Dynamics of metabolic rate in male individuals due to the meal and regular office activities

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Abstract. Metabolic rate is one of the main parameters affecting the thermal balance of the human body and perception of thermal comfort. Typically, we consider a constant value for a specific type of activity (sitting quiet, standing, etc.) despite the time of the day and body built of a person. In this study, we challenged this by undertaking minutely metabolic rate measurements of 3 men in a realistic office layout at 23-27°C operative temperature. The type of activity (sitting and standing quiet work) and their timing were standardized, and the meal ingested (breakfast and lunch) by the participants was also the same. We also measured temporal changes in the heart rate and skin temperature to understand the variation of physiological parameters. A whole day session was split into four 1.5-hour-long sessions, two in the morning (08:30-12:00) and two in the afternoon (13:00-16:30). Thermal comfort between sessions varied within ±1 per ASHRAE seven-point thermal sensation scale, based on the surveys. The metabolic rate varied throughout the day, even for the same activity type, with an apparent effect of the activity performed upon arrival in the morning (e.g., commute to the office) and the thermic effect of food. After a standardized normal-protein lunch, the metabolic rate was about 15% higher for the same activity for all three men. The effect of the prior physical activity on the metabolic rate was smaller than the meal effect. These results revealed that people's metabolic rate is dynamic, and it can be elevated not only because of physical activity but also by diet-induced thermogenesis. All in all, this work is intended to draw attention to the metabolic rate variation in daily life that has been overlooked so far in the field of ergonomics of the indoor environment and to outline possible future perspectives for smart buildings if personalized metabolism could be known.

Keywords: metabolic rate, energy expenditure, indirect calorimetry, thermal comfort, dynamic environment
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1. Introduction

It is well known that thermal comfort is defined as "*conditions of mind that express satisfaction with the thermal environment and is assessed by subjective evaluation*" [1]. The satisfaction comes mainly from the thermal balance of the body with the surrounding environment when there is no thermal discomfort that could disturb a person's mind. Predicted Mean Vote/ Predicted Percentage Dissatisfied (PMV/PPD) method typically used to predict thermal sensation considers the energy balance of the person where the metabolic rate (i.e., heat production or energy expenditure), is one of the main parameters driving this balance. Metabolic rate is measured in *met* which is energy expenditure divided by the overall body skin surface area *W/m²* (1 *met* = 58.2 W/m²). International standard ISO 8996:2004 [2] provides different methods (referred to as levels) of determining the metabolic heat production of humans. **Level 1** called "*screening*" is the simplest one, and it provides a classification of metabolic rate values per occupation (method 1A) or per kind of activity (method 1B). **Level 2** is "*observational*"; time-weighted average metabolic rates based on the noted transient activity types are calculated using the classification determined in level 1. Metabolic rate is determined indirectly from heart rate recording in **Level 3** called "*analysis*". Finally, "*expertise*" **Level 4** outlines 3 methods for measuring metabolic rate in humans directly: (4A) based on the oxygen consumption measurements (indirect calorimetry), (4B) using doubly labelled water (applicable for 1-2 weeks of measurements), (4C) direct calorimetry. Level 4 methods are the most precise but the most complex ones, while level 1 is the least accurate but the simplest one to use in practice. Therefore, practitioners and many researchers in the comfort field use *met* values prescribed for various activities in standards ASHRAE 55:2020 [1] and ISO 7730-2006 [3], as listed in **Tab. 1**.

Tab. 1 – Standardized metabolic rates of different activities (*met* values in parenthesis are calculated more precisely by considering 1 *met* = 58.2 W/m^2).

Activity type	*met*	W/m^2
ISO 7730-2006:		
Reclining	0.8 (0.79)	45
Seated, relaxed	1.0 (1.00)	58
Sedentary activity (office, dwelling, school, laboratory)	1.2 (1.20)	70
Standing, light activity (shopping, laboratory, light industry)	1.6 (1.60)	93
ASHRAE 55-2020:		
Reclining	0.8 (0.77)	45
Seated, quiet	1.0 (1.03)	60
Reading, seated	1.0 (0.95)	55
Typing	1.1 (1.12)	65
Filing, seated	1.2 (1.2)	70
Filing, standing	1.4 (1.37)	80

The standardized values in **Tab. 1** are based on the work by Durin & Passmore (1967) [4], and they were not challenged for nearly 50 years. Recently, Zhai et al. (2018) [5] and Yang et al. (2021) [6] re-evaluated *met* values of typical office activities using indirect calorimetry (level 4A per ISO 886:2004). Measurements on 30 males and 30 females for different office activities at 26°C from Zhai et al. (2018) and sedentary 20 females and 20 males exposed to 14-32°C from Yang et al. (2021) demonstrated that standard *met* values at neutrality did not match with measurements, and metabolic rate was affected by ambient temperature. Although the works fundamentally questioned the *met* values used to design the indoor environment and predict the thermal sensation of occupants, the research methodology did not consider metabolic rate variance potentially due to the time of the day and the meal effect (the meal intake of participants was not standardized).

