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Effect of sitting posture on the thermal insulation of modern office chairs

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ABSTRACT

This study experimentally explored the variability in thermal insulation with different sitting postures and a contemporary selection of chair designs. Also, the insulating effect of three different types of facemasks was evaluated. Measurements were made with a thermal manikin seated in a well-controlled climate chamber at three different room temperatures: 20 ± 0.2 °C, 25 ± 0.2 °C and 30 ± 0.2 °C. Two sitting postures were investigated: back in contact with the chair backrest or not, i.e. leaning slightly forwards. The selected chairs had effective thermal insulation around 0.14–0.17 clo when the manikin was seated with the back in contact with the chair backrest, except the applied executive chair, which provided 0.26 clo. On average, leaning forwards reduced the clothing insulation by 0.09 clo. The tested facemasks all provided the same marginal insulation I_{clu} of 0.05 clo. The measured chair insulation values were well aligned with those from earlier studies. The study confirms that chair insulation is a parameter that should be carefully evaluated and considered when assessing thermal comfort.

1. Introduction

Appropriate assessment of thermal environments in buildings and other indoor or outdoor settings relies on estimates of clothing insulation. In this respect, clothing insulation is a critical but complex parameter to estimate since it may vary between building typologies or seasons, or it can be dynamic and even change frequently during the day with peoples' activities. Inaccurately evaluated clothing insulation of e.g. 20% means that the neutral temperature will deviate by ±0.6 °C and ±1.2 °C with standard summer and winter clothing, respectively, when using the predicted mean vote (PMV) model [1]. Thus, clothing insulation highly impacts thermal comfort assessments with commonly applied evaluation methods that are based on the heat balance of the human body.

The thermal insulation of the clothing quantifies the resistance to dry heat transfer from the body to the surroundings when the temperature is moderate (ISO 9920–2009, [2]). Thermal insulation of clothing depends on a range of factors, including body movement, wind and wind direction, and posture [3–7].

Measurement of clothing insulation requires specialised and expensive instrumentation, such as thermal manikins or guarded hot plates, or human subjects can be used through indirect calorimetry [6–8]. In practice, tabulated data in standards or guidelines are therefore used to quantify clothing insulation (e.g. [9], ISO 9920–2009, ISO 7730–2006 [10]). Initially, data on clothing insulation represented only a limited range of representative attires worn mostly in moderate thermal environments, such as offices or homes, supplemented with work clothes for a few occupational settings. Today, detailed and comprehensive information on clothing insulation is available for a large number of both Western [11] and non-Western [12–14] clothing garments and ensembles. Also, values of clothing insulation for children in Kuwait [15] and older people in China [16] are found in the literature. More recently, a database on overall and local thermal insulation was released, including 57 typical garments and 62 ensembles [17]. These values often represent measurements in still air and with standing thermal manikins.

While the focus of the studies referenced in the literature has been on estimating clothing insulation, fewer studies assessed chair insulation (e.g. for office chairs: [5]; for aircraft seats: [18]). The chair's design, the composition of the clothing ensemble and the chair material may influence the marginal insulation provided by chairs, which can be reduced or increased while seated compared to standing (e.g. [5]). When people perform any seated activity, the overall clothing insulation is composed of the insulation of the air trapped inside the clothing, the boundary air layer surrounding the person, the garment fabrics'

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characteristics, and the chair. For example, a mesh chair with no cushion will compress the enclosed air layers and change the convective flows, thereby reducing clothing insulation [6,19], while cushioned chairs will more likely add to the overall insulation [5]. However, Hedge et al. [20] did not detect significant differences in thermal sensation with seated subjects in identical thermal exposures, despite apparent differences in chair insulation and design (mesh, foam cushion or thermally conductive gel cushion).

Seated occupants have parts of the thighs, buttocks, and back in contact with the chair, changing the insulation compared to a standing posture [5]. In addition to the body surface area in contact with the chair, the sitting posture influences the insulation provided by the chair, partly because the convective boundary air layer surrounding the occupant depends on the inclination of the torso [21]. Graf et al. [22] recorded sitting postures among employees in different occupations and found that general office workers leaned back more often than forward (18% of recordings vs 8%), whereas listeners in an auditorium leaned forwards more than backward (26% vs 8%). Hedge and Ruder [23] found that subjects with typing work made some form of body movement once per minute while typing. The movement frequency was the same with the chair locked in a fixed or unlocked position, where subjects could freely change the backrest recline position. Sitting posture is, therefore, highly dynamic.

