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Breathing dynamics and aerosol emissions from young people during cycling exercise

Jingcui Xu, Haoyu Zhai, Lok Kwan So, Cunteng Wang, Hai Guo *

Air Quality Studies, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China

A R T I C L E I N F O

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A B S T R A C T

Physical activity is important to maintain good physical and mental health. However, transmission of respiratory diseases in exercise facilities indicates the importance of maintaining good indoor air quality in these environments. Aerosols exhaled by infected individuals are a significant source of transmission of respiratory diseases. Thus, understanding breathing behaviour during exercise is critical. This study investigated breathing dynamics and aerosol emissions during cycling exercise and rest from 21 healthy participants (10 female and 11 male subjects, 19–37 years old). Key features such as minute ventilation, breathing patterns, peak inhalation and exhalation flow rate, and respiratory frequency were analysed. The results showed that exercise significantly increased minute ventilation, and the variations of breathing flow rate over time followed a sinusoidal pattern. During maximal exercise, peak inhalation and exhalation flow rates were more than three times higher than those at rest, and respiratory frequency was approximately twice as high as that at rest. In addition, the size distribution of aerosols from breathing during exercise was mainly in the range of 0.3–2.5 μm. Exercise significantly increased aerosol emissions of breathing, with average emission rates during maximal exercise being 9.0 times higher than at rest. These findings suggest that physical activity greatly affects breathing dynamics and aerosol emissions. Exercise facilities have unique characteristics that differ from other indoor settings. This study provides essential information that can serve as boundary conditions for computational fluid dynamics studies, aiding further research on aerosol dispersion, infection risk assessment, and the development of energy-efficient mitigation strategies for exercise facilities.

1. Introduction

Physical activity is an essential component of public health, and the World Health Organization (WHO) advises that adults should engage in moderate to vigorous-intensity physical activity [1]. However, from 2019 to 2023, many cluster infections were reported within exercise facilities, which led to infection waves and superspreading events in the communities [2–4]. Factors such as intense exercise, high occupancy rates, poor ventilation, and closed environments [5] make these exercise facilities high-risk areas for SARS-CoV-2 transmission, especially when they are occupied by pre-symptomatic or asymptomatic individuals [6–8]. These individuals can release millions of virus-containing particles every hour when they breathe, speak, cough, and sneeze [9,10]. Additionally, maintaining mask-wearing, frequent hand hygiene, and social distancing during strenuous exercise can be challenging [11,

* Corresponding author.
E-mail address: ceguohai@polyu.edu.hk (H. Guo).

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12].

Intense physical activity significantly affects emissions of aerosols released from people [13]. Mustch et al. [14] found a 132-fold increase in aerosol emission rates from rest to maximal exercise for both female and male subjects. Aerosol emissions increased modestly at exercise intensities up to 2W/Kg and then exponentially at higher exercise intensities. Orton et al. [15] discovered that aerosol emission rates during vigorous exercise were similar to those during conversational speaking. Exercise-induced hyperpnoea might cause increased aerosol emission rates. Furthermore, Schumm et al. [13] found that indoor endurance exercise generated more aerosols than resistance exercise. Spinning bike endurance exercise was associated with a six times higher risk of simulated infection compared to resistance training. Additionally, older subjects (60–76 years) released more than twice the amount of aerosols per minute during exercise compared to younger subjects (20–39 years) [16]. Sajgalik et al. [17] reported statistically significant increases in aerosol concentration during exercise at or above 50 % of the predicted heart rate reserve. These studies showed a significant association between aerosol emissions and physical exercise.

Increased aerosol emissions mean that exposed people are more likely to inhale the pathogens if an infected person is present at an exercise facility. A recent simulation study showed that the risk of infection might increase by up to 2.5 times when people exercise compared to when resting [13]. Assessing inhaled and exhaled aerosols requires understanding breathing dynamics during exercise, but research focusing on this aspect is limited.

Previous studies have shown that minute ventilation (i.e., air volume inhaled or exhaled from a person's lungs per minute) for elite oarsmen can be as high as 200 L/min [18], whereas for untrained individuals it can exceed 100 L/min during exercise [19]. Mustch et al. [14] reported that during graded cycle exercise, the minute ventilation increased from 9 L/min at rest to 101 L/min for female subjects and from 13 L/min to 160 L/min for male subjects. During exercise, minute ventilation of young subjects was 52 % higher than that of older people [16]. The enhanced breathing activities indicate that aerosols in the exhaled airflow could transport over long distances within exercise facilities. Furthermore, the increased volume of air inhaled allows aerosols to penetrate deep into the respiratory tract [20], increasing the risk of infection. Therefore, more information is needed on the characteristics of breathing during exercise.

