

Interindividual variability of human thermoregulation: Toward personalized ergonomics of the indoor thermal environment

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Abstract

Objective: The study was undertaken to show the magnitude of interindividual differences in energy expenditure (i.e., heat production) under normal living conditions with the aim of providing physiological evidence to support the advancement of a personalized thermal conditioning approach.

Methods: Three sets of experimental protocols with six participants were conducted at neutral and mild cold temperatures. Energy expenditure, local skin temperatures, and core body temperature were measured continuously, while cognitive performance and thermal sensation were surveyed intermittently. The protocols were designed to study the effects of several normal day activities, low-level physical activity and eating a meal, on metabolic and physiological parameters.

Results: Large interindividual differences among the subjects were demonstrated using non-normalized data by design. The resting metabolic rate difference was 58%, the percentage change in energy expenditure during standing compared to sitting was up to 31%, and the difference in mechanical work efficiency between the least and the most efficient individual was 39.1%. Energy expenditure increase due to the meal effect was 11.2% to 23.3% at neutral and 9.9% to 33.9% at mild cold temperatures across individuals.

Conclusions: Large interindividual differences in metabolic rate under typical everyday living and office activities suggest facilitating personalized thermal conditioning instead of providing uniform temperature. Therefore, it is necessary to find noninvasive markers that can be easily measured and used as surrogates for human heat production to individualize the climate control of buildings.

INTRODUCTION

People in modern societies spend the majority of their time indoors, where thermal discomfort avoidance is at the forefront of building design and operations (1,2). However, current comfort settings do not result in

ultimate occupant satisfaction since static comfort conditions were developed for an “average” occupant without considering inter- or intra-individual differences (3,4). Factors such as sex, age, body type, activity level, and menopausal effects in females have been documented as directly affecting one’s optimal comfort zone (5,6). Moreover, daily fluctuations in individuals’ metabolic rate due to feeding status, circadian rhythms, and seasonal changes have barely been considered in

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the ergonomics of the built environment (7–9). Thus, setting indoor thermal environments based on an individual's metabolism could not only increase the satisfaction rate by proper consideration of the dynamics of individual thermoneutral zones but also allow relaxation (e.g., drift beyond thermoneutrality) of the environment to improve health-related parameters of occupants, as highlighted by Pallubinsky et al., van Marken Lichtenbelt et al., and Brychta et al. (10–12), while reducing the energy required for thermal conditioning of buildings. This study was undertaken to show that interindividual differences in energy expenditure (thereby heat production) exist under normal office/living conditions and that these will need to be considered to devise better personalized temperature control systems. The experiments were specially designed to analyze metabolic parameters in people undertaking standardized activities mimicking daily low-level movement and the effects of meal ingestion.

METHODS

Controlled experiments were conducted inside a 25-m³ climatic chamber between December 2020 and March 2021 within the Laboratory of Integrated Comfort Engineering (ICE) at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. Three experimental protocols were used to quantify the energy cost of low-level typical work-related activities in six participants (men M1-M3 and women W1-W3 performed during the follicular phase of the menstrual cycle). Participants represented a set of individuals that might be found sharing the same indoor space (e.g., M1-M2 and W1-W2 were university students and M3 and W3 were spouses who could naturally share the same space). Participants wore standardized clothes (overall insulation 0.8 clo [basic measurement for the thermal resistance of clothing]: underwear, a T-shirt, a sweater, jeans, thick socks, sneakers), and all experiments started at 8:00 AM following an overnight fast. After a 30-minute phase of relaxed sitting in each protocol, participants underwent specific activities:

1. Protocol 1: Energy cost of posture maintenance (standing vs. sitting, 10 minutes each) was compared at *thermoneutrality* (average operative temperature of 24.0±0.2°C determined per the thermal comfort model using predicted mean vote/predicted percentage of dissatisfied [PMV/PPD] method in ISO 7730:2005 (1)).
2. Protocol 2: Postprandial thermogenesis following ingestion of a standardized meal (528 kcal, 17% proteins, 47% carbohydrates, 36% fat) was assessed for 135 minutes after ingestion at both thermoneutral and cold temperatures (16.2±0.2°C). The meal was not adjusted for the individual's metabolic mass to simulate typical canteen settings in which portions are the same for all.
3. Protocol 3: Metabolic rate was assessed during graded low-power 10- to 40-W cycling (5 minutes of cycling at each power output) on an ergometer at thermoneutrality.

