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Human metabolic rate and thermal comfort in buildings: The problem and challenge

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ABSTRACT

Of the six fundamental parameters in the classic heat balance model of human thermal comfort, metabolic rate is probably the most important and yet it is the most crudely assessed in both research and practice. Most studies in thermal comfort domain to date have relied on simple activity diaries to estimate metabolic rate. To better understand the pros and cons of this convenient approach, a literature review of cognate disciplines was conducted with the aim of transferring developments in human metabolic science to the built environmental context. This review leads to the conclusion that the dairy methods prevalent in thermal comfort research and practice are probably not accurate enough to sustain common thermal comfort modeling with any semblance of precision. Additional research effort is needed to develop better metabolic rate estimation methods for building occupants, especially accommodating individual differences in BMI, sex, age, pregnancy and menopause status, and non-steady state scenarios. In particular, three avenues of future research topics hold promise for improving practical metabolic estimation and thermal comfort in buildings were discussed:1) development and validation of new metabolic rate instrumentation, 2) field measurement of human metabolic rate characteristics, 3) determine comfort zones for buildings with specific metabolic rate features.

1. Introduction

Human thermal comfort in the built environment is directly relevant to major contemporary issues of anthropogenic climate change and rising standards of living in developing countries [1,2]. Considering the scale of energy applied to HVAC services in developed countries such as in the United States [3], Europe [4], and in the recently developing countries such as China [5], it is timely to review building occupants' thermal comfort requirements for indoor space conditioning and to better understand the physiological and perceptual processes underpinning those requirements.

Among the factors affecting human thermal comfort, metabolic rate, which represents the heat generated within the body, stands out as the most basic comfort determinant. Fanger's classic "comfort equation" posited metabolic rate as one of the six key factors in determining human body's steady-state heat balance as early as in 1970s [6]. To date PMV as a building environment evaluation index has been adopted by standards such as ISO 7730 [7], ASHRAE Standard 55 [8], CEN 15251 [9] and GB/T 50785 [10]. Generally, it can be expressed as the following function,

$$PMV = f(M, I, T_a, T_r, RH, v) \tag{1}$$

where M is metabolic rate (met, 1met equals to 58 W/m^2), I is clothing insulation (clo, 1 clo equals to 0.155 (m^{2}K)/W), T_a is air temperature (°C), T_r is radiant temperature (°C), RH is relative humidity (%), and v is air velocity (m/s). To see the significance of metabolic rate in thermal comfort prediction, Fig. 1 presents how PMV was affected by metabolic rate given that clothing level equals to 1clo. Changing metabolic rate from 0.9met to 1.5met could result in an over 3.2K variance in thermally neutral temperature (temperatures when PMV equals to 0) or approximately 1.5 unit scale of PMV difference. Not surprisingly, accurate description of human metabolic rate is a basis for thermal comfort study.

The current dairy method prevalent in thermal comfort research and practice rarely considers the influence of gender, age, weight, and real-time activity changes, which would affect the accuracy of thermal comfort modeling. Additional research effort is needed to develop methods which would estimate metabolic rates of building occupants

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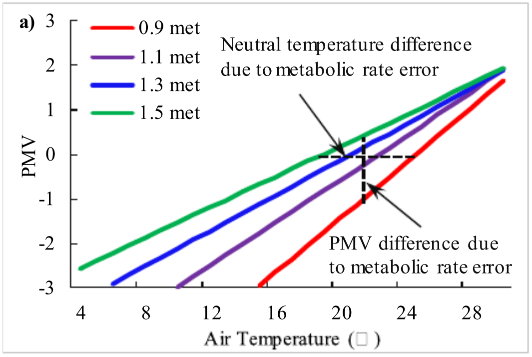


Fig. 1. Effects of metabolic rate change on PMV error [11].

better, particularly considering individual differences in BMI, sex, age, pregnancy and menopause status, and non-steady state scenarios. By comparison, human metabolic rate has been studied for many decades in human physiology research domain, including body's energy expenditures, oxygen consumption, and CO_2 generation, as well as the individual factors that affect these rates. To better understand the current metabolic rate estimation methods, a review of cognate disciplines is needed to transfer the developments in human physiological science to the built environmental context.

For this purpose, this paper aims to summarize the cutting-edge state of metabolic rate research in thermal comfort domain. Firstly, the paper begins with a literature review on metabolic rate and thermal comfort study in building environment, including topics like the impact of metabolic rate on thermal comfort, current estimation method of metabolic rate in practice and research, and the characteristics of building occupants' metabolic rate. Then, the following section presents three future research topics holding promise for improving practical metabolic estimation in buildings.

2. Research overview

2.1. Review method

For the literature review, the database Web of Knowledge was chosen to do the search. The keywords for the search were as follows, “thermal comfort and metabolic rate”, “thermal comfort and human heat production”, “thermal comfort and energy expenditure”, “thermal comfort and metabolism”, “thermal comfort and activity levels”, “thermal comfort, and exercise”. Additional in-depth search was performed by combing above-mentioned keywords with items such as “thermal environment”, “age”, “gender”, “body weight”, and so forth. Some critical standards or handbooks were also searched in order to review the general information of the concept, calculation, and measuring method of metabolic rate. Additionally, the references of the papers gathered above were also used to find additional relevant publications. Google Scholar was used as an alternative way to search these relevant publications.

Through this method, 634 published articles were collected as the literature database. From that database, articles had a direct relation to human metabolic rate and thermal comfort were sorted out based on the title, abstract and conclusions. For more extensive review scope, some important papers studying human energy expenditure but not fully relevant to human thermal comfort were also included. After all these examinations, the most relevant 76 papers were selected for analysis.

2.2. Historical change and geographical distribution

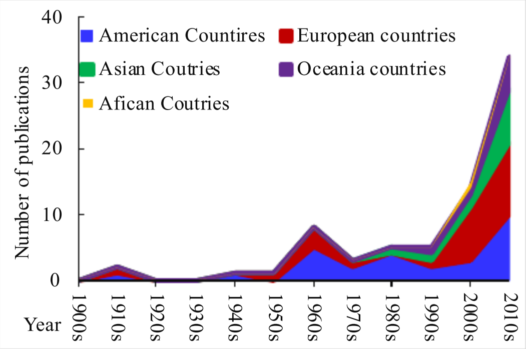


Fig. 2. Annual number of published articles on human metabolic rate and building thermal comfort topics.

Fig. 2 and Fig. 3 illustrate the final 76 papers from the aspect of historical trend and geographical distribution respectively. Research on metabolic rate and human thermal comfort in buildings were gained attention until the 1960s. As the early thermal comfort studies mainly focused on resting state [12], the thermal comfort under higher activity levels was regarded as “general state of unsolved problem” until 1967 [13]. After that, thermal comfort and its relation to activity levels gained increasing interest to U.S. and European researchers like McNall [14,15], Gagge [16] and Fanger [17] in the late 1960s and 1970s. Then, Japanese and Australian researchers began to take notice of this topic in the 1980s and 1990s. After the 2000s, a rapid growth of publications can be observed, especially with the newly emerged force from developing countries like China.