However, existing studies lack detailed information on breathing dynamics, such as inhalation and exhalation peak flow rates, changes in respiratory frequency, and the functional form of breathing during exercise. Additionally, they failed to explore breathing

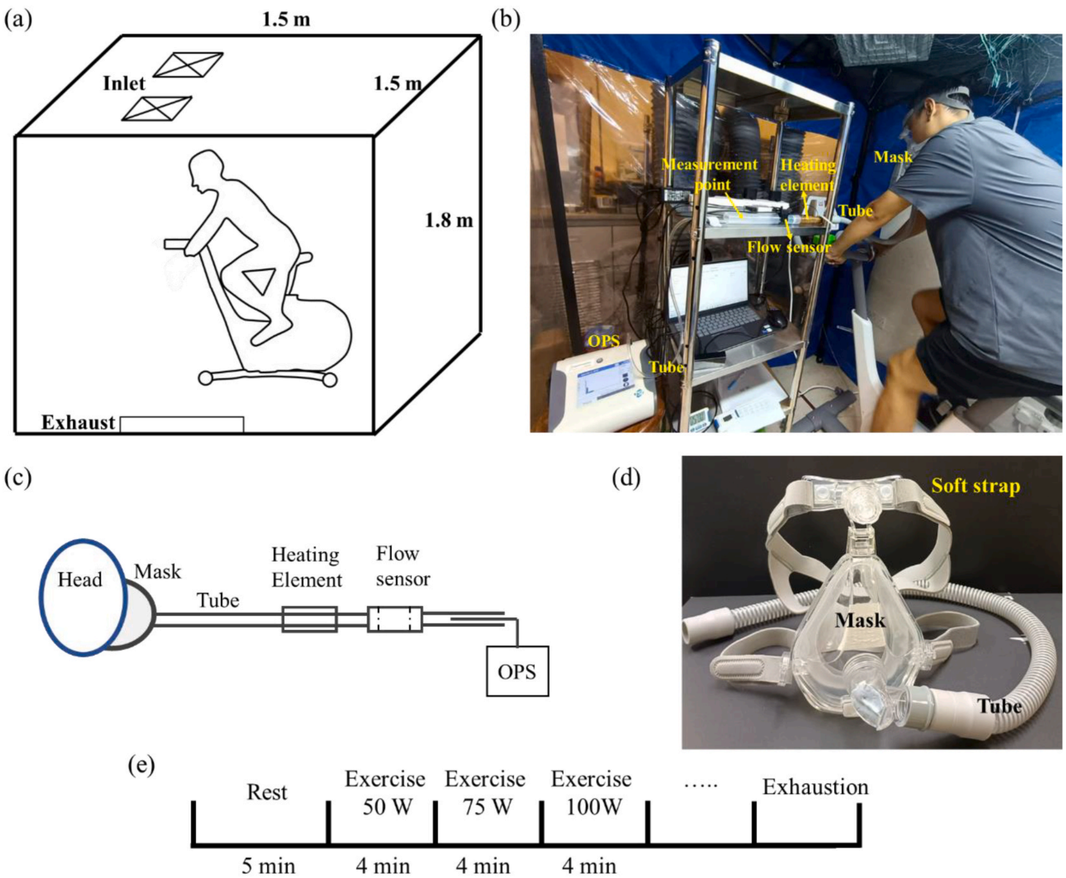

Fig. 1. Illustration of laboratory setup and experimental design. (a) Schematic diagram of the experimental setup, (b) image of a subject exercising inside the chamber, (c) diagram of the custom-designed mask system, (d) image of the mask and the tube, (e) experimental procedure.

dynamics and their correlation with aerosol emissions during exercise. These limitations hinder our understanding of respiratory disease transmission and affect the accuracy of computational fluid dynamics (CFD) simulation studies in exercise facilities. Therefore, exploring breathing behaviour and the correlated aerosol emissions during physical activity is essential.

Our study aims to fill this gap by investigating the characteristics of the breathing process during exercise and rest. We will examine parameters such as respiratory frequency, inhalation and exhalation times, peak flow rates, minute ventilation, and exercise-related breathing patterns. In addition, we will assess aerosol size distribution, concentration, and emission rates during exercise. This study will provide essential information about the breathing behaviour and aerosol emissions of people during exercise, which will help future studies to evaluate infection risks and develop effective control measures for exercise facilities.

2. Materials and methods

2.1. Experimental design and exercise tests

The work involved human participants to investigate breathing dynamics and aerosol emissions during rest and graded cycle exercise tests. The Health and Safety Office and the Institutional Review Board at The Hong Kong Polytechnic University reviewed and approved all procedures in the study. Participants were 10 female and 11 male healthy subjects, aged between 19 and 37 years old. BMI was within the normal range of 18.7–23.8 (Kg/m^2) for females and 18.6–24.8 (Kg/m^2) for males. Participants were asked not to smoke within 4 h and to avoid excessive food or water intake 1 h before the experiments. Before tests, participants underwent antigen testing to screen for SARS-CoV-2, Influenza A and B viruses, and respiratory syncytial virus (RSV) to ensure that they did not have respiratory diseases. Their height, weight, and gender were recorded. All subjects signed informed consent forms prior to the experiments.

