Safe indoor work-outs during the COVID-19 pandemic

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Abstract. Many people go to the gym to work-out or take part in classes to remain in good physical health. During the COVID-19 pandemic, gyms in most countries across the world were obliged to close to prevent the virus from spreading during indoor work-outs. Indeed, the risk of aerosol virus transmission during high intensity exercise is significantly increased due to the increased aerosol production of a potentially infected person and the increased breathing volume of susceptible individuals. However, doing physical workouts is of great importance to stay healthy and enhance the immune system, especially during the pandemic, since it is known that overweight people and people with underlying diseases are at increased risk. Therefore, the objective of this project was to design a ventilation and air cleaning system that significantly reduces the risk of aerosol virus transmission in indoor sport environments. The project aims to contribute to establishing requirements for indoor sport facilities in terms of ventilation and air cleaning such that, during a next lockdown, gyms that fulfil these requirements can remain open. To achieve this objective, a literature survey was conducted to map the current knowledge on the aerosol transmission of COVID-19 and the characteristics of different types of exercise. Based on that, requirements were set for different intensity group classes to maintain the CO_2 concentration below 1200 ppm and the theoretical Wells Riley-infection risk below 5%. In addition, the importance of ventilation efficiency to dilute released contaminated aerosols was well understood in order to apply the Wells Riley-model. A lab- and field study were conducted to test if the model assumptions were met. Also, the possibility to measure aerosols in the field was investigated. Based on these outcomes, a prototype consisting of a ventilation system, air cleaning system and cooling system combined with a smart control algorithm, was designed and installed in a room for group classes. The performance of the systems was tested during exercise classes of yoga, zumba and indoor cycling (spinning).

Keywords. COVID-19, Aerosols, Exercise, Ventilation, Air cleaning.
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1. Introduction

To remain in good physical health, many people go to the gym to exercise. Especially during a pandemic, like the COVID-19 pandemic, this is of great importance since overweight people and people with underlying diseases are at increased risk of getting severe symptoms after infection with the SARS-Cov-2 virus [1]. Besides overweight lower cardiorespiratory fitness and higher waist circumference appaers to be predictors of severe COVID-19 [2]. Moreover, physical activity attributes to the immune system of humans [3]. Although obliged closures of gyms to reduce the reproduction number, there are good reasons to consider a strategy to exclude closures in the strategy for this necessary reduction. However, due to the increased aerosol production of any infected person in a gym and the increased breathing volume of susceptible individuals, the risk of aerosol virus transmission is significantly increased in gyms. Indeed, there are a few outbreak cases in indoor sport facilities [e.g. 4, 5]. The potential additional risk of virus transmission in gyms and the reported cases were probably a driving force to close gyms in most countries across the world during waves of infections.

The objective of this project was to design a ventilation and air cleaning system that significantly reduces the risk of aerosol virus transmission, potentially containing virions, in indoor sport environments. The project aims to contribute to establishing ventilation and air cleaning requirements for indoor sport facilities such that, during a next lockdown, gyms that fulfil these requirements can remain open.

To achieve this objective, a literature survey was conducted to map the current knowledge on the aerosol transmission of COVID-19 and the characteristics of different exercise activities. Based on that, requirements were set for different intensity group classes. A lab- and field study were conducted to test if the model assumptions were met. Also, the possibility to measure aerosols in the field was investigated. Based on these outcomes, a prototype consisting of a ventilation system, an air cleaning system and a cooling system combined with a smart control algorithm, was designed and installed in a room for group classes. The performance of the systems was tested during group classes of yoga (holistic), zumba (aerobic) and indoor cycling (cardio).

2. Requirements for gyms

Starting point for the requirements of the adaptive system is that the following functional demands are met:
1. The theoretical risk of airborne transmission is sufficiently low when one of the persons present is infected.
2. The indoor air quality has no negative impact on health as compared to limits for public health.
3. The temperature in the room is adjusted to the physical intensity of the exercise performed.