Based on the objectives and the results of the selected literature, three topics were classified. First topic is the effects of metabolic rate on human thermal comfort perception. It can be interpreted into three aspects: 1) effects on human body thermoregulation, 2) effects on subjective perception, and 3) effects on thermal comfort prediction. Second topic is about current estimation methods for metabolic rate. It can be categorized into two groups: 1) how do current thermal comfort studies and standards determine human metabolic rate, 2) how to measure metabolic rate. The third topic is about the characteristics of metabolic rate in buildings. It can also be classified into two topics: 1) individual characteristics, which include the impact of race, gender, age, weight etc., 2) dynamic changes, which mean how does human metabolic rate change with activity levels and ambient environmental conditions.

2.3. Effects of metabolic rate on human thermal comfort

2.3.1. Effects on human body thermoregulation

Metabolic activities of the human body can be partitioned into external mechanical WORK and net HEAT production. While the WORK part is greatly dependent on task types, the net HEAT production must be continuously dissipated and regulated to maintain normal body temperatures. Normally, an adult produces about 100 W of heat in a rest state. As most of the heat is dissipated to the environment through the skin, for convenience, the metabolic activity is often characterized in terms of heat production per unit of skin area. A resting person with 58 W/m^2 metabolic rate is called 1 met. Higher metabolic rates are often expressed in times of the resting rate. For example, a person walking at metabolic rate three times the resting rate would have a metabolic rate of 3 met. Body heat balance was determined by metabolic rate and the external heat load collectively. It took about 20 min for human body to re-establish the heat balance by matching heat dissipation with heat production [18]. Insufficient heat loss leads to overheating and excessive heat loss results in body cooling. For an average male, a 335 kJ of heat storage is equivalents to about a 1.4 °C rise in core temperature [19].

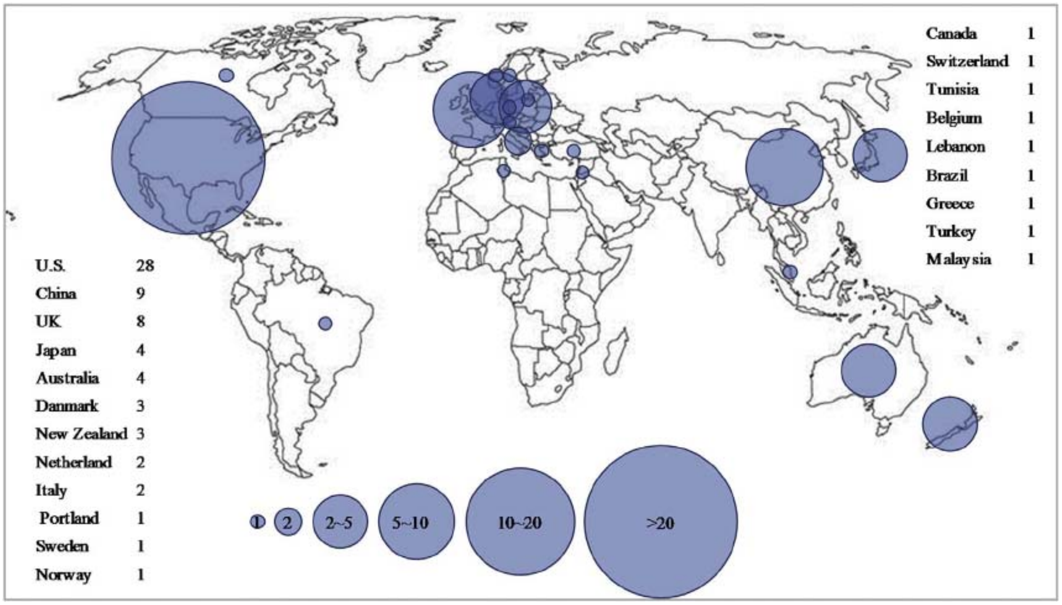


Fig. 3. Regional distribution of research on human metabolic rate and building thermal comfort. (Note, the article sources were based on first author's institute, the background map was Robinson projection world map without Antarctica).

Metabolic rate changes can bring about a number of thermoregulatory responses. One example is the equilibrium body temperature [20]. Usually, the skin temperature associated with comfort at sedentary activities is typically 33–34 °C [21,22], but the situation will change when the metabolic rate changes. According to Fanger's [6], the comfortable (neutral) skin temperature decreases with increasing activity, while the internal temperatures of body rise with activity. A recent work also confirmed this generalization [23]. Another important thermoregulatory response when metabolic rate changed is sweating regulation [24]. Bakkevig and Nielsen [25] tested eight healthy male college students' sweat accumulation under 10 °C and 85% relative humidity with their 30% and 40% of maximum V_{O2}. The results showed the total sweat production was 285 g and 564 g for 30% and 40% of maximum V_{O2} respectively. Gerrett et al. [26] measured local skin wetness and skin conductance in four body segments during different exercise in 10 males and found both skin wittedness and conductance were significantly higher during running state than walking state. More information about thermoregulatory responses under high activity levels can also be found in review works like [27,28].

2.3.2. Effects on subjective perception

Human subjective perceptions like thermal sensation and thermal comfort are products of information from more than one kind of sensing signals. Many studies investigated the correlations between subjective perception and physiological parameters, particularly those important studies conducted by Gagge and Nishi at Pierce Laboratory in the 1960s-80s [12,19]. Among them, Gagge et al. [16] found that the sensation of warmth or cold was strongly affected by skin temperature, which is in turn related to ambient temperature for wide range of continuous exercise levels. Fanger [6] produced experimental evidence to support the generalization that the comfortable rate of sweat evaporation increases as activity increases. Gonzalez [29] found subjects' preferred ambient temperature drops with increasing activity level. The optima occurred at 26.1 °C for sedentary subjects, 21.8 °C for 25% $VO2_{max}$ exercise intensity, and 20.7 °C for 40% $VO2_{max}$ exercise intensity. A recent study [30] tested 21 male and 19 female subjects' thermal comfort perception under three activities, two temperature, and different airflow exposures. Their results also indicated that metabolic rate had a more pronounced effect on thermal comfort than the air temperature in transient and high metabolic rate conditions.

2.3.3. Effects on thermal comfort prediction

The impact of metabolic rate on thermal comfort prediction is significant. For example, Humphreys and Nicol [31] once found that PMV was only applicable to the real situations with less than 1.4 met heat production, and when the activity was 1.8 met, it caused errors up to 1 unit scale. Generally, this can be attributed to two reasons. First, metabolic rate changes may cause faults in some basic assumptions of thermal comfort models. For example, PMV assumes human comfortable state should have the lowest sweating level [6] but this assumption is not applicable to high activity levels. Second, the uncertainty in metabolic rate description can also bring about prediction error. Most thermal comfort models use a single set of metabolic rate data to represent average human body production without considering the individual difference among people and without considering the metabolic real-time changes in daily routine. Alfano et al. [32] analyzed the role of measurement accuracy in PMV calculation. It was found that an error within ± 10% of the nominal value of metabolic rate could result in $[-0.16; 0.14]$ unit scale PMV variation. A similar study was conducted by Ekici [33] but he only considered the uncertainty budget of physical parameters. Yang et al. [34] found occupants' metabolic rate should be limited to a certain range if they want to maintain thermal comfort state.