Measurements were conducted in an enclosed chamber with dimensions of 1.5 m wide, 1.5 m long, and 1.8 m high, as shown in Fig. 1 (a). Two HEPA units located outside the chamber were connected to its inlets. Filtered air entered the chamber through the inlets. The air change rate was more than 200 times per hour to minimize the background aerosol concentration and ensure participants inhaled clean air with minimal aerosols.

Breathing flow rates were measured using a flow sensor (Sensirion AG, Switzerland, SFM3300-AW) with a bidirectional flow range of ±250 L/min. The relative maximum measurement error was 5 % for flow rates below 100 L/min and 10 % for flow rates above 100 L/min. The minimum resolution of the sensor was 0.033 L/min. This device has been tested and used to measure breathing flow rates in previous studies [21,22]. Furthermore, an optical particle sizer (OPS) (Model 3330, TSI, Shoreview, MN, USA) was used to measure the size distribution and concentration of aerosols throughout the entire measurement period [23,24]. The measurement interval was 1 s, and the sampling rate was 1 L/min. The aerosol diameter range measured was 0.3–10 μm. By integrating the flow sensor and OPS, a custom-designed mask system was designed to simultaneously measure the flow rate and aerosol emissions at rest and during exercise, as shown in Fig. 1b–d. All components of the mask system were disinfected before each measurement. The fit of the mask on the subjects' faces could be adjusted with soft straps.

The HEPA units of the chamber were activated 2 h before the measurements. During the measurements, the temperature was maintained at approximately 22 °C with a relative humidity (RH) of 70 %. Initially, the subjects wore the designed mask system and sat on the bicycle ergometer for 5 min. They then cycled for 4 min at an exercise power of 50 W, with the load increasing by 25 W every 4 min until exhaustion, as shown in Fig. 1 (e). During the process, the flow rate of breathing and real-time concentration of aerosols in expired air were continuously measured by the flow sensor and OPS within the mask system, respectively.

The exhaled droplets passing through the mask and tubing underwent evaporation. Studies have shown that sub-micro droplets reach equilibrium in less than 0.1 s, and droplets with an initial diameter of 20 μm can evaporate and equilibrate in approximately 1 s [23–25]. This indicates that there was sufficient time for the exhaled droplets to equilibrate from exhalation to measurement by the OPS instrument. Therefore, the size distribution of 0.3–10 μm measured in our study represented the equilibrium size of exhaled droplets in the sampling environmental conditions.

Exercise may resuspend aerosols on the human body. Additionally, despite efforts to keep the floor clean, foot movements during cycling may cause aerosol resuspension from the floor. We conducted additional measurements to quantify aerosols from external sources to eliminate the influence of exogenously generated aerosols. Three participants (aged 26–32) from the group of 21 followed the same experimental procedures. The main difference was that the tube within the mask system (Fig. 1 d) was extended and positioned outside the chamber. This change ensured that aerosols exhaled through the mask tube were vented outside the chamber. The aerosol measurement point monitored by the OPS remained unchanged. The measurements aimed to evaluate the effect of exogenously generated aerosols on the concentration of breathing aerosols.

2.2. Data processing and statistical analysis

We developed an experimental setup to measure flow rates of breathing and aerosol emissions in humans during graded exercise tests until exhaustion. Breathing parameters during exercise and at rest were analysed, including respiratory frequency, inhalation and exhalation time, peak flow rate, minute ventilation, and functional expression. Subsequently, aerosol size distribution and aerosol concentration were discussed. The aerosol emission rates were evaluated by multiplying the aerosol concentration and minute ventilation. The sphericity and normality of the data were checked and considered in the analysis. Statistical methods of ANOVA, two-way ANOVA, *t*-test, and correlation test were used to analyse the data.

3. Results

3.1. Dynamics of breathing during cycling exercise and at rest

3.1.1. Respiratory frequency

Fig. 2 illustrates the respiratory frequency of male and female subjects at rest and during cycling exercise at different intensities. At rest, the respiratory frequency of females was 16 breaths per minute and males were 15 breaths per minute, based on the mean values. The respiratory frequency of both genders increased as the exercise power increased from 50 W to 175 W (Males) or 125 W (Females). This trend was similar across all exercise power levels. At maximal exercise, female subjects' respiratory frequency reached 30 breaths per minute, while male subjects' respiratory frequency reached 27 breaths per minute. The respiratory frequency at maximal exercise was almost twice that at rest ($P < 0.05$). Overall, cycling exercise led to a substantial increase in respiratory frequency for both males and females ($P < 0.05$). The wider interquartile range (IQR) during exercise for both genders suggests a greater variability of the respiratory frequency during physical activity.