These functional demands are translated to performance criteria based on literature as described below.

2.1 Theoretical risk of airborne transmission

The theoretical risk of airborne transmission can be estimated using the Wells-Riley equation [6, 7]. The risk for each individual in a room to get infected (P), can be estimated based on the ventilation (Q), the number of infected persons present in the room (I), virus emission of susceptible persons (q) the breathing volume (p) and the duration of exposure (t) using equation (1).

$$P = 1 - exp\left(-\frac{Iqpt}{Q}\right) \quad (1)$$

Thereby it is assumed that all people are equally likely of getting infected, their breathing volume is equal and the time spent in the room is the same. Also, it is presumed that the air is fully mixed and a steady state concentration has been reached. By doing so, the estimated risk of persons close to the infected person might be underestimated [8], while the assumption of a steady state might overestimate the risk, especially in rooms with a low ventilation rate, since it takes some time to reach steady state.

Apart from ventilation, other factors that inactivate the virus and/or remove virions, can be included in the model [9]. Filtering of the air can be included based on the air cleaning flow rate (Q_r) and the air filtering efficiency (η). The individual risk of infection can then be calculated according to equation (2).

$$P = 1 - exp\left(-\frac{Iqpt}{Q + Q_r\eta}\right) \quad (2)$$

To calculate the required amount of ventilation and other factors that inactivate the virus and/or remove virions ($Q+Q_r*\eta$), all other parameters of equation 2 need to be addressed.

The limit for the theoretical risk of airborne transmission (P) is set at 5%.

Number of infected persons (I): the model is based on the assumption that one of the athletes or instructors is infected.

Virus emission of infected person (q): the virus emission is expressed in quanta per hour, where one quantum represents a virtual amount of virus that is enough (with a probability of 63%) to infect an average healthy person. Principles for quanta production of the SARS-Cov-2 virus have been published and show large differences between breathing during light and intense activity, talking and screaming [10]. In this model the P95 values as reported by Buonanno are used [10]. The assumption here is that athletes in holistic exercise (yoga, Pilates) talk 10% of the time and in other sports a maximum of 20% of the time. For instructors, the assumption is that they are talking 50% of the time (fitness, holistic exercise) or yelling 50% of the time (aerobics, cardio). For the latter, the aerosol production was calculated with and without the use of a microphone to reduce quanta production. For the virus emission, the time-averaged value has been taken for the hourly-averaged quanta production (Table 1).

Breathing volume (p): the breathing volume is dependent on the intensity of the physical activity. The assumption for the breathing volume during the different types of exercise, has been based on the data published by Salonen et. al. that include the relation between physical intensity and breathing volume [11], (Table 1). Compared to the study of Ramos et al, might be slightly on the low side [12].

Time of exposure (t): in determining the required capacity of the ventilation system in the room for group classes, time of exposure is assumed 1 hour.

2.2 Indoor air quality and health

A limit value of 1200 ppm is used for the CO_2 concentration, which is in line with the National Institute for Public Health and the Environment in the Netherlands [13]. The ventilation required per person for this depends on the CO_2 production and thus the intensity of the athlete or instructor. The intensity of the activities is expressed in MET. For the various categories in, the MET value was determined on the basis of the compendium [14]. In this case, we assume an average basal metabolic rate (BMR) of 6.94 MJ/day, based on an equal distribution between men and women and age (range: 16 and 70 years old) and a respiratory coefficient (RQ) of 0.85 [15]. The resulting CO_2 production per person for the defined exercise intensities [M=MET] was calculated (equation 3). The outcome and the required flow rates are shown in Table 2.

$$V(CO_2) = BMR * M * 0{,}484 * 10^{-3} \quad (3)$$

Tab. 1 – Overview of the estimated values used for the parameters included in the WR-equation based on different exercise activities (wild corona variant).