The current study was triggered by the uncertainty analysis in the clothing insulation values included in the ASHRAE Thermal Comfort Database II [24], as reported in Rupp et al. [25], and for the need to further study the effects of chair design and sitting posture on the thermal insulation. This way, the main objective of the research was to explore experimentally the impact of different sitting postures on the thermal insulation provided by a contemporary selection of chair designs. In addition, the aim was to check if commonly adopted values of chair insulation [5] are still valid for contemporary chairs. Instigated by the preventive measures applied during the recent COVID-19 pandemic, the insulating effect of different facemasks was also evaluated.

2. Method

Measurements of chair insulation were made with a thermal manikin seated in a well-controlled climate chamber at the Technical University of Denmark. The measurements were made to both quantify and compare the insulation by a selection of modern office chairs and the influence of the manikin's sitting posture. In addition, the insulation provided by three different facemasks was quantified.

2.1. Experimental facility and instruments

The climate chamber had a floor area of 28 m^2 and a height of 2.5 m [26]. A displacement ventilation system supplied air at a very low velocity from the entire floor area to the chamber. Air was also supplied between the wall and a finishing fabric so that the surrounding surface temperatures were nearly equal to the room air temperature.

A thermal manikin was used to study the thermal insulation provided by the different combinations of chairs and sitting postures (https://www.ptteknik.dk). The manikin had a body shape representing an average Scandinavian female with a height of 1.7 m. The manikin had 23 individually controlled body parts: left and right foot, left and right lower leg, left and right front thigh, left and right back thigh, pelvis, backside, crown, left and right face, back of the neck, left and right hand, left and right forearm, left and right upper arm, left and right chest, and back.

The thermal manikin was placed close to a desk with the dimensions 1.6 m × 0.8 m × 0.8 m (L × W × H). There was 10 cm between the table and the chest of the manikin. The floor beneath the seated manikin was covered with a wooden board with dimensions of 2.44 m × 2.44 m to reduce the effects of the ventilation air supply on the manikin heat loss.

2.2. Materials

2.2.1. Chairs

Office chairs are available in numerous designs and materials. For this study, we selected seven models representing office chairs commonly found in offices and spanning light (non-cushioned) to heavy insulation (Figure 1). Thus, we aimed to explore chairs with different designs and materials, likely affecting the clothing insulation differently. We also used a reference chair to consider the manikin seated but with negligible chair insulation (Figure 2). With the reference chair, the manikin sat on two thin cylindrical pipes (Ø2 cm) and was supported in the back by an additional pipe. This setup ensured minimal contact area, and the reference chair thus provided minimal insulation. However, the clothing layers may have been compressed locally where the pipes were in contact with the manikin.

2.2.2. Ensemble

During the measurements, the manikin was naked or dressed in standard clothes (long-sleeve shirt, t-shirt, trousers, socks and underwear) with a known thermal insulation of 0.61 clo at standing posture.

2.2.3. Facemasks

We selected three types of facemasks used to provide respiratory protection against COVID-19: surgical, FFP2 and FFP3. The facemasks were made of various fabrics, had different leakage patterns and covered different face areas, as shown in Figure 3. The surgical mask was widely used by the public during the COVID-19 pandemic and was made of a nonwoven fabric with three layers. The FFP2 mask was also made of nonwoven fabric but with five layers. The FFP3 mask had a mesh outer structure, a multi-layer filter, and a soft inner fleece.

2.3. Measuring clothing insulation with a thermal manikin

The thermal insulation measurements were performed using a thermal manikin according to ISO 9920–2009. The experimental conditions consisted of measurements at three temperatures with the thermal manikin naked and dressed in standard clothes, seated in the eight different chairs. In addition, two sitting postures were investigated: back in contact with or not in contact with the chair backrest, i.e. leaning slightly forwards. For the latter, a 4 cm distance between the middle of the manikin's back and the chair's backrest was kept. The experimental conditions were limited to determine the insulation of the three facemasks to the manikin seated in one position (back in contact with the chair) and two chairs (reference and chair #2) for the two ensemble insulations (naked and standard clothes).

