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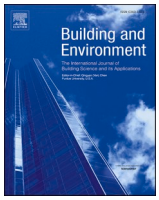

Experimental study to quantify airborne particle deposition onto and resuspension from clothing using a fluorescent-tracking method

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ABSTRACT

The rapid spread and high level of morbidity of the SARS-CoV-2 virus during the COVID-19 pandemic has attracted considerable attention worldwide. Recent studies have shown that clothing is one of the vectors for the transport of airborne particles, including bioaerosols. This study developed a method that can both quantify the deposition of particles onto clothing and the resuspension of particles from clothing using a fluorescent-tracking technology and found that electrical tape can be used as a fluorescent particle collector on irregular clothing surfaces. Results show that 0.07%–6.61% of the fluorescent particles (FPs) previously loaded on the room flooring surfaces moved to the occupant's clothing during the 20-min sampling periods; the percentage depended on the type of activity and the range is for: office work, walking, and vacuuming. Furthermore, both the flooring type (carpet or vinyl composition tile) and flooring condition (clean or dirty) had significant effects on particle resuspension and transport to the occupant's clothing. The average particle deposition factor for carpet flooring was 2.7 (±1.4) times that for vinyl composition tile flooring, while the average particle deposition factor for dirty flooring was 2.4 (±1.6) times that for clean flooring. A multiple regression analysis shows that the activity type had the largest effect on the particle transport among all experimental variables. An additional experiment performed in a full-scale house shows that 46.8% of FPs formerly seeded on clothing resuspended from clothing and dispersed around the house during the 1-h period of light walking at a speed of 60 steps/min.

1. Introduction

Particulate matter has been associated with adverse health outcomes, such as skin allergies, eye irritation, asthma, respiratory illness, cardiovascular illness and infectious illness [1–3]. The COVID-19 pandemic has drawn worldwide attention to the transport of airborne particles [4] because there is significant potential for exposure to viruses in microscopic respiratory particulate matter [5].

In recent years, clothing has been proven to serve as an important vector for airborne particle transport [6], and there is a growing concern regarding the role of clothing in transmitting microorganisms and viruses in hospitals [7]. Clothing may transport particles in two ways. First, clothing acts as a reservoir of particles, including bioaerosols. Second, clothing serves as an indirect source by emitting particles previously deposited, spreading particulate matter from one place to another; in the case of pathogens, this leads to cross contamination and increased number of people who are at risk of exposure [7,8]. The deposition of particles onto clothing and the resuspension of particles from clothing are closely connected; together they define the overall particle transport by clothing.

Specific evidence has been found that clothing can serve as a carrier for biological particles and other indoor pollutants [9]. Jantunen and Saarinen [10] found that pollen can be brought into residential buildings by clothing after being worn while walking through grasslands or just being outdoors. Another research found that clothing fabrics can act as an effective pollen collector [11]. In addition, spores associated with cow barns were detected in the nearby farmers' houses, suggesting the movement of bioaerosols from the barn into the house on the clothes of the residents [12]. Clothing can also serve as a vector for the cross-transmission of aerosols inside buildings. Homaira and colleagues [13] discovered that personnel clothing had been contaminated with respiratory syncytial viral RNA that could facilitate the transmission of viruses in hospitals. The survival time of many medically important fungi on clothing fabrics was longer than a day, which could enable the transfer of viable fungi from clothing [14]. A review by Mitchell et al. [15] concluded that healthcare textiles, including uniforms or apparel

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textiles, were a vector for the transmission of microorganisms that cause infections and illnesses in healthcare workers, patients, and the community. These studies prove that clothing is a vector for particle transport from outdoor to indoor environments, as well as transport within indoor environments. However, evidence that quantifies the importance of this process with regard to particle size, particle aerodynamics, and quantitative characterization remains limited [16]. In addition, differences in particle deposition onto different parts of clothing or the human body have rarely been reported in the published literature, which is important for exposure calculations [17].

Clothing is an airborne particulate source as the initially deposited particles can be resuspended by human movement and become re-airborne; this is a potential source for secondary exposure [16]. Some previous studies have regarded clothing as a particle source by increasing the detachment of skin flakes via friction [18]. However, recent studies have demonstrated that resuspension of outdoor-derived bioaerosols from occupant clothing and indoor surfaces was a stronger source than direct shedding from human bodies [9]. Tian et al. [19] studied the effect of clothing coverage, clothing color, and clothing condition on bioaerosol shedding and resuspension in an environmental chamber, and the particle emission rate while walking with a 90 step/min frequency was calculated using a mass-balance model. Licina and Nazaroff [6] found that 0.3%–3% of deposited particles with a size of 0.5–10 μm were released on average with the movement of the fabric. McDonagh and Byrne [20,21] found that physical activity resulted in up to 67% of the deposited particles being resuspended into the air. These quantitative studies were all conducted in well-controlled experimental chambers, and the accurate data about the dispersion of particulate matter resuspended from clothing in real buildings are still scarce.

While previous research has discovered the role of clothing in transporting particles, some key information is still lacking. First, quantitative analysis of particle deposition onto clothing and resuspension from clothing is scarce. Different from the biological particle tracking methods used in previous studies, this study used a fluorescent particle-tracking method to quantify the deposition and resuspension processes. Engineered fluorescent particles can emit energy at a specific wavelength under irradiation at a specific incident wavelength; the contrast between the target and the background is increased allowing to easily track and count the fluorescent particles. This fluorescent-tracking method has been widely used in indoor aerosol research, including: studies on the resuspension and age of indoor particles [22], particle resuspension from monolayer and multilayer deposits on different surfaces [23] and the transport of indoor particles to hidden interior spaces in residential buildings [24]. This study is expanding the application of fluorescent particles in surface-to-surface transport research. Second, myriad factors – such as the location on clothing and human activity – that affect the deposition of particles onto clothing have not been systematically investigated. This study used multiple linear regression to quantify the importance of each influential factor. Third, few studies investigated resuspension of particles from clothing and the impact of this process on indoor air quality in realistic buildings. This research gap was addressed in this study by conducting experiments in a full-scale three-bedroom/two-bath test house that mimics a real residential building. Overall, this paper provides quantified and transferrable information about the function of clothing as a potential transport vector for particles in buildings.

The specific objectives of this paper are to: (1) develop an accurate methodology that quantifies both the deposition of particles onto clothing and the resuspension of particles from clothing with fluorescent-tracking technology; (2) assess the effect of human activity types, flooring types, flooring conditions, sampling periods, and sampling locations on particle deposition onto clothing; and (3) study the distribution of resuspended particles from clothing in a full-scale residential environment.

2. Methodology

2.1. Experimental design

To quantify the effect of clothing on airborne particle transport, two experimental scenarios were conducted in this research. The first scenario was developed to assess the deposition of fluorescent particles (FPs) onto clothing originally resuspended from flooring under different activities. The second scenario allowed to study the spread of FPs from clothing to a realistic residential environment.

