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Respiratory aerosol particle emission and simulated infection risk is greater during indoor endurance than resistance exercise

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Pathogens such as severe acute respiratory syndrome coronavirus type 2 (SARS-CoV-2), influenza, and rhinoviruses are transmitted by airborne aerosol respiratory particles that are exhaled by infectious subjects. We have previously reported that the emission of aerosol particles increases on average 132-fold from rest to maximal endurance exercise. The aims of this study are to first measure aerosol particle emission during an isokinetic resistance exercise at 80% of the maximal voluntary contraction until exhaustion, second to compare aerosol particle emission during a typical spinning class session versus a three-set resistance training session. Finally, we then used this data to calculate the risk of infection during endurance and resistance exercise sessions with different mitigation strategies. During a set of isokinetic resistance exercise, aerosol particle emission increased 10-fold from 5,400 ± 1,200 particles/min at rest to 59,000 ± 69,900 particles/min during a set of resistance exercise. We found that aerosol particle emission per minute is on average 4.9-times lower during a resistance training session than during a spinning class. Using this data, we determined that the simulated infection risk increase during an endurance exercise session was sixfold higher than during a resistance exercise session when assuming one infected participant in the class. Collectively, this data helps to select mitigation measures for indoor resistance and endurance exercise classes at times where the risk of aerosol-transmitted infectious disease with severe outcomes is high.

aerosol particle emission | exercise | infection risk | pathogen transmission | SARS-CoV-2

Significance

Intensive endurance exercise can increase aerosol particle emission by over 100-fold, and there is evidence that SARS-CoV-2 has spread during indoor group exercise. However, data on aerosol particle emission during resistance exercise (i.e., weightlifting) and for "real-life" endurance or resistance training sessions are limited. To fill this knowledge gap, we measured aerosol particle emission during resistance exercise and real-life exercise sessions. We observed that aerosol particle emission increased 10-fold during resistance exercise. Furthermore, we calculated that the infection risk for a real-life spinning class (i.e., cycle ergometer exercise) is sixfold higher than for a resistance exercise session. Thus, during waves of aerosol-mediated infections with severe consequences, exercisers should mainly do resistance training and do especially high intensity endurance training outdoors.

Airborne aerosol particles can carry pathogens such as the severe acute respiratory syndrome coronavirus type 2 (SARS-CoV-2) or influenza viruses as their cargo and are therefore a key route by which respiratory illnesses are transmitted from person to person (in this manuscript, we use the term "aerosol particles" exclusively for "respiratory aerosol particles"). During exercise, respiratory ventilation increases from approximately 5 to 15 L/min at rest to maxima of over 100 L/min in untrained individuals (1) and 200 L/min e.g., in highly trained rowers (2). Because of the increased respiratory ventilation, infected exercisers will emit more aerosol particles and pathogen, whereas exposed and susceptible individuals will inhale more aerosol particles and pathogen if an infected individual is in the room. Moreover, we have recently demonstrated that the concentration of aerosol particles in expired air increases, too, so that the emission of aerosol particles increases on average 132-fold from rest to maximal cycle ergometer endurance exercise (3). The increased emission of aerosol particles and pathogens during intensive exercise may partially explain why elite athletes have a seven times higher risk of respiratory infection when compared to recreational athletes (4). Moreover, the high emission of aerosol particles and pathogen during intensive endurance exercise may explain earlier SARS-CoV-2 outbreaks during indoor group exercise in poorly ventilated, small venues (5).

Even before the SARS-CoV-2 pandemic, the professional cycling Team Sky tried to prevent respiratory infections (6, 7) as such infections can mean, e.g., the loss of the Tour de France. The prevention of aerosol-mediated infections then became a major research focus during the SARS-CoV-2 pandemic to reduce COVID-19 deaths, severe courses of COVID-19, multi-organ complications (8, 9), and long-term health impairments such as long COVID (10). In athletes, a SARS-CoV-2 infection may also reduce their performance (11) and can lead to myocarditis (12) which is one of the main causes of sudden cardiac death in sports (13). However, while COVID-19 mitigation measures prevented many deaths, the prohibition of sports had a huge, negative impact on sports and the sports economy (14). Thus, a key aim for the future is to quantify aerosol particle emission and infection risk during sport to better match mitigation measures to the actual risk associated with different types of exercise or sport.

While the emission of aerosol particles increases by more than 100-fold from rest to maximal endurance exercise in a graded exercise test, we have no data on aerosol particle emission during resistance exercise (i.e., weightlifting). This is a problem because the World Health Organization (WHO) recommends a combination of endurance and resistance exercise for health (15) and

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because resistance exercise is indoor exercise. Moreover, resistance exercise is a major exercise type in gyms. During resistance exercise, exercisers perform several sets per exercise where they lift a weight typically about 10 times to near fatigue. Each set lasts about 30 s, and respiratory ventilation during resistance exercise (16) appears to increase less than during intensive endurance exercise (3). However, during resistance exercise, exercisers may perform so-called Valsalva maneuvers (17) which may change the aerosol particle emission due to changes in the pattern of ventilation. As we do currently not have data on aerosol particle emission during resistance exercise and no comparison to endurance exercise, we asked the following three research questions:

1) Do respiratory ventilation, aerosol particle concentration, and emission of aerosol particles differ during a set of resistance exercise from rest?
2) Can respiratory ventilation, aerosol particle concentration, and emission values from a graded exercise test to exhaustion be used to model the emission and risk of infection of a typical spinning session?
3) What is the risk of infection during a typical session of endurance and resistance exercise?