Energy expenditure (EE) was assessed with an indirect calorimeter Cosmed Quark CPET with a silicone face mask system, and body composition was assessed by InBody 720. Body surface area was estimated using the DuBois formula (13). Skin temperature was measured using

Study Importance

What is already known?

- There are individual differences (e.g., gender and age) in thermal comfort.
- The metabolic rate of an individual undergoes daily fluctuations because of feeding status, activities, and circadian rhythms; in addition, metabolic rate varies seasonally and (in female individuals) varies owing to menopausal effects.
- Healthy adults with comparable anthropological parameters (non-responding vs. responding metabolism) have heterogeneity in metabolic rate between sitting and standing.

What does this study add?

- Using non-normalized data by design, the large inter-individual differences in metabolic rate are observed in people who might share the same indoor space.
- Under thermoneutral conditions suggested by current standards on the ergonomics of the thermal environment, people can exhibit a different degree of vasoconstriction (consequently a different thermal sensation); thus, this reinforces the need for personalization of the thermal environment.

How might these results change the direction of research or the focus of clinical practice?

- This study promotes synergistic research between applied engineering and basic human physiology to develop new approaches to improve the well-being of individuals through purposeful thermal exposure (e.g., brown adipose tissue stimulation).
- This work sets up an initial step to finding noninvasive biomarkers that can be used as surrogates for human metabolic rate and used as input into the climate control of a building, seeking to maximize potential metabolic benefits for occupants.

contact temperature sensors iButton (accuracy ±0.2°C) at 24 locations as in Zhang et al. (14), including chest and fingertip, to obtain the gradient between central and peripheral body parts. In addition, core body temperature was measured using e-Celsius Performance pills (BodyCap; accuracy ±0.1°C). Although skin and core body temperatures were measured, we focus on presenting EE data because EE varies depending on the magnitude of heat losses from the human body, thus reflecting the changes in core body and skin temperatures. Thermal comfort, sensation, acceptability, and local discomfort were surveyed after each activity in Protocol 1 and every 30 minutes in Protocol 2. In Protocol 2, the change in cognitive performance was evaluated every 30 minutes using Cambridge Brain Sciences tests for short-term memory, alertness, attention, and deductive reasoning. The environment surrounding participants was monitored using two comfort stands with

TABLE 1 Overview of participants and experimental results

Parameter		W1	W2	W3	M1	M2	M3
<i>Personal and anthropological data</i>							
Gender		F	F	F	M	M	M
Age (y)		27	23	37	29	29	36
Height (m)		1.69	1.59	1.64	1.66	1.75	1.78
Weight (kg)		50.2	50.8	62	67.5	73.1	85.6
Body fat (%)		24.7	20.4	31.3	18.1	23.3	23.1
FFM (kg)		37.8	40.4	42.6	55.3	56.1	65.8
BMI (kg/m ²)		17.6	20.1	23.1	24.6	23.9	26.8
A _{surface} (m ²)		1.54	1.48	1.65	1.73	1.86	2.02
<i>Protocol 1: Posture maintenance (standing vs. sitting comparison)</i>							
EE (kcal/min±SD)	Sitting (repeated)	0.965 ± 0.037	0.849 ± 0.071	0.870 ± 0.008	1.074 ± 0.095	1.107 ± 0.069	1.349 ± 0.047
	Sitting	0.937	0.786	0.857	1.142	1.11	1.327
	Standing	1.041	0.841	0.858	1.455	1.146	1.619
Change in chest to fingertip T _{skin} (%)	Sitting	19.7	0.1	16.6	-2.2	-1.2	-0.3
	Standing	25.9	3.6	21.4	-2.6	10.4	0.6
<i>Protocol 2: TEF</i>							
RMR (kcal/min±SD)	At 24.0°C	0.932	0.903	0.843	1.112	1.002	1.335
	At 16.2°C	0.951	0.863	0.705	1.292	1.058	1.408
	% Change ^a	2.0	-4.4	-16.3	16.3	5.6	5.5
TEF (total kcal)	At 24.0°C	37.53	36.56	14.77	20.32	33.24	40.26
	At 16.0°C	14.19	14.03	48.77	57.33	33.08	52.63
<i>Protocol 3: Graded low-power cycling</i>							
EE (kcal/min)	10 W	1.904	2.072	1.575	2.596	2.067	2.055
	20 W	2.356	2.439	1.836	3.085	2.402	2.413
	30 W	2.887	2.865	2.302	3.670	2.929	2.896
	40 W	3.289	3.246	2.637	4.094	3.228	3.165
Work efficiency	Slope	0.469	0.395	0.365	0.508	0.401	0.381
Linear regression	R ²	0.995	0.998	0.986	0.991	0.993	0.999