3.1.2. Inhalation and exhalation time

The inhalation and exhalation time of male and female subjects at rest and during cycling exercise were investigated. As shown in Fig. 3 (a), at rest, the mean expiratory time for females and males was 2.3 s and 2.6 s, respectively. Cycling exercise led to a significant reduction in expiratory time for both genders ($P < 0.05$). At maximal exercise, the expiratory time for females decreased to 1.1 s, while it decreased to 1.2 s for males, resulting in a decrease of up to 50 % compared to that at rest ($P < 0.05$). In each case, the mean expiratory time for male subjects was longer than that for females, but the difference was not significant ($P > 0.05$). Similarly, for the inspiratory time in Fig. 3 (b), cycling exercise led to a decrease in inspiratory time ($P < 0.05$). At rest, the inspiratory time was 1.6 s for both female and male subjects. During maximal exercise, the inspiratory time reduced to 1.0 s for females and 1.1 s for males ($P < 0.05$).

The expiratory and inspiratory times of female and male subjects were compared. The mean expiratory time of both male and female subjects was greater than the inspiratory time, but the difference was not significant ($P > 0.05$). This difference decreased with increasing exercise power. Initially, the expiratory time of females at rest was 1.4 times the inspiratory time, which gradually reduced to 1.1 times during maximal exercise. For males, the ratio decreased from 1.6 times at rest to 1.1 times during maximal exercise.

3.1.3. Peak flow rates of inhalation and exhalation

Fig. 4 shows the peak flow rates during inhalation and exhalation, respectively, during respiratory activity. Our study revealed that the peak flow rates during both inhalation and exhalation increased substantially during cycling exercise compared to the resting state ($P < 0.05$). For female subjects, the mean peak flow rate during inhalation increased from 0.7 L/s at rest to 2.2 L/s during maximal exercise. Similarly, it increased from 0.8 L/s at rest to 2.5 L/s during maximal exercise for male subjects. This means that the peak flow rate of inhalation increased more than threefold due to cycling exercise ($P < 0.05$).

During exhalation, the peak flow rate increased from 0.5 L/s at rest to 2.1 L/s (mean values) during maximal exercise for female subjects. Male subjects exhibited a similar trend, with the peak value rising from 0.6 L/s at rest to 2.1 L/s during maximal exercise. Cycling exercise led to a more than 4 times and 3 times increase in peak flow rate of exhalation for female and male subjects, respectively ($P < 0.05$).

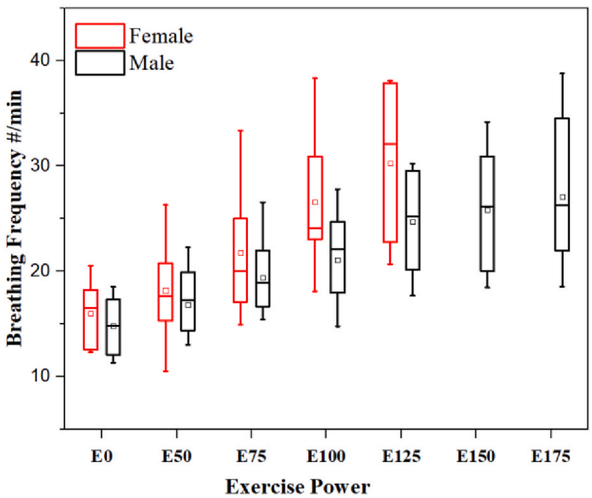

Fig. 2. Respiratory frequency of male and female subjects at different exercise power levels; Note: E0 means participants at rest; E50 means participants cycling a bicycle ergometer at an exercise power of 50 W.

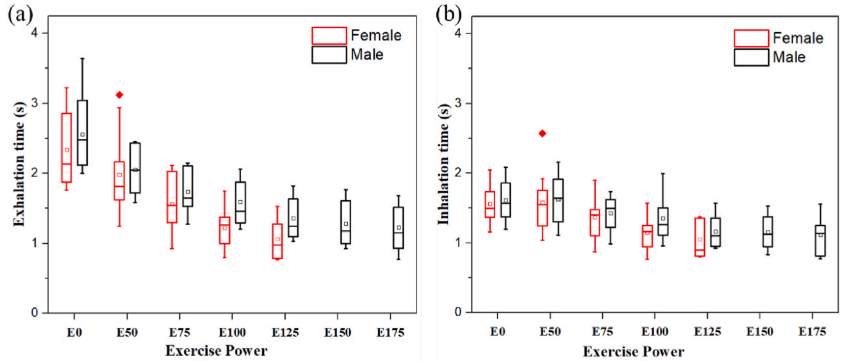

Fig. 3. Time of breathing for subjects at rest and during exercise. (a) exhalation time and (b) inhalation time for subjects at different exercise power levels.