2.4. Prevalent metabolic rate estimation method

2.4.1. Methods in thermal comfort studies and standards

Although metabolic rate is probably the most important parameter in thermal comfort research and practice, the prevalent estimation method of metabolic rate in thermal comfort research domain to date has been simply matching metabolic rate value with activity levels according to the ISO 8996 standard [35], which can be referred as ‘activity diary’, ‘tabulate’, or ‘table looking up method’. Taking the method in ASHRAE Standard 55 for example, it firstly asks one's activity (e.g. sedentary, standing or walking) through questionnaire, and then refers to a table to get the corresponding metabolic rate value [36]. This ‘activity diary’ method is straightforward and convenient for implementing. It, therefore, has been widely applied in thermal comfort

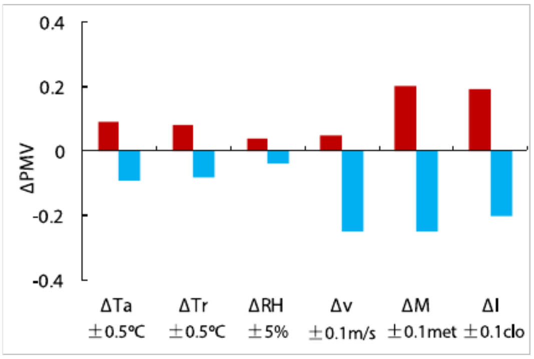


Fig. 4. PMV errors caused by uncertainties of input parameters.

studies, including all the field studies in a global thermal comfort databases underpinned the adaptive thermal comfort model [37–39]. Fanger and Toftum [40] thought one weakness of the adaptive model is that it does not include human clothing or activity, and does not include all four classical thermal parameters that have well-known impacts on human heat balance and therefore on thermal sensation. Hoof [41] in his review paper stated that uncertainties in activity level and clothing insulation are two main weakness of the adaptive model. But one should note that metabolic rate uncertainty will not only affect the database of adaptive comfort model, it affects the PMV calculations as well. For example, Chamra et al. [42] reported that the measurement uncertainty of the metabolic rate, as well as the clothing insulation, constitute the two major sources of the uncertainty of PMV calculation. Havenith et al. [43] showed that the accuracy of current metabolic rate determination method is not sufficient to ensure an accuracy of 0.3 PMV unit scale. Actually, according to ISO 8996 standard, the tabulate (or activity diary) method belongs to the “observation” category that may have errors as high as 20%. Fig. 4 quantitatively compares PMV calculation errors caused by the uncertainty of the six input parameters according to current available measuring precision. It can be seen that metabolic rate is one of the top error sources based on current measurement accuracy.

2.4.2. Measuring technologies of metabolic rate

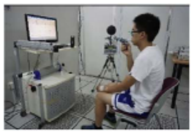
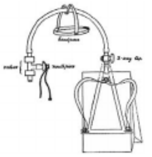
The ‘activity diary’ method described in current comfort standards is for engineering purpose of building design and air conditioning operation. It does not provide metabolic rate for each individual minute by minute. Instead, typical met levels are averaged across a group of people and across a pried of time, representing sample activities in the space being designed or operated. But, this method may not meet the precision requirement for thermal comfort research. That is why many researchers tried to introduce recently emerged wearable or portable metabolic devices into thermal comfort studies. For example, Broday et al. [44] improved PMV's accuracy by integrating two metabolic rate estimating methods - Newton's calculation and metabolic analyzer, a measurement device. They found that the Newton's calculation and the measured result were 178.63 and 145.46 W/m^2 respectively, while the suggested value by ISO 8996 table was 75–125 W/m^2. By applying the Newton's calculation and metabolic analyzer, they built a better correlation between actual thermal sensation and PMV although they did not consider the unsteady-state of metabolic rate. Gilani et al. [45] improved the thermal prediction level of PMV by using mean blood pressure as a bio-marker to modify occupants' metabolic heat production in field thermal comfort studies. Choi et al. [46] investigated the possibility of using heart rate as a human factor for thermal sensation predicting model. Experiments with 14 college-aged subjects were performed in cool chamber (18–20 °C) and warm chamber (25–27 °C) at four activity levels. The results indicated that heart rate is a good metabolic rate indicator. The measured heart rate increased 22%–43% depending on thermal conditions when the metabolic rate increased from lying (0.8 met) posture to cycling (2.5 met). But the correlation between heart rate and metabolic rate built in this study may not suitable for other scenarios. Revel et al. [47] presented thermal comfort monitoring tool with low-cost heart rate sensors to measure human metabolic rate. This solution was reported to regulate real-time metabolic rate uncertainties within 7% in a range of 0.7–3.4 met, ensuring the PMV error within ± 0.05 unit scale. Although this study was based on the assumption that the metabolic rate could be accurately predicted by heart rate, it made an advance in looking into the real-time metabolic rate changes. A similar study by Hasan et al. [48] provided another real-time metabolic rate monitoring approach. They used a built-in accelerometer in a wearable band to infer the wearer's activity level and then convert it into metabolic rate. However, the accuracy of this solution depends largely on algorism of activity and metabolism converting.

In addition to the recently emerged new ideas and portable instruments about metabolic rate measurement for thermal comfort studies, human energy expenditure research field has been paying continuous efforts on human metabolism measurement. Many literature reviews like [49] can be easily searched in this field, here we do not go that deep. Table 1 lists some typical market-ready metabolic rate measuring devices and their features, which could be used in buildings. Among them, wearable motion detector and heart rate meter are the most convenient and easy choices for real-time human body metabolism recording. Due to its convenience and low cost, these two technologies are widely used in people's daily life for health and safety reasons. But the algorithm behind this method should be carefully validated before applying it to different activity scenarios, otherwise it might not be that accurate. From the view of accuracy, the doubly labeled water method and human respiratory chamber, which is based on indirect calorimetry that measures oxygen uptake and carbon dioxide production, are regarded as the gold-standard references of human metabolism measurement. But these two methods are expensive and require specialized skills to operate so that they are not suitable for wide applications. Different from human respiratory chamber, other indirect calorimetry devices like V_{max} Encore metabolic cart and Cosmed K5 portable metabolic analyzer have been well developed. The smaller size and portable function make them much more convenient. However, the 60–80K USD costs are too expensive to be applied in thermal comfort research, especially in large-scale field studies. Finally yet importantly a relatively cheap method called Douglas [50,51] bag is worth mentioning. It takes advantage of indirect calorimetry calculation principle, but it is hard to take continuously metabolism recording minute by minute because it is not easy to measure the air volume in the bag.

