Application of wearable sensory devices in predicting occupant's thermal comfort in office buildings during the cooling season

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Abstract. The mitigation of adverse health consequences, improvement of life quality and the work environment with consequential benefits to wellness and performance of the occupants, arise the need for innovations in predicting thermal comfort in the actual time during which a requirement occurs. Late researches in this field largely neglect user engagement in building energy performance. In this paper, the wearable sensory devices are deployed to provide real-time information in a spatially distributed indoor environment during the cooling season in office buildings. The results imply that wearable devices are an efficient tool for collecting individualized human sensation data such as a precise metabolic equivalent of task (MET) and occupant’s activity level which could generate total energy expenditure of an occupant. In addition to sensor data, documenting indoor environmental conditions such as air temperature, relative humidity and a level of carbon dioxide (CO₂), could be utilized as useful inputs that complete the more sensibly provided feedback of occupants’ work environmental surroundings. Furthermore, this could provide a potentially significant opportunity for achieving a personal indoor environment that is most preferred.

1. Introduction
In the majority of the countries, buildings are responsible for around 38% of the overall primary energy consumption (and also approximately 38% of the carbon dioxide emissions) [1]. Despite significant improvements in the energy efficiency of new buildings in the 1990s and 2000s, most older, less efficient buildings lead to increased energy to ensure optimum thermal conditions for building occupants [2] because of its design [3], operational requirement and condition [4, 5]. Implementation of the institutional framework is faced with certain difficulties since the vast majority of buildings in Europe date back to 1990, and only 16.7% of them were built from 1991 to 2010 [6]. The great number of laboratory and field studies investigated the thermal environment in buildings in order to maintain the building users’ comfort high level [7]. Significant research progress was established on the understanding of perception and satisfaction of the person in the indoor environment and that are important determinants of his/her wellbeing. These are associated with health outcomes with consequential impact on productivity.

The standards use two main models to establish criteria for thermal comfort, Predictive Mean Vote (PMV) [8 - 11] and adaptive models [11–16]. While, the latter is inherently used for naturally ventilated buildings, providing a linear regression of indoor ambient temperatures as a function of
outdoor temperature, according to PMV, occupants' satisfaction with the surrounding thermal conditions can only be maintained when the heat produced by metabolism equals the heat lost from the body. A metabolic rate is a method of estimating the energy expenditure of physical activities, defined as 1 MET equals to the resting metabolic rate when consumed oxygen amount 3.5 ml O₂/kg/min or activity equals to 58W/m² [17, 18]. However, with the metabolic rate being one of the most critical parameters in predicting comfort environment, it is often reduced on simple diary method facing a number of limitations. For example, a higher person would be expected to have a more considerable resting oxygen uptake compared with a smaller person. Also, two persons with the same body mass, but differing in percent body fat and lean body mass, will have different resting metabolic rates. Therefore, energy expenditure values for a given activity vary not only according to body size, but also a level of fitness, skill, and whether or not the activity is performed in a competitive situation. Hence, ASHRAE standards overestimate metabolic rate for sitting, standing and walking activities by 10 to 20% [19]. Figure 1 presents how changing metabolic rate from 0.9 MET to 1.5 MET, with clothing level being 1 clo, results in an over 3.2 K variance in thermally neutral temperature (temperatures when comfort are achieved and PMV equals to 0) or approximately 1.5 unit scale of PMV difference.

![Figure 1. Effects of metabolic rate change](image)

Accordingly, by tracking user activities inside the building, it becomes much easier to estimate the metabolic rate and improve the thermal comfort of the HVAC system.

The main goal of herein presented research was to examine the possibility of using wearable sensory devices in a cooling period as a diagnostic tool for measuring activity and occupant energy consumption, as well as for data acquisition and transmission which could potentially provide more accurate data creation of the model for predicting thermal comfort sensation and occupant satisfaction.

2. Field study

2.1. Technical description of the building facility

The study was conducted in a public building: Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture in Split (Figure 2). The average summer air temperature in the area of the building is in a range from 22 °C to 25 °C. Central heating of the building is achieved using a 1400 kW automatically regulated oil-fired boiler and average annual consumption of 342 tons. Cooling starts in June and lasts until August when collective summer break starts, after which the cooling season continues through September and ends in early October. It is important to note that the building does not have thermal or sound insulation because it was built in the 1960s. The indoor environmental conditions of the two office rooms inside the building were investigated.
2.2. Used measuring equipment

The sensor used for indoor environment air quality data collection is TROTEC BZ 30 data logger, shown in Figure 3, a). It was set in each room to measure temperature (precision ± 1°C), relative humidity (precision ± 5%) and indoor CO₂ level (precision ± 75 ppm). Wearable sensory devices used in this study were Move 3, specialized in measuring dynamics of metabolic rate based on user activity (Fig. 3 b)).