The experiments in the climate chamber were conducted at three different temperatures: 20 ± 0.2 °C, 25 ± 0.2 °C and 30 ± 0.2 °C. Relative humidity was kept between 40 and 50%. Airspeed was below 0.1 m/s. The temperature in the chamber was adjusted at the end of the day to provide enough time to reach thermal equilibrium between the manikin, clothes, chair, and the environment the following day. Then, the experiments continued the next morning. The time to reach steady-state when changing chair, mask or sitting posture was approximately two to three hours.

Each measurement resulted in the surface temperature and the heat loss of each of the 23 body segments ($n = 23$) under equilibrium conditions. These values were used to calculate the total thermal insulation (I_T) according to Eq. (1), extracted from ISO 9920–2009.

$$I_T = \frac{\bar{t}_{sk} - t_a}{H} = \frac{\sum_{i=1}^{n} \alpha_i.(t_i - t_a)}{\sum_{i=1}^{n} (\alpha_i.H_i)} \quad (1)$$

where I_T is the total insulation (m^2•K/W), including the surface resistance surrounding the ensemble or, when nude, the skin surface (i.e. the air insulation, I_a); $\bar{t}_{sk}$ is the mean skin surface temperature (°C); t_a is the air temperature (°C); H is the dry heat loss per square meter of skin area

Fig. 1. Back and front pictures of the investigated chairs.

Fig. 2. Thermal manikin dressed in standard clothes, seated in the reference chair (Chair #1) and wearing a surgical facemask.

(W/m^2); α_i is the weighted surface area of segment i calculated by Eq. (2); t_i is the surface temperature of segment i (°C); H_i is the dry heat loss of segment i (W/m^2).

$$\alpha_i = \frac{\text{surface area of segment } i \ (\text{m}^2)}{\text{total surface area of manikin } (\text{m}^2)} \tag{2}$$

Effective thermal insulation (I_{clu}) of a chair or facemask was calculated using Eq. (3) (ISO 9920–2009). I_{clu} may be interpreted as the marginal increase in insulation provided by a single garment (e.g. facemask) or a chair compared to the nude manikin. This way, the I_{clu} of a chair can be added to the I_{clu} of the ensemble and/or the I_{clu} of a facemask to provide the combined (e.g. chair + ensemble + facemask) intrinsic insulation (I_{cl}), also known as the basic thermal insulation. Eq. (3) gives I_{clu} in m^2•K/W. To convert to clo, we assumed that 1 clo = 0.155 m^2•K/W.

$$I_{clu} = I_T - I_a \tag{3}$$

Firstly, to obtain I_a, measurements were conducted with the naked manikin while seated in the reference chair in the two different postures, at the three air temperatures, following the ISO 9920–2009 procedure. After determining I_a, all conditions with the naked manikin were measured, i.e. measurements using the remaining seven chairs, the two postures and the three temperatures. Then, the manikin was dressed in standard clothes, and the measurements were repeated. Finally, the measurements with the three facemasks were conducted. All experiments were repeated three times.

3. Results

3.1. Air insulation

Table 1 shows the results of the measurements conducted with the naked manikin, sitting straight (i.e. back in contact with the back pipe of the reference chair) at 25 °C room temperature. The surface temperature and the heat loss of a segment are given as mean ± S.D. of a 10-min interval after reaching steady-state. Using information from Table 1 and an air temperature of 25 °C, the numerator and the denominator of Eq. (1) for each segment i of the manikin (Table 1) can be calculated. Dividing the sum of the numerator (7.9) by the sum of the denominator (63.5) (Eq. (1)) yields the insulation of the air layer (I_a) of 0.125 m^2•K/W (0.019 clo) for this experimental condition.

Performing the measurements at 20 °C and 30 °C with the sitting manikin (i.e. naked, sitting straight) and the reference chair resulted in air insulations of 0.121 and 0.130 m^2•K/W, respectively. Since I_a differences at different temperatures were within 10%, it was concluded that I_a was only modestly affected by the ambient temperature and thus by the magnitude of the manikin heat loss. The same I_a results were obtained for the naked manikin, sitting in the reference chair, and leaning slightly forward at the three temperatures.