2.5. Metabolic rate features in buildings

Although the metabolic rate is crucial for thermal comfort studies, it is probably the most inaccurate one of the six fundamental parameters in the classic heat balance modeling of human body. For example, Rowe [61] did a field survey with 1627 respondents in Sydney and reported that the actual metabolic rate ranged from 1.0 met to 1.9 met with a standard deviation of 0.22 met. A Tunisian thermal comfort study conducted by Bouden and Ghrab [62] showed people there had different daily routine thus resulting in metabolic rate variance during the course of a day. Haldi and Robinson [63] conducted a similar field study in Switzerland buildings but observed small variations in occupants' activity (82.7% of answers indicated sedentary activity). This may because their investigation mainly focused on the “right here right now” questions with only 6 activity choices, instead of asking respondents how they changed their activities during the day. Even with those restrictions, there remained 17.3% of answers different from the dominated sedentary activity. With the impact factors like gender, age, nature of the job and environmental conditions, it is reasonable to see some metabolic rate variation in real buildings. Here, we group these

Table 1
Market-ready human metabolic rate measuring devices.

Typical device	Basic principle	Examples	Price (USD)	Advantages	Disadvantages	Application scenarios
Wearable motion detectors [52,53]	Match metabolic rate with body motion		$20 and up	Convenient, real-time activity records	Low accuracy	Chamber experiment or field study
Heart rate meter [54]	Match metabolic rate with heart rate		$20 and up	Convenient, real-time heart rate records	Low accuracy	Chamber experiment or field study
Double-labeled water [55,56]	Isotope tracer	–	–	High accuracy	Inconvenient, expensive	Chamber experiment
Human respiratory chamber [57]	Indirect calorimetry calculation by CO_2, oxynitride production and O_2 consumption		> $100K	Real-time records, high accuracy	Inconvenient, very expensive,	Chamber experiment
V_{max} Encore Cart [58]	Indirect calorimetry calculation by CO_2 production and O_2 consumption		~ $60K	Real-time records, high accuracy	Expensive	Chamber experiment
COSMED K5 portable metabolic device [59,60]	Indirect calorimetry calculation by CO_2 production and O_2 consumption		~ $80K	Real-time records, high accuracy	Expensive	Chamber experiment or field study
Douglas Bag [50,51]	Indirect calorimetry calculation by CO_2 production		–	Low cost, high accuracy	No real-time records	Chamber experiment or field study

factors into two categories - individual difference and real-time changes.

2.5.1. Individual difference

The individual difference means metabolic rate variance caused by personal factors like race, gender, age, weight, etc. A typical example of individual difference analysis is the one by Kingma and Marken Lichtenbelt [64], reporting there indeed existed metabolic difference between sexes – men had higher metabolic rate, claiming the over-cooling of buildings worldwide was to keep men comfortable at the expense of women' comfort. Zhang and Arens [65] analyzed the data from the US army and found that females usually had 10–30% lower metabolic rate than males when they had the same heart rate. Also, Havenith [66] did direct metabolic measurements on kids in class rooms and found that children's metabolic values were lower than adult data for similar activities. A recent paper from Haddad et al. [67] discussed schoolchildren's thermal comfort. It confirmed that children's thermal neutrality was a few degrees lower than adults under identical thermal conditions were. They also attributed this to children's smaller surface area so their metabolic rates in terms of W/m^2 were actually higher than adults were. Regarding the race factor, Qi et al. [68] compared the respiratory CO_2 productions between Chinese and Western, reported that respiratory CO_2 production in 44 Chinese subjects was 15% lower than the values obtained by empirical formula for western populations. All these studies offered some evidence relevant to the metabolic individual differences from various angles. But as there were many confounding factors, these studies failed to offer a systematical description. The alternative approaches needed to elaborate the underlying principle of metabolic individual differences are yet to be produced.

In fact, human heat production has been recognized as an important topic for decades in human metabolism research field [69]. It defines body energy requirement as "the amount of food energy needed to balance energy expenditure in order to maintain body size, body composition and a level of necessary physical activity consistent with long-term good health." A key point in this field is that human energy requirement or heat production can be regarded as several components. One of them is called Basal Metabolic Rate (BMR), which represents the energy essential for life, for example, to maintain the body temperature and cardiac and respiratory functions. BMR is typically measured under conditions of being awake in a supine position after 10–12 h of fasting and 8 h of physical rest in an environment. BMR typically constitutes 45%–70% of daily energy expenditure and is primarily a function of age, sex, body size, and body composition. Based on the body mass data collected from the EPA Exposure Factors Handbook [70], BMR values can be calculated by Schofield method [71,72]. Fig. 5 shows BMR variance caused by factors like age, body mass, and sex.

In addition to basal metabolism, the second largest component of daily energy expenditure is associated with physical activity. According to the report by the Food and Agriculture Organization of the United

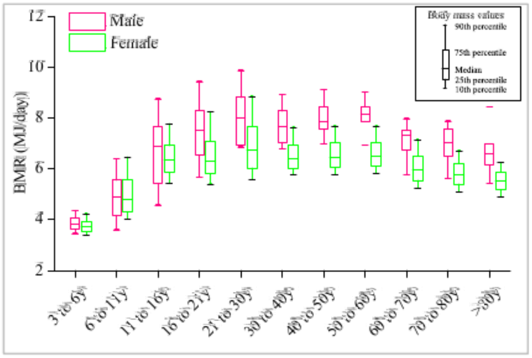


Fig. 5. Variance in BMR associated with factors of age, body mass, and gender.

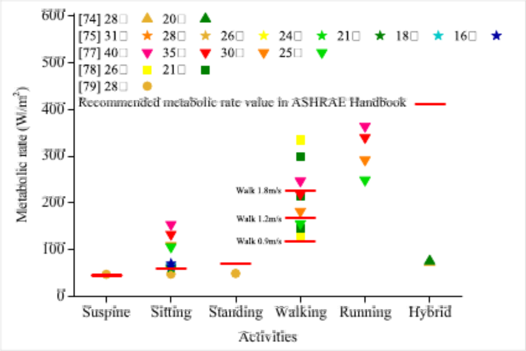


Fig. 6. Variance in metabolic rate caused by activity levels and thermal environment conditions.

Nations (FAO) [72], the rate of energy use of an individual or a group of individuals engaged in a specific activity can be estimated by multiplying the BMR value by a factor that characterizes the specific activity. And this factor can be referred as the physical activity ratio (PAR) [69]. In this way, the influence of age, body mass, gender, and activity levels can be taken into consideration by choosing different BMR and PAR values. Table 2 compares the BMR-PAR heat production estimation methods with activity diary method in ASHRAE handbook for some typical office building activities. The BMR-PAR method indicate a difference between men and women – usually women tend to have slightly lower heat production because their lower BMR.

2.5.2. Real-time changes

Another uncertainty in real building metabolic rate estimation can be named as dynamic changes, which means the real-time changes in metabolic heat production caused by moving around, changing postures, engaging in different jobs, and exposing to different environments. There are two sub-questions regarding this uncertainty.