Abbreviations: A_{surface}, body surface area; EE, energy expenditure; FFM, fat-free mass; M1-M3, men 1-3; RMR, resting metabolic rate; TEF, thermic effect of food; W1-W3, women 1-3.

^aChange in RMR at 16.2°C compared with the baseline at 24.0°C.

air temperature, globe temperature, air speed, and humidity sensors at standardized heights of 0.1, 0.6, 1.1, and 1.7 m. Data from the sensors were used to calculate the operative temperature that is used in the ergonomics of the indoor environment to characterize both convective and radiative thermal effects on the person. All study protocols were approved by the Cantonal Commission for the Ethics of Research on Human Beings (project 2020-02534).

RESULTS

Effects of standing versus sitting on metabolic rate (Protocol 1)

Resting metabolic rate (RMR) during relaxed sitting for 15 minutes on an office chair was measured on five different days over a period of

2 months for all participants at 24.0±0.2°C. Intraindividual variations were low (RMR coefficient of variance ranged between 0.9% and 8.9%, mean 5.3%±3.1%) as expected based on previously published data (15). Large interindividual mean differences in RMR were observed among the six subjects (range 0.849±0.071 to 1.349±0.047 representing a 58% difference; Table 1). Percentage change in EE during standing compared with sitting varied between no measurable change (in W3) to an increase of 31% (Figure 1A). Variability in standing EE compared with sitting was 13% to 51% greater in four of six participants (no change in W2 and -31% in W3). Apparent heterogeneity in the metabolic rate between sitting and standing was also reported in Miles-Chan et al. (16); even healthy adults with similar anthropological parameters (24±1 years old, BMI 22±1 kg/m²) had non-responding (EE change <5%) and responding (EE change >5%) metabolism. Because our participants differed widely on multiple anthropological measurements (e.g., weight, height, sex), nonbiased