Activity	Virus emission (q) [quanta/hour]	Breathing volume (p) [m^3/ hour]
Athlete: holistic	30	1.2
Athlete: aerobic	40	1.8
Athlete: Cardio	40	2.4
Instructor: holistic	50	1.2
Instructor: aerobic	193 (98[a])	1.8
Instructor: cardio	240 (145 [a])	2.4

[a] when using a microphone.

Tab. 2 – Overview of the required ventilation flow rate per person to keep the CO_2 concentration in the room below 1200 ppm.

Activity & corresponding estimated metabolism in [MET]	CO_2 production [l/s / person]	Ventilation rate [m^3/ hour per person]
Athlete: holistic, 4	0.013	60
Athlete: aerobic, 6	0.020	90
Athlete: Cardio, 8	0.027	120
Instructor: holistic, 4	0.013	60
Instructor: aerobic, 6	0.020	90
Instructor: cardio, 8	0.027	120

For the particulate matter, a limit values has been set based on the daily average exposure limit by the WHO of 15 µg/m^3 [16]. This value is adjusted for the breathing volume and thereby the increased dose (concentration * volume), due to the increased breathing volume caused by an increased metabolism during exercise (eq. 4). This results in a limit for the PM2.5 concentration of 6 µg/m^3, 4 µg/m^3 and 3 µg/m^3 for respectively holistic exercise (MET=4), aerobics (MET=6) and cardio (MET =8).

$$Limit\ avg. PM_{2.5} = \frac{1,5}{MET} * 15\ \mu g/m^3\ )(4)$$

2.3 Thermal comfort

In Europe, there are no specific standard that prescribe the thermal environment in sporting facilities. Also in other parts of the world, standards often have only general recommendation for the thermal indoor environments in sport facilities [17]. Sporting federations for indoor sport facilities as recognized by the International Olympic Committee (IOC), describe guidelines for specific games, but these vary widely among different games: for example 16°C-20°C for basketball and 18°C-30°C for badminton [14]. Therefore, it was decided to evaluate thermal comfort and based on that adjust the setpoint where needed. The limits for the temperature were initially set at 16-20°C.

2.4 Overall requirements

Based on the findings in literature, the requirements for the room were calculated for the three different types of group classes. To calculate the required capacity of the ventilation equivalent, the worst-case scenario was used (i.e. the instructor is infected, but was required to wear a microphone to reduce the required voice volume and subsequently the aerosol production) to keep the probability of infection below 5%. Then the required ventilation rate was calculated to keep CO_2-concentration below 1200 ppm in case of occupation of 20 athletes. In case the required fresh air supply is lower than the ventilation equivalent, the remaining is provided using air cleaning. Table 3 shows the required design criteria in terms of the ventilation equivalent, the fresh air supply and the amount of air cleaning.

Tab. 3 – Overview of the required ventilation equivalent, fresh air supply and air cleaning

Activity & estimated metabolism in [MET]	Ventilation equivalent (Q+Qr*η) [m^3/ h]	Ventilation rate (Q) [m^3/ h]	Additional air cleaning [Qr*η] [m^3/ h]
Holistic, 4	1180	1200	0
Aerobic, 6	3440	1800	1600
Cardio, 8	6800	2400	4400

3. Verify model assumptions

3.1 Lab measurements

Experiments were carried out in a small indoor test room to determine whether it is feasible to measure (an indication of) the aerosol production during exercises.

Method

In a test room of 27 m^3 (3.2 x 3.3 x 2.6 meter) measurements were performed when riding a spinning bike at two intensities. The protocol consisted of cycling at moderate intensity (±70% of the maximum heartrate) and high intensity (±90% of the maximum heartrate). During each intensity measurements were performed with a FFP2 mask and repeated without the mask so that the difference could be used as an estimation of the aerosol production while correcting for other factors influencing the particle concentration. Without wearing the mask, the athlete was silent for 6 minutes, talking for 6 minutes and singing loudly for 6 minutes to increase the aerosol production. During all experiments particle concentrations were measured using a GRIMM 1.109 Optical Particle Counter (OPC). All measurement were performed during one day.