Results

Aerosol Particle Emission during a Bout of Isokinetic Resistance Exercise. Fitness centers and gyms typically offer a combination of endurance and resistance exercise (i.e., weight lifting) for their clients. This is in line with the WHO guidelines on physical activity and sedentary behavior who recommend a combination or resistance and endurance exercise for health for all ages (15). To estimate the infection risk during indoor exercise, several groups including us (3) have measured the concentration or respiratory aerosol particles or aerosol particle emission during endurance exercise. However, aerosol measurements during resistance exercise are missing. While the ventilation during resistance exercise seems lower than during high intensity endurance exercise, resistance exercisers often engage in forced breathing or perform Valsalva maneuvers which may increase aerosol particle emission. We used our new measurement method to assess both ventilation and the concentration of respiratory aerosol particles in one experiment.

In the first experiment, we therefore measured respiratory ventilation and the concentration of aerosol particles at rest before and during a dynamic set of leg extensor isokinetic resistance exercise with 80% of the maximal voluntary contraction (MVC) force to exhaustion, with verbal encouragement. We chose this form of exercise as it is a highly controlled type of resistance training. At 80% of the MVC, volunteers were subjectively exhausted after 93 ± 41 s. Ventilation increased significantly from 14 ± 1.7 L/min at rest to 46 ± 18.9 L/min during a set of dynamic, isokinetic resistance exercise ($P < 0.05$) (*SI Appendix*, Fig. S1). At the same time, the mean resting aerosol particle concentration increased significantly by 3.6-fold from 290 ± 600 particles/L at rest to 1,050 ± 1,160 particles/L ($P < 0.05$, Fig. 1*A*). In one subject, the aerosol particle concentration was about sixfold higher with 1,770 particles/L at rest compared to the group mean value and increased to 3,490 particles/L (approximately 3.5-fold higher than mean) during exercise, highlighting that aerosol particle superemission can occur in apparently healthy subjects with no known respiratory disease.

Next, we used the respiratory ventilation and concentration data to calculate the emission of aerosol particles during a set of isokinetic resistance exercise to voluntary fatigue (Fig. 1*B*). During the set of isokinetic resistance exercise, mean aerosol particle emission increased on average 10-fold from 5,400 ± 1,200 particles/min at rest to 59,000 ± 69,900 particles/min ($P < 0.05$). The aerosol particle emission of a subject with exceptionally high aerosol particle concentration increased from 35,700 particles/min at rest to 195,000 particles/min during exercise. Together this demonstrates that aerosol particle emission increases about 10-fold less during a set of resistance exercise than during a graded endurance exercise test to exhaustion. Moreover, it shows that some apparently healthy subjects can have aerosol superemission.

Comparison of Aerosol Particle Emission during an Endurance Cycle (i.e., Spinning) Class versus a Multi-Set Resistance Exercise Session. Few individuals do isokinetic resistance training in the gym and also aerosol particle emission may change over time

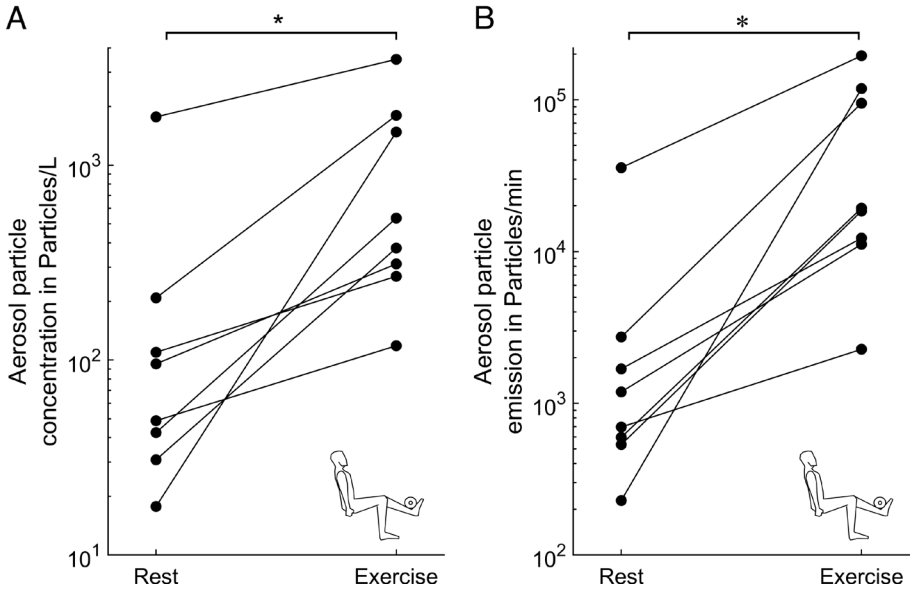

Fig. 1. (*A*) Aerosol particle concentration and (*B*) aerosol particle emission at rest and during exercise of the isokinetic resistance exercise training measurement. *$P < 0.05$.

during constant load endurance exercise, e.g., due to dehydration. We thus aimed to obtain more "real-life" data. To do so, we measured in eight volunteers' aerosol particle emission during a full spinning endurance exercise class. A spinning exercise is a group exercise on stationary bikes where the participants exercise at variable intensity motivated by music and by the words of an instructor (18). We then compared the data of the spinning class to aerosol particle emission data obtained in eight resistance-trained subjects during a three-set resistance training session that was designed to stimulate muscle hypertrophy and strength gains in the arms and legs. Unfortunately, we were unable to simulate a full 10 to 20 set resistance training session, as the head needed to be static during the exercise for the measurement of aerosol particle emission and only these three exercises fulfilled that requirement.

