: Research Article

Volume: 26
Issue: 1
Month: February
Year: 2022
Pages: 74-90

How to cite
Mehmet Furkan ÖZBEY, Aydın Ege ÇETER, Cihan TURHAN; (2022), Determination of Metabolic Rate from Physical Measurements of Heart Rate, Mean Skin Temperature and Carbon Dioxide Variation. Sakarya University Journal of Science, 26(1), 74-90, DOI: 10.16984/saufenbilder.981511
Access link
http://www.saujs.sakarya.edu.tr/tr/pub/issue/67934/981511

Sakarya University Journal of Science 26(1), 74-90, 2022

Determination of Metabolic Rate from Physical Measurements of Heart Rate, Mean Skin Temperature and Carbon Dioxide Variation

Mehmet Furkan ÖZBEY*[1], Aydın Ege ÇETER[1], Cihan TURHAN[2]

Abstract

Thermal comfort depends on four environmental parameters such as air temperature, mean radiant temperature, air velocity and relative humidity and two personal parameters, including clothing insulation and metabolic rate. Environmental parameters can be measured via objective sensors. However, personal parameters can be merely estimated in most of the studies. Metabolic rate is one of the problematic personal parameters that affect the accuracy of thermal comfort models. International thermal comfort standards still use a conventional metabolic rate table which is tabulated according to different activity tasks. On the other hand, ISO 8996 underestimates metabolic rates, especially when the time of activity level is short and rest time is long. To this aim, this paper aims to determine metabolic rates from physical measurements of heart rate, mean skin temperature and carbon dioxide variation by means of nineteen sample activities. 21 male and 17 female subjects with different body mass indices, sex and age are used in the study. The occupants are subjected to different activity tasks while heart rate, skin temperature and carbon dioxide variation are measured via objective sensors. The results show that the metabolic rate can be estimated with a multivariable non-linear regression equation with high accuracy of 0.97.

Keywords: Metabolic rate, thermal comfort, heart rate, skin temperature, carbon-dioxide variation

1. INTRODUCTION

Thermal comfort is a major and significant phenomenon which affects the energy consumption of buildings while satisfying productivity and healthy indoor environments to the occupants [1]. A well-known thermal comfort model, Fanger's Predicted Mean Vote (PMV) and Percentage of Predicted Dissatisfied (PPD) method, categorizes parameters that affect thermal comfort as environmental and personal [2]. Environmental parameters such as air temperature, relative humidity, air velocity, and mean radiant temperature are measured via objective sensors. Moreover, ISO 7726 [3] provides guidance on measuring environmental parameters to calculate thermal comfort. Besides, personal parameters such as clothing value and

* Corresponding author: m.furkanozbey@gmail.com
[1] Atılım University, Institute of Science, Mechanical Engineering
E-mail: aege.ceter@gmail.com
ORCID: https://orcid.org/0000-0002-5813-3514, https://orcid.org/0000-0002-1048-9642
[2] Atılım University, Faculty of Engineering, Department of Energy Systems Engineering
E-mail: cihan.turhan@atilim.edu.tr
ORCID: https://orcid.org/0000-0002-4248-431X

metabolic rate generally are based on direct-look up tables which are given in International Standards such as ASHRAE 55 and ISO 7730 [4,5]. Clothing value is an influencing parameter

which reduces the heat exchange between the human body and thermal environment [6]. ISO 9920 [7] estimates the resistance of garments to dry heat loss and evaporative heat loss in steady-state conditions. However, a noteworthy finding of previous research clearly indicates that the metabolic rate is the most sensitive parameter on the PMV calculation errors among all influencing parameters of thermal comfort [8-10].

Metabolic rate (M) is defined as "the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism" [4]. Generally, the metabolic rate expresses heat production rate in W/m^2 on a human body. It is worth to note that a 100 W heat is produced by an adult at rest time, and 1 met equals to 58 W/m^2 for a resting person. Further details on the heat balance on a human body and metabolic rate calculation can be found in [2,4,11]. Metabolic rate is the most influencing parameter on the accurate PMV calculation. For instance, Khan and Pao [12] stated that the metabolic rate is an expected parameter on the calculation of the PMV, for this reason, further studies are required for an adequate explication of thermal sensation. Moreover, Luo et al. [10] indicated that metabolic rate is the most problematic parameter on thermal comfort since yet researches and practices on the parameter are crudely evaluated. The authors concluded that more studies and experiments are needed for better understanding in built environmental and thermal comfort contexts. In addition, determining inadequate metabolic rates causes errors on the PMV value in real environments [13-15]. For instance, Humpreys and Nicol [14] found that the PMV value is underestimated above 1.4 met, which causes up to 1 unit error. The authors also stated the reason of this error as high sweating levels on high metabolic rates. Fanger and Toftum [16] represented the weaknesses of the adaptive thermal comfort model as not taking the metabolic rate into account on thermal sensation. On the other hand, Chamra et al. [9] showed that the PMV model is only acceptable for 1 met values. At higher metabolic rate levels, uncertainty analysis is needed for a better understanding of the impact of metabolic rate levels on thermal comfort.

Conventional methods to determine the metabolic rate refer to tabulate methods such as in ASHRAE 55 [4] and ISO 7730 [5]. In metabolic rate tables, the sample activities represent typical metabolic rate values which are averaged across a group of people. However, metabolic rate always changes by time which causes significant errors on the PMV measurements. For instance, Havenith [6] indicated that the tabulate methods have an error of up to 20% on obtaining metabolic rate. Similarly, Broday et al. [17] compared metabolic rate tables with real-time measurements and concluded that there is a significant difference up to 20 W/m^2 between the measurements and tables.

Metabolic rate can be measured by direct or indirect calorimeters; however, the measurement method is quite inconvenient for real-time applications since the subjects should wear uncomfortable masks which measure oxygen intake and carbon dioxide outtake [18]. For this reason, the researchers aim to predict the metabolic rate from physical indicators of the parameter. It is worth to note that thermoregulatory responses of occupants to discomfort are used as indicators of thermal comfort. Similarly, for the metabolic rate, Heart Rate (HR) and Skin Temperature (ST) are used separately as an indicator of the parameter [11]. For instance, Choi et al. [19] stated that metabolic rate is meaningfully related with the HR, specifically in males with high body mass index occupants. Moreover, the HR is changed with different activities based on the response of thermoregulation. In addition to this study, Revel et al. [20] predicted metabolic rate with in-situ measurements by measuring the HR of occupants with low-cost sensors. The authors indicated that uncertainty in the estimation of metabolic rate changes the accuracy of PMV as ±0.05. Behind all these measurements, ISO 8996 [11] shows a protocol to predict metabolic rate from the HR. The standard limits the measurements with only neutral thermal environments. Similar to the HR, the ST can be used to predict the metabolic rate of the occupant since the sweating rate highly affects the thermal sensation of occupants. Indeed, the ST is one of the main parts of the thermoregulatory center with core temperature, and the sweat glands are significant thermoregulatory effectors [21]. Bligh [21] proved that sweat rate is affected by metabolic rate by receiving more impulses with the increase of metabolic rate. On the other hand, Le Blanc et al. [22] showed a significant correlation between the ST and thermal sensation. However, the subjects were exposed to experiments only with resting activity. Additionally, Shapiro et al. [23] predicted metabolic rate with sweat loss with respect to activity level. Zhang et al. [24] determined metabolic rate inversely from the proposed PMV method by taking the effects of physiological adaptation on metabolic rate into account. The authors determined a linear model of metabolic rate as a dependent parameter by using indoor air temperature (T_i) and air velocity (v_a) as independent parameters in the model. However, the authors also stated that the model is valid for a specific given activity task and should be repeated and re-developed for different activities. On the other hand, researchers showed that carbon dioxide production of the human body reflects the rate of body metabolism [25-28]. For instance, Na et al. [29] developed a deep learning system which predicts the M with the parameters of CO_2 concentration apart from the HR. However, the authors included only 8 activity tasks in the paper. Detailed studies on the relationship of metabolic rate with the physical parameters can be found in [30-32].

According to the authors' knowledge, there is no study in the literature which determines metabolic rate from real-time measurements of the heart rate, mean skin temperature and carbon dioxide variation. Since older adults generally show a lower metabolic rate than younger, subjects with different ages, sex and various body mass indices are also investigated in this study.