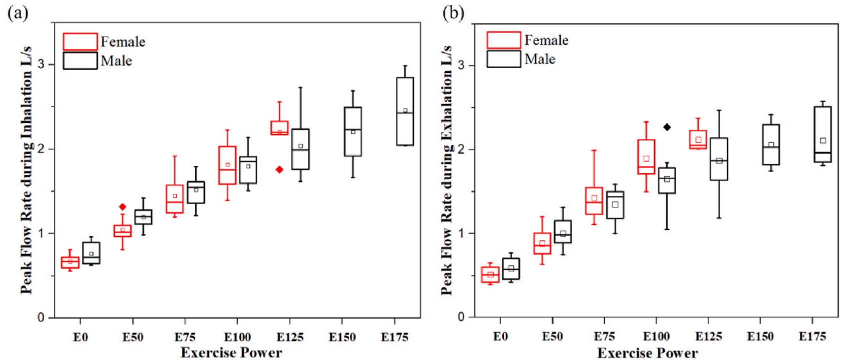

Fig. 4. Peak flow rate of (a) inhalation and (b) exhalation of subjects during exercise and at rest.

3.1.4. *Minute ventilation*

It is a well-known phenomenon that minute ventilation increases during exercise. Our study confirmed this trend ($P < 0.05$). As shown in Fig. 5 (a), the mean minute ventilation of female subjects increased from 12 L/min at rest to 55 L/min during maximal exercise. Similarly, it increased from 13 L/min at rest to 54 L/min during maximal exercise for male subjects. This represented a fourfold increase in minute ventilation for both genders due to cycling exercise ($P < 0.05$). There was no significant difference between females and male subjects ($P > 0.05$). Throughout the exercise, Fig. 5 (b) shows that the mean minute ventilation was 36 L/min for females and 35 L/min for males, which was almost three times that at rest.

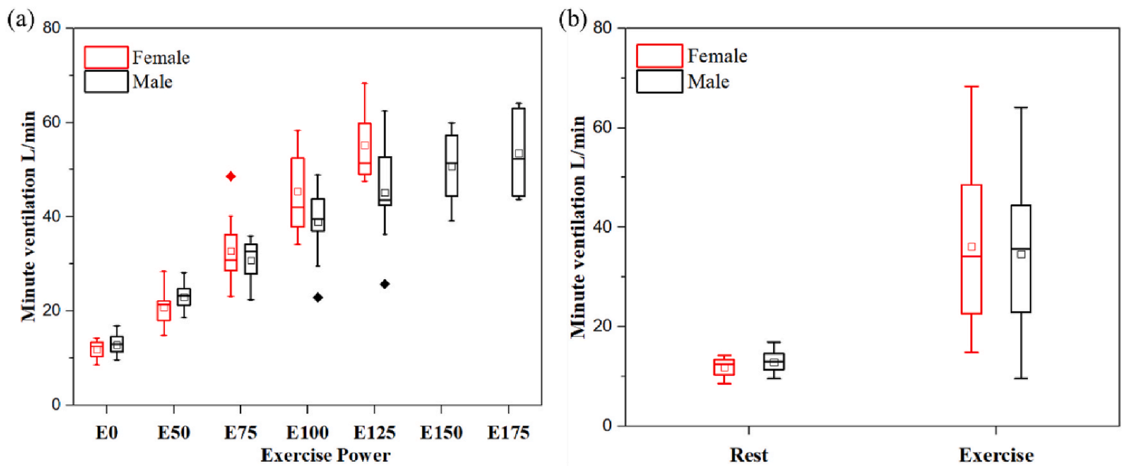

Fig. 5. Minute ventilation (a) at each exercise power and (b) during the entire exercise process.

3.1.5. Functional form of breathing

In the above sections, our results revealed significant differences in breathing at rest and during exercise. Furthermore, understanding the functional expressions of breathing patterns under these conditions is important for further research and CFD simulation studies. Fig. 6 shows typical breathing flow rates over time at rest and during cycling exercise. Previous research [26] explored the expression of breathing at rest using a sine wave. For the functional expression of breathing patterns during cycling exercise, we found that the sinusoidal form could also effectively represent these patterns, as shown in equation (1):

$$y = A\sin(2\pi / T \times t) \tag{1}$$

Given the differences in exhalation and inhalation time, as well as the different peak flow rates of inhalation and exhalation during cycling exercise, we represented the functional expression of the breathing patterns as a segmented function (2):

$$y = \left\{ \begin{array}{l} A_{in}\ \sin\left(\dfrac{2\pi}{T_{in}}t\right), y \geq 0 \textit{ for inhalation} \\ A_{ex}\ \sin\left(\dfrac{2\pi}{T_{ex}}t\right), y \leq 0 \textit{ for exhalation} \end{array} \right\} \tag{2}$$

where A_{in} and A_{ex} represent the peak flow rate of inhalation and exhalation, respectively. T_{in} and T_{ex} mean the periods of inhalation and exhalation, respectively.