The first question is whether and how much building environment will cause variance in occupants' metabolic rate. Fig. 6 summarizes the major result of some studies discussing this issue. The huge discrepancy illustrated in the figure shows the impact of activity and thermal environment on metabolic rate. Among them, Johnson et al. [73] reviewed the evidence of a causal link between thermal exposures and increases in obesity prevalence. It showed a graded association between acute mild cold and human energy expenditure reduction over the range of temperatures. Warwick et al. [74] let 19–35-year old subjects stayed in a respiration chamber twice for 24 h, once at 20 °C and once at 28 °C. It was reported that subjects' 24 h energy expenditure was 5% higher during the 20 °C than the 28 °C. Luo et al. [75] carried out an experimental with 30 college-aged subjects and found the cold condition (0.42clo, 16 °C) had 15.5% higher metabolic rate than the neutral case (0.42clo, 26 °C). Langeveld et al. [76] exposed healthy volunteers to either mild cold or thermoneutrality for 2.5 h and found the mild cold exposure group expended 40 KJ more energy than the thermoneutrality group. Sun and Zhu [77] found that subjects engaged in media physical labor had 23% higher metabolic rate when exposed to 40 °C.

The second sub-question is about the real-time changes of building occupants' metabolic rate. In the real world, the metabolic rate will change even when people stayed in the same environment because of various daily activities. So, how much time it takes a person to reach a new steady state once his/her metabolic rate changed from one level to another. Some studies discussed this issue. Goto et al. [78] studied step-change metabolic rate and its effect on thermal comfort. They investigated 24 subjects' thermal sensation and thermophysiological responses to metabolic changes with different intensities and durations. It was found that subjects' thermal sensation started to rise or decline immediately (within 1 min) after a change of activity but it took 15–20 min to reach another steady-state after the activity change. Tikuisis and Ducharme [79] studied how could postural changes influence body temperature and metabolic rate. They tilted subjects from upright posture into supine position and then back to the original upright position. It was found that it took nearly 2 h (ranging from 92.6 min to 124.1 min) to reach new steady state once the position was changed.

3. Discussion

The above review leads to the conclusion that the current metabolic estimation methods prevalent in thermal comfort research and practice are probably not accurate enough. Additional research effort is needed to develop better metabolic rate estimation methods for building occupants. Therefore, some possible research topics holding promise for improving practical metabolic estimation and thermal comfort in buildings are discussed.

Table 2
Heat production comparison for typical building activities (taking age range 30–40 for example)[72].

	Heat production (W//m^2) from ASHRAE Handbook	Male		Female	
		Average PAR	Median Heat production (W//m^2) from PAR calculation	Average PAR	Median Heat production (W//m^2) from PAR calculation
Sleeping	**40**	1.0	**49.4**	1.0	**40.3**
Seated quietly	**55**	1.2	**59.3**	1.2	**48.4**
Reading	**55**	1.22	**60.3**	1.25	**49.2**
Office worker-Writing	**60**	1.4	**69.2**	1.4	**56.5**
Office worker-Typing	**65**	1.8	**88.9**	1.8	**68.6**
Standing	**70**	1.4	**69.2**	1.5	**60.5**
Walking slowly	**100**	2.8	**138.4**	3.0	**121.0**

3.1. New metabolic instrumentation development

Having a metabolic rate measuring device with merits like low cost, high accuracy, and easy to use would be of great value for the thermal comfort study, as well as to validate other metabolic rate estimation methods which might have less accuracy, such as the heart rate and the wearable devices. Among the current measurement technologies, indirect calorimetry is regarded as the one with high accuracy and feasibility [80]. Based on O_2 consumption and CO_2 production measurement, human body metabolic rate can be calculated. Equation (2) is a typical one among all the algorithms [81].

$$M = \frac{21(0.23RQ + 0.77)Q_{O_2}}{A_d} \tag{2}$$

Where M is metabolic rate (W/m^2), RQ is respiratory quotient calculated by molar ratio of Q_{CO_2}(L/min) exhaled to Q_{O_2}(L/min) inhaled, Q_{CO_2} and Q_{O_2} are the volumetric rate of carbon dioxide production and oxygen consumption respectively (ml/s, at conditions of 0 °C, 101.3 kPa), and A_d is the Dubois surface area (m^2) which can be determined by an empirical equation with H (height, m) and W (weight,kg) [82].

Equation (2) shows that the key point of metabolic rate estimation is to measure the O_2 consumption and CO_2 production accurately. Taking CO_2 measurement for example, Fig. 7 breaks down its measuring process and points out the challenges using this method. In order to obtain the CO_2 production through breathing, its concentration in both the incurrent and ex-current airflows should be accurately measured. But the air velocity, air pressure and CO_2 concentration all tend to change dynamically during the breathing process, thus making it extremely difficult to measure the real-time airflow volume and CO_2 concentration of breathing. Especially for the measurement within the timescale of seconds, it requires very high precise airflow meter and gas analyzer and might result in marked measuring uncertainty [83].

However, it is worthy to note that the vast majority of thermal comfort studies only have to consider metabolic rate changes in the timescale of minutes and hours rather than of seconds. It is, therefore, possible to avoid this measurement inaccuracy and difficulty. This study proposed a novel and simple way to measure human metabolic rate by using a container with a fixed air volume, which can be a sealed cabin or a small box, to restore respiratory air. Then the key point of the measurement should be focused on CO_2 concentration changes in the sealed cabin or the box. This fixed-volume container can largely reduce the above measurement difficulties. Fig. 8 illustrates such an example by showing a 2 m × 2 m × 2 m airtight chamber with less than 0.03 time/h air exchange rate when the door was closed. CO_2 sensors can be uniformly arranged with a fan mixing up the air. As the volume of the cabin or box is fixed, thus there is no need to measure the real-time breathing airflow. Table 3 analyzes the error of this method. It can be seen that this method only needs high precision O_2 and CO_2 measurement to achieve accurate metabolic rate measurement.

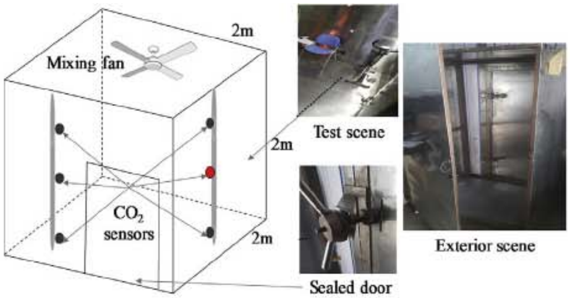


Fig. 8. Configuration of a sealed room for CO_2 production measurement.

Table 3
Error analysis of the fixed-volume-container method.