Generally, the metabolism of humans is comprised of 3 main components (i) resting metabolic rate, (ii) thermic effect of food, (iii) activity-induced thermogenesis [7]. With the current advancements in dynamic HVAC controls and personalized sensing, understanding the dynamics of metabolic rate is an important step forward toward personalized and occupant-centric buildings. While resting metabolic rate largely depends on the relatively constant fat-free mass of individuals [8], time-scale is important for the post-prandial (after-meal) thermogenesis as it is a transient phenomenon, and residuals of metabolism from the previous meal intake superimpose any further activities [9]. Since our understanding of the metabolic rate variation during daily activities is still limited, this work demonstrates *met* values variation that can be observed in 3 males during a full-day experiment imitating typical office routines. To this aim, indirect calorimetry was used for continuous measurements of metabolic rate in recruited participants during sedentary and standing work. The meal was standardized to observe comparable post-prandial effects across participants. In addition, measured metabolic rates of individuals are compared to standard approaches to determining *met* values; thus, demonstrating potential discrepancies when standard methods are used.

2. Methodology

The study was conducted in February 2021, and it was approved by the Cantonal Commission for the Ethics of Research on Human Beings (Switzerland). Hereafter, details of participants, experimental procedures, sensing approach, and surveying are provided.

2.1 Participants

We originally planned to conduct experiments with 3 males and 3 females; thus, 6 participants were recruited. However, the experiments with 2/3 females failed, and only the results for males are provided in this paper. Anthropological characteristics and basal metabolic rate (BMR) of male participants are listed in **Tab. 2**. The body composition analyzer InBody 720 was used for weight, fat-free mass (FFM), and BMR measurements. BMR measured in *kcal* converted to *W/m^2* and *met* is also provided in Tab. 2. Two participants S2-S3 were nearly identical in terms of BMI, FFM, and BMR, while S1 was slightly heavier. Nevertheless, the FFM percentage was quite similar in all of them (76-81%). The body surface area (BSA) was determined using the DuBois formulation [10]. Typically, the average BSA of an adult is considered 1.7 m^2 (1.9 m^2 for adult males). In our sample size, the BSA of S2 was close to the average one, the BSA of S3 was close to the average for males, and S1 was off the average values.

Tab. 2 – Anthropological characteristics of participants

Parameter	S1	S2	S3
Age (y. o.)	36	29	29
Height (cm)	178	166	175
Weight (kg)	85.6	67.5	73.1
FFM (%)	76.8	81.9	76.7
BMI (kg/m^2)	26.8	24.5	23.9
BSA (m^2)	2.02	1.73	1.86
BMR (kcal/day)	1790.5	1564.0	1582.3
BMR (W/m^2)	42.9	43.8	41.2
BMR (met)	0.73	0.75	0.71

2.2 Overview of the experimental design

The experimental protocol had objectives to determine the day-long dynamics of metabolic rate variation of individuals during typical office activities such as sitting and standing work. Each participant performed a specific sequence of office activities, as listed in the experimental timeline in **Fig. 1,** from 8:30 till 16:30. There were four 1.5- hour sessions in total (2 in the morning and 2 in the afternoon), each session had alternating sitting and standing work, 30 min each. An electric height adjustable desk was used in the study for an easy switch between sitting and standing positions. Participants were allowed to do the work of their choice (2/3 of participants were working on their laptop, while 1 participant was reading and taking notes occasionally). There was a 30-min long morning (10:00-10:30) and afternoon (14:30-15:00) break when a person could have some refreshments of their choice (water, tea, and coffee), the amount of liquid intake was not limited. During the lunch break, a standardized lunch meal was provided. Participants were free to go out of the research facility during the breaks.

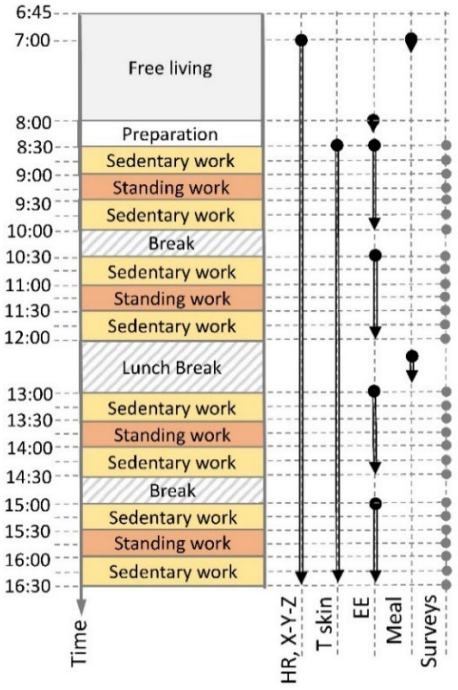

Fig. 1 – Experimental timeline with an indication of activities and measurements.