Fig. 2 shows the course of the average aerosol particle emission during the two real-life exercise classes. The maximal aerosol particle emission during the spinning class is about 3.4 times higher than the highest aerosol particle emission value during the resistance exercise. Overall, the average aerosol particle emission per minute over the whole class is 4.9-fold higher in the endurance compared to the resistance exercise. This difference is caused by the higher ventilation rate as well as the higher aerosol particle concentration during endurance exercise (*SI Appendix*, Figs. S2 and S3).

In our previous work, we generated aerosol particle emission data for different workloads during a graded cycle ergometry test to exhaustion (3). However, during a real-life exercise class, e.g., airway dehydration or other factors may additionally change aerosol particle emission over time. To find out whether the aerosol particle emission during a graded exercise test at a given workload predicts aerosol particle emission during a spinning class, we compared the real-life spinning class measurements to those obtained during a graded exercise test (i.e., if the subject was exercising with 300 W, we used the aerosol particle emission at 300 W for this time point). Data that illustrate this comparison are in the *SI Appendix*.

Aerosol particles that are expired into a room by one infected individual are only one factor that determines the infection risk during an indoor exercise class. In addition, factors including room size, room ventilation, and duration of the exercise session will additionally affect infection risk. Thus, to estimate the actual infection risk for an exerciser or non-exerciser during an indoor endurance or resistance exercise class with different mitigation measures, we performed a mathematical simulation of the infection risk.

Calculation of the Infection Risk and Estimation of the Effect of Mitigation Measures. Using the measured aerosol particle emission and ventilation data, we found that for the 1 h endurance exercise in a non-ventilated 315 m^3 room (air exchange rate = 0.5 1/h) the individual infection risk increases on average by a factor of 8.3 ± 5 for a non-exerciser assuming that one infected subject is exercising. The infection risk for a healthy, exercising person increases on average by a factor of 15.4 ± 10.9 if an infected subject is present and exercising in the same room. The difference between the exerciser and resting person is explained by the fact that the exerciser will inspire more air than the resting person. Depending on the aerosol particle emission of the infected subject, there may be a great variability in the infection risk. Using our measured data, we simulated that the infection risk varies from a 3.9 to 20.6-fold increase in non-exercisers and 8.0 to 42.8-fold increase in healthy exercisers.

Based on the 0.45 h long resistance exercise session, we found that the infection risk increases on average by 5.3 ± 2.6-fold (range: 2.3 to 9.8) for an exerciser. For a non-exercising subject, the infection risk increased by a factor of 3.2 ± 1.9 (range: 1.1 to 7.0) if they are in the room (315 m^3, air exchange rate = 0.5 1/h) with an infected subject performing resistance training.

To compare the increase of infection risk between endurance and resistance exercise, we compared the infection risk increase after 0.45 h. This results in higher infection risk increase factors than after 1 h for the endurance exercise. This is caused by the exponentially

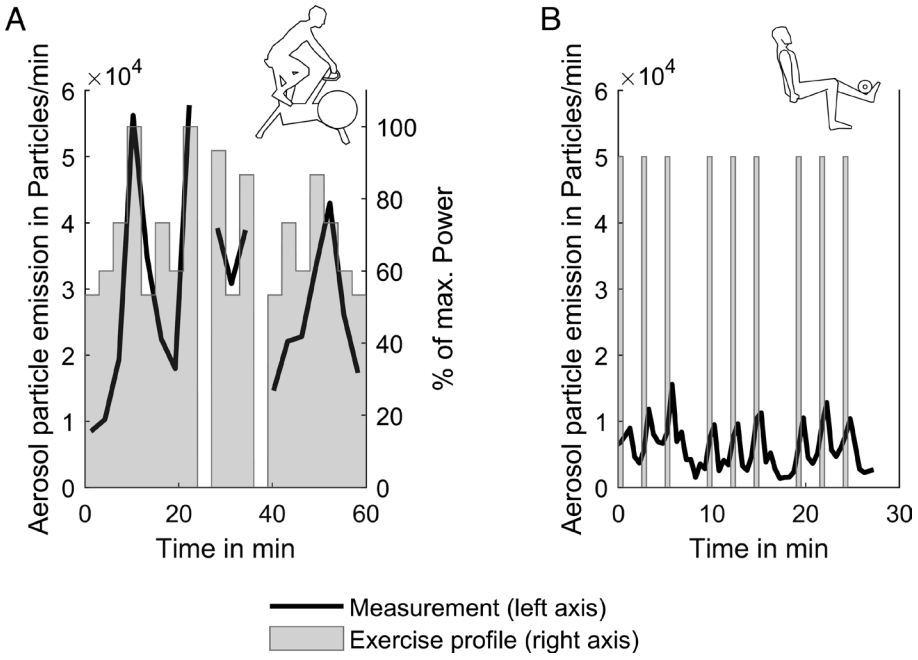

Fig. 2. Mean aerosol particle emission during (*A*) the spinning class and (*B*) the resistance exercise (note that the *y* axis for aerosol particle emission is identical). The intensity profile for the spinning class is shaded in the background. For the resistance exercise, the sets 1 to 3 were leg extensions, 4 to 6 biceps curls, and 7 to 9 overhead presses. Note the different timescales between *A* and *B*. This figure does not show error bars for clarity. A figure with SDs is in the *SI Appendix* (*SI Appendix*, Fig. S4).

