Actimetry for estimating occupant activity levels in buildings

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Actimetry for estimating occupant activity levels in buildings: A step towards optimal and energy efficient indoor conditioning

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Abstract **– Utilising actimetry, this study proposes an improved approach for assessing occupant thermal comfort and, in turn, more efficient indoor conditioning. Occupant activity level is an important determinant of required comfort conditions and thus, building energy use. For nine volunteers, the activity pattern of during typical office days was monitored using the Sensewear Armband®. Detailed profiles of occupant activity levels were obtained and using clustering analysis, divided into Sedentary and Active groups. While occupants were in their respective Sedentary cluster for 80% or more time, the Sedentary cluster was not limited by the currently used metabolic level for estimating sitting at a desk and working. Overall, just 30.7% of the recorded activity levels were less than or equal to the desk-work activity levels. These findings point to the need for revising typical activity rates used in designing indoor conditioning systems and defining control set-points for thermal comfort in offices. And we propose the use of extended actimetry based studies for guiding such revisions.**

I. BUILDING ENERGY USAGE AND INDOOR THERMAL COMFORT STANDARDS

Modern humans spend an overwhelming part of their life indoors [1], and as such, the built-environment accounts for nearly 40% of global energy use and 38% of global greenhouse gas (GHG) emissions [2]. Of building energy usage, a considerable fraction goes towards conditioning the indoor climate for occupant thermal comfort and yet, comfort and health related complaints remain common in many buildings [3]. Indoor thermal conditioning tries to minimise any thermal stress on human body, by controlling indoor temperature, humidity, thermal radiation, and air movement to suit occupant needs. For deciding the requirements in spaces used by groups of people (like open-plan offices), a widely prescribed model in standards is the Predicted Mean Vote (PMV) model [4]. The PMV model takes a steady state heat balance approach for the human body. Human beings rely on their internal metabolism and thermoregulation to maintain a stable core temperature. When environmental heat loads are such that surplus metabolic heat cannot be dissipated or heat gets drained off too quickly, thermal discomfort arises. PMV evaluates thermal comfort based on four environmental parameters (air temperature, humidity, radiant temperature, and air velocity) and two personal parameters (metabolic activity and clothing insulation), on a seven point scale, starting from Cold (3) to Hot (3), with Neutral being 0. PMV calculations are particularly sensitive to metabolic activity. For thermal comfort calculations, metabolic activity is estimated in terms of Mets, one Met being equivalent to 58.15 W per m^2 body surface area. Change of 1 met in activity level can lead to a change of up to 3.5 on the PMV scale [4]. If activity rate differs by 1 met, the temperature set-point would need to differ by 7.5 °C. To put it into perspective, increasing cooling set-points by 3 °C or reducing heating set-points by 1 °C can, on an average, reduce indoor conditioning energy usage by over 20% [5]. Hence, assumed activity levels contribute to dissatisfied occupants and energy wastage.

Metabolic rate measurements typically use either direct or indirect calorimetric methods [6]. These are either confined to controlled laboratory spaces or involve some significant participant inconvenience. Hence, for indoor conditioning, default values are assumed from databases [4], depending on the building's purpose. However, assumed values, based on laboratory studies, may not be similar for activities performed under field condition. Also, over the long service life of a building, the intended purpose may change or activity patterns and indoor space usage may evolve. For example, the offices of today, owing to penetration of IT, have very little in common with offices of three decades back.

Improving occupant comfort and optimal energy use need better estimates of activity levels. Accelerometers are used extensively in a variety of wearable, consumer electronics. They may be utilised for identifying wearer activity. Actimetry is an easy to use, inexpensive, non-invasive, and reliable means of measuring occupant activity [7]. It

is also suitable for continuous monitoring, while minimally interfering with wearer's routine, thus allowing comprehensive assessment of occupant activity.

With targets of near zero energy buildings drawing closer, such monitoring can aid in optimizing building energy use. An energy efficient built environment can lead to 30-50% energy usage and 35% GHG emissions reductions [2]. These can prove vital in working towards a sustainable future. In particular, it correlates strongly with the UN Sustainable Development (UNSD) Goal 11 — Sustainable Cities and Communities — and Goal 13 — Climate Action. The built environment also has an important role in health and well-being [8] (UNSD Goal 3). Thus, better design and operation of building indoor climate is of overwhelming importance at this juncture.