A day before the experiment, every participant was instructed to avoid any strenuous physical activity, alcohol, and any medication. It was advised to consume a regular-sized evening meal no later than 19:30 and to go to sleep no later than 23:30. On the day of the experiments, subjects were asked to wake up no later than 6:45. Upon arousal, they needed to put on a heart rate monitor and an accelerometer (abbreviated as X-Y-Z in Fig. 1) provided in advance. Participants were instructed to consume at 7:00 a standardized breakfast meal with a glass of water. Subjects were asked to arrive at the research facility by 8:00 on foot or by car/bus. Right upon arrival at the research facility, a participant put on a silicon face mask for metabolic measurements for a few minutes (this session is hereafter called "pre-session"). During this time, a participant completed a short arrival questionnaire. Afterward, a subject was asked to change into the standardized clothing of 0.8 clo (a cotton T-shirt, thick ankle socks, a cotton sweater, cotton jeans, and sneakers were provided, a contribution of the mesh chair was also included). Finally, skin temperature sensors were placed using medical tape at selected locations. After the preparations, a participant was guided inside the experimental office room a couple of minutes prior to 8:30. Once a participant was comfortably seated at the office desk, metabolic rate measurements were restarted. During each experimental session, the participant was alone in the room.

2.3 Sensing overview

Two groups of sensors were used in the study – *wearable sensors* to measure physiological parameters and *environmental sensors* to monitor the environment around participants.

Wearables: Real metabolic rate of each participant was determined using the indirect calorimeter COSMED Quark CPET by sampling oxygen consumption and carbon dioxide production of the person (accuracy of gas sampling ± 3%) and applying Wier's formulation [11]. The frequency of gases sampling was 5 s. Local skin temperature (T_{skin}) was measured using rugged iButton® temperature loggers DS1922L (accuracy ± 0.2°C, calibrated in-house); the temperature at each site was measured every 10 s. We used a 14-point scheme per ISO 9886:2004 [12] to determine the mean skin temperature ($T_{skin,mean}$) variation. The temperature difference between the right chest and the right fingertip ($\Delta T_{chest\text{-}fingertip}$) was used to determine the magnitude of vasomotion and potential deviation of the participant's thermal state from neutrality. Heart rate (HR) was measured by using the wireless ECG recorder Camntech Actiheart 5 every 30 sec.

Environmental sensing: To characterize the thermal environment surrounding the person, operative temperature T_{op} (accuracy ± 0.5 °C) was measured at 12 positions in the vicinity of the participant using two vertical stands. Four sets of sensors at heights of 0.1, 0.6, 1.1, 1.7 m, as suggested by the ISO 7726:1998 [13], were placed on each stand. Each set had a shielded dry-bulb temperature sensor PT100, a globe temperature sensor (a grey ball 38 mm with the PT100 inside), and an omnidirectional anemometer (Sensor Electronic) connected to H HOBO UX120-006M (Onset) data logger. The frequency of measurements was 1 s. The placement of comfort stands is illustrated in **Fig. 2**. Relative humidity was measured in the center of the room using a HOBO U12-012 (Onset). The mean operative temperature (averaged over 12 locations) is used to illustrate the dynamics of the thermal environment during the experiments.

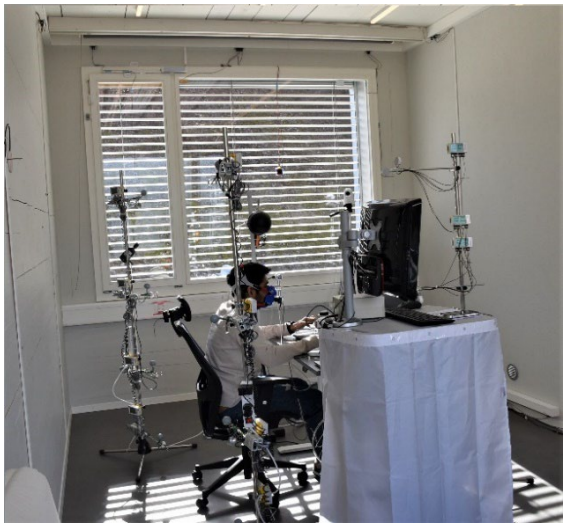

Fig. 2 – Photo of the experimental setup and placement of comfort stands (S window with direct solar exposure, the office desk behind the calorimeter stand)

2.4 Experimental facility and temperature regulation

An experimental office room of 20 m^3 (3 x 6.3 m^2 floor area) was used for mock-up office activities. It had two large windows (N and S oriented). To avoid direct sunlight on participants from the S window, external shades were lowered, and the slats were half-open, as seen in **Fig. 2**. Radiant ceiling panels were used to maintain the temperature setpoint in the room, while fresh air (1.15 ACH) was supplied already pre-conditioned. The initial intention was to keep the operative temperature in the room relatively neutral (around 24^oC). Due to the dynamic variation of solar radiation and significant internal heat gains from the experimental equipment, indoor temperature tended to drift towards higher values (up to 27^oC in some cases) during morning sessions. To avoid significant heating indoors, the side section of the N window was slightly opened after the temperature drift was noted. In terms of airspeed in the room, it was below 0.2 m/s in the vicinity of the participant during all experimental sessions; therefore, there was no risk of the draft.