There was no ventilation in the room (infiltration ± 9 m^3/hour) during the experiments. Between different experiments, the room was ventilated and cleaned using a large air cleaner to remove airborne particles so that each experiment started with low background concentrations.

Results and discussion

Except for the measurement when the athlete was singing and cycling at high intensity, the increase in the number of particles (0.250-30µm) per second during one experiment was smaller during the course of the day (Figure 1). A similar pattern was observed for the increase in PM1 concentration. Based on these results, the larger increase during singing at high intensity might be attributed to the increased aerosol production. However, the differences between cycling experiments with and without mask, appears to be not the only factor of concern. It is hypothesized that the bicycle itself or infiltration of surrounding air were sources of particles in the experimental chamber, sources for which the contribution decreased during the day. This confounding effect appears to be larger than the aerosol production of the athlete (except for singing at high intensity).

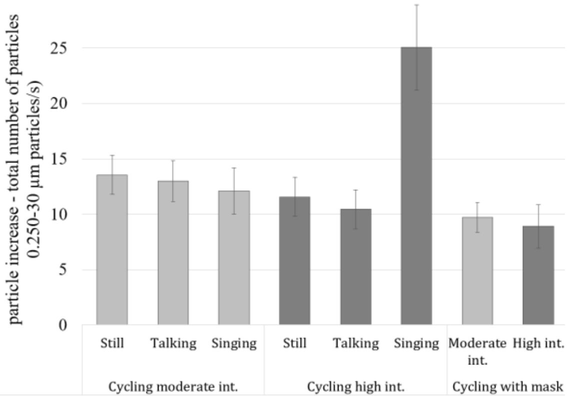

Fig. 1 – Particle increase per second during the different experiments during the course of the day (chronological) (average ± 95% confidence interval).

Already in this tightly controlled experiment, without ventilation, and with a standardised protocol, the aerosol production by the athlete is overruled by other (not constant) sources. Also the contribution of bioaerosols released by the athlete is relatively small: the increase in PM1 during high activity and singing, corresponds with an increase of 3,8 µg/m^3 per hour if no particles settle and there is no ventilation at all. In practise it will therefore not be possible to attribute an increase of particles to an increase aerosol production.

3.2 Field measurements

Based on the outcomes from literature and lab study, a prototype combining ventilation, air cleaning and cooling coupled to a smart control algorithm, was designed and installed in a room for group classes. The performance of the system was first tested in an empty room that is normally used for group classes. The objectives of the measurements were:

- Determine the obtained ventilation and air cleaning performance.
- Determine the ventilation efficiency.

The system was installed in a room for group classes with a volume of 477 m3 (Figure 2 and 3). The system consists of an air handling unit (AHU) which provides fresh air to the room via four textile air ducts (Figure 2). Dependent on the required ventilation equivalent, air from the room is recirculated and mixed with the fresh air and filtered and cleaned using an ASPRA cylindrical Electrostatic Air Precipitator (ESP) combined with an open structure static filter: particles are charged inside the ESP section, and captured directly on the filter. Additionally, a standalone fancoil unit was used for cooling, heating and cleaning (ASPRA cylindrical ESP) recirculated air.