2.1.1. First scenario

The first scenario was conducted in a well-controlled stainless-steel environmental chamber with a size of 3 × 3 × 3 m. The temperature and humidity in the chamber were kept the same and recorded by HOBO data loggers (UX100-003, Onset, Inc., Bourne, MA) (Table 1). A male volunteer (who is also the first author of the paper) with a height of 1.75 m and weight of 70 kg remained in the chamber to simulate three common activities typical for an office or a home environment; these are office work (reading a book while occasionally putting down the book and walking for 30 s every 5 min), walking (with a constant speed of approximately 60 steps/min), and vacuuming (with a lightweight vacuum cleaner that did not have a brush roll), as shown in Fig. 1. The volunteer was well protected with protective apparel (Model Tyvek TH122S, DuPont, Inc., Wilmington, DE), a mask (Model 6001, 3M Corp., St. Paul, MN), examination gloves (Model G10, VWR Corp., Radnor, PA) and glasses. It should be noted that the protective apparel was made of high-density polyethylene fibers randomly laid and compressed, whose material and weave pattern are different from ordinary clothing. The protective apparel was chosen for its non-linting and anti-static properties [21].

Fig. 1 shows the locations of the samples and instruments in the first part of the experiments. There were nine sampling points, referred to as “on-body samples” on the apparel: three on the chest (C1 – C3), three on the arms (A1 – A3), and three on the legs (L1 – L3). Another nine samples, referred to as “static samples”, were set in groups of three at heights of 1.5 m, 1.0 m, and 0.5 m on a support in the center of the chamber, corresponding to the on-body samples on the chest, arms, and legs (denoted by SC1 – SC3, SA1 – SA3, and SL1 – SL3, respectively). In addition, three particle counters (Model 9306-V2, TSI, Inc., St. Paul., MN) were placed on a support at the same three heights as the static samples in the corner of this chamber to measure the real-time airborne particle concentrations.

Four cases involving different flooring types and conditions were investigated in the first scenario, as shown in Fig. 2; i.e., dirty carpet flooring in case 1, dirty vinyl composition tile (VCT) flooring in case 2, clean carpet flooring in case 3, and clean VCT flooring in case 4. Carpets and VCTs are two common flooring types on the market [25]. The “dirty” flooring condition was generated by uniformly releasing ultrafine test dust (A1 dust, Power Technology, Inc., Arden Hills, MN) into the chamber prior to the seeding of FPs. The A1 dust-loading density was 14.1 g/m^2 (shown in Table 1), which was large enough to form multilayer particle-to-particle deposits [26]. In real situations, the particle-loading density has been measured to be 6.2–20.3 g/m^2 [26,27].

In addition to the flooring types and dirty/clean conditions, the other settings and procedures for the four cases were similar. The 1st step was A1 dust generation and seeding (not applied to cases 3 and 4). A total of 130 g of A1 dust was injected into the chamber with a homemade generator for 5 min and left to settle for 2 h. Four mixing fans in the corners were used to uniformly distribute the particles. The 2nd step was FP generation and seeding. Fifteen glass slides (Premiere 9101-E) were uniformly placed on the floor prior to this step. FPs were injected into the chamber for 6 h (details provided in Section 2.2). The mixing fans remained on during the injection. The chamber was left unoccupied for approximately 16 h to provide sufficient time for the deposition of FPs.

Table 1
Experimental condition for different cases (average ± standard deviation).

Case No.	Flooring	Experiment location	A1 dust loading (g/m^2)	FP loading on floor (#/cm^2)	Temperature (°C)	Humidity (%)
1	Carpet-dirty	Chamber	14.1	2269 ± 425	22.4 ± 2.5	41.2 ± 3.5
2	VCT-dirty	Chamber	14.1	2586 ± 327	22.9 ± 3.1	43.7 ± 2.5
3	Carpet-clean	Chamber	/	2359 ± 415	23.4 ± 1.7	42.6 ± 2.5
4	VCT-clean	Chamber	/	2644 ± 345	23.1 ± 2.3	43.1 ± 3.2
5	VCT	Test house	/	/	18.4 ± 0.7	51.2 ± 1.5

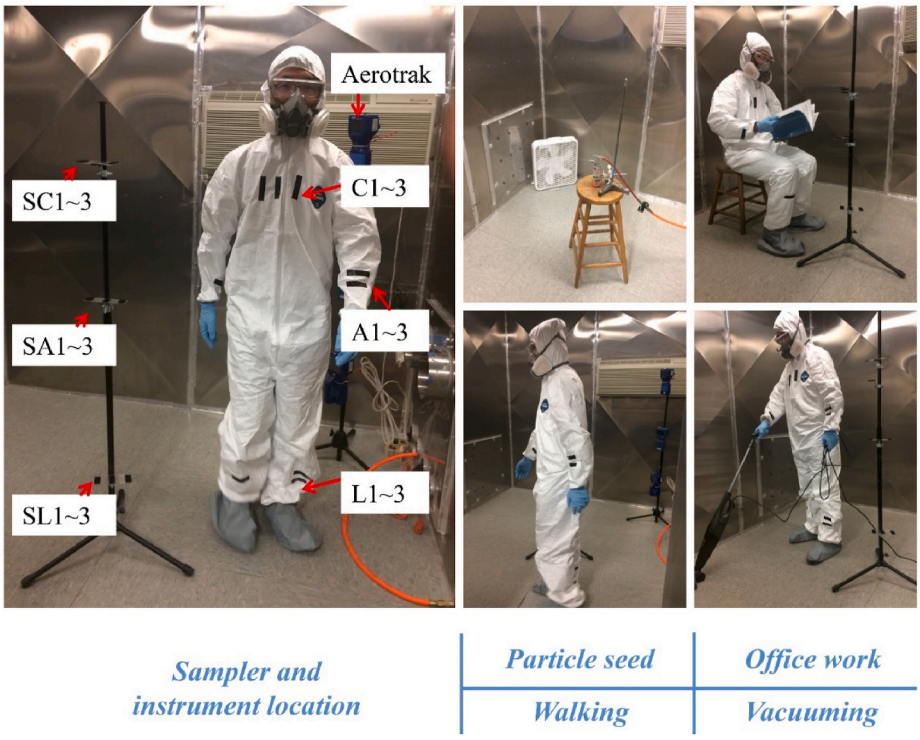

Fig. 1. Specific locations of samples and instruments and photos of the activities in the first scenario.

Then, the glass slides were collected to count the FP-loading density on the flooring. As summarized in Table 1, the initial FP-loading density was very similar in all cases (with the largest relative difference <15%). The 3rd step was office work activity. On the following day, 1 h of office work was conducted in the chamber by the volunteer. Three groups of on-body samples were collected, each sampled for 20 min. At 20 min and 40 min, the on-body samples were carefully collected by another researcher and replaced with a new set of samples. However, the static samples were not replaced during the 1-h activity. Thus, 36 samples were collected in one activity: 9 on-body samples (0–20 min interval) + 9 on-body samples (20–40 min interval) + 9 on-body samples (40–60 min interval) + 9 static samples = 36 samples. The 4th step was walking activity. The 5th step was vacuuming activity. The settings in the 4th and 5th steps were similar to those in the 3rd step. The 6th step was cleaning. All surfaces in the chamber, including the floor, walls, monitors, and mixing fans, were cleaned (which included washing with water) at least twice to prevent cross-contamination between different experimental cases. For each activity, a new protective apparel was used. In total, 108 samples were collected in one case, and 432 samples were collected in this scenario. The FP-density on each sample was then counted and computed (details provided in Section 2.2).