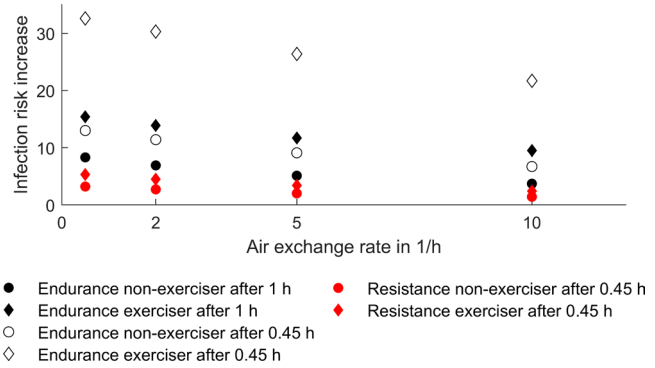

Fig. 3. Infection risk increase versus air exchange rate for endurance and resistance exercise for both exerciser and non-exerciser in a room with 315 m^3 and an exercise time of 1 h or 0.45 h for the endurance and 0.45 h for the resistance exercise. Infection risk increase factor for the endurance exerciser after 0.45 h is higher compared to 1 h due to the exponentially increasing infection risk for the passive reference case (one infected and one non-infected subject at rest).

increasing infection risk for the passive–passive reference case, which causes a more than 3.3 times higher infection risk after 1 h compared to 0.45 h. The infection risk increase for the endurance exerciser is about sixfold higher when compared to the resistance exerciser with 32.6-fold for the endurance and 5.3-fold for the resistance exerciser. For the non-exercisers, the difference is smaller with 13.0-fold increase in the endurance exercise class compared to 3.2-fold in the resistance exercise class. This shows that even the non-exerciser in the endurance setting has an about 2.5-fold higher infection risk when compared to the resistance exerciser.

Increasing the air exchange rate reduces the infection risk in both endurance and resistance exercise for exercising and non-exercising subjects. This relationship is shown in Fig. 3. Increasing the air exchange rate from 0.5 1/h to 10 1/h reduces the simulated infection risk increase after 1 h from 8.3 to 3.7 for the non-exerciser and 15.4 to 9.5 for the endurance exerciser. When comparing the infection risk increase after 0.45 h in the endurance exercise class, the increase can be reduced from 32.6 to 21.7 for the exerciser and from 13.0 to 6.7 for the non-exerciser. In the resistance exercise class, the infection risk factor can be reduced from 3.2 for the non-exerciser and 5.3 for the exercising subject to 1.4 and 2.4, respectively.

Discussion

The first finding of this study is that the emission of aerosol particles increases ≈10-fold during one set of isokinetic leg extensor resistance exercise at 80% of the MVC until exhaustion (Fig. 2). This is ≈10-fold less than the 132-fold change of aerosol particle emission that we had previously reported for a graded cycle ergometer test to exhaustion (3). The second finding is that aerosol particle emission per minute is 4.9-fold higher during a real-life spinning cycle endurance class when compared to a real-life resistance training session. The third finding is that the simulated infection risk (based on the real-life exercise session data) is sixfold higher during the spinning cycle endurance exercise class than during the resistance training assuming one infected participant in the room.

Fitness training in gyms is typically a combination of endurance and resistance exercise, and the WHO recommends a mix of endurance and resistance exercise for health. While some publications report aerosol particle concentrations during different types of endurance exercise, aerosol particle concentration and emission data are lacking for resistance exercise. During maximal resistance exercise, we found aerosol particle concentrations of 1,050 ± 1,160 particles/L which was lower than during rapid in- and exhalation with 2,800 particles/L (19), but higher than particle concentration with 450 particles/L caused by coughing (20). Even though there is no comparable data for the aerosol particle emission during endurance or resistance exercise, there are a few studies on the particle concentration caused by endurance exercise. One study found that aerosol particle concentration increased during endurance exercise at 70% of maximal heart rate (HRmax) (21). The aerosol particle concentration was 58-times higher at 70% of HRmax compared to rest. This fold increase is about six times higher than the one we found for resistance exercise, supporting the assumption that endurance exercise causes a greater particle emission than resistance exercise, even though the measurement setup was different. In all studies on aerosol particle concentration and endurance exercise (3, 21, 22), high interindividual differences were reported. The same is true for the data on aerosol particle concentration and emission during resistance exercise. As we see high interindividual variation in both male and female subjects, the determination of influencing factors should be substance of future studies. Two possible explanatory parameters of interest could be age and the body mass index (BMI) of the subjects, which correlate with the concentration of emitted aerosol particles (22, 23). While the ventilation seems to be generally lower during resistance exercise than high intensity endurance exercise, exercisers do perform specific breathing patterns during resistance exercise such as the Valsalva maneuver (17, 24). During the Valsalva maneuver, air is pressed is against a closed glottis before a rapid expiration. The effect of the Valsalva maneuver on aerosol particle concentrations and emission is currently still unknown.