2. MATERIALS AND METHODS

The methods of the study consist of measurements and experiments on weekdays between 8.30 and 17.30 from 11th of August to 20th of October 2020 and data analysis. University Human Research Ethics Committee has given ethics approval to the activity to be carried out within the scope of this research study.

2.1. Measurements

The experiments were conducted in an air-tight climate chamber (Length: 4.7 m, Width: 3.25 m, Height: 2.8 m) under neutral thermal conditions (T_i=22°C and RH=50%) (Fig.1). Environmental parameters were controlled via a Heating, Ventilating and Air-Conditioning (HVAC) system, which was existed in the climate chamber. However, the climate chamber has a fixed air volume in order to store respiratory air. Even though the impact of environmental parameters on metabolic rate is very small in low variations of the parameters [28-33]. environmental parameters were measured and checked via objective sensors every 10 minutes in order to satisfy neutral thermal conditions. DHT22 [34] was used for the air temperature and relative humidity measurements, while an anemometer – TESTO 425 [35] – was placed in order to measure air velocity inside the chamber.

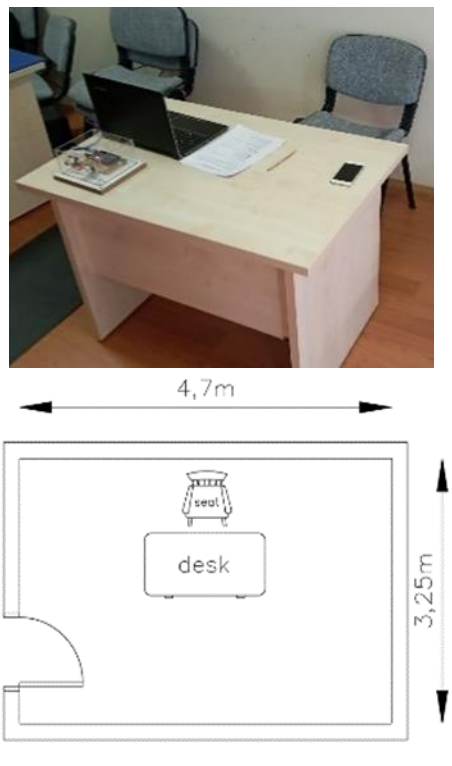

Figure 1 Climate-chamber used in the study.

The door of the chamber was fully sealed and kept closed during experiments. The airtightness of the chamber was calculated as 0.1 1/h.

ISO 8996 [11] advice to use the measurement of carbon dioxide production to determine the metabolic rate with metabolic carts. However, metabolic carts are quite expensive and difficult to use for resting activities. For this reason, CO_2 production was assumed to be equal to the difference of CO_2 variation between pre-and post-activities, respectively (Eq.1).

$$\Delta CO_2 = CO_{2aa} - CO_{2ref} \quad (1)$$

Where ΔCO_2 depicts the carbon dioxide variation in the air-tight climate chamber, CO_{2aa} is carbon dioxide concentration level after activity, while CO_{2ref} is the reference carbon dioxide concentration level of unoccupied climate chamber and is 400 ppm [36].

CO_2 concentration level was measured with the MG811 [37] sensor. Before the experiments, the uniformity of CO_2 distribution was tested and validated by measuring the CO_2 concentration level at different locations of the chamber. It is worth to note that CO_2 measurements were taken automatically by using microcontrollers in order to avoid researcher existence in the test chamber.

The sensors were placed at a 1.1 m level according to ASHRAE 55 [4]. Heart Rate was measured with a smart wristband – Xiaomi Mi Band 3 [38] – and skin temperatures were taken from 8 different points of the human body with an infrared thermometer – EXTECH 42530 [39] – simultaneously (Fig.2). The specifications of the measurement devices were given in Table 1.

Table 1 The Specifications of the measurement devices used in the study.

Device	Model	Specifications
Temperature and Relative Humidity Sensor	DHT22 [34]	RH Range: 0-100% Temperature Range: -40-80 °C RH Accuracy: +/- 3% (Max +/- 5%) Temperature Accuracy: < +/- 0.5°C
Infrared Thermometer	EXTECH Instruments 42530 [39]	Range: -50 °C to 538 °C Accuracy: ±2% Resolution: 0.1 °C
Anemometer	Testo 425 [35]	Range:0-20 m/s Accuracy: +/- (0.03 m/s +5% of Measured Value) Resolution: 0.1 m/s
Carbon Dioxide Sensor	MG811 [37]	Range: 350-10000 ppm Accuracy: ± 2% (depends on air temperature) Resolution: 1 ppm (depends on air temperature)
Wrist Band	Xiaomi Mi Band 3 [38]	Range: 0-150 bpm Accuracy: 2-4 bpm

The instruments, which were required for doing the activities, such as bed, office chair and desk and sports equipment were placed inside the chamber before the experiments. Experimental conditions inside the chamber are given in Table 2.

Table 2 Experimental conditions in the climate chamber.

	Unit	Average
Indoor Air Temperature	°C	22.1±0.3
Relative Humidity	%	50±2.1
Air Velocity	m/s	0.1±0.01
CO_2 Level	ppm	641±11

2.2. Experiments

Goldman [40] states that the minimum subject in thermal comfort studies should be at least 6 occupants. To this aim, for the experiments, 21 male and 17 female healthy volunteer subjects of different age (from 20 to 66 years) and body mass indices (from 20.23 to 43.44 kg/m^2) were recruited from Ankara/Turkey. The individual physical data of all subjects and demographic information of the subjects are given in Tables 3 and 4, respectively.

Table 3 The physical data for all subjects used in the study.

Subject Number	Age (years)	Gender	Body Mass Index (kg/m^2)
1	35	Male	22.99
2	26	Male	26.87
3	26	Female	23.66
4	23	Male	43.44
5	66	Male	25.95
6	26	Female	23.05
7	20	Male	21.65
8	20	Female	21.01
9	36	Male	33.18
10	38	Male	40.19
11	40	Male	26.38
12	24	Female	26.11
13	61	Male	31.28
14	54	Male	24.15
15	21	Male	28.89
16	21	Female	35.24
17	27	Male	21.98
18	65	Female	26.54
19	62	Female	24.87
20	31	Male	26.57
21	39	Male	24.45
22	40	Female	38.75
23	39	Male	31.54
24	35	Male	22.28
25	31	Male	39.65
26	24	Female	40.15
27	22	Female	34.25
28	23	Female	21.58
29	22	Female	29.61
30	26	Female	28.65
31	22	Male	30.05
32	21	Female	25.43
33	20	Male	20.96
34	29	Female	21.68
35	25	Male	20.23
36	36	Female	25.55
37	39	Male	29.81
38	41	Female	37.86

Table 4 The physical data for all subjects used in the study.

	Female	Male	Total
Subject Number	17	21	38
Age (years)	31.05 ±13.38	34.66±11.6	33.05±13.06
Body Mass Index (kg/m^2)	28.47±6.19	28.21±6.40	28.32±6.31

All subjects were free of hypertension, asthma, coronary heart disease, or type 2 diabetes since these diseases can cause disorders of respiration and metabolic rate [41]. Before the experiments, the subjects were informed of the aim and procedure of the study. Moreover, a commitment form, which explains that students are avoided from the factors such as vigorous physical activity before the experiments, caffeine, alcohol and smoking, which affect metabolic rate, heart rate and skin temperature, was designed to sign for all subjects. Additionally, the subjects were requested to wear the same garments (underwear, T-shirt, shorts, socks, and gym shoes) with a clothing value of 0.42 clo. The experiments were conducted in 19 different activity tasks, including sleeping, writing, dancing, and house cleaning. The activity tasks, which were included in the study, are depicted in Table 5. It is obvious that some activity tasks, i.e., handling 50 kg bags, were not suitable for female and/or older subjects. Therefore, these activities were only requested for younger (below 35 ages) male subjects. In the table, average values are taken for the activity tasks, which have a range of met values.

Table 5 The physical data for all subjects used in the study.