Different from previous studies [24], electrical tape was used to collect particles instead of glass slides (shown in Fig. S1). In the first scenario, the majority of samples were on-body samples. Tape was more adaptable to different body parts and could not slip or fall during activities. Preliminary experiments were conducted to prove the feasibility of this method. First, the sampling accuracy of the tape and glass slide was compared. Three commonly used kinds of tapes were compared: electrical tape, medical tape, and black duct tape (Fig. S1). Five of each sampling medium were placed randomly in a 1 × 1 × 1 m stainless-steel chamber (Fig. S2). FPs were injected into the chamber for 10 min, and two small mixing fans were used to mix the generated particles well. After generation, the FPs were left to deposit for 24 h. Then, the samples were collected and the number of particles on these samples were counted. This experiment was repeated three times. The results are summarized in Fig. S3. Results show that only the number of FPs on the electrical tape samples was sufficiently close to that on the glass slides, with a relative difference of 2.4%. It is possible that the rough surfaces of the medical tape and black duct tape may reduce the detection of FPs on them by fluorescent microscope. In the follow-up experiments, we checked whether the deposited particles on the electrical tape could be lost during the tape-removal process (the tape used for sampling could be removed from clothing in the experiments). FPs were seeded on ten tape samples. For each sample, we taped the electrical tape on clothing and then removed it. This process was repeated three times. The initial number of particles and the numbers after being removed for the first, second, and third times were counted. As shown in Figs. S4 and 97.5% of particles remained on the tapes after the first removal, and 92.1% of particles remained after the third removal. These preliminary experiments proved that electrical tape performed as well as glass slides in collecting particles, and this tape is more suitable for use on irregular surfaces, e.g., the human clothing.

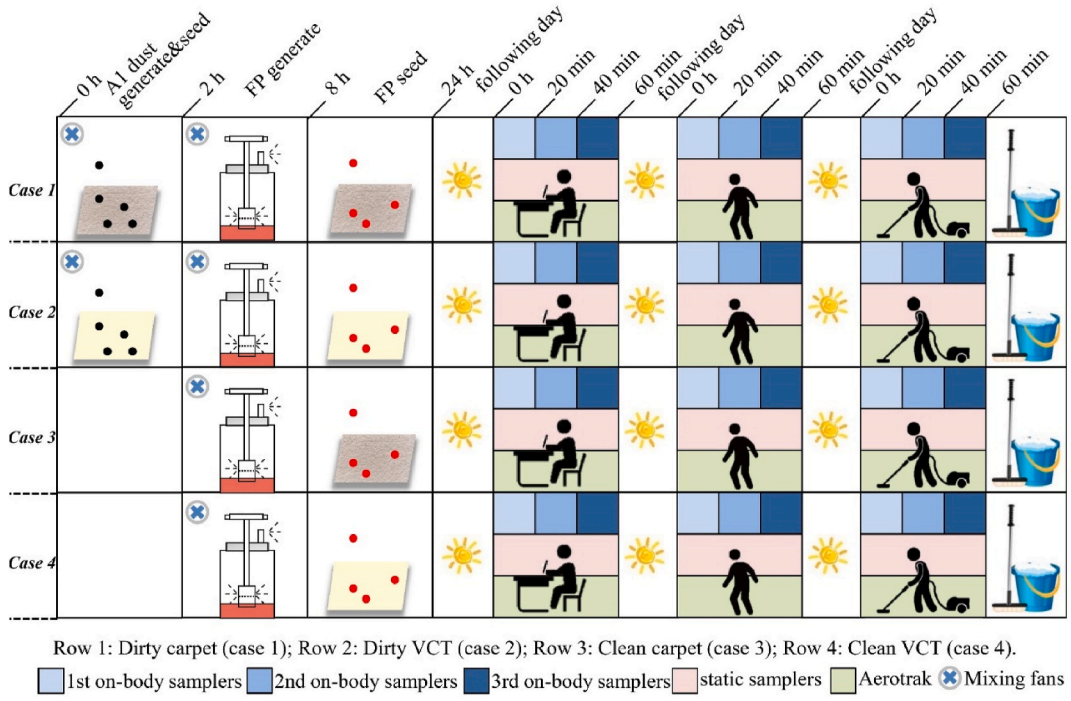

Fig. 2. Experimental diagram for the first scenario.

2.1.2. Second scenario

The second scenario was conducted in an unoccupied one-living room/three-bedroom/two-bath test house [24] in Austin, TX, with a floor area of 111 m^2. A detailed description of the test house can be found in Ref. [28]. There was minimal furniture inside the house, i.e., a few tables and chairs. Although there were two heating, ventilation, and air conditioning (HVAC) systems, the house air-handling units were turned off during experiments to prevent particle deposition in HVAC components and avoid its impact on particle transport. The average temperature and humidity during experiments were 18.4 °C and 51% RH (Table 1). During experiments, all exterior doors and windows were closed while all interior doors were open except the doors of closets, which allowed for temperature difference and buoyancy driven air circulation between rooms. Thirty-nine sampling points were set on the floor, and each point had three glass slides; therefore, 117 samples were collected from the house floor. The layout diagram of the test house and samples is shown in Fig. S5.

The experimental procedures consisted of the seeding of FPs on clothing and walking in the test house wearing the clothing. A protective apparel was placed flatwise on the floor at the center of the chamber used in the first scenario. Fifty electric tape samples were uniformly attached to the apparel on the front and back sides. FPs were then injected into the environmental chamber and left for 24 h to settle. The protective apparel was turned over and seeded with FPs on the other side for another 24 h. The FP density on the samples was counted to represent the on-cloth particle density. The seeded protective apparel was carefully transported from the chamber to the test house and dressed by the volunteer. The volunteer walked in the living room at a speed of approximately 60 steps/min according to the walking route shown in Fig. S5 for 1 h. Afterwards, the house was left unoccupied for 24 h. Then all on-flooring samples were carefully collected, and the density of FPs on them was counted using fluorescent microscope.

2.2. Generation and tracking of fluorescent particles

A full description of the fluorescent-tracking technology used in this work can be found in previous studies [23,24], and it is summarized as follows.

This study used monodispersed fluorescent particles with a diameter of 3.2 μm (Model R0300B, Thermo Scientific, Inc., Waltham, MA). This size was selected because the particle diameter of 3.2 μm can be used as a representative of biological aerosols in buildings [27]. A Collison nebulizer (Model CN24, BGI, Inc., Waltham, MA) was used to inject the FP solution (1% FPs by weight and 91% medicinal alcohol in water) into the chamber with pressurized air for 6 h (Fig. 1).

A fluorescence stereoscope (Model MZ16 FA, Leica Microsystems GmbH Wetzlar, HE, DE) was used to count the number of FPs on each sample. The settings of the fluorescence stereoscope (exposure time, gamma, gain, etc.) are summarized in Table S1. For each sample, 416 images were taken by a black and white camera (Model Leica DFC350 FX) from setting locations with the MultiStep bidirectional scan function, and they were concatenated into one photo, as shown in Fig. S6.

All samples were successively scanned by a fluorescence stereoscope, and a database was established containing all images. The number of FPs on samples was automatically counted by a program [23] in MATLAB (MathWorks, Inc., Natick, MA). Finally, the average and standard deviation (SD) of the concentrations of FPs at each sampling location were computed.

2.3. Data interpretation

In this study, we define "the particle deposition factor" for the first scenario and "the particle resuspension factor" for the second scenario. The particle deposition factor for the i^{th} sample (DF_i) can be defined by the following equation:

$$DF_i = \frac{N_i}{N_{floor}} \times 100\% \quad (1)$$

where N_i is the number of FPs on sample i (particles/cm^2), and N_{floor} is the number of seeded FPs on the flooring (particles/cm^2).