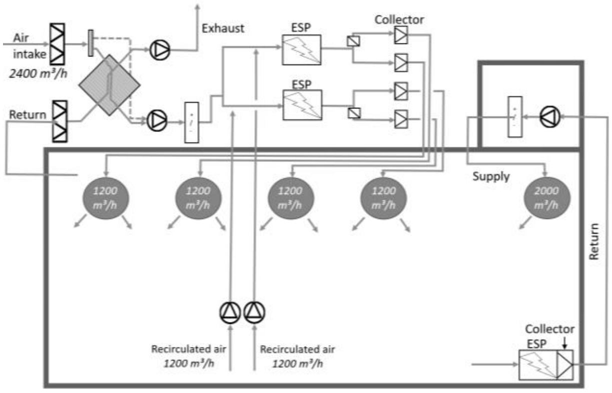

Fig. 2 – Schematic illustration of the principle

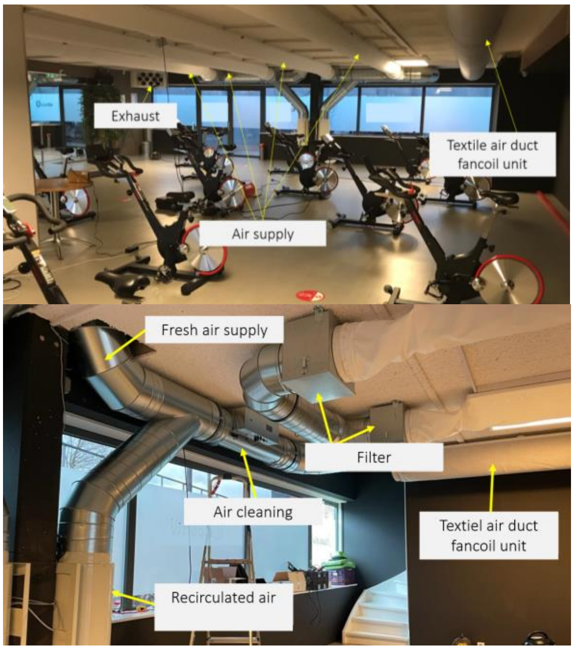

Fig. 3 – Room where the system was installed.

Performance of the ventilation and recirculation system was determined a grid of CO_2 sensors placed in the room and a GRIMM 1.109 Optical Particle Counter (OPC) (Figure 4).

The air change per hour (ACH) of the ventilation and air cleaning was determined based on the decay rate (equation 5). CO_2 extinguishers were used to generate CO_2 and thus determine the decay rate at each measurement location. The ventilation rate was calculated as the average of the ACH per location. To determine the total ventilation equivalent, a smoke machine was used to generate particles, to ensure a high PM1 concentration as a starting point. The decay rate was calculated and based on that the air change rate was determined. Note, the decay rate of CO_2 determines the ventilation rate and the decay rate of particles the air changes (equivalent ventilation).

$$Concentration\ time = \ t\,(C_t) = C_0 * e^{-\lambda t} \quad (5)$$

C_0 = concentration at time [ppm of $\mu g/m^3$]
t = time [hours]
λ = ventilation (equivalent) rate (ACH) [$hours^{-1}$]

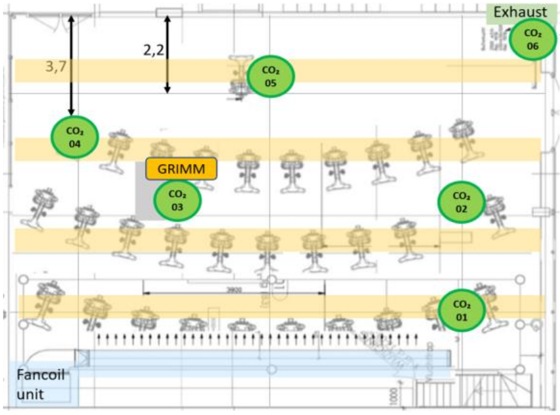

Fig. 4 – Locations of the CO_2-sensors and GRIMM (schematic).

Whether the air in the room is well mixed, was determined based on the Air Change Effectiveness (ACE) index [18] using equation (6).

$$\text{ACE}\ index = \frac{ACH\ location}{ACH\ room} = \frac{\lambda}{\tau} \quad (6)$$

The measurements of the ventilation and ventilation equivalent were performed in the setting for the high intensity activity (8 MET). Outdoor measurements of the air temperature CO_2-concentration, relative humidity and PM2.5 were performed on April 7th 2021, had a duration of 8 minutes and a measurement interval of 1 second (PM2.5) and 1-minute (Temp, CO_2 and RH) (Table 4).