The second main finding is that the average aerosol particle emission per minute during a real-life spinning class is 4.9-fold higher than during a real-life resistance training session. Key reasons for the difference are that resistance exercisers ventilate less during the exercise and that there are several minutes long rest periods in-between the exercises and sets of one exercise.

Next, we used the real-life exercise session data to simulate infection risk during a spinning cycle endurance class session versus a resistance exercise session assuming one infected exerciser in the room. We simulated infection risk for exercisers who will inhale more gas and for non-exercisers with a resting ventilation. We do not report the absolute risk of infection because the simulation is only a rough estimate, since the effect of contributing variables such as number of viruses leading to an infection is only poorly understood. The risk estimates presented are therefore always related to the risk of infection that arises for a healthy person in the presence of an infected person, with both persons at rest. We found that the infection risk after 0.45 h of exercise is on average sixfold higher in the endurance exercise when compared to the resistance exercise, with an increase factor of 32.6 and 5.3, respectively. The infection risk for the non-exercisers in both exercise settings is also about fourfold higher in the endurance setting, with 13.0-fold increase compared to 3.2-fold increase respectively. Even the non-exerciser in the endurance exercise setting has a 2.5-fold higher infection risk compared to the resistance exerciser. We see four reasons for the higher infection risk during the spinning cycle class endurance when compared to the resistance exercise session. First, aerosol particle emission is higher during endurance than during resistance exercise. Second, exercisers exercise at higher intensities for longer during endurance than during resistance exercise. Third, endurance exercisers typically exercise continuously, whereas resistance exercisers perform minute-long rests between exercises and sets, where aerosol particle emission declines. Fourth, endurance exercisers ventilate more than endurance exercisers, and this means

that they will also inhale more pathogen and aerosol-contaminated air.

The infection risk for both endurance and resistance exercise can be lowered by increasing the air exchange rate (Fig. 3). An increase of air exchange rate from 0.5 1/h to 5 1/h reduces the simulated infection risk increase for both exercising and non-exercising individuals in both training settings by about 20 to 40%. An air exchange rate of 6 1/h, which is recommended for indoor facilities (25, 26), would be even better. The importance of air exchange rate for the aerosol particle concentration in the room and thus the infection risk has also been shown in the literature (27). They reported that a high-efficiency particulate air (HEPA) filter reduced the concentration of aerosol particles generated during a 20-min endurance exercise trial by up to 96%, compared to the same 20-min endurance exercise trial without a filter. However, this extreme reduction in aerosol particle concentration can only be obtained with very high air exchange rates resembling outdoor settings. These results imply that high intensity endurance intervals should be performed in well-ventilated rooms or outdoors at times where the risk of consequential infections is high.

This study has several limitations. First, the endurance and resistance exercise aerosol particle emission data are not obtained from the same subjects. The rationale behind this is that we wanted to investigate trained exercisers, who regularly perform either endurance or resistance training. Trained exercisers are familiar with their preferred type of exercise, and because of their training status, they can exercise at higher intensities than novices.

For the real-life spinning exercise class, we needed to select one of many possible intensity profiles. Our intensity profile might not represent the intensity profile of the "average" spinning exercise class, but the average intensity profile is unknown. Thus the specific, used intensity profile has to be considered when interpreting this data.

For the real-life resistance training, we measured the aerosol particle emission for during three exercises that could be performed in the clean air tent and where the subjects could keep their head in the same position which was necessary for the measurement. However, a resistance exercise training session comprises more than three exercises with three sets each depending on the training status of the individual. Nonetheless, this data should give a good idea about aerosol particle emission during a resistance exercise session. Another issue of the resistance exercise session was that each set lasted around 30 s and so we shortened the sampling time to obtain data on the fluctuation of aerosol particle emission during and after a set of resistance exercise. The shorter sampling time increased the noise in the aerosol particle concentration data but when averaged over all subjects, it gives a good idea of the time course of aerosol particle concentrations during a resistance exercise session.

Lastly, we measured aerosol particle emission in young, uninfected subjects. However, age and respiratory infections increase aerosol particle emission (23), and so our data will probably be on the lower end when compared to the whole population and lower than in SARS-CoV-2 infected individuals.

In conclusion, we found that during a set of isokinetic resistance exercise, the increase in aerosol particle emission is 1.3-fold lower compared to the value at maximal exercise in an endurance graded exercise test. Comparing real-life exercises, the difference is even bigger with 4.9-fold higher aerosol particle emissions during the endurance spinning session compared to a resistance exercise. This is mainly due to 2.7-fold lower ventilation rates and different training intervals. Maximum aerosol particle concentration values measured are twofold higher during resistance exercise, when comparing isokinetic resistance exercise to the values at maximum intensity at the graded exercise test, but when comparing the real-life exercises, aerosol particle concentrations during endurance exercise are 1.9-fold higher. This result is further supported by the fact that the numerical simulations of infection risk showed markedly greater increases in infection risk with endurance training than with resistance exercise (factor 4 to 9). Even though exercise seems to impose a higher risk of getting infected, exercise holds many health benefits and should not simply be avoided. Thus, during periods with many consequential infections, the first focus should be to, for example, limit the number of people in endurance exercise classes, increase the air exchange rate of the facility, or to perform high intensity workouts outdoors.

Materials and Methods

We conducted an observational, monocentric human cohort study with the main aim to continuously measure respiratory ventilation, the concentration of aerosol particles in the expired air and aerosol particle emission at rest and during a realistic spinning class and a realistic resistance exercise with three exercises, each with three sets at 80% of the MVC. Also, another group performed a dynamic resistance leg press exercise at 80% of the MVC to exhaustion.