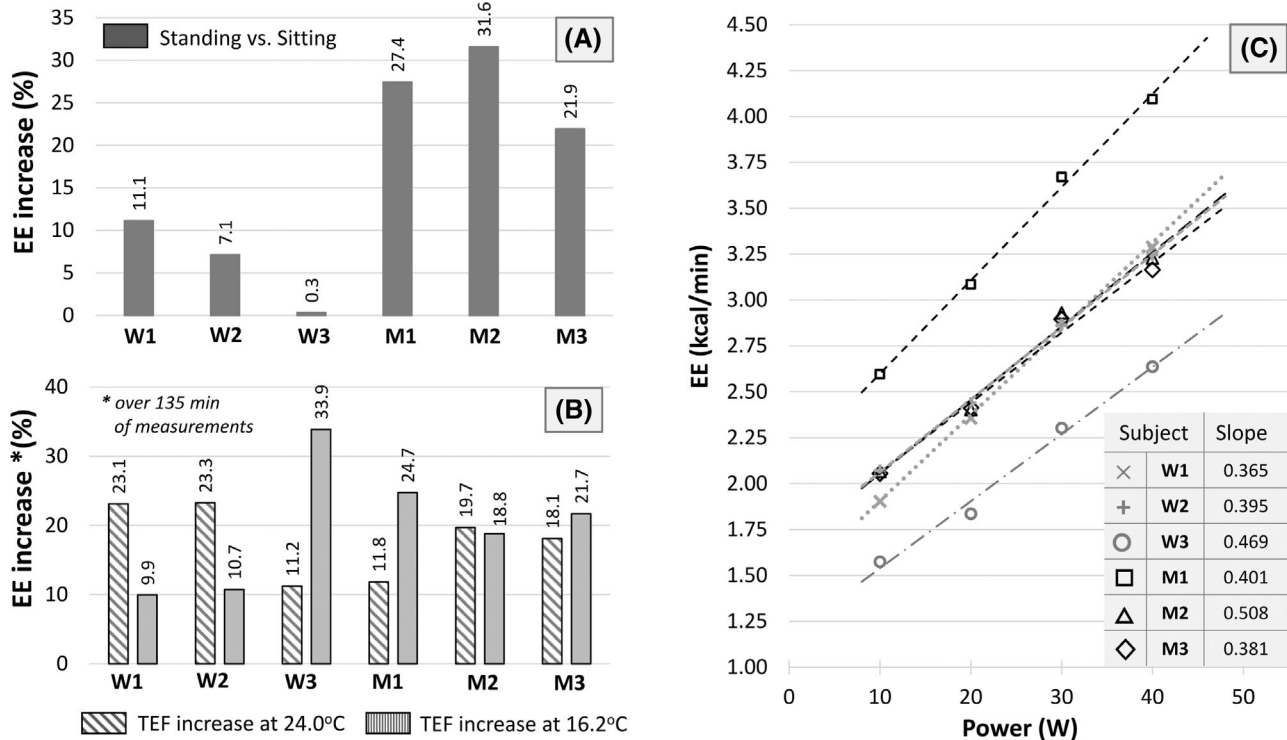


FIGURE 1 Overview of the experimental results corresponding to each human subject. (A) Increase in EE due to standing vs. sitting at 24°C (Protocol 1). (B) Increase in the TEF over 135 minutes after the meal intake at 24°C and 16°C (Protocol 2). (C) EE as a function of power output between 10 and 40 W during cycling ergometry at 24°C (Protocol 3). EE, energy expenditure; M1-M3, men 1-3; TEF, thermic effect of food; W1-W3, women 1-3