Measuring	Possible error	Error analysis	Possible error in M (%)
$\frac{\Delta Q_{CO2}}{Q_{CO_2}}$ (L/min)	± 2%	$< \left\lvert\frac{\Delta Q_{CO2}}{Q_{CO_2}}\right\rvert \cdot 100\%$	< 2%
$\frac{\Delta Q_{O_2}}{Q_{O2}}$ (L/min)	± 2%	$< \left\lvert\frac{\Delta Q_{O_2}}{Q_{O2}}\right\rvert \cdot 100\%$	< 2%
H (m)	1 cm	$0.725 \cdot \left\lvert\frac{\Delta H}{H}\right\rvert \cdot 100\%$	< 0.5%
W (kg)	0.1 kg	$0.425 \cdot \left\lvert\frac{\Delta W}{W}\right\rvert \cdot 100\%$	< 0.5%

3.2. Alternative estimation method for metabolic rate

To better characterize metabolic rate in building occupancies, Fig. 9 presents a possible research framework on this topic. For the individual

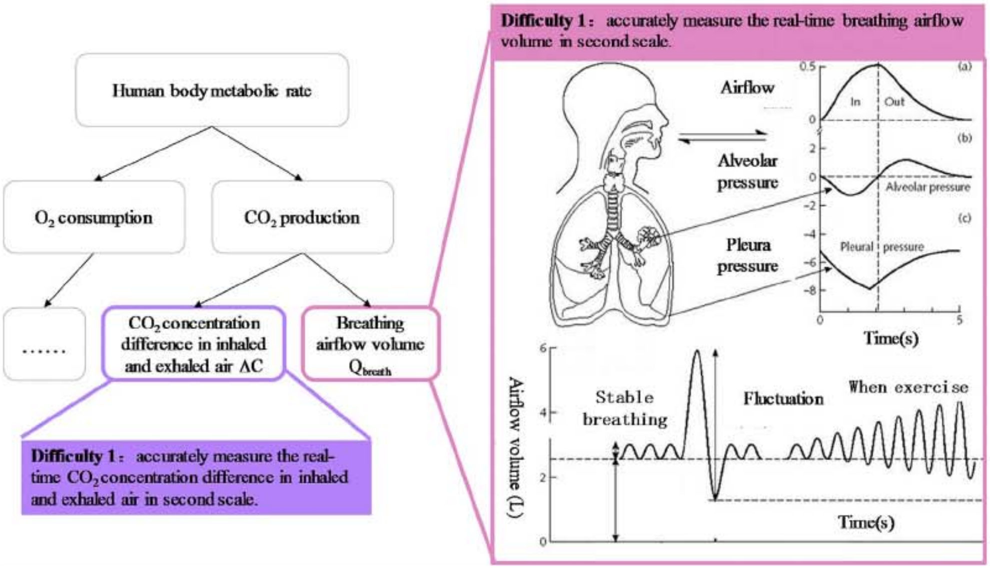


Fig. 7. Breakdown of CO_2 production measurement.

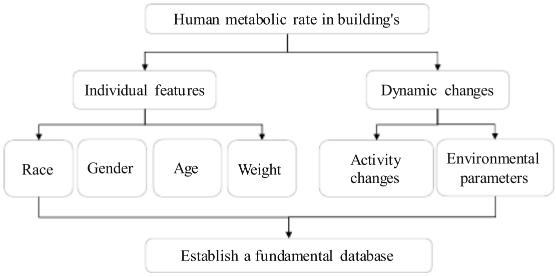


Fig. 9. Building occupants' metabolic rate estimation.

features, Fig. 5 and Table 2 present a promising approach by introducing indexes like BMR and PAR. In this new approach, the explicit BMR database can take factors like age, gender, and body mass into consideration, whilst PAR can represent the physical activity levels. But this method should be further developed and its accuracy should also be validated in future studies. For the dynamic changes, field studies and laboratory experiment can be designed to investigate occupants' diurnal variation of metabolic rate. A possible approach to achieve this goal is to introduce wearable or portable devices such as step meter, heart rate meter and blood pressure meter into thermal comfort field studies. In this way, a better understanding of how frequently and how significantly building occupants change their metabolic rate can be achieved. But before doing this, the algorithms of metabolic rate calculating in these wearable or portable devices should be carefully calibrated.

3.3. *Comfort zones for buildings with specific metabolic features*

Characterizing building occupants' metabolic rate has its practical value. For example, as most current thermal comfort models did not consider the individual difference and the real-time changes in metabolic rate, dynamic thermal load model that considers the variation of metabolic rate is in demand. This improved model can be applied to determine the comfort parameters for building environments with specific metabolic features like sports venues, teaching buildings for teenagers, beerhouses, and so on. Secondly, better measures could be taken to improve the thermal environment once we know occupants' metabolic rate characteristics in real buildings. Solutions like moving the air can be introduced to improve occupants' thermal comfort when they are in transitional space [84,85], non-sedentary office area [86], sports center [87], and even outdoor spaces [88].

4. Conclusions

This paper reviewed the progress of metabolic rate research in building thermal comfort research domain. It leaded to the conclusion that the current activity dairy methods prevalent in thermal comfort research and practice are probably not accurate enough to sustain common thermal comfort modeling with high precision. Additional research efforts are needed to develop better metabolic rate estimation methods for building occupants, especially with considerations of individual differences in BMI, sex, age, and pregnancy, and non-steady state scenarios. Three possible topics were proposed to improve practical metabolic estimation in buildings: 1) develop new devices for metabolic rate measurement, 2) develop alternative methods for building occupants' metabolic rate estimation, 3) determine comfort zones for buildings with specific metabolic rate features.