The subjects were young (age: 21 to 37), healthy and showed no signs of respiratory infections. The BMI of the participants ranged between 20.7 kg/m^2 and 37 kg/m^2, with the high BMI values in the resistance exercise groups due to high muscle mass. In this trained group, a high BMI (BMI > 24.9 kg/m^2) does not correlate to their health status (28). In the endurance exercise group, the BMI ranged from 20.7 kg/m^2 to 26.5 kg/m^2. The detailed participant statistics is shown in the *SI Appendix*, Table S1.

All measurements and procedures were approved by the medical ethical committee of the Technical University Munich. Prior to each test, participants and staff were tested for SARS-CoV-2 with an antigen test. Before any tests were performed, subjects signed an informed consent.

We recruited 24 participants: eight of them for the endurance training session, eight for a resistance training, and eight for an isokinetic resistance training. In each training setting, four women and four men participated.

Participants were screened for cardiovascular, pneumological, neuroplastic, orthopedic, metabolic, and other chronic diseases. The exclusion criteria were assessed during the obligatory medical pretesting, where a resting electrocardiogram (ECG) was taken and blood pressure was measured. Participants were excluded from the study if any health aspects potentially interfered with a submaximal or maximal strength testing. Additionally, participants were excluded if they were corona positive, had just recovered from a recent corona or any other respiratory infection within the last 4 wk, or were aware of any chronic lung disease.

For the isokinetic resistance training, subjects were recruited based on their strength performance (= one repetition maximum (1 RM) of squat performance relative to body weight) with an inclusion performance for women of at least 1.5 × body weight and for men 2 × body weight.

Improved Method to Measure Aerosol Particle Emission in One Experiment. In our previous study (3), we measured respiratory ventilation in one experiment and the concentration of respiratory aerosol particles in a second experiment. We then used the data from both near-identical experiments to calculate aerosol particle emission. For this study, we aimed at measuring both ventilation and the concentration of respiratory aerosol particles in one experiment. The improved experimental setup is illustrated in Fig. 4.

We used a calibrated spiroergometry device (Metalyzer; Cortex Medical™) to measure respiratory ventilation parameters. Aerosol particle concentration was measured using an optical particle counter [Palas Promo 3000 particle spectrometer using a Welas 2300 sensor (Palas GmbH)]. A volume flow of 5 L/min was extracted from the exhaled air after the spirometry sensor to the particle spectrometer via a controlled pump and used to determine the aerosol particle concentration. All measurements were performed in a clean air tent with reduced aerosol particle concentration (<150 particles/L compared to >30,000 particles/L in the ambient air). The airspace in the tent was flooded with cleaned air (H14 filter

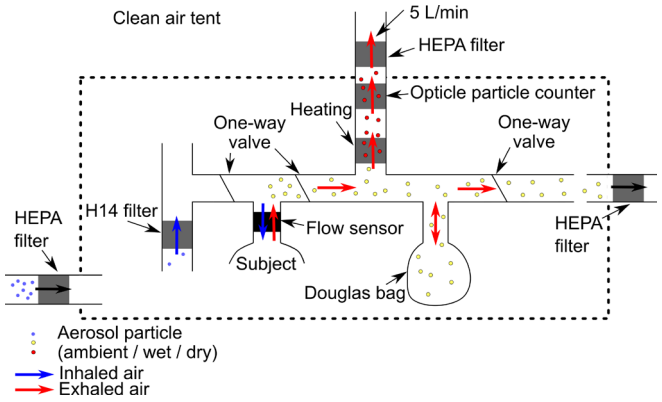

Fig. 4. Experimental setup. Detailed image of the aerosol particle and respiratory ventilation measurement system—including flow sensor, mask, and the tubes leading to the optical particle counter.

quality). In addition, the subjects directly inhale filtered air (H14 filter quality) with less than 30 aerosol particles/L via a supply hose, a Y-valve, and a breathing mask. The aerosol particle emission was calculated from respiratory minute ventilation and aerosol particle concentration.

For the practical exercise sessions, the whole measurement equipment starting with the spirometry sensor right in front of the subjects head, the valves, and the tubing up to the particle counter was heated to 40°C to 45°C to avoid condensation and the resulting particle separation on the surfaces. Only in the one-way valves flow separation of larger particles may have occurred due to sharp redirections.

Isokinetic Resistance Exercise. The resistance testing regime consisted of two major components:

1. Isokinetic MVC test for leg press at 90° hip angle.
2. One dynamic set of as many repetitions as possible at 80% of the MVC during which respiratory ventilation and aerosol particle emission was measured.

The whole test was structured as follows:

1. Lung function test (Metalyzer; Cortex Medical™, Germany).
2. Warm-up (5 min rowing, three sets of two preparatory movements).
3. Isokinetic MVC [Newton(N)–(IsoMed2000, D&R Ferstl GmbH)] testing for leg press.
   a. Two test trials.
   b. Three trials with 4 min breaks in between.
   c. Calculation of mean of three trials–determination of load for dynamic set (80% MVC).
4. Break of 5 min.
5. Standing respiratory ventilation and aerosol particle concentration measurement for 4 min (in clean space <150 particles/L compared to >30,000 particles/L in the ambient air).
6. Seated respiratory ventilation and aerosol particle concentration measurement for 4 min.
7. Dynamic set of leg press exercise at 80% of mean MVC until failure with respiratory ventilation and aerosol particle concentration measurement (in clean space)
8. Seated cooldown 5 min respiratory ventilation and aerosol particle concentration measurement (in clean space).