N_i was positively correlated with the particle mass flux due to the same sampling period in different cases [29]:

$$DF_i \cdot N_{floor} = N_i \propto J_{PM} \quad (2)$$

The particle mass flux (J_{PM}) can be calculated by the following

equation [29]:

$$J_{PM} = C_{PM} \cdot v_d \tag{3}$$

where C_{PM} is the fluorescent particle concentration (μg/m^3), and v_d is the particle deposition velocity (m/h).

Because N_{floor} was approximately the same among all cases in the first scenario (Table 1), according to Eqs. (2) and (3), DF was positively correlated with C_{PM} and v_d:

$$DF \propto C_{PM} \cdot v_d \tag{4}$$

Although a quantitative formula is not given due to the complexity of particle deposition onto the human body, the qualitative relationship derived in Equation (4) can still be used in the discussion of the results in this study.

The particle resuspension factor (RF_i) was defined for the second scenario:

$$RF_i = \frac{N_i}{N_{clothing}} \times 100\% \tag{5}$$

where N_i is the number of FPs on the ith sample on the floor in the second scenario (particles/cm^2), and $N_{clothing}$ is the number of seeded FPs on clothing (particles/cm^2).

The clothing release fraction (CRF) is defined as the ratio of released to deposited FPs on clothing [6]:

$$CRF = \frac{\sum_{i=1}^{n} RF_i \cdot S_{floor}}{n \cdot S_{cloth}} \tag{6}$$

where RF_i is the particle resuspension factor measured at point i; S_{floor} is the floor area of the test house, 111 m^2; S_{cloth} is the area of the protective apparel, which is approximately the same as the person skin surface area (only the face was not covered by the protective apparel); n is the number of samples on the floor, which is 117. The skin surface area is estimated to be 1.85 m^2 in this study by using the height and weight of the volunteer [30]. It would be more accurate to measure the CRF in a smaller environmental chamber instead of the test house. However, the experiment in the test house can better simulate the distribution of resuspended particles from clothing in a real environment.

Apart from the tracking of FPs on tape samples in the first scenario, three particle counters (Model 9306-V2, TSI, Inc., St. Paul, MN) were used to measure the airborne particle concentrations every 30 s. Because the FPs have a diameter of 3.2 μm, the real-time particle number concentration in the size bin of 2.5–5 μm was used to calculate the particle resuspension rate by the following equation:

$$r = \frac{V}{A_r L_{(t)}} \left[\frac{C_i(t + \Delta t) - C_i(t)}{\Delta t} + k_n C_i(t) \right] \tag{7}$$

where r is the resuspension rate (min^{-1}); V is the chamber volume (m^3), 27 m^3 in this study; A_r is the resuspension area (m^2), 9 m^2 in this study; $L(t)$ is particle loading in the size range of interest (particles/m^2); C_i is the particle number concentration in the size range of interest (particles/m^3); and k_n is the deposition loss rate (min^{-1}), which is 0.015 min^{-1} for a particle size of 3.2 μm [31]. The continuous monitoring method by particle counters has been widely used to calculate particle source strength or particle resuspension rate. The specific calculation method and process can be found in previous studies [31,32].

Statistical analysis was conducted in SPSS version 22 (Armonk, NY: IBM Corp.). Student's t-test was used to analyze the variables. The Pearson correlation test was used to analyze the correlation between two variables. Multiple linear regressions were performed to calculate the best-fit models for the particle deposition factor and experimental variables (flooring type, flooring condition, different activities, etc.). A p-value less than 0.05 was considered to be significant across all statistical tests.

2.4. Uncertainty analysis and quality assurance

In this study, the uncertainty of the results was not caused by the uncertainties associated with the detection and quantification of FPs on a given sample but rather the spatial distribution of deposited FPs at a sampling point. To decrease the influence caused by measurement error, three sampling samples were placed at each sampling point. The measured concentrations of FPs at each sampling point were averaged, and the corresponding standard deviations were calculated. In addition, all three particle counters used to measure airborne particle concentrations were calibrated with the more accurate aerodynamic particle sizer (APS) (Model 3321, TSI, Inc., St. Paul., MN). Trial experiments (data not reported here) were conducted for both the chamber and test house scenarios when developing the experimental methodology to ensure adequate repeatability of the particle seeding and tracking methods.

3. Results

The results from the experiments in the environmental chamber (cases 1 to 4 from the first scenario) characterize the particle deposition factor while results from the experiment in the full-scale house (the second scenario) define the particle resuspension factor.

3.1. Particle deposition factor

The following subsection describes how the particle deposition factor depends on different activities (office work, walking, and vacuuming), flooring conditions (clean or dusty) and materials (carpet or vinyl), sampling periods, and sampling locations on clothing, as well as on applied statistical analysis.

3.1.1. Effect of activity type

Fig. 3 shows the particle deposition factors which quantify transport from the floor to clothing; the four graphs summarize the results for cases 1–4 in the first scenario (experiments conducted in the environmental chamber with different floor surfaces) and show the dependency of particle deposition factors on the activity level and position on clothing. During the 20-min periods of the three activities, the average particle deposition factor ranged from 0.07% to 6.61%. A large variation in the deposition factor exists amongst different activity types within the same case ($p < 0.05$).

Specifically, results in Fig. 3 show that the deposition factor is larger for walking; the average particle deposition factor for office work and vacuuming in each case is 16.3%–55.6% and 16.4%–41.9% of the average deposition factor for walking. It is not surprising to find that the particle deposition factor during office work was smaller than that during walking due to the relatively lighter activity strength of office work. Equation (4) shows that the deposition factor is positively correlated to the particle concentration in the air, which has been reported in previous studies to increase with the activity strength. Bhangar et al. [33] reported that walking was associated with a 5–6 times increase in the occupant emission rate of fluorescent biological aerosol particles than sitting. Ferro et al. [34] found that the $PM_{2.5}$ strength of dancing on a rug was three times larger than walking on the same rug. The source strength of two persons walking and sitting on furniture almost tripled that of one person performing the same activity. Qian and Ferro [32] observed that a heavy and fast walking style was associated with higher resuspension than a less active walking style. In the current study, walking resuspended more particles compared to office work, which caused at least 1.8 times more particles from the floor to deposit onto clothing.

The finding that vacuuming was associated with smaller particle deposition factors than walking in this study does not agree with some of the previous studies [34,35]; this is probably due to the different type of vacuum cleaning devices used. It is likely that the vacuum cleaner used