Having determined I_a, Eq. (3) was used to calculate the effective thermal insulation (I_{clu}) of the different chairs, ensemble and facemasks.

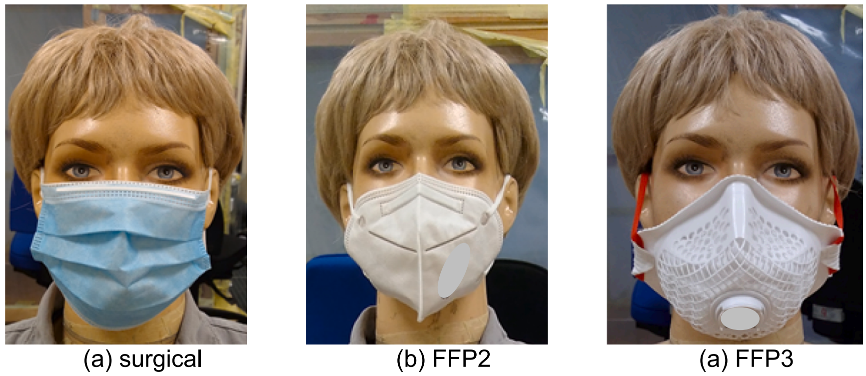

Fig. 3. The three types of facemasks studied in this work.

Table 1
Results of a measurement. Experimental condition: reference chair, manikin naked, sitting straight, air temperature = 25 °C.

Chair	Segment	Surface area (m^2)	Weighted surface area - α (Eq. (2)	Surface temperature (°C)		Heat loss of segment (W/ m^2)		Σ (Eq 0.1)	
				Mean	S.D.	Mean	S.D.	Numerator	Denominator
Reference	L.Foot	0.0430	0.0291	32.5	0.0	71.7	0.8	0.2	2.1
	R.Foot	0.0430	0.0291	32.6	0.0	70.8	0.6	0.2	2.1
	L.Low.Leg	0.0900	0.0608	32.6	0.0	69.8	0.6	0.5	4.2
	R.Low.Leg	0.0900	0.0608	32.8	0.1	65.8	0.7	0.5	4.0
	L. Front thigh	0.0800	0.0541	32.9	0.1	64.0	0.4	0.4	3.5
	R. Front thigh	0.0830	0.0561	33.1	0.0	61.8	0.4	0.5	3.5
	L. Back thigh	0.0800	0.0541	32.9	0.0	64.9	0.3	0.4	3.5
	R. Back Thigh	0.0830	0.0561	32.8	0.0	66.1	0.0	0.4	3.7
	Pelvis	0.0550	0.0372	33.1	0.0	60.8	0.1	0.3	2.3
	Back side	0.1100	0.0744	32.9	0.0	64.6	0.2	0.6	4.8
	Crown	0.0500	0.0338	35.0	0.0	25.6	0.1	0.3	0.9
	L. Face	0.0258	0.0174	33.3	0.0	57.2	0.3	0.1	1.0
	R. Face	0.0258	0.0174	33.2	0.0	58.9	0.1	0.1	1.0
	Back of neck	0.0248	0.0168	33.4	0.0	56.0	0.2	0.1	0.9
	L. Hand	0.0380	0.0257	32.4	0.0	73.7	0.3	0.2	1.9
	R.Hand	0.0370	0.0250	32.8	0.0	66.4	0.2	0.2	1.7
	L.Forearm	0.0500	0.0338	32.7	0.0	68.5	0.5	0.3	2.3
	R.Forearm	0.0500	0.0338	32.9	0.0	64.8	0.2	0.3	2.2
	L. Upper arm	0.0730	0.0493	32.7	0.0	68.2	0.3	0.4	3.4
	R.Upper arm	0.0780	0.0527	32.9	0.0	64.5	0.2	0.4	3.4
	L.Chest	0.0700	0.0473	33.2	0.0	58.5	0.1	0.4	2.8
	R. Chest	0.0700	0.0473	33.2	0.0	59.8	0.1	0.4	2.8
	Back	0.1300	0.0879	32.9	0.0	64.5	0.3	0.7	5.7
	All	1.4794	1.0000	33.0	0.0	63.5	0.1	7.9	63.5

3.2. Thermal insulation of different chairs or individual components

Table 2 presents the thermal insulation of the studied chairs considering the two sitting postures for the manikin naked and dressed in standard clothes. All values are the average of three measurements, which did not differ by more than 10%. Most of the selected modern chairs had effective thermal insulation around 0.14–0.17 clo when the manikin was seated with the back in contact with the chair backrest. When the manikin leaned slightly forward, most chairs provided thermal insulation of only 0.09 clo. The executive chair (#6) had higher

Table 2
Estimation of the effective thermal insulation of eight different chairs considering two sitting postures and two ensembles. The effective thermal insulation of the chairs is highlighted in yellow, and the insulation of the ensemble (in reference chair) is highlighted in orange.