The current study was organised with an exploratory set up for examining applicability of actimetry to estimate activity levels of occupants in an open-plan office. In choosing suitable indoor conditioning requirements for office space, the relevant standards recommend that office occupants mostly have a sedentary activity level, between 1 and 1.3 met. This study intended to verify how accurate this estimate is when factoring in modern office-worker. We also look towards a future where actimetry may play an integrated and continual role in determining indoor conditioning needs.

This connection is illustrated through the schema in Figure 1. The study findings would help in better understanding occupant needs of thermal comfort and would also help in standardising applications of actimetry for improving indoor thermal comfort specifications.

II. SETTING UP A CASE STUDY IN AN OPEN-PLAN OFFICE

A. Study location and participants

Open-plan office refers to floor spaces that focus on open spaces with a number of people working in the area, while minimizing or eliminating private offices and even enclosed cubicles. The study took place in an open-plan office space on the sixth floor of "Building 6" in the campus of the Eindhoven University of Technology, during May and June 2016. The space has a floor area of ~120 m², ceiling height of ~5 m, and seats between 12 and 20 persons, the variability being due to flexible working schedules.
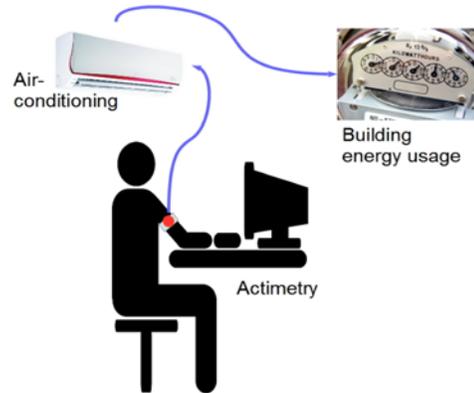

Fig. 1. In the vision for future, actimetry provides input for control of indoor conditioning systems, impacting building energy usage

For this study, nine occupants (3 female and 6 male) who worked in this space were recruited on a voluntary basis. During the study period, participants only had their regular workload and there were no teaching or extra-academic tasks. No participant suffered from any form of repetitive strain injury, had had any recent major surgery or illness, were diagnosed with any form of metabolic disorder, or were pregnant during or immediately prior to the study. The work followed Dutch human subjects regulations and the Dutch Medical Research Involving Human Subjects Act (WMO) did not apply. While an official ethical approval was not required, all necessary steps were taken to ensure anonymity and confidentiality for the participants. Participants were informed regarding the purpose of the study, that their participation was voluntary, that they may discontinue their participation at any time, and that all data would be processed anonymously, solely for research purposes. Two participants contributed two days, one four days and one six days. The others contributed three days of their time. The complete data set had about 281 hours of time spent in the office space. Participant demographics have been summarized in Table I, in the form: mean (standard deviation).

TABLE I
PARTICIPANT DEMOGRAPHICS

Age	Height	Weight	BMI	Smokers
29.2	1.74	71.8	23.7	None
(2.6)	(0.08)	(12.9)	(4.4)	

B. Actimetry and monitoring occupants

Actimetry, in built environment, has a more extensive history of use in sleep studies [9, 10]. However, it has yet to see application in modulating indoor conditioning. In this work, the Sensewear Armband® (Sensewear) was utilised for activity level measurements. This device has been clinically tested and validated as a multi-sensor system for body monitoring [7]. Participants wore it on their upper right arm, from arrival at their desk till they left for home. The Sensewear logged activity level, skin temperature, and skin heat flux every minute.

C. Analysis of responses

The devices were collected from the participants once they had completed their desired number of days of the study. Data pre-processing and analysis was conducted in the R statistical environment (https://www.R-project.org/). Data gathered for each individual, on each day of his/her participation, was analysed separately since participants need not have had similar engagements on different days. Because of the nature of typical office work — time spent at a desk interspersed with time in meetings, breaks etc. — it was assumed that occupants would have had two distinct groups of activity: "Sedentary" and "Active". This was done to contrast with the typical design assumption — discussed in the introductory section — that office work is assumed to be sedentary. To clarify, Sedentary is not being used for its literal meaning but to denote a range of activities that correspond to typical office work: seated at a desk reading (1 met), typing (1.2 met), or filing, standing (1.4 met) [4]. Active is being used to denote all other activities that may go on during an office day, e.g., taking a lunch break, moving from office to meeting rooms etc. The hypothesis is that the major portion of the day would be spent in a range of activities that fall within the Sedentary phase.