Tab. 4 – Outdoor conditions during measurements

	Average	Standard deviation	Unit
PM2.5	17	9	$\mu g/m^3$
CO_2 concentration	428	5	ppm
Relative Humidity	46	2	%
Temperature	11	0.3	°C

The results of the measurements show that the air was well mixed within the room: ACE is between 0,96 and 1.07 (Table 5). The measured ventilation rate is slightly (9%) lower as compered the design value.

Figure 5 illustrates the decay of the PM1 concentration. As illustrated the natural logarithm of this decay shows a linear drop during the first 8 minutes, this interval is used to determine the slope (0.215 min^{-1} = 12.9 h^{-1}). Thereby providing a representative value of the ACH of the ventilation equivalent. Similar to the ventilation rate, the ventilation equivalent is 10% lower as compared to the design value (Table 5).

Tab. 5 – Comparison between the required and measured performance of the system during the cardio settings.

	Cardio / high intensity design	measured (avg ± stdev)
Ventil. rate 20 ath. [m^3/h]	2400	2195 ± 98
ACH ventilation (h^{-1})	5.0	4.6 ± 0.2
ACE index (range)	0.90 – 1.10	0.96 – 1.07
Ventilation equiv. [m^3/h]	6800	6142
ACH Ventilation equiv. (h^{-1})	14.3	12.9

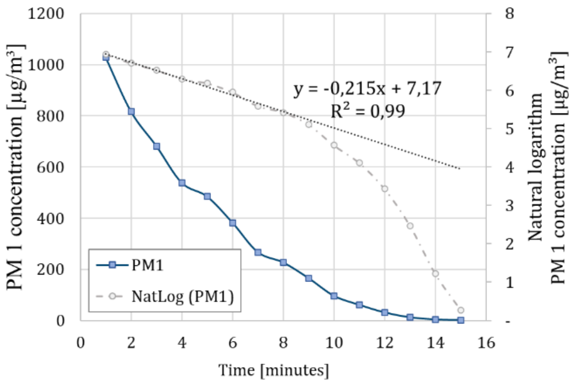

Fig. 5 – Decay of the PM1 concentration (primary x-axis) and the natural logarithm (secondary x-axis).

Conclusion

Based on the measurements it can be concluded that the air in the room is well-mixed, but the decay rate of CO_2 and the PM 1 showed a slight underperformance. However, the ventilation rate is still within acceptable limits for a field environment.

4. Prototype

To test whether the system performed as expected during occupation, field measurements were carried out to evaluate the indoor environmental parameters and the experiences of the athletes. Also, the data was used to validate the assumed MET values per sport.

4.1 Method

Measurements were performed during two days, whereby the same program was carried out each day. This program consisted of three types of group classes: yoga (holistic ±4 MET), zumba (aerobic ±6 MET) and spinning (cardio ±8 MET). During the first day, the “standard settings” were used: fixed ventilation rate based on the national guidelines (1200 m^3/ hour, so that 20 persons can participate), air cleaning switched off, and cooling system switched on. During the second evening the settings as specified in Table 3 were used for the “prototype”. All classes had a duration of 45 minutes.

During each classes, 20 athletes could participate (partly the same participants during both days). Of each person, the age, gender, weight and length was collected to calculate the expected BMR using the Harris and Benedikt Formula [19], see table 6. After each class, participants were asked to fill out an online questionnaire to indicate how they experienced the indoor environment. The results of the questionnaire were compared using a t-test. P-values <0.05 were considered significant (indicated with * and p<0.01 **), p-values <0.1 were considered a trend (indicated with #).

During all classes temperature, relative humidity CO_2-concentration and PM1, PM2.5 and PM10 were measured continuously.

Tab. 6 – Number of athletes per class and their calculated BMR (average).

	Average BMR [kcal/day]	Number of athletes (incl. instructor)
Yoga day 1	1393	17
Yoga day 2	1516	17
Zumba day 1	1471	18
Zumba day 2	1394	18
Spinning day 1	1618	20
Spinning day 2	1620	20

4.2 Results

During the zumba class and spinning class the peak CO_2-concentrations were lower on day 2 (prototype settings) as compared to day 1 (standard settings). Still 1200 ppm CO_2 was exceeded during spinning on day 2 and achieved at the end of the class (Figure 6). The difference between both Yoga classes were more equal due to the same setting of the ventilation rate.