![TROTEC BZ 30 data logger](image)

Figure 3. a) TROTEC BZ 30 data logger, b) Biosensor Move 3

The measured parameters were compared to the values prescribed by standards. In Table 1, the ASHRAE manual’s recommendations on the air quality parameters and their limits for public buildings during the cooling season (summer) are given.

| Indoor parameters                        | Limits                        | Recommendation                          |
|------------------------------------------|-------------------------------|-----------------------------------------|
| Air temperature                          | fall/winter 23 to 28°C        | ASHRAE Standard 55-2010, ISO 7730       |
| Relative humidity                        | 30% to 65%                    | ASHRAE Standard 55-2010, ISO 7730       |
| Level of carbon dioxide in the air       | to max 700 ppm above the     | ASHRAE Standard 62.1-2016               |
|                                          | external value                |                                          |

The survey questionnaire was used collecting the thermal sensation votes of the occupants and their satisfaction with the thermal surrounding. The questionnaire contained ten questions; five of which...
related to the user's data including the clothing level, and five questions questioned the occupant's satisfaction with the thermal conditions in the room at a given time. Users filled out the questionnaire three times a day during the measurement period, at 8:30 AM, 12 AM, and at 3 PM to observe the changes in clothing and satisfaction level. A total number of 84 responses were collected and used for further analysis.

2.3. Methodology in brief
Four respondents participated in the survey, placed in the room by two. The occupants share an office during office hours. Given that age and gender are the primary sources of individual differences [15], this research focuses on differences in the perception of thermal comfort between users with regard to their age and sex (Table 2.).

| Table 2. Occupant sample |
|--------------------------|
| Gender | Age |
| Total | Men | Women | 35-50 | 51+ |
| 4     | 1   | 3     | 3     | 1   |

Monitoring and measurement were performed 7 days during the summer period in the building. Each of the 4 occupants wore a biosensor on the belt during the working day. It monitored and recorded his/her number of steps and level of physical activity in a 1-minute time interval. From these data, the metabolic rate of each occupant was obtained.

3. Results and discussion

3.1. Environmental conditions
Perceived indoor air quality include the values of air temperature, stuffy air (present level of CO$_2$ in the air), and dry/humid air [22]. Air temperature is the most know parameter affecting the thermal comfort sensation. On the other hand, the perception of “dry air” can be associated with mucous membrane irritation of the eyes (e.g., dry eyes) and upper airways in the presence of strong sensory irritants [23] often an indicator of the sick building. The immediate perception of odor and “stuffy air” which is connected to a level of CO$_2$ in the room, increase upon an increase of relative humidity (RH) [24]. However, alteration of the inhalable particle chemical composition, the deposition, and resuspension that occur from surfaces may differ at different RH.

Furthermore, the CO$_2$ generation rates have application in characterizing building ventilation and indoor air quality [25]. Hence, the measurement of temperature, RH and CO$_2$ level were performed for each office with occupant sensation recording three times a day. The results are shown in Figure 4.
During the cooling period, relative humidity in the building was within the range between 35% and 55%. Users perceive air in the office as humid when relative humidity exceeds 50%.

The levels of carbon dioxide in the building ranged from an average of between 500 ppm and 700 ppm. At the end of the working day, there was an increase in the value, indicating a shortage of space ventilation in the afternoon. Generally, users are mostly satisfied with ventilation, and dissatisfaction occurs after the CO$_2$ level in the air approaches the value of 700 ppm. Since the values of CO$_2$ concentrations prescribed by standards between 1000 and 1200 ppm, it can be concluded that users of the observed building in Split are more suited to lower concentration levels, why they are prone to more frequent air changes in space. This is explained by the fact that the office windows are more often in the open than in a closed position.

### 3.2. Metabolic Rate

The statistical program IBM SPSS was used to investigate the effect of metabolic rates on total energy expenditure (TEE). In more detail, the ANOVA one-way test of significance was performed. The measured data of occupant 3 was used to examine the behavior of metabolic rate. The results are shown in table 3, and the plot of means is shown in Figure 5.