During the dynamic exercise set, the force-time curve was examined throughout the trial to ensure proper execution. The set-length can be seen in *SI Appendix*, Table S2.

Practical Exercise Measurements. For an endurance exercise, we use a spinning class protocol with an average intensity of 63% of the maximum power determined in a graded exercise test until exhaustion. The protocol consisted of a 5 min rest period at the beginning of the measurement as a reference and a 1 h exercise period with 2 × 3 min short drinking breaks. At the beginning and toward the end of the exercise period, the intensity was increased and decreased in steps. Each exercise level was maintained at a constant intensity for 3 min. Fig. 5*A* shows the intensity profile of the spinning class.

The graded exercise test was performed with each subject at least 2 d apart to the spinning session protocol. The test started with 50 W, and the power was increased by 25 W every 4 min until exhaustion.

All endurance exercises were programmed and run on a cycle ergometer (Ergoline Ergoselect 200, Lode B.V., Netherlands). Four women and four men performed this cycling session during which aerosol particle concentration measurement and respiratory ventilation parameters were assessed.

Both, the graded exercise test and the spinning class session were performed with the aerosol particle measurement system running. By using the same setting, it is possible to check the transferability of the results of the graded exercise test to the practical spinning session.

For this purpose, the respective ventilation and aerosol particle concentration values of the graded exercise test are used according to the power profile of the spinning session, so that a chronological progression can be created.

For the infection risk assessment in a typical gym, also a resistance training study with four women and four men and three different exercises was performed. As in the endurance study, the protocol started with a 5-min resting period as reference. The exercises were leg extensions, biceps curls, and overhead presses. These exercises were selected because they could be performed in the clean air tent, and also the subjects could keep their heads steady and connected to the measurement equipment. For each exercise, three sets with 8 to 10 repetitions were performed. The resistance was adjusted for each exercise and subject to approximately 80% of the 1 RM. Subjects started the sets every 150 s. The individual sets had a duration of approximately 30 s (19 to 42 s). After the third set of each exercise, the break was 4 min long. Fig. 5*B* shows the exercise protocol.

Due to the short measurement time for these exercise phases (19 to 42 s), the sometimes-low aerosol particle concentration (<80 particles/L), and the counting efficiency of the optical particle counter, it is possible that no particle at all is measured during the exercise phase (19 to 42 s). In these cases, the aerosol particle concentration was set to the resting value.

Data Processing and Statistical Analysis. All data were extracted and processed with MATLAB (Version R2021b). Data were analyzed using PRISM [GraphPad Prism 9.0.0(121)]. Normality and sphericity were tested and accounted for. Either two-way ANOVA, ANOVA, or Kruskal–Wallis test was used, respectively.

Factor Calculation. Based on the practical session studies for resistance and endurance exercise, increase factors were calculated for the infection risk modeling in comparison with the resting values of respiratory ventilation, aerosol particle concentration, and aerosol particle emission.

Numeric Modeling. The predictive theoretical approach proposed by refs. 29 and 30 allows an a priori estimate of the SARS-CoV-2 risk of infection of susceptible individuals due to airborne transmission route when exposed to virus-laden aerosol particles emitted by an infected subject in an indoor environment (29). Such an

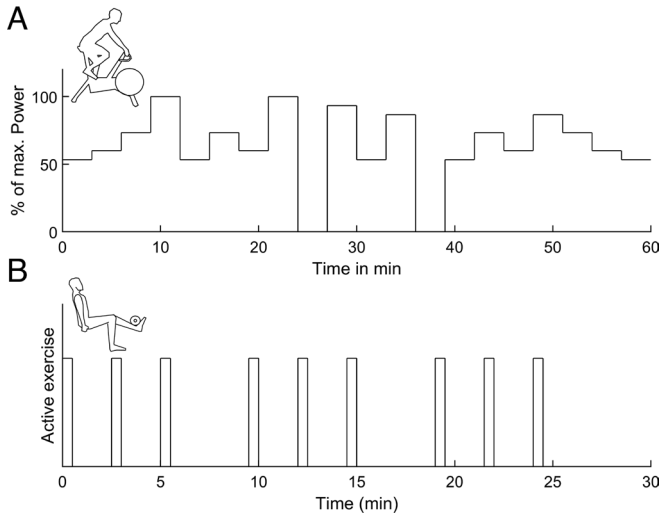

Fig. 5. (*A*) Spinning session protocol. (*B*) Resistance exercise session. Exercise 1 to 3: leg extension, exercise 4 to 6: biceps curls, exercise 7 to 9: overhead presses.