Temperature was significantly lower at day 2 (19.0 ± 0.37) as compared to day 1 (20.3 ± 0.70) (Figure 7). During the standard settings temperature increased during the evening with a median temperature of 20.8°C during spinning class. At day 2 temperature during the all classes was around 19.0°C.

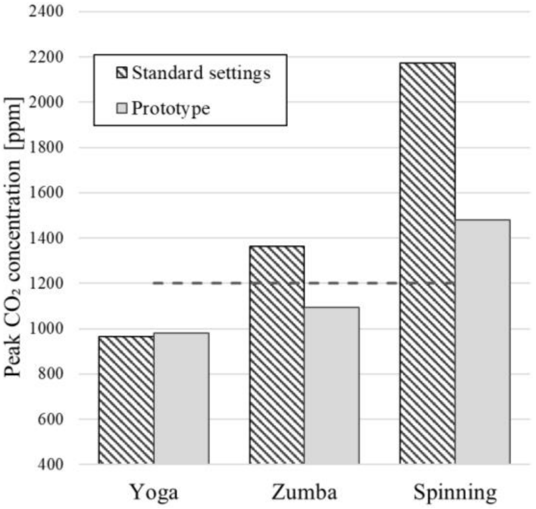

Fig. 6 – Peak CO_2-concentration during each class.

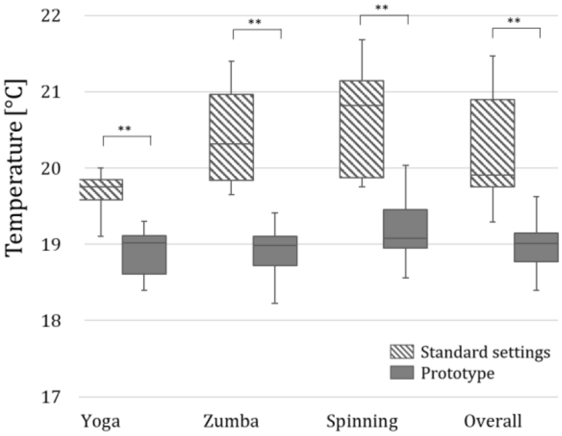

Fig. 7 – Air temperature day 1 (standard settings) versus day 2 (prototype).

In line with the measurements of CO_2-concentration and temperature, the participants of the zumba and spinning class were significantly more satisfied with the indoor air quality and temperature when the settings of the prototype were used as compared to the standard settings (Figure 8 and 9). For the yoga class participants did not experience a difference but were on average satisfied with the temperature and indoor air quality during both sessions. Also, the thermal sensation was closer to neutral during the zumba and spinning class when the settings of the prototype were used (Figure 10).

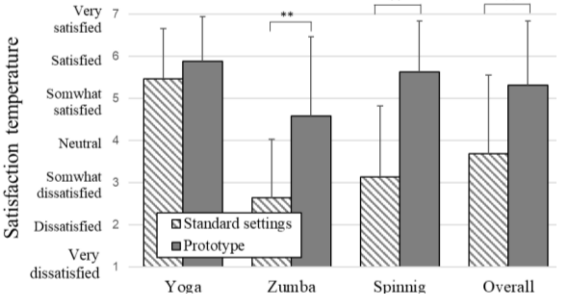

Fig. 8 – Satisfaction with the air quality.