Test Activity	Activity Code	Met value in ASHRAE 55	W/m^2
Resting			
Sleeping	R1	0.7	40
Reclining	R2	0.8	45
Walking			
0.9 m/s, 3.2 km/h	W5	2	115
1.2 m/s, 4.3 km/h	W6	2.6	150
1.8 m/s, 6.8 km/h	W7	3.8	220
Office Activities			
Reading, seated	O8	1	55
Writing, seated	O9	1	60
Typing, seated	O10	1.1	65
Filling, seated	O11	1.2	70
Filling, standing	O12	1.4	80
Walking about	O13	1.7	100

Lifting, packing	O14	2.1	120
Miscellaneous Occupational Activities			
House Cleaning*	MOA15	2 to 4	115-200
Seated, heavy limp movement	MOA16	2.2	130
Handling 50 kg bags**	MOA17	4	235
Miscellaneous Leisure Activities			
Dancing, social	MLA18	2.4 to 4.4	140-255
Calisthenics, exercise	MLA19	3 to 4	175-235
***The subjects were requested to clean desk and floor in the climate chamber**			
**** This activity is requested just for young male subjects (below 35 ages)**			

Subjects were allowed to enter to the climate chamber in order and requested to do 19 different activity tasks, as shown in Table 5. Each subject was exposed to each activity for 30 minutes (Fig.3). Once the experiment was completed on a subject, a 10-minutes break was given not to lose neutral thermal conditions in the chamber for the next activity.

After the experiment days for an activity task for all subjects, another activity was conducted the day after. In the experiments, heart rate, mean skin temperatures and carbon dioxide concentration levels were taken after 10 minutes later from the beginning of the activity with 1-minutes interval. Simultaneously, environmental conditions including air temperature, relative humidity and air velocity were measured in order to ensure consistent neutral thermal conditions. The heart rate of subjects was taken from their wrist while skin temperatures were measured from 8 different points of the human body as advised in the ASHRAE 55 [4] (Fig.2).

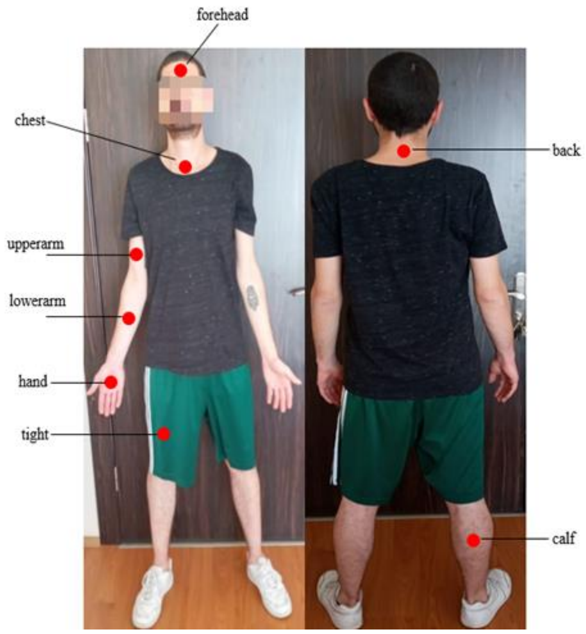

Figure 2 Measurement points on the human body (Note: All measurements were taken from naked skin of the human body).

The eight-point weighted method was used to calculate mean skin temperature (MST) according to Eq.2 [42].

$$\text{MST} = 0.07T_{forehead} + 0.175T_{chest} + 0.175T_{back} + 0.07T_{upperarm} + 0.07T_{lowerarm} + 0.05T_{hand} + 0.19T_{thigh} + 0.2T_{calf} \quad (2)$$

Figure 3 A sample subject while doing different activities during experiments a) seated, quiet (R3); b) typing, seated (O10); c) filling, seated (O11); d) standing, relaxed (R4); e) standing, filling (O12); f) sleeping (R1).

Once all experiments with 19 different activity tasks for a subject were completed, a set of experiments were conducted for other subjects with the same experimental procedure. The collected data were then automatically uploaded on a computer through a data acquisition interface which was developed by the authors. The general methodology of the experiments is shown in Figure 4.

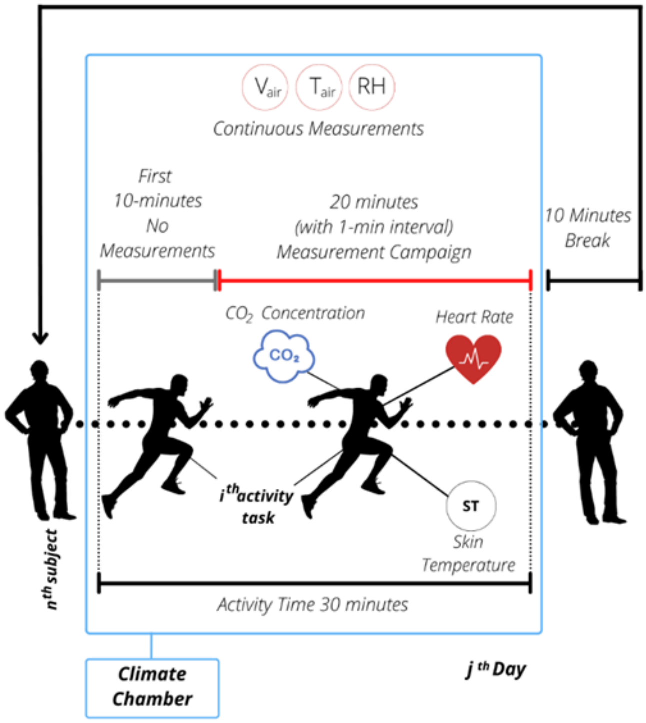

Figure 4 The methodology of the experiments.

2.3. Data Analysis

For data analysis, Multivariable Non-Linear Regression (MNLR) analysis method was used in MATLAB [43]. The MNLR is used to explain the relationship between one dependent variable and two or more independent parameters [44,45]. A general expression for a non-linear regression equation involving multiple parameters is shown in Eq.3.

$$M = a(HR)^{e} + b(MST)^{f} + c(\Delta CO_2)^{g} + d \quad (3)$$

The results of the equation, then, compared with the ASHRAE 55 [4] table and expressed in terms of statistical error, i.e., Normalized Root Mean Squared Error (NRMSE) according to Equation 4. The Determination of Multiple Coefficient (R^2) was used in order to validate the accuracy of the equation by using the following formula (Eq.5). One sample t-test was used in the study for comparison. The significance was tested and accepted at a .05 p-value.

$$R^2 = \frac{\sum_i(\hat{y}_i - \bar{y})^2}{\sum_i(y_i - \bar{y})^2} \quad (4)$$

$$NRMSE = \frac{\sqrt{\sum_{i=1}^{n}\frac{(\hat{y}_i - y_i)^2}{n}}}{y_{max} - y_{min}} \quad (5)$$

Where y_i represents the observed value for i^{th} data. Besides, $\hat{y}$, $\bar{y}$, y_{max} and y_{min} refer to the predicted value of data for observation *i*, the mean value of data set, maximum and minimum values of data, respectively. Additionally, it is worth to say that n represents the total amount of data.

Sensitivity analysis is used to investigate the most influencing parameter on the models. To this aim, the model was subjected to sensitivity analysis to determine the effect of each input variable on the metabolic rate. A detailed procedure on sensitivity analysis used in the study is found in [46].

3. RESULTS AND DISCUSSION

A total number of 16.781 data from 38 subjects were investigated in order to determine metabolic rate from the heart rate, mean skin temperature and carbon dioxide variation. 80% of the data was used for calibration of the equation, while the rest was used for validation. Table 6 represents the model statistics in detail.