Then, we normalized the function of breathing with the peak flow rate of exhalation and inhalation, as shown in equation (3):

$$Y = y / A_x \tag{3}$$

This resulted in the following normalized function (4):

$$Y = \left\{ \begin{array}{l} \sin\left(\dfrac{2\pi}{T_{in}}t\right), y \geq 0 \\ \sin\left(\dfrac{2\pi}{T_{ex}}t\right), y \leq 0 \end{array} \right\} \tag{4}$$

Considering the inhalation time τ_{in} (half of T_{in}) and exhalation time τ_{ex} (half of T_{ex}) during one breathing process, as shown in Fig. 3, we further revised the function to (5)

$$Y = \left\{ \begin{array}{l} \sin\left(\dfrac{\pi}{\tau_{in}}t\right), Y \geq 0 \textit{ for inhalation process} \\ \sin\left(\dfrac{\pi}{\tau_{ex}}t\right), Y \leq 0 \textit{ for exhalation process} \end{array} \right\} \tag{5}$$

Finally, the function of normalized breathing flow rate (Y) at rest and during cycling exercise was determined as function (6):

$$Y = \sin(\pi / \tau_x \times t) \tag{6}$$

In this equation, τ represents the inhalation or exhalation time, and the subscript x is replaced by '*in*' to represent inhalation and '*ex*' to represent exhalation. By combining the functional expression (6) with the parameters in Figs. 2–5, we could obtain the functional form

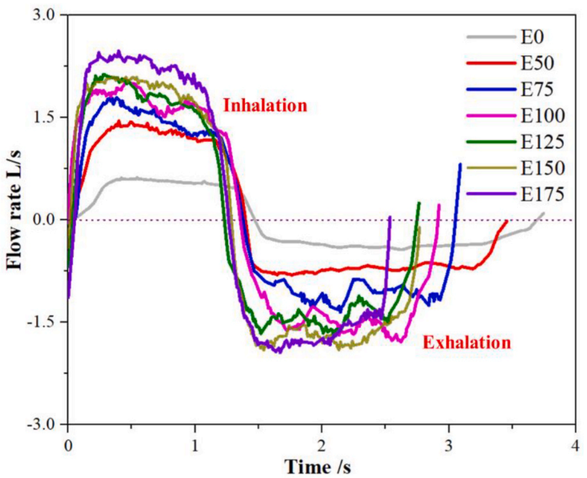

Fig. 6. Breathing flow rate over time for a subject at different exercise intensity levels.

of the breathing flow rate over time during cycling exercise.

3.2. Size distribution, concentration, and emission rates of aerosols

The concentrations of exogenous aerosols during the measurements (Tables S1 and S2 in supplementary information) were subtracted from the measured concentration of breathing aerosols. Fig. 7 presents the mean values of the aerosol size distribution released by all subjects. The data revealed that the shape of the size distribution was consistent regardless of whether the individuals were at rest or engaged in physical exercise. Specifically, in both cases, the aerosols predominantly fell in the range of 0.3–2.5 μm. However, physical exercise significantly increased the concentration of these aerosols ($P < 0.05$). This suggests that although the size distribution of aerosols does not change with physical activity, the number of aerosols in this size range increases.

Fig. 8 (a) presents the aerosol concentrations released by female and male subjects at rest and during cycling exercise. At rest, the mean aerosol concentration for females was 3.1 (#/ml), which was lower than that for males (6.4 (#/ml)). In addition, there was considerable variation in the male data, indicating a wider range of aerosol concentrations. Cycling exercise led to increased aerosol concentrations for both genders ($P < 0.05$). For females, the aerosol concentration during maximal exercise was 1.6 times that at rest. For males, concentration during maximal exercise was more than doubled compared to resting state. Furthermore, we found no significant difference in aerosol concentrations between female and male subjects during exercise ($P > 0.05$).

The aerosol emission rates were the product of the aerosol concentration and the corresponding minute ventilation. Fig. 8 (b) illustrates the aerosol emission rates of female and male subjects at rest and during cycling exercise. At rest, the emission rates of aerosols in the size range of 0.3–10 μm were 3.6×10^4 #/min for females and 8.7×10^4 #/min for males. Exercise significantly increased mean aerosol emissions ($P < 0.05$). During maximal exercise, the mean aerosol emission rates were 7.4 times higher for females and 9.0 times higher for males compared to the resting state ($P < 0.05$). There was considerable variability between individuals, as indicated by a wide distribution of aerosol emission rates. Outliers were observed at exercise powers above 75 W, indicating that some individuals might release higher levels of aerosols than others. Compared to the mean emission rates at rest, abnormal values during maximal exercise were 14 times higher for females and 28 times higher for males.

Fig. 9 shows the correlation between aerosol emissions at rest and various exercise powers. For female subjects, the correlations were significant at all power levels except 125 W ($p < 0.05$). This exception may indicate a threshold beyond which other physiological factors had a greater impact on aerosol emissions. For male subjects, significant correlations were consistently observed at all exercise levels ($p < 0.05$), suggesting that aerosol emissions during exercise and at rest had a good linear relationship.