2.5 Surveys

Thermal comfort votes (TCV) and thermal sensation votes (TSV) were surveyed every 15 min starting 8:30 until 16:30 (**Fig. 1**). There were 7 discrete response options for both questions:

- TSV: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), hot (+3)
- TCV: very uncomfortable (-3), uncomfortable (-2), slightly uncomfortable (-1), neutral (0), slightly comfortable (3), comfortable (+2), very comfortable (+3).

2.6 Standardized meal

Two standardized normal-protein meals were provided to participants. The *breakfast* consisted of 2 slices of toast (121 kcal) with butter (108 kcal) and jam (49 kcal), and a 200 ml of protein drink (250 kcal). The total energy value was 528 kcal. The *lunch* meal included 1 serving of pasta Bolognese (589 kcal), a pack of whole-grain crackers (172 kcal), and a bottle of orange juice (123 kcal). The total amount of calories was 884 kcal.

2.7 Methods for metabolic rate comparison

The primary method of determining the metabolic rate of people in this study is based on indirect calorimetry. This method is classified as "level 4A, *expertise*" per ISO 8996:2004. For the comparison of the metabolic rate with other simplified methods, we denote as M1 actual metabolic rate measurements converted to W/m^2 (further converted to units of *met*) using the actual BSA of each participant. Four more additional metabolic rate options (M1-M4, M0) were defined. As M2 and M3, we denote metabolic rates calculated based on indirect calorimetry measurements, but with the BSA of an average adult (1.7 m^2) and an average adult male (1.9 m^2), respectively. As M4, we used the "level 3, analysis" approach based on HR measurements which are supposed to be more precise compared to the classification of the metabolic rate based on the activity type. At last, "level 1, *screening*" was considered, denoted as M0, where sedentary work was considered as 1.2 *met* and standing work was considered as 1.4 *met*.

3. Results

First of all, we present the dynamics of parameters from the experiments. This includes metabolic rate and T_{op}, HR, $T_{skin,mean}$, $\Delta T_{chest\text{-}fingertip,}$ and TSV & TCV responses. A comparison of metabolic rates determined per different methods is provided afterward.

3.1 Dynamics of experimental data

Experimental results are presented in **Fig. 3.** Seven parameters are plotted as a function of time from 7:30 till 17:00. Four experimental sessions and pre-session (8:00-8:30) are highlighted using different color schemes. Three intervals of different activities types within each session and the break time are also marked. To understand what could be the metabolic rate of individuals upon their arrival to the office, as described in section 2.2, metabolic rate was briefly measured during the pre-session. It was measured for 3 min for a participant S2 (8:00-8:03) and for 8 minutes for participants S1 and S3 (8:00-8:08). The duration of measurements was not standardized; thus, it was not homogenized between participants (the duration was determined ad-hoc). Continuous measurements of T_{op}, HR, $T_{skin,mean}$, and $\Delta T_{chest\text{-}fingertip}$ are also shown during the pre-session and breaks to explain some variation in metabolic rate right afterward.

Metabolic rate: Measured 5-sec data points are interpolated using the 3^d degree of the polynomial

shown as bold lines in **Fig. 3**. It is obvious that the metabolic rate is elevated upon arrival. In participants S1-S2 (all sessions) and S3 (only sessions 1 and 4), we can observe the tendency of the metabolic rate to drop during sedentary work and to increase during standing work. The degree of the drop and increase depends on the time of the day and on the activity prior to the session. During the 1st sitting activity of almost every session, metabolism is elevated, and it gradually drops towards the end of the 30-min session. Once the participant stands up, the metabolic rate increases reaching its peak in the middle of the 30-min long activity. During the sitting work after the standing one, the metabolic rate reaches the minimum of the session. The trends are the most pronounced during morning session 1, which can be explained by the elevated metabolic rate of participants upon arrival to the facility on foot. The metabolic rate during the morning session 2 is lower compared to the 1st one, perhaps, due to the reduced activity in-between and faded thermic effect of food past 3.3 hours after the breakfast intake. An increase in the metabolic rate during the 3d session (after lunch) is due to the combination of the increased activity prior to the session (all participants went outside the facility during the lunch break) and the thermic effect of the lunch meal. We observe similar dynamics during the last session as in the 2nd session but at higher metabolic rate values. Elevated metabolic rate in the afternoon compared to the morning session is due to the thermic effect of a larger meal compared to the breakfast meal. The spikes in raw *met* values within the sessions are due to the participants changing their posture from sitting to standing and from standing to sitting.