Position	Condition	Estimation of the effective thermal insulation of chair, ensemble or combination (clo)							
		Reference chair	Chair 2	Chair 3	Chair 4	Chair 5	Chair 6	Chair 7	Chair 8
Back in contact with chair	Naked	0	0.14	0.16	0.17	0.17	0.26	0.10	0.16
	Clothed	0.61	0.72	0.77	0.79	0.77	0.90	0.68	0.73
Back not in contact with chair	Naked	0	0.09	0.09	0.09	0.09	0.18	0.05	0.11
	Clothed	0.53	0.66	0.69	0.69	0.69	0.78	0.59	0.70
Average	Naked	0	0.12	0.13	0.13	0.13	0.22	0.08	0.14
	Clothed	0.57	0.69	0.73	0.74	0.73	0.84	0.64	0.72

thermal insulation in both postures (0.26 and 0.18 clo).

The standard clothes provided an effective insulation of 0.61 clo when the manikin was seated with the back in contact with the reference chair. However, the insulation value was lower when the manikin leaned slightly forwards, i.e. 0.53 clo. The combination of chair and ensemble insulation resulted in a somewhat different clo-value than the sum of the individual components due to the compression of the ensemble by the chair.

Table 2 also shows the average clo-values for the two sitting postures as suggested values to be used in practice assuming that people will sit half of the time with the back in contact with the chair backrest and the other half of the time with the back not in contact with the chair backrest.

3.3. Thermal insulation of different facemasks

The effective thermal insulation of the facemasks is shown in Table 3. The thermal insulation of the three facemasks was consistently 0.05 clo when measured with the naked manikin. The facemasks had a negligible additive effect on the effective thermal insulation when the manikin was clothed and sitting in the reference chair. When the manikin was seated in chair #2, a small increment in thermal insulation was measured for the manikin naked and dressed in standard clothes.

Despite the low clo-value of the facemasks (0.05 clo), the temperature on the face of the manikin increased by about 0.8 °C. Still, the covered skin area seemed too small to significantly affect the marginal insulation provided by the masks (Figure 4).

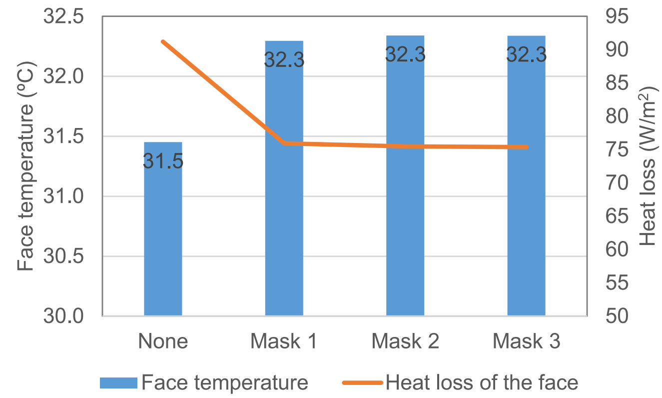

Fig. 4. Influence of wearing a facemask on face temperature and heat loss for the manikin dressed in standard clothes, sitting straight in the reference chair at 20 °C of room temperature.

3.4. Sensitivity of operative temperature corresponding to neutral thermal sensation to chair thermal insulation

In an earlier study, Rupp et al. [25] showed that accurate prediction of clothing insulation and proper consideration of the thermal insulation provided by chairs was crucial for the prediction of PMV by quantifying the sensitivity of the PMV prediction to the clothing insulation. Rupp et al. also showed that the agreement between PMV predictions and the actual mean vote (AMV) improved noticeably by accounting for the chair insulation.