**Figure 4.** Air quality of Room 1 and Room 2

![Air quality of Room 1 and Room 2](image-url)
Table 3. One-way ANOVA test significance results

|                      | Sum of Squares | df | Mean Square | F       | Sig.  |
|----------------------|----------------|----|-------------|---------|-------|
| Between Groups       | 752959,078     | 265| 2841,355    | 11083,870 | 0,000 |
| Within Groups        | 39,222         | 153| ,256        |         |       |
| Total                | 752998,300     | 418|             |         |       |

Figure 5. Influence of MET on TEE

As can be seen in Table 3 and Figure 5, TEE of an occupant depends on his/her metabolic rate. The F value in one-way ANOVA is a tool to help to answer the question about variance between the means of two variables. Since the F value is greater than 1, this is statistical evidence that variable metabolic rate has a statistical influence on the variable TEE with the level of significance being 0,000. As the MET value increases, the TEE will increase as well. This is why it is important to estimate the MET value accurately.

Figure 6 shows the results of measured MET values in comparison to standard table values of typical office activity for the four occupants during working hours.
Figure 6 shows all the weaknesses of the estimation of the metabolic rate from tables of activities and their corresponding met values provided in guidebooks and standards. The MET dynamically changes during the day, and it is highly personal variable depending on age, sex and physical fitness level of an occupant. Although these occupants all have similar daily activities, their metabolic rate differs significantly one from another.

The occupant 1 expends the most energy on average between 10 and 10:30 am, and the average energy expenditure of this user ranges between 100 W and 200 W during one working day. The occupant 2 expends significantly more energy during the working day, and its average energy expenditure ranges from 100 W to 250 W. The occupant 3 expends the most his inner energy in the period between 10 and 11:30, while the average level of energy expenditure is between 150 W and 400 W. The occupant 4 uses the most energy in the first part of the day. Average inner energy expenditure of the occupants ranges from 90 W to 210 W. All occupants expend the most energy during the daily break time due to increased activity (walking up and down the stairs, rushing back to the office rooms, etc.).

In addition, Figure 5 shows that mental work increases the MET value as well. It was noticed that metabolic rate is higher for men compared to women for the same type of work. Therefore, it is erroneous to limit the metabolic rates only to tabular activity logs, not taking gender into account. Also, elderly people have on average lower activity levels, which mean a lower rate of metabolism, so the comfort sensation is higher for older people than for the younger ones. Older people are less sensitive to changes in the thermal environment and are more susceptible to extreme thermal conditions. The acceptable range of comfortable temperatures for the elderly is narrower than for the young, probably because the ability of thermoregulation tends to decline with age.

4. Conclusion
The use of a new type of feedback, occupants' cooling behavior with wearable sensory devices Move 3 along with the measurements of the air quality in their office rooms were explored.

Generally, older people prefer lower temperatures in the warmer period of the year. Given the gender, the female population is more critical than the internal conditions of thermal comfort and is also more sensitive to the deviation from the requirements of optimal thermal comfort. In detail, the research has shown that occupants consider the average office temperature of 26 °C high and relative air humidity of 40% perceives users as "dry to satisfactory" air. The average level of carbon dioxide of 670 ppm is considered to be very satisfactory, and dissatisfaction occurs after the CO₂ concentration in
the air approaches 700 ppm. Moreover, the conducted study showed that the carbon dioxide level is an essential factor in thermal comfort, as the values of CO\textsubscript{2} concentrations in the investigated offices are considerably lower than those prescribed by the standards. It is important to note that this parameter is mostly influenced directly by the occupants.

This research has noticed that total energy expenditure makes people feel different regarding comfort sensation. TEE directly depends on the metabolic rate of the occupants. It has been proved that the value of metabolic rate changes over time for the same occupant, but it also varies with people who carry out similar daily activities. The role of the human as a dynamic sensor is interesting and offers a potentially significant opportunity for achieving a personal indoor environment that is most preferred. Work which demonstrated metabolic rate could be utilized as useful input that complements the more sensibly provided feedback.

Future research would be focusing on one-year measurement for the development of personal comfort models to predict individuals' thermal preference. The progress of this area is promising. Personal comfort models could be used to understand specific comfort needs and desires of individual occupants better to satisfy their thermal comfort in a given space. Such information could inform the design and control decisions of a building or a system to provide optimal ventilation and conditioning for improved comfort satisfaction and energy efficiency.

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