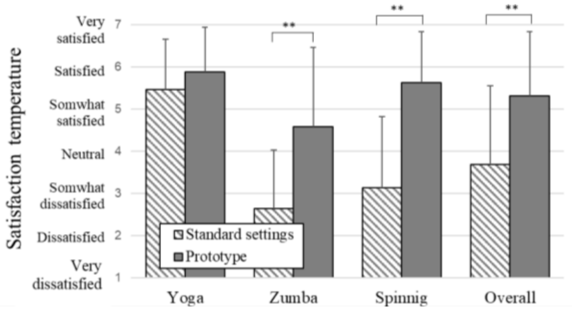

Fig. 9 – Satisfaction with the temperature.

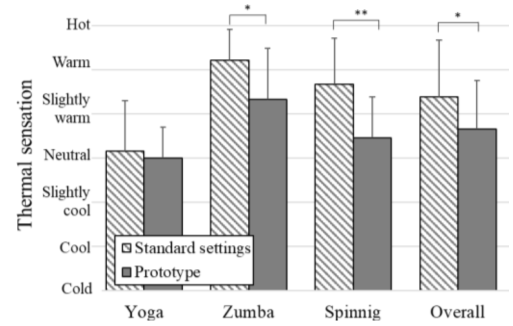

Fig. 10 – Thermal sensation of participants.

Based on the peak CO_2-concentrations at t=45 minutes, the CO_2-production of the athletes was calculated for each class (Table 7). For the yoga and zumba classes the assumed MET values of 4 and 6 seemed to be adequate estimates. However, for the spinning class 8 MET underestimated the physical activity of the participants: at day 1 the calculated MET value was on average around 10 and at day 2 on average 10,5.

4.3 Conclusion

The new settings of the prototype improved the indoor air quality as compared to the standard settings. Based on the data it was concluded that the participants of the spinning class had an average MET value of around 10, which is higher than the assumed 8 MET. As a result, the CO_2-concentrations exceeded the 1200 ppm during this lesson. Still the subjective response about the indoor air quality and temperature of the participants of the Zumba and spinning class significantly improved as compared to the standard settings.

5. Conclusion

Due to the increased breathing volume and quanta production, indoor exercising poses an increased risk of transmission of viruses in case of insufficient ventilation. Especially when the intensity is high, ventilation rates need to be extremely high to sufficiently reduce the risk of transmission of the SARS-Cov 2 virus. A theoretical approach for determining the required ventilation equivalent is recommended since explorative measurements indicate that it is not possible to measure the aerosol production during exercise in the field. A combination of ventilation and air cleaning can both ensure a good indoor air quality and a safe environment in an energy efficient way. It must be noted that mutation of the virus and changing infectivity of the virus, may change the required performance.

Moreover, the results show that the general guidelines for the amount of ventilation per person are insufficient for moderate and high intensity activities. Dynamic settings based on the intensity of the activities performed, are needed to provide an adequate indoor climate, both in terms of temperature and indoor air quality.

The study demonstrates that it is possible to anticipate on the transmission of viruses by increasing ventilation and air cleaning rates in sport accommodations, thereby allowing safe indoor exercising during a pandemic when staying physically healthy is of upmost importance.

Tab. 7 – Calculated MET value using the measured CO_2 concentrations, the average BMR, the occupation and the ventilation rate.

	Ventilation rate [m^3/hour]	**CO_2 production MET=1 / pers. [m^3/min]**	**Number of athletes [-]**	**Peek CO_2 concentration [ppm]**	**Calculated sport intensity [MET]**
Yoga day 1	1200	0.000169	17	964	3.8
Yoga day 2	1200	0.000184	17	981	4.0
Zumba day 1	1200	0.000179	18	1364	6.7
Zumba day 2	1800	0.000169	18	1093	6.7
Spinning day 1	1200	0.000197	20	2172	10.1
Spinning day 2	2400	0.000197	20	1480	10.7

6. Acknowledgement

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Conflict of interest

Conflict of interest: EK and FF are co-founders of iVention, which is a commercially available HVAC solution which emerged from this research project.

Data Statement

The datasets generated and analysed during the current study are not publicly available because it was collected to test the effectiveness of the described innovation. The paper presents the relevant outcomes. Upon reasonable request, the data that support the findings are available from the corresponding author.