approach was experimentally validated against viral concentration measurements in a controlled environment (31) and was also able to reproduce the attack rate of documented outbreaks (30). Thus, this approach allowed to perform prospective assessments simulating different exposure scenarios (in terms of type of indoor environment, expiratory activity, etc.) (32–35. The approach is based on the evaluation of i) the quanta emission rate (ER_q), ii) the exposure to quanta concentration in the microenvironment, iii) the dose of quanta received by exposed susceptible subjects, iv) the probability of infection on the basis of a dose-response model, v) the individual risk of the exposed person, and, finally, vi) the event reproduction number. The above-mentioned "quanta" is a measure to quantify the virus emission or concentration, and it is defined as the infectious dose for 63% of susceptible by inhalation of virus-laden particles. In particular, the evaluation of the ER_q (quanta 1/h) was described in our previous papers taking into account the viral load (c_v, RNA copies 1/mL), the infectious dose (*HID*63, RNA copies; i.e., the human infectious dose for 63% of susceptible subjects), the respiratory ventilation (*VE*, m^3/h; depending on the activity level), and aerosol particle volume concentration (V_d, mL/m^3) expelled by the infectious person depending on the expiratory activity (29, 34):

$$ER_q = \frac{c_v \cdot VE \cdot V_d}{HID_{63}} \text{ (quanta 1/h)}. \quad [1]$$

Viral load and infectious dose values typical of Delta/Omicron variants of concern were adopted (36, 37); in particular, we considered the lognormal c_v distribution (mean and SD of 7.1 and 0.70 $\log_{10}$ RNA copies /mL, respectively) provided by ref. 38 and a HID_{63} value of 7×10^2 RNA copies as recently estimated by ref. 36.

Aerosol particle volume concentration for breathing expiratory activity just standing was obtained from refs. 20 and 39; it was equal to 2×10^{-2} mL/m^3. Then, the effect of the intensity level on the particle concentration was included by multiplying the concentration for standing by the ratios measured for different intensity levels and reported in the results section. Similarly, expiration/inhalation rate for a standing person while breathing was obtained from refs. 40 and 41 and it was equal to 0.54 m^3/h. Then, the effect of the intensity level on the inhalation rate was included by multiplying the *VE* for standing by the ratios measured for different intensity levels and reported in the results section. The variability of viral load, aerosol particle concentration, and inhalation rate were taken into account by calculating the product of the two Gaussian variables then obtaining a distribution of ER_qs, i.e., the probability density function of ER_q. We point out that the quanta emission model represents a major step forward to properly simulate and predict infection risk in different indoor environments via airborne transmission since previous studies were performed adopting ER_qs obtained from rough estimates based on retrospective assessments of infectious outbreaks only at the end of an epidemic (42, 43).

The indoor quanta concentration over time, $n(t,ER_q)$, is evaluated, for each possible ER_q value, adopting a simplified mass balance equation as

$$n(t, ER_q) = n_0 \cdot e^{-(AER+k+\lambda)\cdot t} + \frac{ER_q \cdot I}{(AER+k+\lambda)\cdot V} \cdot \left(1 - e^{-(AER+k+\lambda)\cdot t}\right) \text{ (quanta/m}^3\text{)}, \quad [2]$$

where n_0 represents the initial quanta concentration (i.e., at time $t = 0$), air exchange rate (1/h) is the air exchange rate, k (1/h) is the particle deposition rate on surfaces, λ (1/h) is the viral inactivation rate, I is the number of infectious subjects, and V (m^3) is the volume of the indoor environment.

The dose of quanta (D_q) received by a susceptible subject exposed to a certain quanta concentration for a certain time interval, T, can be evaluated by integrating the quanta concentration over time as

$$D_q(ER_q) = VE \int_0^T n(t, ER_q)\, dt \text{ (quanta)}, \quad [3]$$

where *VE* (m^3/h) is the inhalation rate of the exposed subject which is a function of the subject's activity level and age (40, 41). The inhalation rates of the exposed subjects doing exercise were calculated by multiplying the VE for standing by the ratios measured for different intensity levels and reported in the results section, whereas for exposed subject just attending the lesson (not doing the exercise) was adopted an inhalation rate of 0.54 m^3/h (i.e., standing activity).

The probability of infection [$P_I(ER_q)$,%] of exposed persons is the conditional probability of the infection, given a certain ER_q, and it is evaluated on the basis of simple Poisson dose-response model (44, 45) as

$$P_I(ER_q) = 1 - e^{-D_q(ER_q)} \text{ (\%)}. \quad [4]$$

The individual risk of infection (R) of an exposed person for a given exposure scenario is then calculated integrating, over for all the possible ER_q values, the product between the conditional probability of the infection for each ER_q [$P_I(ER_q)$] and the probability of occurrence of each ER_q value (PER_q):

$$R = \int_{ER_q} \left(P_I(ER_q) \cdot P_{ER_q}\right) dER_q \text{ (\%)}. \quad [5]$$

Modeled Scenarios. The estimates of the risk of infection were provided for two different exercises: endurance (1 h) and resistance (0.45 h). The intensity levels of the two exercises are reported in Fig. 5. Both the exercises were carried out in a 315 m^3 gym room. Simulations were performed considering one infected subject for both the exercises; all the subjects (infected and exposed) were considered breathing during the exercise. The infection risk was calculated for both cases (endurance and resistance training) considering each tested subject once as infected and calculating the risk of infection for a simultaneous exercising subject with the median minute ventilation. As a comparison, the infection risk was also calculated for a passive non-exerciser present in the room during the exercise. The infection risk increase factors are calculated by dividing the individual infection risks through the infection risk of a non-exerciser present in the same setting when the infected person is also a passive non-exerciser, which is considered as the lower baseline.

RNA copy concentrations, dose received by exposed subject, and their individual risk were evaluated for different air exchange rates, ranging from 0.5 [typical of room not equipped with mechanical ventilation systems (46)] to 101/h.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

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