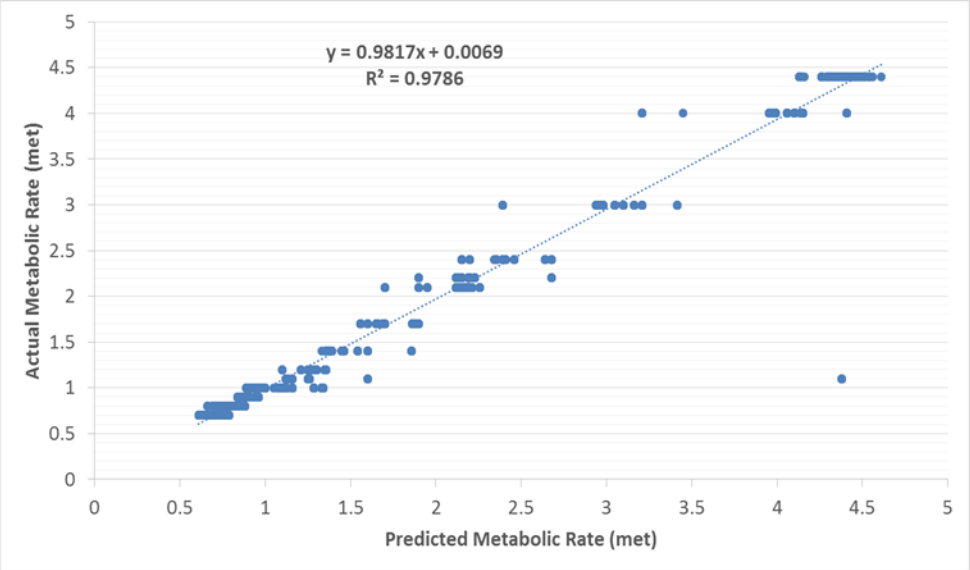

Figure 5 Comparison between predicted and actual metabolic rate.

Table 6 Model statistics for metabolic rate prediction.

	Unit	Model	t-value	p-value
Intercept (d)	-	0.19**	2.59	.009
HR	bpm	0.03**	2.68	.007
MST	°C	0.06**	2.58	.009
ΔCO_2	ppm	0.05*	2.17	.031
R^2		0.97		

NOTES
1) e, f and g were found as 0.3, 0.2 and 1.1, respectively.
2) * significance at 5%, ** significance at 1%

Performing the values in Table 6, the Equation 3 is formed as;

$$M = 0.03(HR)^{0.3} + 0.06(MST)^{0.2} + 0.05(\Delta CO_2)^{1.1} + 0.19 \quad (6)$$

The estimating equation with three independent parameters determines the M with an accuracy of 97% and NRMSE of 3.9×10^{-5} "met" value. The model result indicated that there is a significant and positive relationship between HR and M at 1% significance. Similarly, MST is significant at 1% with a positive coefficient. However, ΔCO_2 is found to be significant at 5% with a positive coefficient. Figure 5 depicts the relationship between actual and predicted M values. It is worth to remind that actual values are "met" values in the direct look up table, which is standardized in the thermal comfort standards. On the other hand, predicted values are obtained from the Equation 6. The figure indicates that there is a minor difference in small "met" values (i.e., resting activity tasks) while larger discrepancies are found in larger "met" values (i.e., miscellaneous leisure activities). The reason of this discrepancy may be the variety of the state of doing activities with large "met" values of subjects. For instance, one subject can dance in a fast way while another is slow. However, "dancing, social" has an average "met" value of 3.4 for both genders. This assumption reduced the accuracy of the model. In addition, body mass indices of male subjects are generally higher than female ones. With high activity tasks, high body mass index values limit subjects to do activities in proper ways.

Figure 6 represents the heart rate variation for several activity tasks for males. The thin lines depict the standard deviation of the values, while the black boxes show the average heart rate with respect to the corresponded activity task. The largest HR is found with "Dancing, social" (MLA18) activity tasks with 111 bpm, while the lowest HR is seen in sleeping (R1) with 70 bpm for males. Shifting activity from sleeping to reclining changes HR as 1 bpm for male subjects.

Figure 7 indicates the HR variation with several activity tasks for females. Unlike the males, the lowest HR is found while “sleeping (R1)” and “filling, seated (O11)” activity tasks.

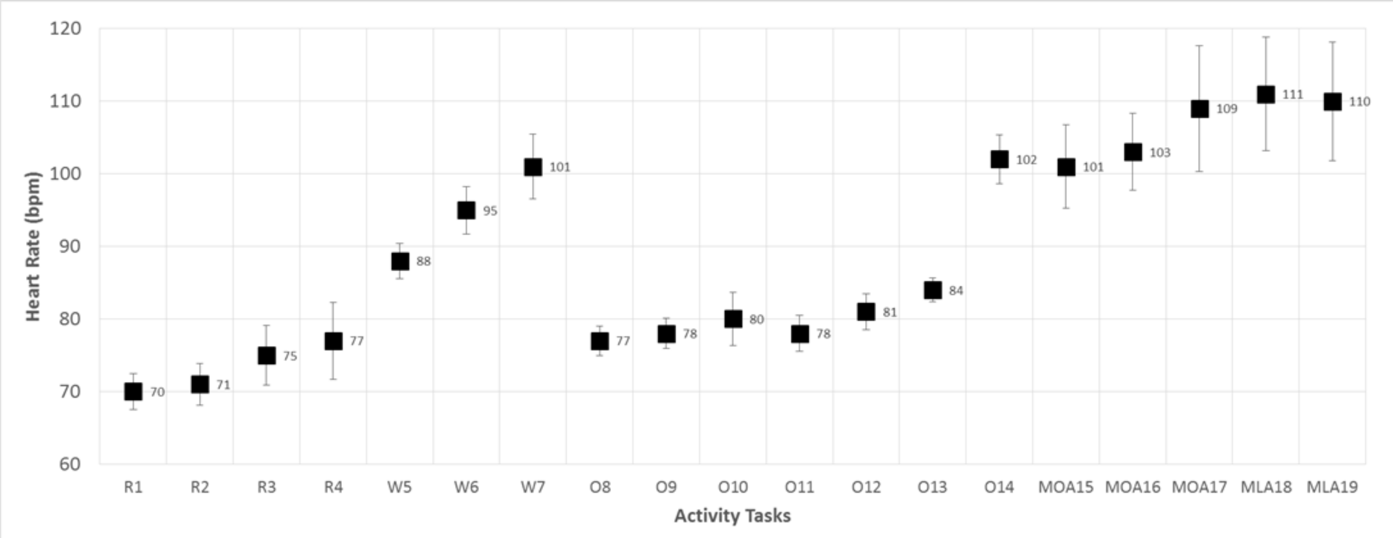

Figure 6 Heart rate variation with different activity tasks for males.

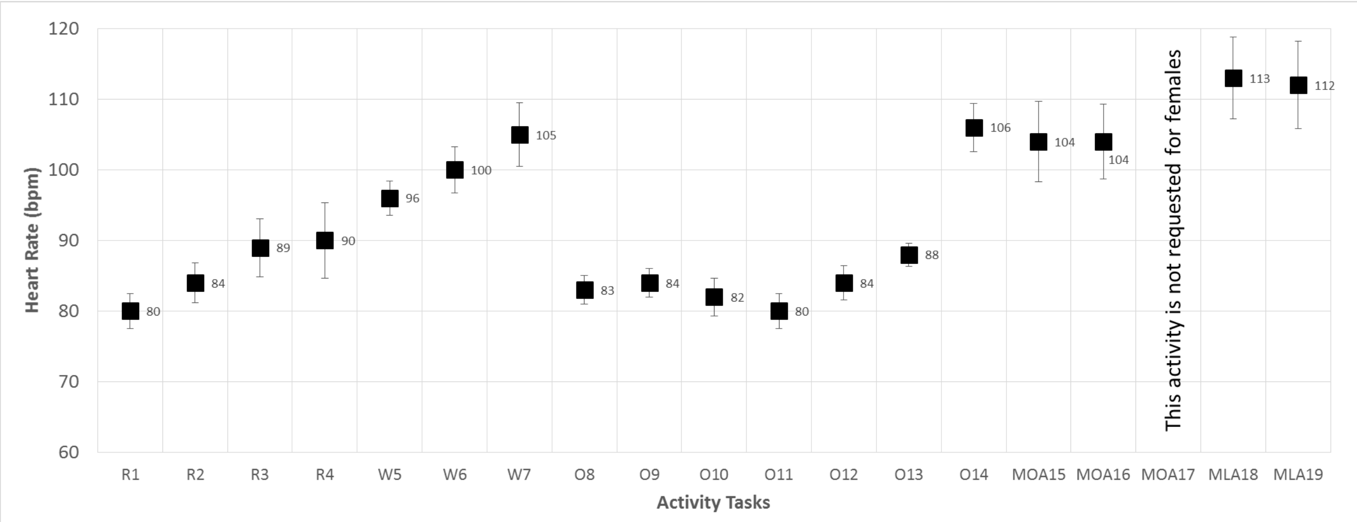

Figure 7 Heart rate variation with different activity tasks for females.