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References

[1] R.J. de Dear, T. Akimoto, E.A. Arens, G. Brager, C. Candido, K.W.D. Cheong, B. Li, N. Nishihara, S.C. Sekhar, S. Tanabe, J. Toftum, H. Zhang, Y. Zhu, Progress in thermal comfort research over the last twenty years, Indoor Air 23 (6) (2013) 442–461.
[2] M. Luo, R. de Dear, W. Ji, C. Bin, B. Lin, Q. Ouyang, Y. Zhu, The dynamics of thermal comfort expectations: the problem, challenge and implication, Build. Environ. 95 (2016) 322–329.
[3] U.S. Energy information Administration, Annual Energy Outlook, (2012).
[4] European Parliament and Council, Directive 2010/31/EU of the european parliament and of the council of 19 may 2010 on the energy performance of buildings, Official Journal of the European Union 153 (2010) 13–35.
[5] National Bureau of Statistics of China, China Statistical Yearbooks, China Statistics Press, Beijing, China, 1990-2012http://data.stats.gov.cn.
[6] P.O. Fanger, Thermal comfort. Analysis and Application in Environment Engineering, Danish Technology Press, Copenhagen, Denmark, 1970.
[7] Technical Committee ISO/TC 159 and Technical Committee CEN/TC 122 ISO 7730: 2005, 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, European Committee for Standardization, UK, 2006.
[8] ASHRAE, Thermal Environmental Conditions for Human Occupancy, ASHRAE Standard 55 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, 2013.
[9] CEN, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings: Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, EN 15251 European Committee for Standardization, Brussels, 2007.
[10] GB/T, Evaluation Standard for Indoor Thermal Environment in Civil Buildings, GB/T 50785 Ministry of Housing and Urban-Rural Development of the People's Republic of China, Beijing, 2012 (in Chinese).
[11] E. Arens, M. Humphreys, R. de Dear, H. Zhang, Are 'Class A' temperature requirements realistic or desirable? Build. Environ. 45 (1) (2010) 4–10.
[12] A.P. Gagge, J.A.J. Stolwijk, J.D. Hardy, Comfort and thermal sensations and associated physiological responses at various ambient temperatures, Environ. Res. 1 (1967) 1–20.
[13] E. Asmussen, Exercise: general state of unsolved problems. In "Physiology of Muscular Exercise", Circ. Res. XX and XXI (Supplement I) (1967) 2–5.
[14] P.E. McNall, J. Jaax, F.H. Rohles, R.G. Nevins, W.E. Springer, Thermal comfort (thermally neutral) conditions for three levels of activity, Build. Eng. 73 (1) (1967) I.3.1-I.3.14.
[15] P.E. McNall, P.W. Ryan, F.H. Rohles, R.G. Nevins, W.E. Springer, Metabolic rates at four activity levels and their relationship to thermal comfort, Build. Eng. 74 (1) (1968) IV.3.1-IV.3.17.
[16] A.P. Gagge, J.A.J. Stolwijk, B. Saltin, Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures, Environ. Res. 2 (3) (1969) 209–229.
[17] P.O. Fanger, Calculation of thermal comfort, Build. Eng. 73 (1967) Part II, III.4.1-III.4.20.
[18] R.R. Gonzalez, L.G. Berglund, A.P. Gagge, Indices of thermoregulatory strain for moderate exercise in the heat, J. Appl. Physiol. 44 (1978) 889–899.
[19] A.P. Gagge, J.A. Stolwijk, Y. Nishi, An effective temperature scale based on a simple model of human physiological regulatory response, Build. Eng. 77 (1971) 247–262.
[20] B. Saltin, L. Hermansen, Esophageal, rectal and muscle temperature during exercise, J. Appl. Physiol. 21 (1966) 1757–1762.
[21] H. Liu, J. Liao, D. Yang, X. Du, P. Hu, Y. Yang, The response of human thermal sensation perception and skin temperature to step-change transient thermal environments, Build. Environ. 73 (2014) 232–238.
[22] J. Xiong, X. Zhou, Z.W. Lian, J.X. You, Y.B. Lin, Thermal perception and skin temperature in different transient thermal environments in summer, Energy Build. 128 (2016) 155–163.
[23] H. Wang, S. Hu, Experimental study on thermal sensation of people in moderate activities, Build. Environ. 100 (1) 127–134.
[24] J.W. Snellen, Mean body temperature and the control of thermal sweating, Acta Physiol. 19 (1966) 99–174.
[25] M. Bakkevig, R. Nielsen, The impact of activity level on sweat accumulation and thermal comfort using different underwear, Ergonomics 38 (5) (1995) 926–939.
[26] N. Gerrett, B. Redortier, T. Voelcher, G. Havenith, A comparison of galvanic skin conductance and skin wittedness as indicators of thermal discomfort during moderate and high metabolic rates, J. Therm. Biol. 38 (8) (2013) 530–538.
[27] Z. Schlader, S. Stannard, T. Mundel, Human thermoregulatory behavior during rest and exercise. A prospective review, Physiol. Behav. 99 (3) (2010) 269–275.
[28] A. Flouris, Z. Schlader, Human behavioral thermoregulation during exercise in the heat, Med. Sci. Sports 25 (S1) (2015) 52–64.
[29] R.R. Gonzalez, Exercise physiology and sensory responses, Stud. Environ. Sci. 10 (1981) 123–144.
[30] A. Ugursal, C. Culp, Gender difference of thermal comfort perception under transient environmental and metabolic conditions, Build. Eng. 119 (2) (2013) 52–62.
[31] M.A. Humphreys, J.F. Nicol, The validity of ISO-PMV for predicting comfort votes