4. Discussion

The main finding of this study was the breathing dynamics and aerosol emissions during physical activity. Key parameters of breathing dynamics such as respiratory frequency, inhalation and exhalation time, peak flow rate, minute ventilation, and functional expression were provided at different exercise levels. Additionally, the emission rate of aerosols (0.3–10 μm) during cycling exercise was much higher than that at rest. Our findings show the significant impact of physical activity on the dynamics of breathing and aerosol emissions. This knowledge will be crucial for future studies that will investigate aerosol dispersion in exercise facilities and develop data-driven mitigation solutions for indoor group exercise.

During exercise, the peak exhalation flow rates in this study were within the range of peak cough flow rates (1.6–6.0 L/s) observed in female subjects by Gupta et al. [27]. This suggests that the exhalation dynamics during exercise can reach levels similar to those of coughing in females. Airborne aerosols carried by these high-frequency breathing jets may travel considerable distances, which

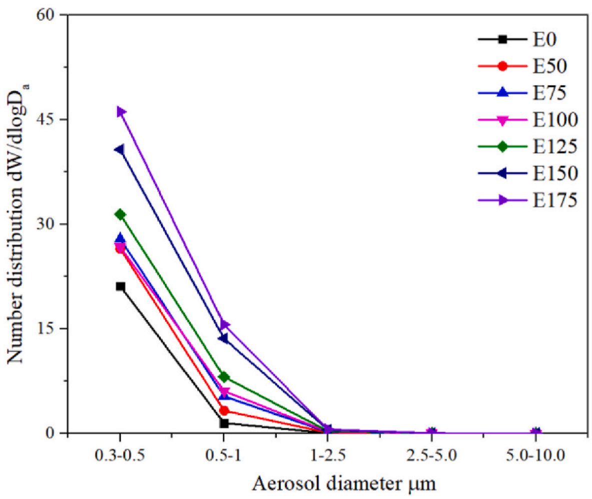

Fig. 7. Average values of size distribution at rest and during exercise.

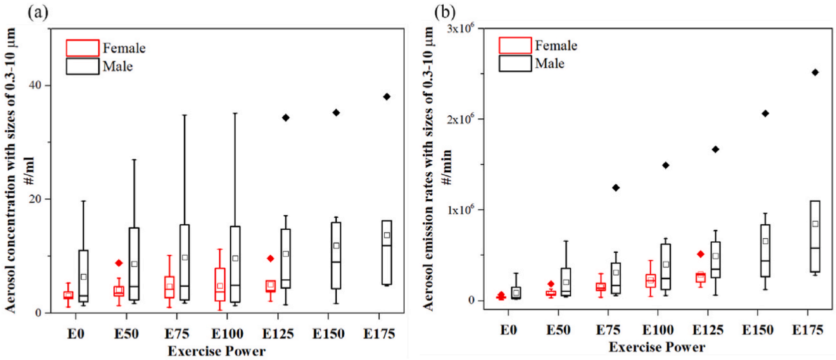

Fig. 8. Aerosol number concentration and emission rates from breathing for subjects at rest and during exercise. (a) Concentration of aerosols and (b) aerosol emission rates for subjects at different exercise power levels.

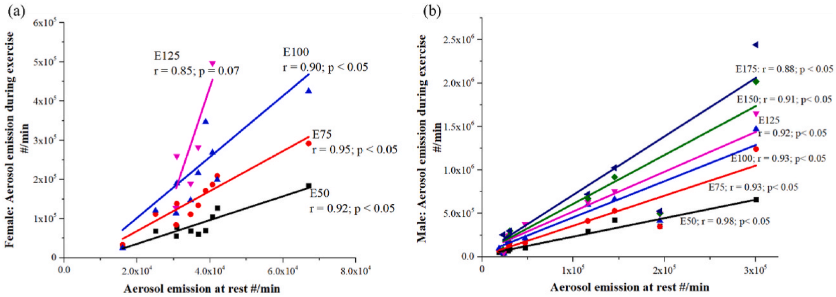

Fig. 9. Correlation between aerosol emissions at rest and during exercise for (a) female subjects and (b) male subjects.

suggests the importance of maintaining social distancing and employing personal protective control measures in exercise facilities. The breathing behaviour during exercise indicates the unique characteristics of exercise facilities, which suggests that general control measures, such as social distancing and advanced ventilation systems, may need to be modified. Thus, further research is needed to explore their effectiveness and how to improve their performance in exercise facilities. Developing appropriate and effective control measures for exercise facilities should become a new focus of future research.

In addition, the increased inhalation flow rate during cycling exercise suggests that more aerosols can be inhaled in confined spaces such as fitting rooms. This may enhance the risk of infection if there are infected people in the exercise facilities. As a result, healthy people exposed to such environments should take some measures to protect themselves.