However, the largest HR is obtained while “dancing, social (MLA18)” activity similar to the males. It is worth to remind that “handling 50 kgs bags (MLA17)” is not requested for female subjects due to the activity can cause injury problems.

Figure 8 and 9 show MST variation with respect to different activity tasks. The largest MST values are obtained in MLA19 activity task as 38.2 and 38.4°C for male and female, respectively. The lowest MST values are in sleeping activity (R1) with 35.4 and 36.1°C for male and female, respectively. The carbon dioxide variation shows a strong relationship with activity tasks (Figs.10 & 11). For instance, the change in carbon dioxide concentration during the high metabolic conditions was higher than the others. The lowest carbon dioxide variation is found in “reclining” activity (R^2) for each gender. One can think the least ΔCO_2 could be found in “sleeping” (R1) activity task. However, it is worth to remind that there are three main stages of sleeping such as light sleep, REM and deep sleep [47]. In the REM stage, the brain is very active, which means that CO_2 production is the same or even larger than other light activities. The subjects in the study could be in the REM stage while sleeping, which increases the carbon dioxide variation in the climate chamber. Another noteworthy result is that the ΔCO_2 value is always larger for male subjects than female subjects in every activity tasks. The reason is the larger CO_2 production of male subjects, as indicated in [33].

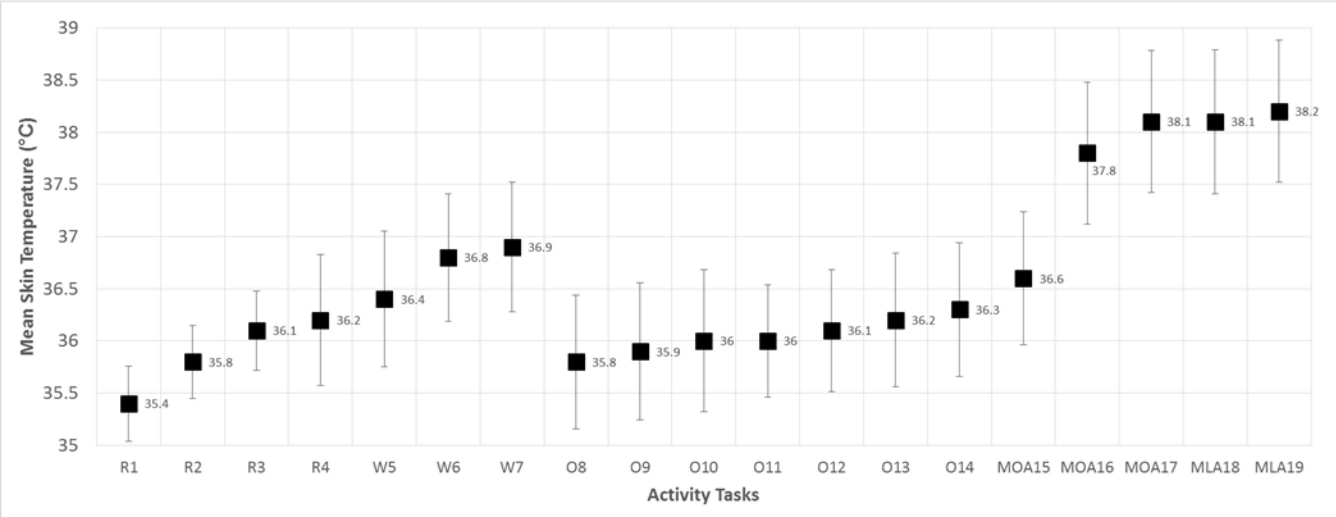

Figure 8 Mean skin temperature variation with respect to different activity tasks for males.

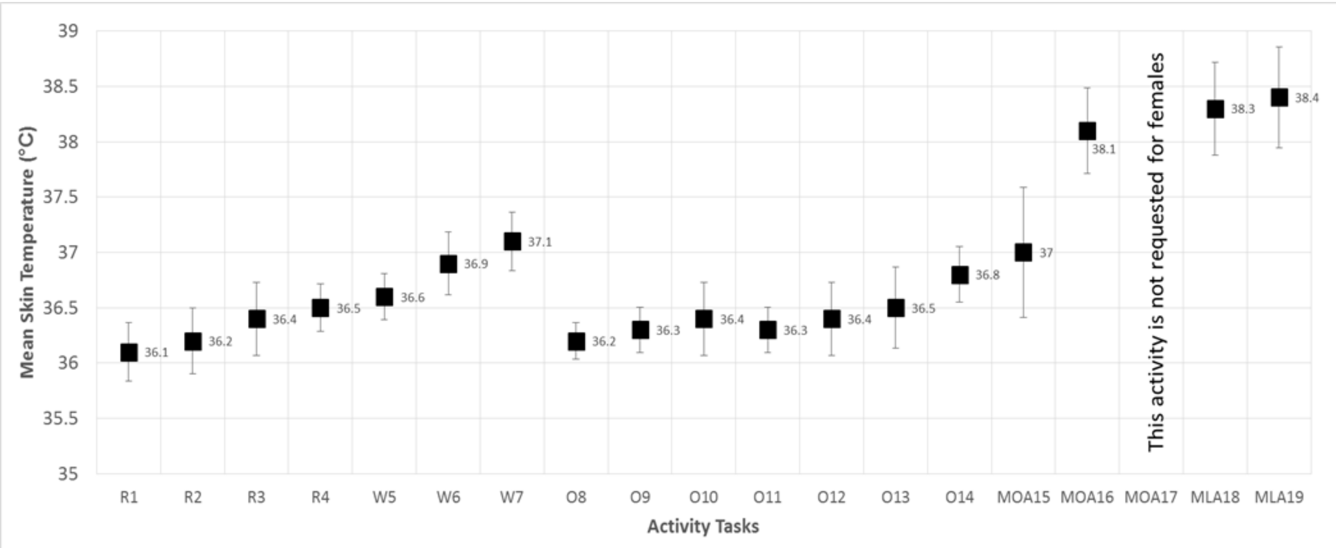

Figure 9 Mean skin temperature variation with respect to different activity tasks for females.

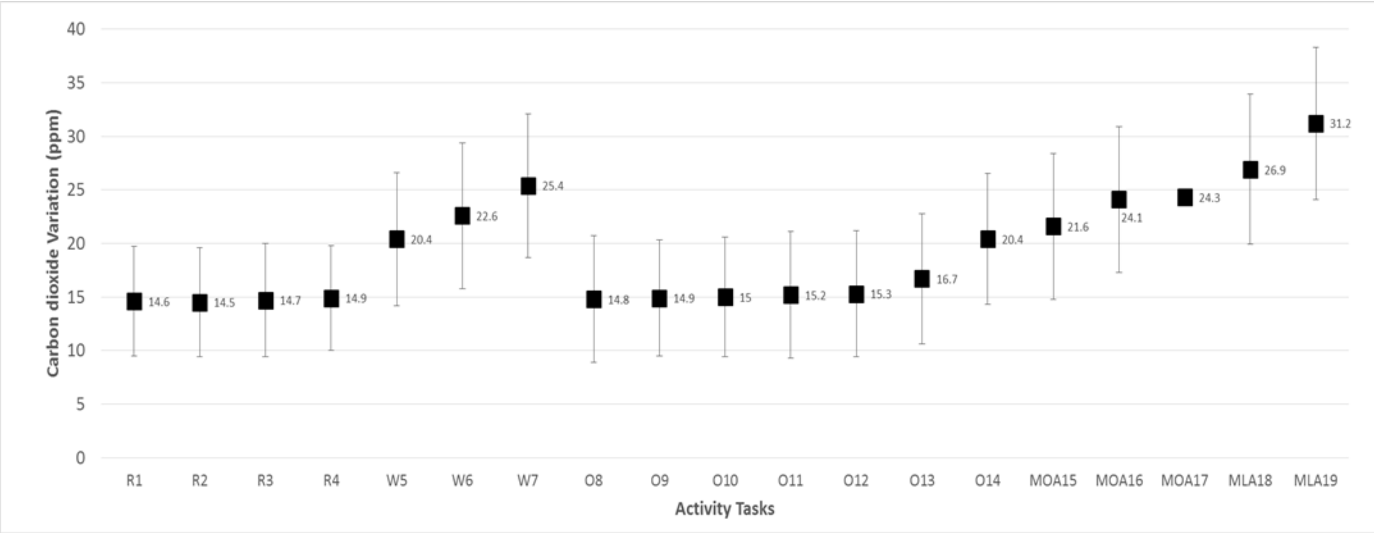

Figure 10 Carbon dioxide variation with respect to different activity tasks for males.