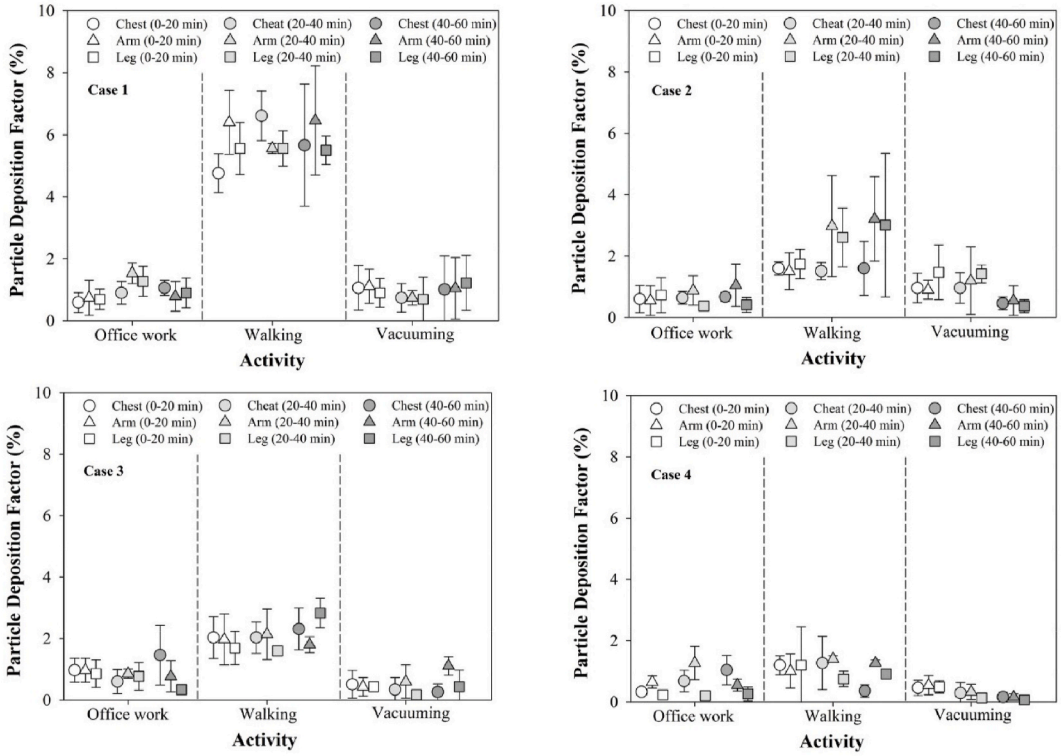

Fig. 3. The particle deposition factors measured by on-body samples in experiments conducted in the environmental chamber (scenario one). Cases 1, 2, 3, and 4 represent: dirty floor for carpet, dirty floor for VCT, clean floor for carpet, and clean floor for VCT, respectively.

in this study compared with the previous studies [34,35] cleaned the floor surface by resuspending particles and also successfully removing them by the vacuuming cleaning bag, the overall result of which was fewer suspended particles in the air. Lewis and colleagues [36] also found that vacuuming resulted in a much lower resuspension rate of dust and allergens than walking.

Fig. 4 shows the effect of human activity on the in-chamber airborne particle concentration in the size range of 2.5–5.0 μm. It should be pointed out that the graphs for cases 1 and 2 (cases with dirty floor for carpet and VCT, respectively) have a different scale than for cases 3 and 4 (cases with clean floor for carpet and VCT, respectively). Also, the airborne particles measured by particle counters included FPs (cases 1–4) and A1 dust particles (cases 1 and 2). The gray area represents the three 20-min activity periods for each activity type in each case.

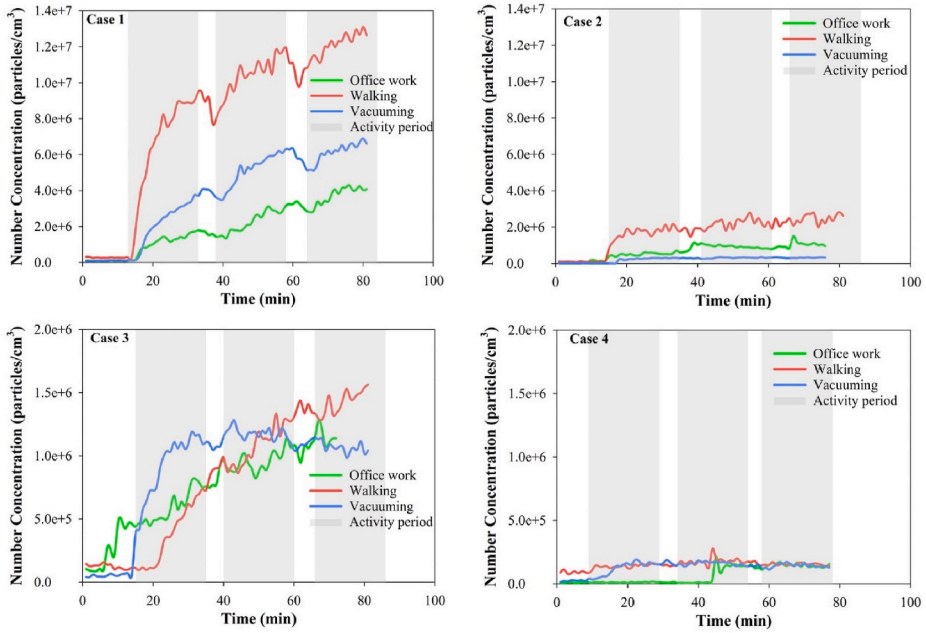

Fig. 4. The average airborne particle number concentration measured by three particle counters in the size range of 2.5–5.0 μm in the first scenario. Cases 1, 2, 3, and 4 represent: dirty floor for carpet, dirty floor for VCT, clean floor for carpet, and clean floor for VCT, respectively. It should be noted that the graphs for cases 1 and 2 have a different scale than the graphs for cases 3 and 4. The gray area represents the activity periods.

Between every two activity periods, particle concentrations decayed to some extent; however, the gap time was not long enough for the airborne particle concentrations to decay to the background level. Additional results on effect of flooring on airborne particle concentration can be found in Fig. S7. Coinciding with the first 20-min activity event during walking, concentrations of particles in the size range of 2.5–5.0 μm rose sharply to orders of magnitude higher than the background level except for case 4. This observation agrees with those of Thatcher and Layton [37] and Qian and Ferro [32], both of which reported walking-induced resuspension of 0.3–25 μm particles. Compared with the other two activities, walking introduced at least twice more particles by resuspending them from the dirty floor (cases 1 and 2), which explains the higher deposition factor for walking in these two cases (Fig. 3). In contrast, in cases 3 and 4 where the floor was not pre-loaded with dust, the number concentrations of resuspended particles during the three activities are similar (Fig. 4). The higher deposition factor for walking in these two cases shown in Fig. 3 can be attributed to a higher particle deposition velocity to clothing during walking. As shown in Equation (4), the particle deposition factor is positively correlated to v_d (particle deposition velocity to the clothing) in addition to C_{PM} (fluorescent particle concentration). Wang and Chow [38] discovered that human walking increased the local air velocity and subsequently the deposition of 0.5–20 μm droplets on a vertical wall.

3.1.2. Effect of flooring condition and type

Fig. 5 summarizes the effect of flooring types and conditions on the particle deposition factor. It should be noted that the effects of other variates (i.e., sampling period and sampling location) have not been distinguished in this graph and will be discussed in the following sections. For each activity type, the average deposition factor in case 1 with dirty carpet is the highest, followed by case 2 with dirty VCT or case 3 with clean carpet, and lastly case 4 with clean VCT. Especially for the walking activity, the average particle deposition factor in case 1 (5.79 ± 0.59%) was 2.6, 2.8, and 5.6 times the deposition factors in case 2 (2.20 ± 0.74%), case 3 (2.04 ± 0.37%), and case 4 (1.04 ± 0.33%), respectively. Therefore, both the flooring type (carpet/VCT) and condition (clean/dirty) have significant effects on particle deposition factors, and the deposition factor for walking is the most sensitive to these two factors.