K-means clustering [11] was used on the recorded values of longitudinal and transverse acceleration, skin heat flux and temperature, and activity levels to divide each day's data, for each participant, into the two aforementioned groups.
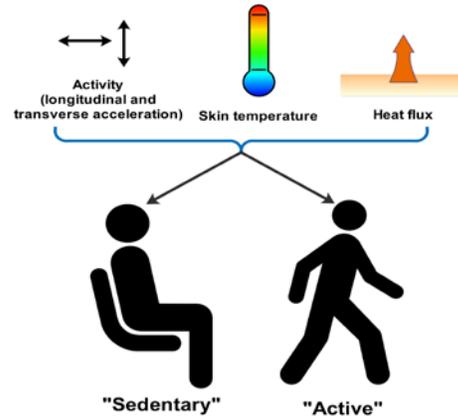

Fig. 2. Clustering was used on physiological records to classify activity levels into two clusters

This approach is schematically represented in Figure 2. The cluster with a lower mean activity rate value would be the "Sedentary" cluster. For correlations, Pearson product moment correlation was used [11]. Using clustering algorithm, we need not impose any presumptions regarding what activity level should be ascribed for Sedentary phase in office work. Also, taking other physiological variables into account, apart from just the activity level, should improve result integrity. The mean values for Sedentary and Active cluster for each participant was determined by taking a weighted mean of the day-wise cluster means, weighting factor being the time a participant spent in the particular cluster for each of his/her participation days. So, for example, if the mean activity value of the Sedentary cluster of participant S1 was M1, M2, and M3 on the three days when s/he volunteered, these value were weighted using the minutes S1 spent on each of the three days in the Sedentary cluster, to obtain S1's overall mean value for Sedentary activity cluster.

III. OFFICE OCCUPANTS' ACTIMETRY DATA

A summary representation of the physiological data recorded using the Sensewear has been provided in Table II. Cumulative frequency distribution plots for the data, clustered into Sedentary and Active groups, have been provided in Figure 3. Well above 80% of the recorded values were below 2 met. However, there were still short spurts of quite high activity levels (some point values even exceeding 8 met).

These likely corresponded activities such as climbing stairs and moving across meeting rooms or buildings.

TABLE II SUMMARY OF RECORDED PHYSIOLOGICAL DATA

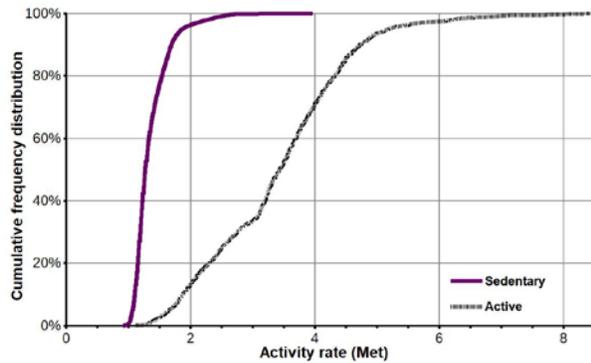|	Mean	Median	Max	Min
Activity rate (Met)	1.6	1.3	8.4	0.9
Skin temperature (°C)	31.4	31.3	34.5	22.7
Skin heat flux (W/m^2)	69.5	63.2	328.8	-11.5

Fig. 3. Cumulative frequency distribution plots for respectively Sedentary and Active clusters

Taking all participants into consideration, 85.3% time was spent in the Sedentary clusters. Overall, 30.7% of the recorded activity levels were ≤1.2 met, the value used for desk work, and 75.3% were ≤1.6 met, the value used for 'light office activity, standing' [4]. Mean met values of Sedentary and Active clusters and the time fraction spent in Sedentary cluster, for each participant, have been given in Table III.

The mean met values, as explained in the Analysis of responses Section, were a weighted mean for each participant, based on the cluster analysis of the data from each of his/her days of participation. The mean value of the Sedentary clusters for different participants had a smaller range than the mean values of the Active cluster. From every day's data, the mean value for Sedentary cluster varied between 1.2 and 1.7 met while variations of the mean for Active cluster was between 1.6 and 4.1 met. The analysis thus indicated two clear groupings of activity over the office day for all nine participants. In Table III, it may be observed that 80% or more time was being spent by occupants in their respective Sedentary clusters. Due to the small subject pool,

any significant correlations between mean values of the activity clusters and participant physical features were not expected. The mean values of Sedentary cluster best correlated to BMI (r=−0.51, p = 0.16) and mean values of Active cluster best correlated to participant height (r = 0.68, p = 0.043).