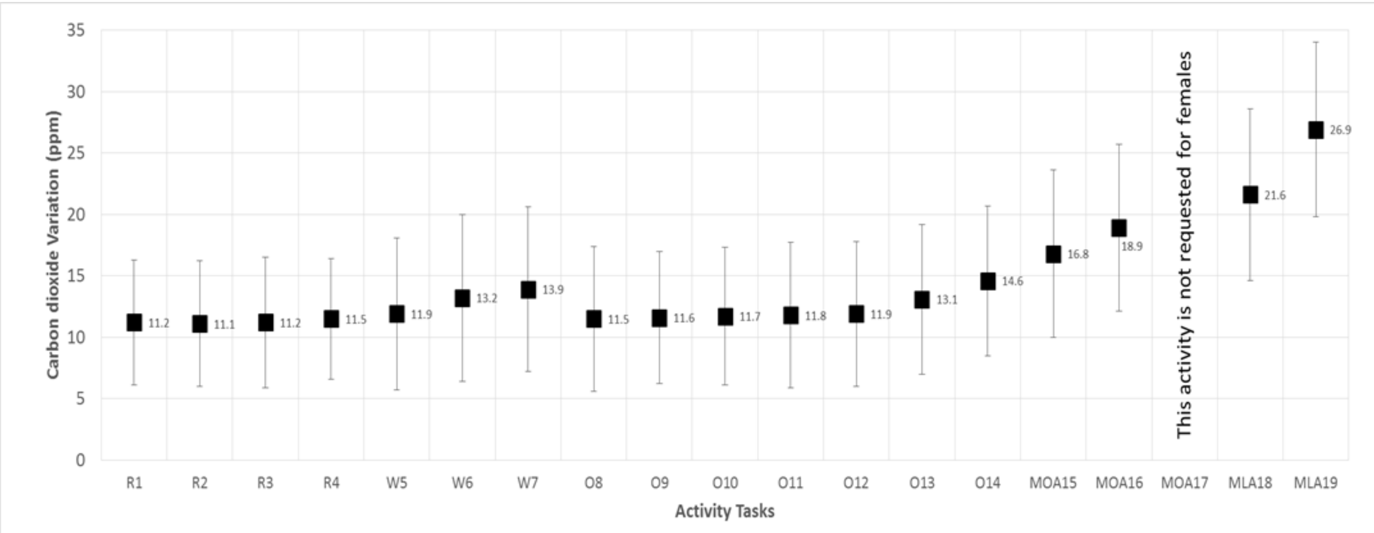

Figure 11 Carbon dioxide variation with respect to different activity tasks for females.

As an additional study, a sensitivity analysis was displayed for the study and the results were shown in Figure 12. Three parameters of the M formula were included in the analysis. The figure represents that HR is the most influencing parameter with 40% sensitivity while ΔCO_2 was found to be the least impact on determining the M. However, the results indicate that none of the parameters could be eliminated from the formula since the sensitivities of the parameters are above 20%.

Finally, the sensitivity analysis is re-obtained for age and gender variations, as shown in Figure13. It is worth to note that the subjects below 35 ages are assumed as young in the analysis.

Notwithstanding the HR is found as the most influencing parameters for each gender and age group, the effect of HR increases with age in the M prediction. A noteworthy finding is that the MST affects the M in female subjects lower than male subjects. The reason could be the variations of blood flow in females. Slower blood flow than male subjects affect the importance of the MST in the M prediction as indicated in [48].

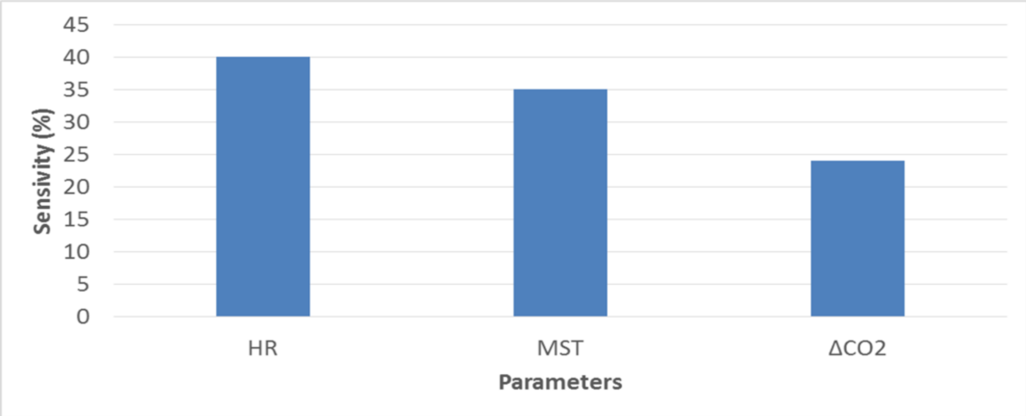

Figure 12 Results of sensitivity analysis for metabolic rate formula.

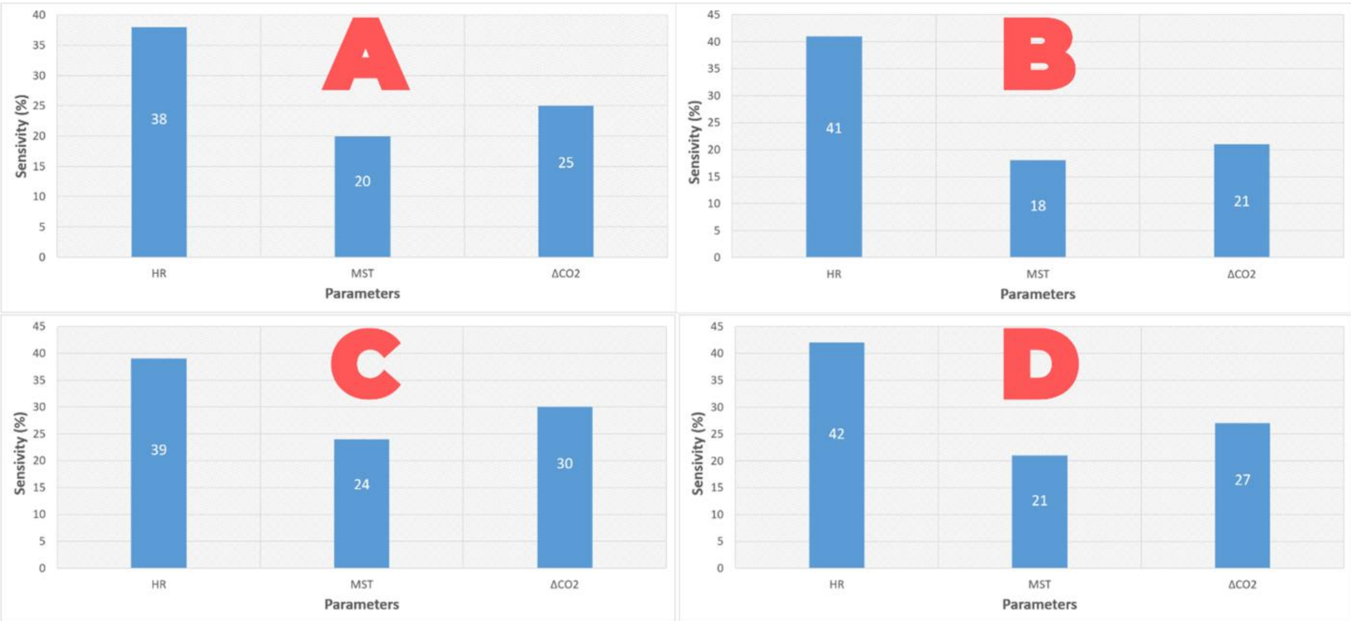

Figure 13 Sensitivity analysis for a) young female subjects b) adult female subjects c) young male subjects d) adult male subjects.