The ratio of the deposition factor on carpet over VCT under the same flooring condition (clean/dirty) is shown in Fig. S8. The average particle deposition factor for carpet flooring was 2.71 ± 1.40 times that for VCT flooring, which was mainly caused by the difference in the particle resuspension rate. As shown in Fig. S7, the concentration of resuspended particles is higher for carpet than VCT regardless of the flooring condition (clean/dirty) and activity type. Table 2 shows the resuspension rates of FPs and A1 dust in cases 1 and 2 which were calculated by using the airborne particle number concentration reported in Fig. 4 and Equation (7). The particle resuspension rates for carpet were 3.05, 2.75, and 2.85 times those for VCT under office work, walking and vacuuming, respectively. These results agree with those from previous studies related to activity-induced particle resuspension conducted in chambers and real buildings. Tian et al. [39] discovered that for particles in the size range of 3–10 μm, the resuspension rate for carpet was 2–4 times higher than that for VCT flooring. Qian and Ferro [32] found that resuspension rates for carpet from human activities were significantly higher than those for vinyl tile flooring for particles in the size range of 1.0–10 μm. Shaughnessy and Vu [31] found that carpet displayed 2.5–5.0 times higher resuspension rates than VCT in both chamber conditions and classroom environments at similar floor loadings and particle size ranges. Ren et al. [25] found that the mean $PM_{2.5}$ and PM_{10} concentrations in classrooms with carpet were approximately 1.8 and 3.8 times higher than those with VCT flooring during an on-site measurement in 39 high school classrooms.

The ratio of the deposition factor on dirty flooring over clean flooring for the same flooring type (carpet/VCT) is shown in Fig. S9. The average particle deposition factor for dirty flooring was 2.43 ± 1.57 times that for clean flooring. The numbers of seeded FPs on the floor surfaces were similar in all 4 cases (Table 1), but the resuspended FP concentration from dirty or clean flooring was different. A multilayer particle structure was formed on the dirty flooring in this study because the A1 dust-loading density of 14.1 g/m^2 was higher than the threshold (approximately 6.2 g/m^2 according to previous in-chamber and on-site experimental studies [26,27]). Resuspension of FPs which were on the top of multilayer particle structure was considerably greater than FPs which were on the clean floor as monolayer deposits; this was likely due to reduced particle-to-particle adhesion forces, resuspension in the form of larger aggregates, and possible saltation effects for multilayer deposits [26]. A coupled CFD and particle resuspension model developed by Al Assaad et al. [40] also found that a decrease in surface roughness can increase adhesive forces and reduce the effect of vibrations (wind, human activity, etc.) on enhancing resuspension. Dust loading also has a significant effect on particle resuspension [36].

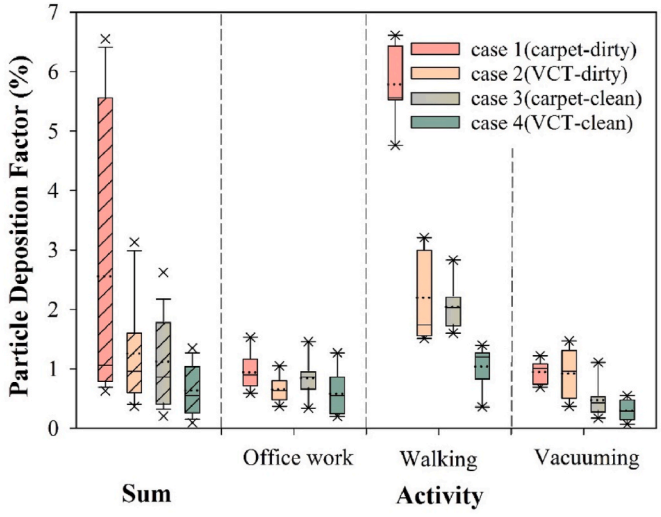

Fig. 5. The effect of flooring types and conditions on the particle deposition factor. The × symbols below and above the boxes are outliers (1st and 99th percentiles); the lines below and above the boxes are the 5th and 95th percentiles; the bottom and top of the boxes are the 25th and 75th percentiles; and the solid lines in the boxes are the medians and the dotted lines are the averages.

3.1.3. Effect of sampling period

For the chamber experiments conducted for this study, the particle deposition factor ratios for the sampling periods can be defined by the following equations:

$$R_{time\_a} = \frac{DF_{20-40\ min}}{DF_{0-20\ min}} \tag{8}$$

$$R_{time\_b} = \frac{DF_{40-60\ min}}{DF_{0-20\ min}} \tag{9}$$

These two particle deposition factor ratios are presented in Fig. 6. Results show that the sampling period has no significant effect on the measured particle deposition factors ($p > 0.05$). For all cases, the average (±standard deviation) R_{time_a} is 1.09 ± 0.49, and the average R_{time_b} is 1.09 ± 0.67. However, for vacuuming activity, the particle

Table 2
Particle resuspension rates for the two flooring types in cases 1 and 2 (average ± standard deviation, min^{-1}).

Flooring type	Office work	Walking	Vacuuming
VCT	(3.05 ± 0.59)E−03	(1.52 ± 0.22)E−02	(2.52 ± 0.32)E−03
Carpet	(9.29 ± 0.42)E−03	(4.18 ± 0.22)E−02	(7.18 ± 0.62)E−03

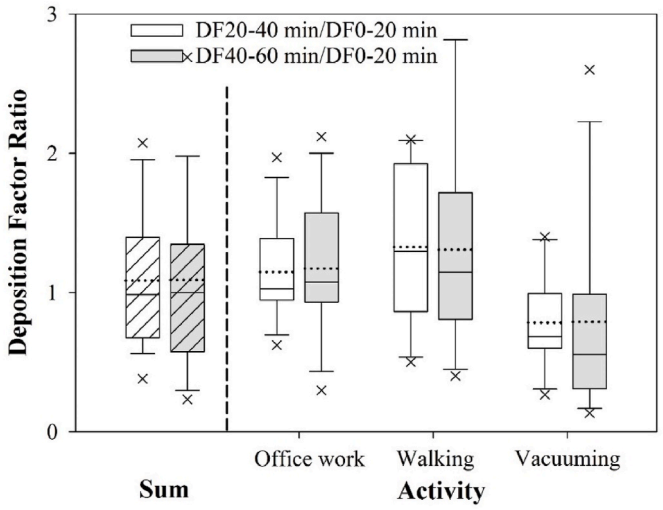

Fig. 6. The effect of the sampling period on the particle deposition factor.

deposition factors during different sampling periods are different: $R_{time\_b} < R_{time\_a} < 1$. One possible reason for this is the difference in the particle concentration in the air (Equation (4)). The particle deposition velocity should be the same for the three 20-min periods during the same activity, it is possible that the difference in the particle deposition factor for different sampling periods was caused by the variation of the particle concentration in the air. The increasing or constant concentration of resuspended particles in walking or office work activities (shown in Fig. S7) can explain why ratios R_{time_a} and R_{time_b} are larger than or close to one. However, vacuuming activity has a similar trend (increasing or constant concentration as shown in Fig. S7), but it has ratios mostly less than one. One possible reason for this discrepancy is the fact that in this specific experiment, the majority of FPs could be collected in the vacuum bag during vacuuming activity; however, this discrepancy does not change the fact that the sampling period has no significant effect on the measured particle deposition factors.