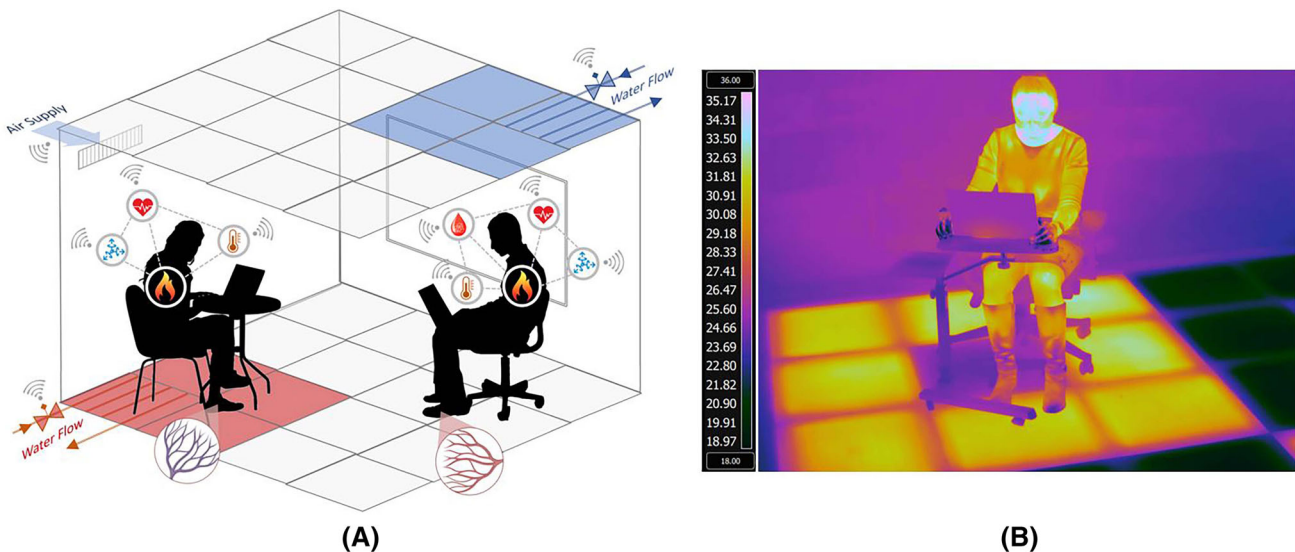


FIGURE 2 Human–building symbiosis. (A) Conceptual illustration of indirect measurements of EE using personalized biomarkers linked with the local temperature control system of a building. (B) Infrared image of the actual climatic chamber at the Laboratory of Integrated Comfort Engineering (ICE) at EPFL that can provide integration of physiological inputs with localized temperature control (e.g., heating/cooling only sections of the floor or ceiling) [Color figure can be viewed at wileyonlinelibrary.com]

estimates of vasoconstriction at the same thermal exposure were calculated by subtracting fingertip from chest skin temperatures (expressed as a percentage change), with positive percentages suggesting higher vasoconstriction (range -2.2% to $+19.7\%$ for sitting and -2.6% to $+25.9\%$ for standing as listed in Table 1).

Effects of a standardized meal on metabolic rate (Protocol 2)

Standardized meals (528 kcal) provided to participants at 8:30 AM following an overnight fast (last meal at 7:30 PM) either at 24.0°C or

16.2°C resulted in large interindividual differences in the thermic effect of food (TEF as an area under the curve above RMR for 135 minutes after ingestion is provided in Table 1; percentage change above RMR is shown in Figure 1B). Large variations in the total number of calories expended and no clear directional differences were observed when comparing thermoneutral with cold.

Different mechanical efficiencies at low-level work (Protocol 3)

Cycle ergometry was used to measure the effects of different standardized workloads on metabolic rate as a substitute for normal daily activity such as walking and taking the stairs without considering the body mass effect (Table 1; Figure 1C). During graded cycling, we observed strong linearity of EE as a function of power output, as expected (17). EE varied largely among the participants, with M1 having an average of 21.1% higher total EE across the different workloads compared with W3. The slope of the regression (i.e., mechanical work efficiency) also varied among the participants, with a range of 0.365 to 0.508 kcal/min/W representing a 39.1% difference between the most and least efficient individuals.

Change in cognitive performance due to thermal exposure

To examine how cognitive performance varies depending on thermal sensation, the relative performance was calculated per Lan et al. (18). In most individuals, short-term memory and attention were not largely affected by thermal sensation. Half of the participants were more alert and they had improved deductive reasoning when they felt “cool” (but not “cold”). We can infer that people’s subjective perception of temperature greatly affects alertness and deductive reasoning. Our results are consistent with findings in the literature (19,20) in which optimal performance in humans occurred in the range of thermal sensation “slightly cool” to “cool.”

DISCUSSION

We provide clear evidence of large interindividual differences in metabolic rate under typical everyday living/office activities. Measuring these differences among people of different ages, sexes, and other anthropological measures without normalizing the data is by design as these are representative of typical building occupants. Rethinking our approach to indoor thermal conditioning and, instead of providing uniform temperature to all, facilitating personalized conditioning could put physiological and psychological benefits of the occupants at the forefront. Going forward, the goal will be to find noninvasive markers that can be easily measured and used as surrogates for metabolic rate (i.e., heat production). These measures will be deployed as input into the building’s temperature control

system, allowing for personalized changes depending on an individual’s current heat output, metabolic status, and location. The algorithms will be devised to minimize building energy use and maximize potential metabolic benefits (e.g., stimulate brown adipose tissue). In the past, attempting to create personalized climate control was limited by the lack of technologies capable of continuously tracking individuals’ physiological parameters (e.g., heart rate, skin temperature) and their normal daily activities. Many of these limitations no longer exist with the advancement of smartwatches, miniature wearable sensors, and computer vision-based noninvasive recognition of individuals’ attributes and temperatures, thus opening the possibility to input human physiological parameters into personalized smart climate control systems, as illustrated in Figure 2. Data presented in this paper and the experimental setup are proof of principle with the aim of outlining an approach that will guide future studies in integrating human physiology with thermal conditioning systems in buildings.○

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CONFLICT OF INTEREST

The authors declared no conflict of interest.

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