In addition, the importance of the MST decreases with increased ages for each gender. Similarly, the influence of the carbon dioxide variation decreases when the age increases for each gender. The reason could be the higher BMR of the young subjects than adults. Indeed, the BMR highly affects the exhalation and thus carbon dioxide production, as indicated in [49].

3.1. Limitations

Individual differences, such as personal factors like race, gender, age, weight, etc., can cause different metabolic rates as indicated in [50,51]. The experiments in this study were conducted with only Turkish subjects. The cultural differences and ethnical background may limit the use of equations and findings of the study for other populations. More accurate results would be obtained with subjects from different populations.

On the other hand, metabolic rates are only predicted based on activities. However, the Basal Metabolic Rate (BMR), which represents the energy essential for life, for example, to maintain the body temperature and cardiac and respiratory functions of each subject, is different. By adding the BMR to the calculations (i.e., with Harris-Benedict formula [52] more accurate results would be obtained to predict the M. A report of the Food and Agriculture Organization of the United Nations advised that the M can be calculated by multiplying the BMR with a factor that characterizes the specific activity tasks [53].

Sweat rates could also affect the accuracy of metabolic rate determination, as indicated in [54]. However, this parameter varies with individuals and requires depth examination. The investigation of the effect of sweat rate on the M was out of the scope of this paper.

Dynamic changes of activity and environmental parameters should also be taken into consideration. Occupants are usually prone to do different activities during day, therefore, a combined approach is required to predict metabolic rates.

In the study, all subjects were requested to wear the same garments with a calculated 0.42 clo value. When the subjects have wider tolerance to adopt their garments to the real environments, i.e., living laboratories or residential buildings, the values in this study can lead to different results as indicated in [55].

In the present study, predicted M values derived from commonly used multivariable non-linear regression equation. Machine Learning techniques such as Artificial Neural Network [56,57] and Fuzzy Logic [58,59] models should also be derived for the prediction. These artificial intelligence models successfully predicted the thermal comfort of the occupants in past studies [1,56]. By applying similar strategies to the M prediction, the accuracy of the model would be increased.

Finally, in study of Luo et al. [60] it is indicated that the metabolic rate may change without activity changes. The authors concluded that the variation of ambient parameters affects the metabolic rate. Even though this study estimates the metabolic rate from ambient parameters and compares the results with “met” values in activity tables, further studies should focus on this issue for improving the accuracy of the models.

4. CONCLUSIONS

This paper aimed to predict metabolic rate from field-measurements of heart rate, mean skin temperature and carbon dioxide variation. A mathematical model was established according to experimental data. The results showed that metabolic rate could be predicted with high accuracy (R^2=0.97). HR and MST were found as significant in 1%, while carbon dioxide variation was significant at 5% in the M estimation. However, some discrepancies were found between the measured metabolic rate and existing international comfort standards. Larger differences were obtained with higher metabolic rates for each gender.

Future studies will include basal metabolic rate in metabolic rate estimations and develop better metabolic rate equations by taking other individual differences such as pregnancy situation and race of the subjects into account.

The outcome of this study can enlighten architects and engineers to calculate M in different functional architectures such as sports venues and educational buildings and, nevertheless, to design energy-efficient and fully comfortable environments for occupants.

Funding

The authors have not received any financial support for the research, authorship, or publication of this study.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The authors contributed equally to the study.

The Declaration of Ethics Committee Approval

University Human Research Ethics Committee has given ethics approval to the activity to be carried out within the scope of this research study.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

REFERENCES

[1] Z. Deng, and Q. Chen, "Artificial neural network models using thermal sensations and occupants' behavior for predicting thermal comfort", Energy and Buildings, vol. 174, pp. 587-602, 2018.

[2] P. O. Fanger, "Thermal comfort. Analysis and applications in environmental engineering", Copenhagen, Denmark: Danish Technical Press, 1970.

[3] Ergonomics of the thermal environment-instruments for measuring physical quantities, 7726, International Standardization Organization, Geneva, Switzerland, 1998.

[4] Thermal Environment Conditions for Human Occupancy, 55, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA, 2020.

[5] Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 7730, International Standardization Organization, Geneva, Switzerland, 2005.

[6] G. Havenith, I. Holmér, and K. Parsons. "Personal factors in thermal comfort assessment: clothing properties and metabolic heat production", Energy and Buildings, vol. 34(6), pp. 581-91, 2002.

[7] Ergonomics of the thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble, 9920, International Standardization Organization, Geneva, Switzerland, 2007.

[8] J. Van Hoof "Forty years of Fanger's model of thermal comfort: comfort for all?", Indoor Air, vol. 18(3), pp. 182-201, 2008.

[9] L. M. Chamra, W. G. Steele, and K. Huynh, "The uncertainty associated with thermal comfort". ASHRAE Transactions, vol. 109, pp. 356-365, 2003.

[10] M. Luo, Z. Wang, K. Ke, B. Cao, Y. Zhai, and X. Zhou, "Human metabolic rate and thermal comfort in buildings: The problem and challenge". Building and Environment, vol. 131, pp. 44-52, 2018.

[11] Ergonomics of the thermal environment - Determination of metabolic rate, 8996, International Standardization Organization, Geneva, 2004.

[12] M. H. Khan, and W. Pao, "Thermal comfort analysis of PMV model prediction in air conditioned and naturally ventilated buildings". Energy Procedia, vol. 75, pp. 1373-1379, 2015.

[13] F. R. Alfano, B. I. Palella, and G. Riccio, "The role of measurement accuracy on the thermal environment assessment by means of PMV index". Building and Environment, vol. 46(7), pp. 1361-1369, 2011.

[14] M. A. Humphreys, and J. F. Nicol, "The validity of ISO-PMV for predicting comfort votes in every-day thermal environments". Energy and Buildings, vol. 34(6), pp. 667-684, 2002.

[15] C. Yang, T. Yin, and M. Fu, "Study on the allowable fluctuation ranges of human metabolic rate and thermal environment parameters under the condition of thermal comfort". Building and Environment, vol. 103, pp. 155-164, 2016.

[16] P. O. Fanger and J. Toftum, "Extension of the PMV model to non-air-conditioned buildings in warm climates". Energy and Buildings, vol. 34(6), pp. 533-536, 2002.

[17] E. E. Broday, A. A. de Paula Xavier, and R. de Oliveira, "Comparative analysis of methods for determining the metabolic rate in order to provide a balance between man and the environment". International Journal of Industrial Ergonomics, vol.44(4), pp. 570-580, 2014.

[18] Y. Zhai, M. Li, S. Gao, L. Yang, H. Zhang, E. Arens, and Y. Gao, "Indirect calorimetry on the metabolic rate of sitting, standing and walking office activities". Building and Environment, vol. 145, pp. 77-84, 2018.

[19] J. H. Choi, V. Loftness, and D. W. Lee, "Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models". Building and Environment, vol. 50, pp. 165-175, 2012.

[20] G. M. Revel, M. Arnesano, and F. Pietroni, "Integration of real-time metabolic rate measurement in a low-cost tool for the thermal comfort monitoring in AAL environments". Ambient assisted living, Springer International Publishing, Cham, pp. 101-110, 2015.

[21] J. Bligh, "Thermoregulation: what is regulated and how?" in New trends in thermal physiology, Y. Houdas, and J. D. Guieu, Eds., Paris, France, Masson, pp. 1-10, 1978.

[22] J. LeBlanc, B. Blais, B. Barabe, and J. Cote, "Effects of temperature and wind on facial temperature, heart rate, and sensation". Journal of Applied Physiology, vol. 40(2), pp. 127-131, 1976.

[23] Y. Shapiro, K. B. Pandolf, and R. F. Goldman, "Predicting sweat loss response to exercise, environment and clothing". European Journal of Applied Physiology and Occupational Physiology, vol. 48(1), pp. 83-96, 1982.

[24] S. Zhang, Y. Cheng, M. O. Oladokun, Y. Wu, and Z. Lin, "Improving predicted mean vote with inversely determined metabolic rate". Sustainable Cities and Society, vol. 53, 101870, 2020.