3.1.4. Effect of sampling location

As shown in Fig. 3, the average numbers of FPs on arm samples were 11%–37% times larger than those on chest and leg samples. The particle deposition factor ratio for different sampling locations was calculated by the following equations, and the results are shown in Fig. 7:

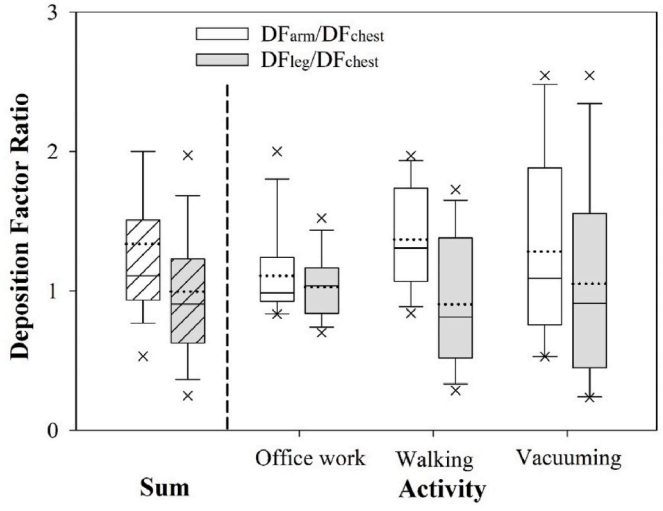

Fig. 7. The effect of sampling location on the particle deposition factor.

$$R_{location\_a} = \frac{DF_{arm}}{DF_{chest}} \tag{10}$$

$$R_{location\_b} = \frac{DF_{leg}}{DF_{chest}} \tag{11}$$

The average $R_{location\_a}$ for office work, walking, vacuuming and the sum of all activity types was 1.11 ± 0.32, 1.37 ± 0.37, 1.28 ± 0.68, and 1.34 ± 0.75, respectively. In contrast, the numbers of FPs on leg and chest samples were similar, with the average $R_{location\_b}$ for office work, walking, vacuuming and the sum being 1.03 ± 0.23, 0.97 ± 0.47, 1.05 ± 0.70, and 1.00 ± 0.49, respectively. Equation (4) can help to identify the two possible reasons for this phenomenon. First, the concentrations of resuspended FPs in the arm area were higher because the lifting force by thermal plume and activity-induced airflow together with particle gravity may determine the resuspended FP concentrations at different heights. This is confirmed by previous studies that have found that human activity-induced particles were nonuniformly spatially distributed. Rim and Novoselac [41] found that occupant thermal plumes played a significant role in transporting pollutants from the floor level to the breathing zone with a particle source at the floor level. Tao et al. [42] found that the airflow generated by the moving body could also affect the spatial dispersion of walking-induced particles. Second, the deposition velocity of FPs onto different body areas may be different due to different shapes and bending angles. The deposition velocity of particles onto human surfaces was measured by the continuous airborne particle counting method in previous studies [29,43]. However, the differences in particle deposition velocity onto different body areas could not be easily achieved by using their methods. The fluorescent-tracking method can be used in further studies on particle deposition velocity onto different body areas.

3.1.5. Multiple regression analysis

In this study, the particle deposition factor was affected by many experimental variables. Therefore, a multiple regression analysis [44] was conducted to achieve the best-fit models for the particle deposition factor and other experimental variables. Five characteristics discussed before were considered in the modeling: activity type (office work/-walking/vacuuming), flooring type (carpet/VCT), flooring condition (clean/dirty), sampling period (0–20 min/20–40 min/40–60 min), and sampling location (chest/arm/leg). The assumptions of multiple regression have been tested in SPSS. The assignment instructions for the multiple regression analysis are summarized in Table S2, and the modeling results are presented in Table 3. According to the statistical results, the relationship between the particle deposition factor and three characteristics was significant ($p < 0.05$): flooring type, flooring condition, and activity. This discovery is consistent with the discussions in sections 3.1.1 to 3.1.4 where each of the five variables is analyzed individually. The ratios of the particle deposition factors amongst different sampling periods and sampling locations are close to one, which makes these two factors unlikely to be important in the multiple linear regression. In addition to excluding these two factors, Table 3

Table 3
Multiple regression results of the best-fit models for the particle deposition factor and other experimental variables.

	Unstandardized coefficients		Standardized coefficients	t-ratio	p-value
	B	Standard error	β		
Constant	3.433	0.292		11.753	0.000
Carpet/VCT	−0.891	0.195	−0.301	−4.578	0.000
Clean/Dirty	1.029	0.195	0.348	5.282	0.000
Activity	−1.054	0.119	−0.582	−8.838	0.000

shows that the activity type has the largest absolute value of the standardized coefficient ($|\beta|$), which indicates that the activity type had the largest effect on the particle deposition factor in this study. Unlike the flooring type and flooring condition which affected the particle deposition factor solely by the concentration of resuspended particles, the activity type had an extra impact on the deposition velocity onto clothing.

3.2. Particle resuspension factor

The results of particle resuspension from clothing in the test house in the second scenario are presented in Fig. 8. The color code (from bright to dark) shows the distribution of resuspended FPs from clothing in different sections of the test house. Results show a widespread distribution of particles. The particle resuspension factor calculated by Equation (5) in the test house experiment ranges from 0.08% to 1.85% at different sampling points (Fig. 8), and the average value is 0.78%. Although the volunteer only walked in the living room (lower half of Room 2 in Fig. 8) following the route, the FPs resuspended from clothing were transported to every room in the test house. This particle movement was driven by the natural convection flow because there was no air handling unit or fan operating during the experiment. The resuspension factor is higher in the kitchen (upper half of Room 2) which have a wide opening to the living room where the volunteer walked compared to other rooms which are either connected to the living room by a doorway or not directly connected. Tang et al. [24] conducted detailed work on the movement of indoor particles in the same test house and found that the aerosols released indoors could disperse across open spaces and even settle inside closets with closed doors. The air circulation between rooms and hidden spaces was primarily driven by buoyancy forces caused by temperature differences between them.

The clothing release fraction calculated by Equation (6) is approximately 46.8%. This value indicates that nearly half of the particles previously loaded onto clothing were found on the floor after the volunteer walked in the clothing for 1 h. This result is comparable to the finding by McDonagh and Byrne [21]. They seeded monodispersed, tracer-labeled, powders onto clothing samples attached to a room suit worn by a volunteer and found that the fraction of particles that resuspended from clothing of a person engaged in low physical activity (walking for 20 min) is from 8 to 52%. They also found that, during high physical activity (running for 10 min), between 3 and 67% of the particles formerly deposited on various clothing types resuspended from the clothing. The release fraction in the study by McDonagh and Byrne was much larger than a similar study reported by Licina and Nazaroff [6]. Licina and Nazaroff seeded particles onto fabric and deployed a programmable robot to reproducibly stretch or rub the fabric with different intensities or durations. In their study, significantly smaller fraction ranging from 0.3% to 3% of deposited particles were subsequently released with fabric motion. This may have been caused by the fact that the fabric in their study was horizontally placed and thus more difficult for the resuspension of particles.

4. Discussion

The following subsections provide discussions on relevancy of the previously presented results and show the study limitations.