In addition to the analyses carried out by Rupp et al. [25], further analyses were carried out in the present study to quantify the effect of different chairs on the operative temperature for achieving a neutral thermal sensation (i.e., PMV = 0). For the following analyses, air speed was assumed to be 0.1 m/s, relative humidity was assumed to be 50% and metabolic rate was assumed to be 1.2 met (sedentary activity, offices and spaces with similar activity). It was assumed that the air and mean radiant temperatures were identical. An ensemble clo value of 0.61 clo was assumed corresponding to the actual clothing during the measurements as described earlier. The operative temperature corresponding to PMV = 0 at these settings was 24.5 °C.

Table 4 shows the change in the operative temperature corresponding to PMV = 0 when adding the thermal insulation of the chair. The values of 0.1, 0.16 and 0.26 clo are representative values for back in contact with chair, 0.05, 0.09 and 0.18 clo are representative values for back not in contact with chair, and 0.08 and 0.22 clo are representative values for average posture based on Table 2.

The results in Table 4 show that the inclusion of chair insulation can reduce the operative temperature corresponding to a neutral thermal sensation by 0.3 to 1.7 °C. Although the change in values around and below 0.5 °C might not have noticeable effects in practice, values above 1 °C could have remarkable effects in practice both during the design and operation phases of a building.

Considering the chair thermal insulation value properly during the design phase could help design a building and size its systems more accurately, and during the operation phase, it could help with more appropriate control mainly due to more accurate selection of room temperature setpoints. This has the potential to improve thermal comfort of occupants in buildings and energy savings due to more appropriate temperature setpoints.

4. Discussion

When several individuals occupy a space, there is never only one uniform level of clothing insulation. This variability in clothing insulation may exacerbate differences between occupants in thermal perception. In other situations, for example, when occupants dress to accommodate their thermal disposition [27] and expectations, it may moderate the differences and promote a more even thermal perception. To add to the complexity, this study showed that the sitting posture affects the thermal insulation provided by chairs.

The influence on the added insulation of the sitting posture varied with the type of chair in the range of 0.03 to 0.12 clo. In agreement with McCullough et al. [5], this study found that the more cushiony chairs added more insulation and even more when the back of the manikin was in contact with the backrest. Also, McCullough et al. [5] found that the insulation provided by the chair increased with the area of the manikin

Table 3
Estimation of the effective thermal insulation of different facemasks considering two chairs and two ensembles. The effective thermal insulation of the chairs is highlighted in yellow, the insulation of the ensemble is highlighted in orange, and the insulation of the masks is highlighted in green.

Position	Chair	Condition	Mask			
			No mask	Mask 1	Mask 2	Mask 3
Back in contact with chair	Reference	Naked	0.00	0.05	0.05	0.05
		Clothed	0.61	0.61	0.61	0.61
	Chair 2	Naked	0.14	0.16	0.16	0.16
		Clothed	0.72	0.78	0.78	0.77

Table 4
Change in operative temperature corresponding to PMV = 0 when adding the thermal insulation of the chair.

Parameter	Condition	Representative values for back in contact with chair			Representative values for back not in contact with chair			Representative values for average posture	
	Chair (clo)	0.1	0.16	0.26	0.05	0.09	0.18	0.08	0.22
	Ensemble + chair (clo)	0.71	0.77	0.87	0.66	0.70	0.79	0.69	0.83
Optimum operative temperature (°C)	24.5	23.9	23.5	22.8	24.2	23.9	23.3	24.0	23.1
Change in optimum operative temperature (°C)	–	-0.6	-1.0	-1.7	-0.3	-0.6	-1.2	-0.5	-1.4

in contact with the chair. For chair #8, the insulation added when the manikin leaned towards the backrest seemed too small to be relevant for the practical thermal comfort assessment. The backrest of chair #8 was made of a non-cushioned fabric mesh; therefore, the contribution of the backrest to the overall chair insulation was only modest. For the other chairs, the average effective insulation added by the posture with back-chair contact was 0.09 clo, corresponding to a change in PMV of around 0.15 scale units or a decrease in neutral temperature of 0.6 °C at 25 °C, 50% relative humidity, 0.1 m/s air velocity, and seated activity (1.2 met). This magnitude is equivalent to the insulating effect of a standard office chair or the increment in the insulation of using an executive chair instead of a standard office chair when predicting comfort with PMV [25,28]. Through its effect on thermal perception, chair and clothing insulation may influence employee performance with consequences for the economy of a business [29]. Chair insulation *per se* may not play the most prominent role in work performance, but it contributes to the overall thermal exposure. Therefore, for individuals to adapt to their thermal environment, they should be allowed or even encouraged to modify clothing insulation to optimise their comfort and performance. This implies that strict dress codes do not support building sustainability.