[25] D. Willner, and C. Weissman, "Carbon dioxide production, metabolism, and anesthesia", Capnography, J. Gravenstein, M. Jaffe, N. Gravenstein, and D. Paulus, Eds., Cambridge UK: Cambridge University Press, pp. 239-249, 2011.

[26] J. Takala, "Oxygen Consumption and Carbon Dioxide Production: Physiological Basis and Practical Application in Intensive Care", in Proceedings of the 11th Postgraduate Course in Critical Care Medicine, Trieste, Italy, pp. 155-162, 1996.

[27] J. Orr, "Evaluation of a Novel Resting Metabolic Rate Measurement System.", korr.com. https://korr.com/wp-content/uploads/ReeVue-Evaluation-of-a-Novel-Resting-Metabolic-Rate-Measurement-System_Orr_2002.pdf (Accessed Jul. 15, 2021).

[28] M. Luo, X. Zhou, Y. Zhu, and J. Sundell, "Revisiting an overlooked parameter in thermal comfort studies, the metabolic

rate". Energy and Buildings, vol. 118, pp. 152-159, 2016.

[29] H. Na, H. Choi, and T. Kim, "Metabolic rate estimation method using image deep learning". Building Simulation, vol. 13(5), pp. 1077-1093, 2020.

[30] J. Timbal, M. Loncle, and C. Boutelier, "Mathematical model of man's tolerance to cold using morphological factors". Aviation, Space, and Environmental Medicine, vol. 47(9), pp. 958-964, 1976.

[31] E. H. Wissler "A mathematical model of the human thermal system". The Bulletin of Mathematical Biophysics, vol. 26(2), pp. 147-166, 1964.

[32] Y. Zotterman, "Special senses: thermal receptors". Annual Review of Physiology, vol. 15, pp. 357-372, 1953.

[33] W. Ji, M. Luo, B. Cao, Y. Zhu, Y. Geng, and B. Lin, "A new method to study human metabolic rate changes and thermal comfort in physical exercise by CO2 measurement in an air-tight chamber". Energy and Buildings, vol. 177, pp. 402-412, 2018.

[34] DF Robots, "DHT22, Temperature & Relative Humidity Sensor Datasheet", wiki.dfrobot.com. https://wiki.dfrobot.com/DHT22_Temperature_and_humidity_module_SKU_SEN0137 (Accessed Jul. 15, 2021).

[35] Testo, "Testo 425 Anemometer Datasheet", testo.com. https://www.testo.com/en-UK/testo-425/p/0560-4251 (Accessed Jul. 15, 2021).

[36] Global Monitoring Laboratory 2020. "Trends in Atmospheric Carbon Dioxide", esrl.noaa.gov. https://www.esrl.noaa.gov/gmd/ccgg/trends (Accessed Jul. 15, 2021).

[37] DF Robots, "MG811 Carbon-dioxide Sensor Datasheet", wiki.dfrobot.com. https://wiki.dfrobot.com/CO2_Sensor_SKU_SEN0159#target_0 (Accessed Jul. 15, 2021).

[38] Xiaomi, Mi Band 3, "Wrist Band Datasheet". mi.com https://www.mi.com/uk/mi-band-3/specs (Accessed Jul. 15, 2021).

[39] Extech Instruments, "Extech 42530, Infrared Thermometer Datasheet", extech.com. http://www.extech.com/products/resources/42530_DS-en.pdf (Accessed Jul. 15, 2021).

[40] R. F. Goldman "Environmental ergonomics: Whence what wither". in 11th International Conference on Environmental Ergonomics, Ystad, Sweden, pp. 39-47, 2005.

[41] R. E. Hasson, C. A. Howe, B. L. Jones, and P. S. Freedson, "Accuracy of four resting metabolic rate prediction equations: effects of sex, body mass index, age, and race/ethnicity". Journal of Science and Medicine in Sport, vol.14(4), pp.344-351, 2011.

[42] D. Mitchell, and C. H. Wyndham, "Comparison of weighting formulas for calculating mean skin temperature". Journal of Applied Physiology, vol. 26(5), pp. 616-622, 1969.

[43] MathWorks. MATLAB, R2018b, 2018.

[44] C. Turhan, and G. G. Akkurt "Assessment of thermal comfort preferences in Mediterranean climate: A university office building case". Thermal Science, vol. 22(5), pp. 2177-2187, 2018.

[45] A. S. Nazih, E. Fawwaz, and M. A. Osama, "Medium-term electric load forecasting using multivariable linear and non-linear regression". Smart Grid and Renewable Energy, vol.2(2), pp.126-135, 2011.

[46] C. Turhan, T. Kazanasmaz, I. E. Uygun, K. E. Ekmen, and G. G. Akkurt, "Comparative

study of a building energy performance software (KEP-IYTE-ESS) and ANN-based building heat load estimation". Energy and Buildings, vol. 85, pp. 115-125, 2014.

[47] B. Gothe, M. D. Altose, M. D. Goldman, and N.S. Cherniack. "Effect of quiet sleep on resting and CO2-stimulated breathing in humans". Journal of Applied Physiology, vol. 50(4), pp. 724-730, 1981.

[48] A. Bollinger, and M. Schlumpf, "Finger blood flow in healthy subjects of different age and sex and in patients with primary Raynaud's disease". Acta chirurgica Scandinavica. Supplementum, vol. 465, pp. 42-47, 1976.

[49] N. Meunier, J. H. Beattie, D. Ciarapica, J. M. O'Connor, M. Andriollo-Sanchez, A. Taras, C. Coudray, and A. Polito, "Basal metabolic rate and thyroid hormones of late-middle-aged and older human subjects: the ZENITH study". European Journal of Clinical Nutrition, vol. 59(2), pp. 53-57, 2005.

[50] B. Kingma, and V. M. Lichtenbelt, "Energy consumption in buildings and female thermal demand". Nature Climate Change, vol. 5(12), pp. 1054-1056, 2015.

[51] G. Havenith "Metabolic rate and clothing insulation data of children and adolescents during various school activities". Ergonomics, vol. 50(10), pp. 1689-1701, 2007.

[52] J. A. Harris, and F. G. Benedict, "A biometric study of human basal metabolism". National Academy of Sciences of the United States of America, vol. 4(12), pp. 370, 1918.

[53] United Nations University, & World Health Organization, "Human Energy Requirements: Report of a Joint FAO/WHO/UNU Expert Consultation: Rome, 17-24 October 2001 (Vol. 1)", Food & Agriculture Organization.

[54] S. Haddad, P. Osmond, S. King, and S. Heidari "Developing assumptions of metabolic rate estimation for primary school children in the calculation of the Fanger PMV model", in 8th Windsor Conference: Counting the Cost of Comfort in a Changing World, Windsor, UK, pp. 10-13, 2014.

[55] G. Brager, M. Fountain, C. Benton, E. A. Arens, and F. Bauman "A comparison of methods for assessing thermal sensation and acceptability in the field", in Proceedings, Thermal Comfort: Past, Present, and Future, Watford, UK, pp.17-39, 1993.

[56] C. Turhan, T. Kazanasmaz, and G. G. Akkurt, "Performance indices of soft computing models to predict the heat load of buildings in terms of architectural indicators". Journal of Thermal Engineering, vol. 3(4), pp. 1358-1374, 2017.

[57] Z. Karapınar Şentürk, "Artificial Neural Networks Based Decision Support System for the Detection of Diabetic Retinopathy", Sakarya University Journal of Science, vol. 24, no. 2, pp. 424-431, 2020.

[58] Von Grabe J. "Potential of artificial neural networks to predict thermal sensation votes". Applied energy, vol. 161, pp. 412-424, 2016.

[59] M. Erdoğan, "A New Fuzzy Approach for Analyzing the Smartness of Cities: Case Study for Turkey", Sakarya University Journal of Science, vol. 25, no. 2, pp. 308-325, 2021.

[60] M. Luo, W. Ji, B. Cao, Q. Ouyang, and Y. Zhu "Indoor climate and thermal physiological adaptation: Evidences from migrants with different cold indoor exposures". Building and Environment, 98, 30-38, 2016.