4.1. Comparison between on-body and static samples

In addition to on-body samples in experiments related to the first scenario, nine "static samples" were placed on a support in the center of the chamber corresponding to the heights of on-body samples. Fig. 9 shows the comparison between the on-body samples and these static samples. Three groups of on-body samples (0–20 min +20–40 min +40–60 min) were collected for each activity type in 1 h, while only one group of static samples was collected in 1 h. Therefore, the number of FPs on three groups of on-body samples was summed for comparison

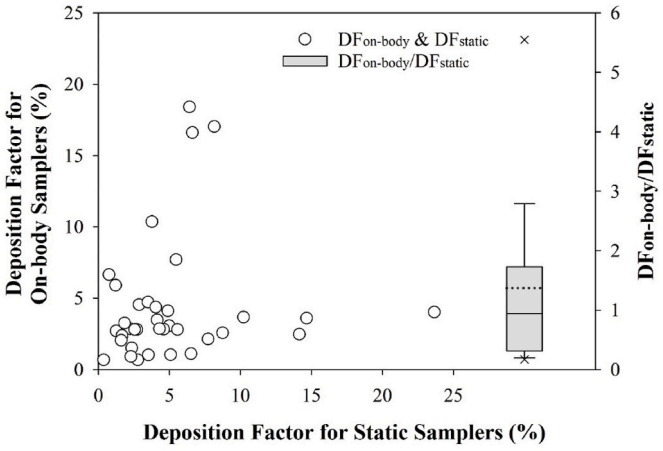

Fig. 9. Comparison of particle deposition factors between on-body samples and static samples.

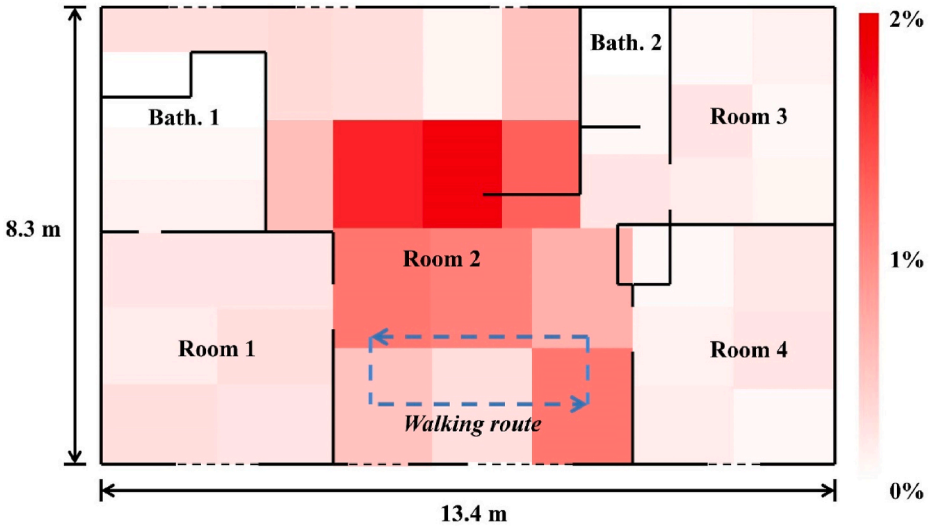

Fig. 8. The distribution of resuspended FPs from clothing in the test house. The percentage is the particle resuspension factor.

with the static samples.

Results in Fig. 9 illustrate that most of the deposition factors for on-body samples were higher than those for static samples. The average $DF_{on-body}/DF_{static}$ was 1.37 ± 0.67. Although the resuspended FP concentration at the same height during the same experiment should be similar, the orientation of samples can affect the particle deposition velocity, which affects the particle deposition factor. The particle deposition velocity onto on-body samples (approximately vertically placed) and static samples (horizontally placed) can be different. Kong et al. [8] also found that the numbers of cooking-generated particles collected by horizontally placed sampling sheets and those collected by vertically placed sampling sheets were significantly different in the same situation. Furthermore, the on-body samples moved as the volunteer performed the three activities, which makes the friction velocity for the on-body samples higher than the static samples. A higher friction velocity is associated with a higher deposition velocity [45], so the on-body samples were more likely to have a larger particle deposition factor than the corresponding static samples. In this study, there was no significant linear relationship between the FP concentration in on-body samples and static samples according to the statistical results ($p > 0.05$). This indicates that to accurately measure the particles deposited on the human body, on-body samples should not be replaced by static samples.

4.2. Limitations and future outlook

There are limitations in this study that should be addressed in future research. First, the experiments in each case were not repeated. In this study, although sufficient and repeated pre-experiments were conducted and multiple samples at a given sampling point were installed, the measurement quality can be further improved by conducting replicate experiments concerning key parameters and cases. Second, because the experimental results are based on some specific settings and only one size of particle, the values reported in this study cannot be directly translated to all situations and all particle sizes. For example, for the comparability of this study with previous studies and the safety of the volunteer, the same type of protective apparel was worn by the volunteer in all cases. Some previous studies have found that the clothing weave pattern can also influence on-clothing particle resuspension [20]. A volunteer with medium height and weight conducted all activities, and the walking speed was approximately 60 steps per minute during the walking activity. In fact, human weight, walking speed, way of walking, shoe type, etc., are likely to affect on-flooring particle resuspension [27,46], and they may also affect the rate of particle resuspension and deposition on clothing. Temperature and humidity can also affect particle resuspension and deposition [39]. This study did not study the effects of temperature and humidity. Finally, in the experiments related to the first scenario, after the office work and walking activity in each case, the resuspended FPs were left to settle for 12 h and reused rather than being cleaned and reseeded. We acknowledge that some FPs could have settled on clothing and could have decreased the total on-flooring FPs for the next experiment. However, the number of FPs deposited onto clothing was very small compared to the original seeded FPs on the floor. Thus, this may have had a very limited effect on the following experiment.

It would be of value to continue studying the effect of ordinary clothing other than protective apparel on particle deposition and resuspension. It is also worthwhile to further study the effect of other factors on particle deposition onto and resuspension from clothing, such as temperature/humidity, static electricity on clothing, different kinds of vacuum cleaners, different vacuuming behaviors, and so on.

5. Conclusion

In this study, we developed a novel and accurate sampling method to measure the deposition of particles onto clothing and the resuspension of particles from clothing with fluorescent-tracking technology. Electrical tape was proven to perform as well as glass slides in particle collection and is more suitable for use on irregular surfaces.

Particle deposition onto clothing were quantified for different activities, flooring types and conditions, sampling period, and sampling locations in a room-size chamber. During 20 min of activities (i.e., office work, walking, and vacuuming) on a floor loaded with fluorescent particles (FPs) in a chamber, the average ratio of the surface concentration of FPs on the clothing worn by a volunteer over the FP loading on the flooring ranged from 0.07% to 6.61% in different setups. Both the flooring type (carpet/VCT) and flooring condition (clean/dirty) had significant effects on particle deposition onto clothing. The average particle deposition factor for carpet flooring was 2.71 ± 1.40 times that for VCT flooring, which was mainly caused by the difference in the particle resuspension rate. The average particle deposition factor for dirty flooring was 2.43 ± 1.57 times that for clean flooring. Sampling periods had no significant effect on the measured particle deposition factors. The number of FPs on arm samples was 11%–37% times larger than that on chest and leg samples. A multiple regression shows that the relationship between the particle deposition factor and three characteristics (flooring type, flooring condition and activity) was significant ($p < 0.05$). The activity type had the largest effect on the particle deposition factor in this study. To accurately measure the particles deposited on the human body, on-body samples should not be replaced by static samples, even though static samples are easier to place and collect.

Particle resuspension from clothing was also quantified in a test house. After the volunteer walked (with a speed of 60 steps/min) in the living room of the test house for 1 h, approximately 46.8% of FPs formerly deposited on clothing were found to resuspend. The resuspended particles from clothing were transported to every room in the test house driven by natural convection flow.

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.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108580.

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