Heart rate: HR variation during experimental sessions is similar to metabolic rate dynamics. It is increased during standing work, and it is decreased during sitting work. HR is slightly lower during the 2nd session compared with the 4th one in participants S1 and S3, while it is obviously higher in participant S2. Relatively constant HR between sessions 2-3 in participant S3 can be explained by reduced physical activity at lunch break. The participant went outside the facility at the beginning of the break, but came back shortly and was working seated on his laptop from 12:30-13:00. Generally, three participants spent their lunch break differently (S1 was relatively active during the entire break, S2 was walking around during the 2nd half of the break, S3 walked only at the beginning of the break), and this influenced their metabolism right after lunch. For example, there was no increase in metabolic rate in participant S3 during the 3d session which can be due to the reduced lunch break activity and individual metabolic response to the meal. These HR

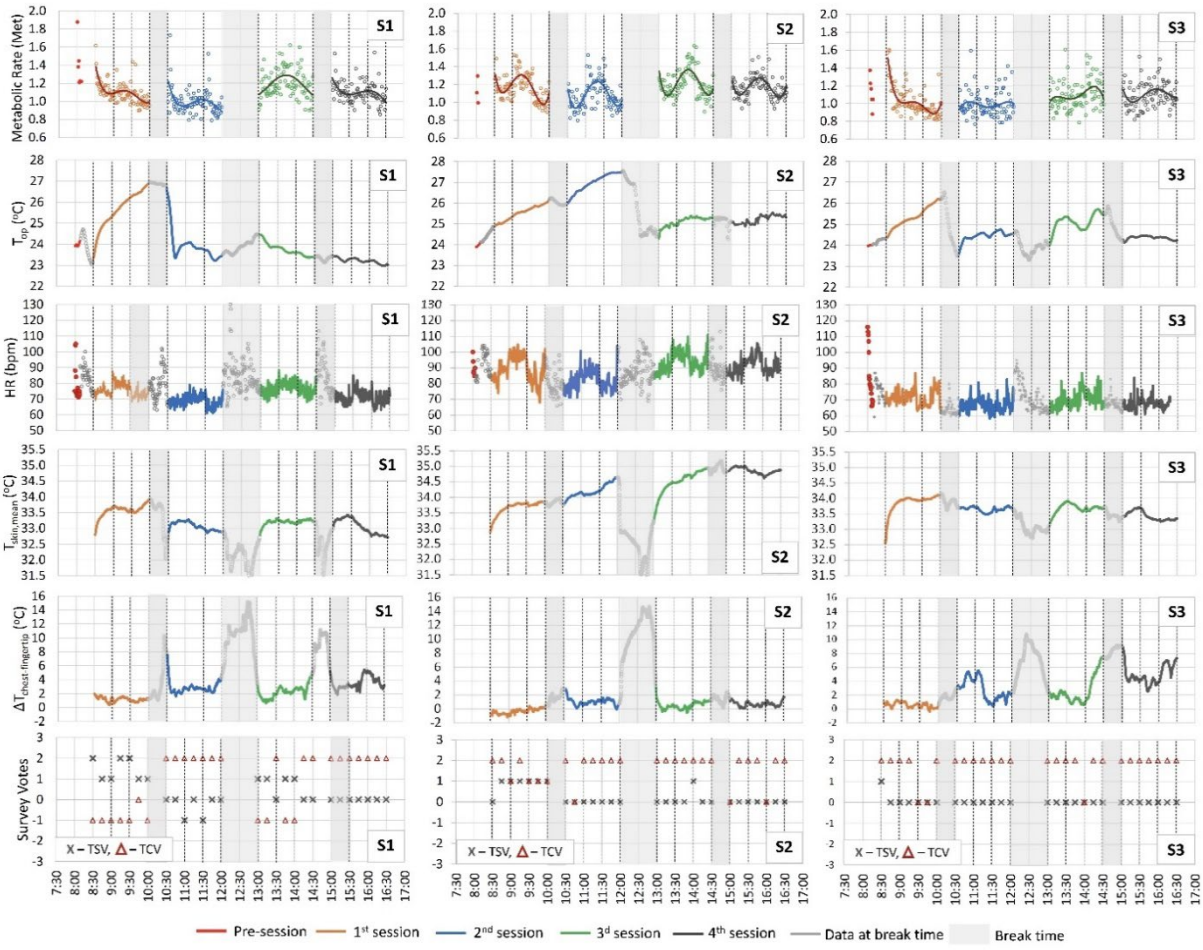

Fig. 3 - Dynamics of metabolic rate, indoor operative temperature, heart rate, mean skin temperature, chest-fingertip temperature difference, and comfort/sensation votes during experiments with 3 participants S1-S3

measurements are used further to determine the metabolic rate per "level 2, analysis". The minimum heart rate at rest required for calculations is taken as the minimum value observed in the experiments