The significant correlations between aerosol emissions at rest and during exercise in our study suggest that resting aerosol emissions can be used as a non-invasive biomarker to predict aerosol emissions during physical activity. Such predictions are useful for indoor air quality management because they can better predict aerosol emissions in environments where physical activities occur. This information can be used to guide ventilation strategies and other interventions to reduce aerosol-related health risks in indoor environments. Mutsch et al. [14] found that aerosol emission at rest only moderately predicted aerosol emissions during exercise, possibly due to the different aerosol size ranges measured and the physical fitness levels of the participants. That study [14] measured aerosols ranging from 0.2 μm to 10 μm and included both trained and untrained participants, while our investigation measured aerosols from 0.3 μm to 10 μm and included only untrained participants.

The increase in aerosol emissions due to cycling exercise observed in our study is consistent with previous findings, but the rate of increase is different from those studies [13–15]. One reason for this discrepancy is the different size ranges of aerosols that were measured. Our study focused on aerosols between 0.3 and 10 μm, whereas other studies measured size ranges of 0.2–10 μm [13,14] and 0.54–20 μm [15]. Another factor is the ethnic composition of the participants. The participants in our study were Asian. Moreover, there are differences in the types of measurement devices used. Different measurement intervals and their precision may also contribute to the reported differences.

Our study demonstrates that cycling exercise has a significant impact on aerosols emissions. However, there is considerable variability in aerosol emissions, with some individuals releasing much more aerosols than others, which may explain the "super-spreading" events during the COVID-19 pandemic [28,29]. Factors such as airway dehydration during exercise possibly contribute to increased aerosol emissions. More research is needed to understand the factors that influence individual variability in aerosol emissions during exercise.

The dynamics of breathing and aerosol emissions from our study provide essential information that can be used as boundary conditions for CFD studies in exercise facilities. By incorporating factors such as the geometric design of fitting rooms, population density, and ventilation systems, we can investigate aerosol dispersion, assess the risk of infection, and propose energy-efficient mitigation strategies in exercise facilities.

This study has several limitations. Firstly, only healthy participants were recruited. Aerosol emissions and breathing dynamics may differ in individuals with COVID-19 [30]. Infected individuals may produce more aerosols than healthy controls [31], suggesting that infected individuals may release more aerosols during exercise. However, we were unable to carry out such tests safely. High-intensity exercise in patients with COVID-19 may also raise ethical issues due to risks such as myocarditis.

Secondly, the additional resistance of the mask system might make it difficult to breathe. Participants with the mask may be exhausted at an early stage compared to when they are not wearing the mask system, which may potentially influence the outcomes. We also did not consider possible changes in the hydration state of an individual, although hydration levels can affect aerosol emissions. To more thoroughly investigate exercise-induced dehydration, the status before and after hydration should be recorded. The potential deposition of aerosols on the tube surfaces of the mask system may lead to lower aerosol concentration and subsequently affect the calculated aerosol emission rates. Furthermore, we did not differentiate between nose and mouth breathing. Participants could decide their breathing patterns during exercise based on their preferences, which might cause different aerosol emissions.

Our study focused on cycling exercise. Other forms, such as running and weightlifting, may have different results and need further investigation. Additionally, this work specifically considered young people aged 19 to 37 with a normal BMI. BMI and age are important factors affecting aerosol emissions and breathing dynamics. More research is needed to explore their effects on breathing dynamics and aerosol emissions. Furthermore, the limited sample size of 21 participants within this age range may affect the applicability of our findings. To better understand the age-related differences in breathing dynamics and aerosol emissions, future studies should involve a larger and more stratified sample size.

5. Conclusions

This study investigated the dynamics of breathing and aerosol emissions of individuals during cycling exercise and at rest. Key parameters such as inhalation and exhalation time, peak flow rate, and functional expression of breathing patterns were analysed. In addition, the size distribution and emission rate of aerosols were evaluated. The main findings of this study are.

1) Breathing dynamics were greatly affected by physical exercise. The respiratory frequency at maximal exercise was nearly two times of the resting conditions. The peak inhalation and exhalation flow rate increased to more than three times that at rest. Minute ventilation increased fourfold for both genders during cycling exercise. In addition, the sinusoidal form could be effective to represent the functional expression of breathing patterns during cycling exercise.
2) Cycling exercise significantly increases aerosol emissions. During maximal exercise, the mean aerosol emissions were up to 9.0 times higher than at rest. The large difference in emissions suggests a possible cause for “superspreading” events.
3) The increase in flow rate and aerosol emissions during cycling exercise indicates that exercise facilities require special considerations to prevent respiratory disease transmission, unlike other environments such as offices, restaurants, and classrooms.
4) Further studies are needed to investigate the effects of different physical activities, including aerobic and anaerobic exercises, on breathing dynamics and aerosol emissions.

CRediT authorship contribution statement

Jingcui Xu: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haoyu Zhai:** Methodology, Investigation, Data curation. **Lok Kwan So:** Methodology, Formal analysis, Data curation. **Cunteng Wang:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Hai Guo:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.112232.

Data availability

Data will be made available on request.

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