Accounting for the effect of the sitting posture when evaluating comfort is probably not feasible, as most people's posture changes intermittently and repeatedly during a workday. Nevertheless, the sitting posture may differ between, e.g. auditoria and office or meeting rooms and affect the thermal perception [22]. The findings of this study add to our understanding of the many factors that may affect comfort and the variation in comfort between occupants. Unless more specific information about the posture is available, a simple arithmetic average of the values presented in Table 2 seems to be the best estimate to use in comfort predictions in practice.

In earlier analyses of the ASHRAE global thermal comfort database, it was found that many studies did not report the chair and clothing insulation [24,25]. McCullough et al. [5] suggested that one reason why field studies often find lower preferred temperatures than predicted is the omission of the chair insulation when using thermal prediction models (e.g. PMV). They suggested that the added chair (effective) insulation for thermal comfort prediction should be 0.1–0.3 clo. Even though there are around 30 years between McCullough et al.'s and this study, and as chair design may have changed during this period, the effective insulation values of the tested chairs corresponded well with these earlier findings. The highest measured effective clothing insulation was 0.26 clo provided by chair #6 when the back of the manikin was in contact with the backrest. Chair #6 resembled the executive chair McCullough et al. [5] applied, which had a measured effective clothing insulation of 0.3 clo. Also, Wu et al. [18] measured the thermal insulation of an aircraft seat and found that the added insulation ranged from 0.15 to 0.35 clo, depending on the clothing worn. The area of the body in contact with the aircraft seat is larger than most office chairs, contributing to the insulation provided by the aircraft seat.

In previous research [25], we showed the importance of accounting for the thermal insulation provided by chairs for thermal comfort assessments. In this work, we further analysed and quantified contemporary office chairs' thermal insulation. A potential application of the findings of this work is that appropriate and individual chair selection may be used to adapt the range of temperatures that are considered comfortable and could be used to address differences in thermal preference as caused by, e.g. gender or thermal disposition [27], saving energy in buildings.

The use of facemasks became common during the COVID-19 pandemic, and considering the timing of the present study, measurement of the insulation added by different types of facemasks was relevant. The tested facemasks all provided the same marginal insulation, I_{clu} ~0.05 clo, corresponding with that provided by, e.g. thick ankle socks or a singlet (ISO 9920–2009).

5. Conclusions

This study explored the influence of the sitting posture on the thermal insulation provided by seven contemporary office chairs and quantified the insulation provided by different facemasks. The main findings of this work are the following:

- The sitting posture affects the thermal insulation provided by chairs. On average, leaning forwards reduced the chair insulation by 0.09 clo. A reduction of this magnitude is relevant to account for in the assessment of thermal comfort in rooms where people spend most time leaning forwards, such as auditoria.
- The thermal insulation provided by the selection of contemporary office chairs is similar to previous studies, i.e. chair insulation values in the usually recommended range from 0.1 to 0.3 clo are still valid for office settings. Still, a more realistic range of insulation values to be added to the effective insulation value of other garments is probably from 0.08 to 0.22 clo, when assuming that people will sit half the time with the back in contact with the chair backrest and the other half leaning forward.
- Facemasks provide a small but not insignificant effective thermal insulation of 0.05 clo, equivalent to the insulation provided by thick ankle socks or a singlet.

The study confirmed the chair insulation values suggested in earlier studies and that both sitting posture and chair insulation should be carefully considered and included when assessing and predicting thermal comfort. Appropriate and individual selection of chairs by occupants may reduce individual differences in thermal perception, improving thermal comfort, e.g. a person more sensitive to heat [27] may select an office chair with lower thermal insulation. The findings of this study add to our understanding of the many factors that may affect thermal comfort, highlighting the variability in thermal insulation between individuals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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