Thermal environment: Mean operative temperature T_{op} variation inside the experimental room shown in Fig. 3 indicates that the temperature climbed up in the mornings (in session 1 of participants S1 and S3, and sessions 1-2 of participant S2). As described in section 2.4, there was little control of the temperature during the direct sunlight exposure on the S-oriented window in the mornings. There was better control of the temperature in the afternoons, the thermal environment was relatively stable in all 3 experiments. Of course, a substantial temperature increase in the mornings could have an effect on metabolic rate due to the triggered thermoregulatory adjustments when the body is beyond neutrality. However, this contribution might be small compared to the physical activity effect and thermic effect of food, as we see from metabolic rate dynamics.

Skin temperature and thermal comfort: $T_{skin,mean}$ and $\Delta T_{chest\text{-}fingertip}$ can be objective indicators of the thermal state of the person. Thus, they are plotted in **Fig. 2** together with the survey votes on TCV and TSV. Mean skin temperature $T_{skin,mean}$ plotted in Fig. 2 shows that it follows a variation of the mean operative temperature T_{op} in participants S1 and S3. It is elevated during the 1st session, and relatively stable during the following sessions 2-4 ($T_{skin,mean}$ of S1 was 0.5°C lower than S3). Although participant S1 felt slightly warm and slightly uncomfortable during the 1st session in the morning, there was a negligible difference between his right chest and right fingertip skin temperature $\Delta T_{chest\text{-}fingertip}$. The same was observed in S3 that, oppositely to S1, felt comfortable and neutral during all 4 sessions. $\Delta T_{chest\text{-}fingertip}$ increased up to 4-6°C in the later afternoon in both participants. In participant S2, $T_{skin,mean}$ had a tendency to increase towards the end of the day, a similar pattern can be observed in his HR measurements, despite the stable mean operative temperature of 25-25.5°C in the afternoon. His $T_{skin,mean}$ reached 35°C in the afternoon, the highest value among all 3 participants. Interestingly, there was a negligible difference between the right chest and right fingertip temperature $\Delta T_{chest\text{-}fingertip}$ for S2 in all 4 sessions. TCV and TSV-related responses also indicate that the person was feeling neutral, and the temperature was found to be comfortable in sessions 2-4, while there was a slight warm discomfort during the morning session 1.

3.2 Met comparison with standard methods

Effect of individuals' BSA: The measured metabolic rate indicates that it varies dynamically, and averaging it over a prolonged time interval (for instance, 30 min) will not appropriately show this. Therefore, for the comparison of metabolic rates determined per different methods M1-M3, the data was averaged over 10-min intervals. The averaged values are compared with the standard values of 1.2 *met* for sedentary work, and 1.4 *met* for standing work (M0 method). The percentage of met variations for 3 participants is presented in **Fig. 4**. Generally, the measured *met* values considering individuals' BSA (method M1) are lower than what we typically consider for a particular activity type. Only on a few occasions (first 10 min of session 1 for S1 and S3, and the first 10 min of the 3d part of sessions 3 and 4 or S3) were measured *met* values are slightly greater (<8%). In the rest of the cases, the measured values were lower (i) standing work: 35.5% for S1, 22.2% for S2, and 38.8% for S3, (ii) sedentary work: 24.1% for S1, 21.6% for S2, 24.2 for S3. As illustrated on the plot, the percentage of variation in met is activity-, time-, and person-specific. If we consider the average adult BSA of 1.7 m² (method M2) or specifically adult *male* BSA of 1.9 m² (method M3), the percentage of variation decreases. It actually increases for S1 per method M2 up to 22%. For participants S2-S3, *met* values per M2 are the closest to standardized values. Consideration of average adult BSA reduces the percentage variation in *met*, while consideration of average *male* BSA is not so straightforward. For instance, the metabolic rate of participant S3 does not differ much between M1 and M3 since his actual BSA (1.86m²) is close to the average male one. Overall, our analysis demonstrates that individuals' BSA needs to be considered to have more precise *met* values.