TABLE III ACTIVITY CLUSTERS FOR INDIVIDUALS

	S1	S2	S3	S4	S5
Active cluster mean (met)	3.1	2.4	2.4	3.2	3.4
Sed. cluster mean (met)	1.2	1.2	1.2	1.4	1.3
Sed. cluster time fraction (%)	82	87	86	83	90
	S6	**S7**	**S8**	**S9**	
Active cluster mean (met)	3.5	3.2	3.6	2.7	
Sed. cluster mean (met)	1.4	1.5	1.6	1.3	
Sed. cluster time fraction (%)	80	89	87	84	

IV. DISCUSSIONS

Affective computing trends are moving towards commercially available wearables, with multiple sensors for noninvasive monitoring of people [12, 13]. Amongst these sensors are also the ones that make actimetry possible using simple wearable electronics. We hypothesized that this can consequentially also impact indoor thermal conditioning decisions and energy use.

Actimetry is a suitable solution to estimate occupant activity rate and provides a detailed picture. The wearable device was non-intrusive and none of the participants reported any issues of discomfort. Being an exploratory study, the number of participants was small. However, the results suggest that the methodology can be easily extrapolated to larger populations, both for short term surveys and for long-term monitoring.

Today's offices are no longer "typical". Changing office layouts, work hours, and work from home practice mean that we cannot design thermal comfort for offices of this century using assumptions from the last one. This study showed that office activities may yet be classified into two distinct groups.

Occupants spent over 80% of their time in their respective Sedentary groups (Table III). But, the spread of the Sedentary cluster went beyond 1.2 met. Over 44% of the time, occupant activity rate was between 1.2 and 1.6 met, questioning the typical values used for office work in calculating PMV. Significant inter-individual variations were noted, reinforcing the need for personalised thermal comfort systems and models [14]. Such models can benefit from actimetry data. The wide distribution of activities also brings to fore the need for moving towards thermal comfort indices that can handle the dynamic nature of human activities from the current steady state PMV model.

Considering the ease of use and easy repeatability of actimetry, and the long service life of buildings, it would be advisable to repeat such surveys with the contemporary occupants of a building. For the future, we may envisage a continual and proactive approach towards ensuring indoor thermal comfort [15], aided by actimetry. An in-use building would be continually monitored, gathering occupant activity data (Step 1), the data analysed for occupant needs (Step 2), and steps taken by the building management system (BMS) to provide suitable comfort conditions, with efficient use of energy (Step 3). This becomes an iterative process to anticipate occupant discomfort and take proactive measures. It may move on to actimetry on networked devices, possibly even smartphones, and relying on a combination of Internet of Things and cloud based data processing to take care of both the monitoring and analysis. Additionally, wearable electronics actimetry also holds the future potential to better understand space usage in offices, indoor occupancy, improving health and well-being of the users [16] and contributing towards smart healthcare [17].

V. CONCLUSION

Actimetry provides a viable option for monitoring occupant activity under field conditions. It is easy to use and nonintrusive and hence may be implemented multiple times over a building's life. The data gathered can be used to update activity values used for indoor thermal comfort design. Considering how sensitive human thermal comfort can be to activity level, this would be an important step towards energy efficient indoor conditioning. The future could hold use of wearable devices for actimetry that provide continual monitoring of individual thermophysiological profiles to improve the control of not just HVAC systems with centralised control, but also for systems with more localised effect and control options.

Our investigations showed that the activity levels of office occupants may be categorised into Sedentary and Active groups. Occupants spent a considerable part of their days at activity levels over the typical used value of 1.2 met for seated desk work. Inter-occupant variations existed for typical office workers' days. So, while occupants may spend over 80% of their office hours in their personal Sedentary activity cluster, the actual metabolic rate often varied from that for sitting and working at a desk. These findings imply that the occupant activity rates assumed for indoor climate conditioning in building design need a careful revision and actimetry can provide the means to building a new database using field observations. At the same time, actimetry can also contribute during operational phase of buildings, based on its integration in wearable electronics, to better identify occupant activity levels and aid BMS in real time decisions for energy efficient comfort conditioning.

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Asit Mishra's (asit.mishra@aalto.fi) research interests focus on indoor climate quality in low energy buildings and occupant comfort and well-being. His has worked on thermal comfort in naturally ventilated classrooms in tropics, smart-grids and building energy flexibility, and non-intrusive, long-term, indoor monitoring.

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