in every-day thermal environments, Energy Build. 34 (6) (2002) 667–684.
[32] F. Alfano, B. Palella, G. Riccio, The role of measurement accuracy on the thermal environment assessment by means of PMV index, Build. Environ. 4 (7) (2001) 1361–1369.
[33] C. Ekici, Measurement uncertainty budget of the PMV thermal comfort equation, Int. J. Thermophys. 37 (2016) 48.
[34] C. Yang, T. Yin, M. Fu, Study on the allowable fluctuation ranges of human metabolic rate and thermal environment parameters under the condition of thermal comfort, Build. Environ. 103 (2016) 155–164.
[35] ISO. EN ISO 8996, Ergonomics of the Thermal Environment — Determination of Metabolic Rate, International organization for Standardization, Geneva, 2004.
[36] ASHRAE, Handbook Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2013.
[37] R. de Dear, Global database of thermal comfort field experiments, Build. Eng. 104 (1998) 1141–1152.
[38] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build. 34 (6) (2002) 563–572.
[39] R. de Dear, V. Foldvary, H. Zhang, E. Arens, M. Luo, T. Parkinson, X. Du, W. Zhang, C. Chun, S. Liu, Comfort is in the mind of the beholder: a review of progress in adaptive thermal comfort research over the past two decades, The Fifth International Conference on Human-Environment System. Nagoya, Japan, 2016.
[40] P.O. Fanger, J. Toftum, Extension of the PMV model to non-air-conditioned buildings in warm climates, Energy Build. 34 (6) (2002) 533–536.
[41] J. van Hoof, Forty years of Fanger's model of thermal comfort for all? Indoor Air 18 (2008) 182–201.
[42] L. Chamra, W. Steele, K. Huynh, The uncertainty associated with thermal comfort, Build. Eng. 109 (2) (2003) 356–365.
[43] G. Havenith, I. Holmer, K. Parsons, Personal factors in thermal comfort assessment: clothing properties and metabolic heat production, Energy Build. 34 (6) (2002) 581–591.
[44] E. Broday, A. Xavier, R. Oliveira, Comparative analysis of methods for determining the metabolic rate in order to provide a balance between man and the environment, Int. J. Ind. Ergon. 44 (4) (2014) 570–580.
[45] S. Gilani, M. Khan, M. Ali, Revisiting Fanger's thermal comfort model using mean blood pressure as a bio-marker: an experimental investigation, Appl. Therm. Eng. 109 (Part A) (2016) 35–43.
[46] J. Choi, V. Loftness, D. Lee, Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models, Build. Environ. 50 (2012) 165–175.
[47] G. Revel, M. Arnesano, F. Pietroni, Integration of Real-Time metabolic rate measurement in a Low-Cost tool for the thermal comfort monitoring in all environments, Ambient Assisted Living (2015) 101–110.
[48] M. Hasan, F. Alsaleem, M. Rafaie, Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation, Build. Environ. 110 (2016) 173–183.
[49] A. Hills, N. Mokhtar, N. Byrne, Assessment of physical activity and energy expenditure: an overview of objective measures, Frontiers in Nutrition 1 (2014) 5.
[50] C.G. Douglas, A method for determining the total respiratory exchange in man, Proc. Aust. Physiol. Pharmacol. Soc. 42 (1911) 17–22.
[51] R.J. Shephard, A critic examination of the Douglas Bag technique, J. Physiol. 127 (3) (1955) 515–524.
[52] C. Yang, Y. Hsu, A review of accelerometry-based wearable motion detectors for physical activity monitoring, Sensors 10 (8) (2010) 7772–7788.
[53] S. Mukhopadhyay, Wearable sensors for human activity monitoring: a review, IEEE Sensor. J. 15 (3) (2015) 1321–1330.
[54] M. Wallen, S. Gomersall, S. Keating, U. Wisloff, J. Coombes, Accuracy of heart rate watches: implications for weight management, PLoS One 11 (5) (2016) e0154420, , http://dx.doi.org/10.1371/journal pone.0154420.
[55] Dale A. Schoeller, Recent advance from application of doubly labelled water to measurement of Human energy expenditure, Nutrition 129 (10) (1999) 1756–1768.
[56] P.J. Butler, J.A. Green, I.L. Boyd, J.R. Speakman, Measuring metabolic rate in the field: the pros and cons of the doubly labelled water and heart rate methods, 18 (2) (2004) 168–183.
[57] E. Ravussin, S. Liiiioja, T. Anderson, L. Christin, C. Bogardus, Determinants of 24 hour energy expenditure in man. Methods and results using a respiratory chamber, J. Clin. Invest. 78 (6) (1986) 1568–1578.
[58] K. Wines, A. Rzepecki, A. Andrews, R. Dechert, Validation of the Vmax metabolic cart in a simulated pediatric model, J. Parenter. Enter. Nutr. 39 (3) (2015) 353–358.
[59] C. Baldari, M. Meucci, F. Bolletta, M.C. Gallotta, G.P. Emerenziani, L. Guidetti, Accuracy and reliability of COSMED K5 portable metabolic device versus simulating system, Sport Sci. Health 11 (1) (2015) 1–101.
[60] R. Duffield, B. Dawson, H.C. Pinnington, P. Wong, Accuracy and reliability of a COSMED K4b2 portable gas analysis system, J. Sci. Med. Sport 7 (1) (2004) 11–22.
[61] D.M. Rowe, Activity rates and thermal comfort of office occupants in Sydney, J. Therm. Biol. 26 (4–5) (2001) 415–418.
[62] C. Bouden, N. Ghrab, An adaptive thermal comfort model for the Tunisian context: a field study results, Energy Build. 37 (9) (2005) 52–963.
[63] F. Haldi, D. Robinson, Modelling occupants' personal characteristics for thermal comfort prediction, Int. J. Biometeorol. 55 (2011) 681–694.
[64] B. Kingma, W. van Marken Lichtenbelt, Energy consumption in buildings and female thermal demand, Nat. Clim. Change 5 (2015) 1054–1056.
[65] H. Zhang, E. Arens, Using a driving game to increase the realism of laboratory studies of automobile passenger thermal comfort, SAE Technical Paper Series 2003-01-2710.
[66] G. Havenith, Metabolic rate and clothing insulation data of children adolescents during various school activities, Ergonomics 50 (10) (2007) 1689–1701.
[67] S. Haddad, P. Osmond, S. King, Revisiting thermal comfort models in Iranian classrooms during the warm season, Build. Res. Inf. 45 (4) (2017) 457–473.
[68] M. Qi, X. Li, L. Weschler, J. Sundell, CO2 generation rate in Chinese people, Indoor Air 24 (6) (2014) 559–566.
[69] A. Persily, L. de Jonge, Carbon dioxide generation rates for building occupants, Indoor Air 27 (2017) 868–879.
[70] EPA, Exposure Factors Handbook, U.S. Environmental Protection Agency, Washington DC, 2011 EPA/600/R-09/052F.
[71] W.N. Schofield, Predicting basal metabolic rate, new standards, and review of previous work. Human Nutrition, Clin. Nutr. 39 (1) (1985) 5–41.
[72] FAO, Human Energy Requirements. Report of a Joint FAO/WHO/UNU Expert Consultation Geneva: Food and Agriculture Organization of the United Nations, Food and Nutrition Technical Report Series 1 (2001).
[73] F. Johnson, A. Mavrogianni, M. Ucci, A. Vidal-puig, J. Wardle, Could increased time spent in a thermal comfort zone contribute to population increases in obesity? Obes. Rev. 12 (2011) 543–551.
[74] P.M. Warwick, R. Busby, Influence of mild cold on 24h energy expenditure in ‘normally’ clothed adults, Br. J. Nutr. 63 (1990) 481–488.
[75] M. Luo, X. Zhou, Y. Zhu, J. Sundell, Revisiting an overlooked parameter in thermal comfort studies, the metabolic rate, Energy Build. 118 (2016) 152–159.
[76] M. Langeveld, C.Y. Tan, M.R. Soeters, S. Virtue, G.K. Ambler, L.P.E. Watson, P.R. Murgatroyd, V.K. Chatterjee, A. Vidal-Puig, Mild cold effects on hunger, food intake, satiety and skin temperature in humans, Endocrine Connect. 5 (2016) 1–9.
[77] Y. Sun, N. Zhu, Experimental research on human metabolism in hot environment, Adv. Mater. Res. 599 (2012) 241–244.
[78] T. Goto, J. Toftum, de Dear, et al., Thermal sensation and thermophysiological responses to metabolic step-change, Int. J. Biometeorol. 50 (5) (2006) 323–332.
[79] P. Tikuisis, M. Ducharme, The effect of postural changes on body temperatures and heat balance, Eur. J. Appl. Physiol. Occup. Physiol. 72 (5–6) (1996) 451–459.
[80] G.P. Kenny, S.R. Notley, D. Gagnon, Direct calorimetry: a brief historical review of its use in the study of human metabolism and thermoregulation, Eur. J. Appl. Physiol. 117 (9) (2017) 1765–1785.
[81] Y. Nishi, Measurement of thermal balance in man, in: K. Cena, J.A. Clark (Eds.), Bioengineering, Thermal Physiology and Comfort, Elsevier, New York, 1981, pp. 29–39.
[82] D. Dubois, E. Dubois, A formula to estimate approximate surface area, if height and weight are known, Arch. Intern. Med. 17 (1916) 863–871.
[83] J. Lighton, Limitations and requirements for measuring metabolic rates: a mini review, Eur. J. Clin. Nutr. 71 (2017) 301–305.
[84] N. Ghaddar, K. Ghali, S. Chehaitly, Assessing thermal comfort of active people in transitional spaces in presence of air movement, Energy Build. 43 (10) (2011) 2832–2842.
[85] Y. Zhun, J. Li, B. Yang, T. Olofsson, G. Zhang, Temporarily occupied space with metabolic rate initiated thermal overshoots – a case study in railway stations in transition seasons, Build. Environ. 122 (2017) 184–193.
[86] Y. Zhai, E. Arens, K. Elsworth, H. Zhang, Selecting air speeds for cooling at sedentary and non-sedentary office activity levels, Build. Environ. 122 (2017) 247–257.
[87] Y. Zhai, C. Elsworth, E. Arens, H. Zhang, Using air movement for comfort during moderate exercise, Build. Environ. 94 (1) (2015) 344–352.
[88] K. Tsuzuki, Y. Tochihara, T. Ohnaka, Y. Nagai, The effects of wind and thermal radiation on thermal responses during rest and exercise in a cold environment, J. Therm. Biol. 18 (5–6) (1993) 633–637.