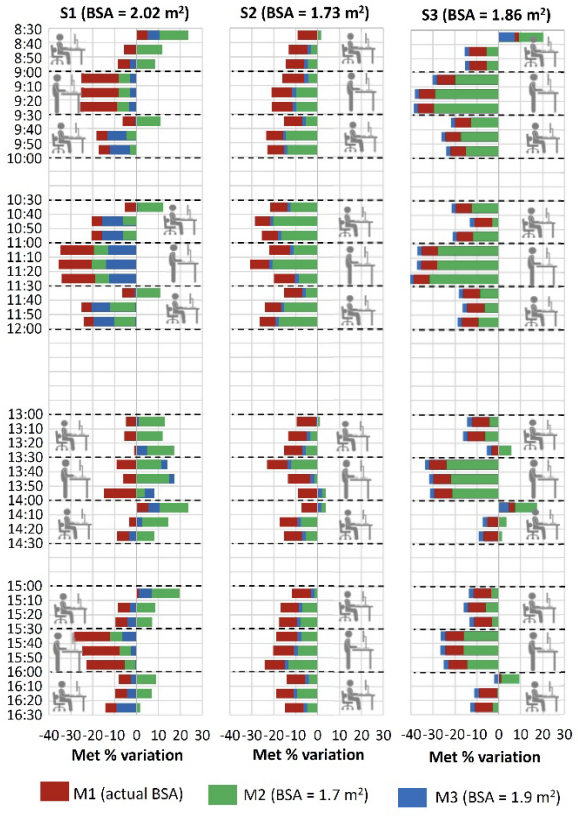

Fig. 4 – Metabolic rate percentage variation for 3 approaches of determining met rates M1-M3 compared to the M0 approach (classification of activity types)

HR-based evaluation: In method M4, we used measured HR data to evaluate *met* values. Activity-

type comparison (30-min averaged) is provided in **Tab. 3**. Generally, HR-based evaluation of *met* values is substantially higher than what was actually measured using an indirect calorimeter. Although the expected accuracy is supposed to be ±10% per ISO 8996:2004, it is substantially lower in our experiments. In HR-based met calculations, age, weight, heart rate at rest (HR_o), and metabolic rate at rest (M_o) are considered. Since age and weight are determined precisely, small errors might be coming from (i) HR_o estimation as the minimum from our experimental measurements, (ii) M_o considered as BMR from InBody measurements (see **Tab. 2**). If actual HR_o is greater than what we considered (61 *bpm* for S1, 66 *bpm* for S2, and 58 *bpm* for S3), then *met* values increase. An increase is also expected if M_o is greater than what we've taken (42.9 *met* for S1, 43.8 *met* for S3, 41.2 *met* for S3). Therefore, the source of significant discrepancy is not on actual the subject-specific values we considered but rather on the conditions that the method could be applicable. It is noted in ISO 8996:2004, that the HR-based method should be applied for HR values in a neutral climatic environment. As discussed in section 3.1, there were moments in the mornings when the indoor temperature was high; however, this did not result in increased HR. Therefore, there was no thermal stress that could affect HR-based *met* values estimation. To further investigate the source of discrepancy, it might be necessary to go to the original source of the method described in the standards to better understand underlying assumptions that are not explicitly mentioned in the text of the standard.

Tab. 3 – Comparison of metabolic rates determined by methods M0-M4 (30-min averaged per each activity)

Participant	Method	Session 1			Session 2			Session 3			Session 4		
		8:30-9:00	9:00-9:30	9:30-10:00	10:30-11:00	11:00-11:30	11:30-12:00	13:00-13:30	13:30-14:00	14:00-14:30	15:00-15:30	15:30-16:00	16:00-16:30
	Work Type	Sitting	Standing	Sitting	Sitting	Standing	Sitting	Sitting	Standing	Sitting	Sitting	Standing	Sitting
All	M0	1.20	1.40	1.20	1.20	1.40	1.20	1.20	1.40	1.20	1.20	1.40	1.20
S1	M1	1.16	1.10	1.03	1.01	0.98	0.98	1.15	1.28	1.17	1.17	1.10	1.07
	M2	1.38	1.30	1.22	1.20	1.16	1.16	1.37	1.52	1.39	1.39	1.30	1.27
	M3	1.23	1.16	1.10	1.08	1.04	1.04	1.22	1.36	1.24	1.24	1.16	1.14
	M4	1.89	2.32	1.77	1.31	1.62	1.24	1.90	2.34	1.95	1.95	1.81	1.47
S2	M1	1.16	1.28	1.05	0.99	1.22	1.03	1.15	1.34	1.14	1.14	1.26	1.11
	M2	1.18	1.31	1.06	1.00	1.24	1.05	1.17	1.36	1.16	1.16	1.28	1.13
	M3	1.05	1.17	0.95	0.90	1.11	0.94	1.05	1.22	1.04	1.04	1.15	1.01
	M4	2.36	3.20	2.10	1.80	2.40	1.81	2.55	3.32	2.79	2.79	3.12	2.44
S3	M1	1.13	1.00	0.94	1.00	0.96	1.01	1.08	1.04	1.18	1.18	1.11	1.12
	M2	1.24	1.09	1.02	1.09	1.05	1.10	1.18	1.13	1.29	1.29	1.22	1.22
	M3	1.11	0.97	0.91	0.98	0.94	0.99	1.06	1.01	1.15	1.15	1.09	1.10
	M4	1.77	1.74	1.74	1.33	1.39	1.34	1.39	1.67	1.67	1.67	1.45	1.26

4. Discussion

Our experimental measurements of three individuals' metabolic rates confirm its transient nature that depends on the physical activities and time of meal intake. While the indoor thermal environment was not strictly controlled during the experiments, and we even had a temperature up to 27°C, participants found the environment acceptable and most of the time comfortable, except for a warm discomfort in the mornings. The same is confirmed from objective measurements of the skin temperature difference chest-fingertip that was relatively low despite the elevated indoor temperature. Per standardized requirements, typical indoor temperature setpoints are much lower than what we had during our experiments. For instance, in Switzerland, the operative temperature setting in offices in winters should be 21°C according to the national standard SIA 180:2017 [14] guided by temperature recommendations in ISO 7730:2015. To determine how much thermal sensation could be off neutrality due to the elevated indoor temperatures, we determined dynamic variation of PMV by accounting for measured environmental parameters and *met* values for each individual using the PMV/PPD model. Surprisingly, results plotted in **Fig. 5** show that most of the time PMV values were within the comfortable interval of [-0.5; +0.5]. Interestingly, the cool sensation is supposed to be expected in subjects S1 and S3 during session 2, when the metabolic rate was at the minimum. However, the sensation is near neutrality during the remaining sessions, even during morning session 1 when the indoor temperature was increasing. Overall, our study shows that: (i) dynamics of the metabolic rate and indoor thermal environment observed during the experiments are beyond what we typically consider based on standardized recommendations, (ii) the thermal state of people was near neutrality even when the indoor temperature was beyond the standard comfortable range due to the dynamics of the metabolic rate. Thus, constant values of metabolic rates that have been used so far based on the classification of activity types should be used with a great degree of caution. Dynamics of the metabolic rate should be accounted for in the design and operation of buildings and indoor climate systems to advance the transition toward a human-centric built environment.

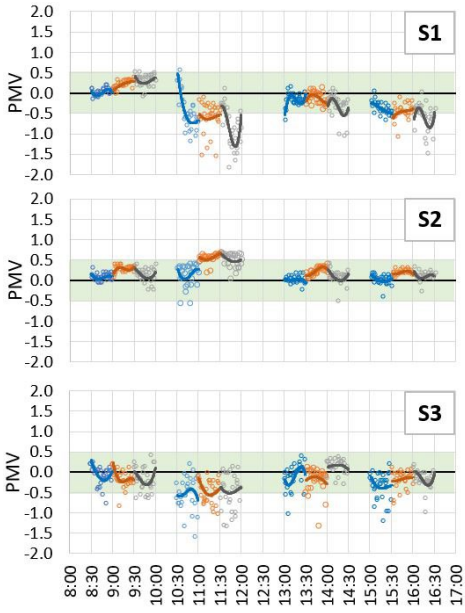

Fig. 5 – Dynamics of PMV variation using measured metabolic rates and environmental parameters

5. Conclusions

The human metabolism considerably impacts the body's thermal balance with its surrounding environment and, consequently, affects the individual's thermal sensation. The metabolic rate estimation based on the classification of activity types is less accurate compared to the measurements using indirect calorimetry that we performed in our experiments with 3 male subjects. Despite the lack of gender consideration, our results still demonstrate that the metabolism of individuals varies throughout the day, not only due to physical activities but also due to the thermic effect of food. Therefore, we could expect that metabolic rates might also vary from day to day depending on the kind of meal eaten and individual specifics of the digestion system. Dynamics of subjects' metabolism and indoor thermal environment in our experiments resulted in their neutral sensation most of the time, despite the fact that the actual metabolic rate was lower than what we typically consider, and indoor temperature was higher compared to what we typically set in office buildings. To further investigate the magnitude of metabolic rate variation in individuals, more participants should be involved to reach statistically significant results. In addition, the timing of meal intake and all activity types should be standardized for a firm comparison. Our study, even with limited participants, points out the importance of considering individuals' metabolism and its daily dynamics if we want to transition towards the design of human-centric indoor spaces. The major challenge of considering the min-by-min change in metabolic rate in practice is how to measure it non-invasively and even remotely. With the availability of low-cost wearable sensors, estimation of human metabolism is more feasible nowadays than a decade ago. However, while HR-based predictions of human metabolism are widespread, they hardly can capture the thermic effect of food. Still, it is the parameter that directly affects intra-day and inter-day variability of metabolic rate in humans. Overall, if transience the individuals' metabolism could be indirectly measured, it could be used as input to climate controls in future human-centric buildings.

6. Data statement

The datasets generated during and/or analyzed during the current study are not available because of privacy issues, but the authors will make every reasonable effort to publish them in the near future in anonymized form.

7. Acknowledgment

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