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Thermal Comfort and Indoor Environment with Wearing a Mask

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ABSTRACT

The purpose of this study is to clarify the respiratory characteristics and productivity with wearing a mask, and to propose the indoor control strategy to maintain the thermal comfort. With the worldwide spread of biological hazards including COVID-19, it has become common to wear a mask as a countermeasure against infection in public places. Because of this influence, it is necessary to take measures against health hazards caused by wearing a mask (increased respiratory load and oxygen poverty due to wearing a mask for a long time, heat stroke in summer). In this study, there are two stages of methods; (1) clarification the characteristics of exhalation and inspiration when wearing a mask, (2) understanding the causes of reduced work efficiency that cause oxygen deficiency and destruction of the human body heat balance. Respiratory characteristics from the human body differ depending on the type of mask, the amount of metabolism due to exercise, and the surrounding environment. Therefore, we measure changes in respiratory characteristics (respiratory cycle, CO2 concentration, temperature, humidity) and build a predictable numerical model. By measuring changes in work efficiency and intellectual productivity due to various changes in the indoor environment, the effects of oxygen deficiency and destruction of the human body heat balance due to wearing a mask are clarified, and indoor air and thermal environment control that can respond to them It will be a great achievement for the proposal of the law. In this study, we conducted a subject experiment on the simple work efficiency and the expiratory/inspiratory characteristics when wearing a mask and confirmed the deterioration of the air taken into the human body and the damage of exhaust heat. In addition, new standards for the indoor environment were set based on the findings obtained.

INTRODUCTION

Due to the worldwide spread of COVID-19, guidelines (ASHRAE, 2020; REHVA, 2020; ISHRAE, 2020) have been created to prevent infectious diseases in various countries around the world. Under the influence of these global efforts, wearing masks in public places has become common. As a result of this, long-term wearing a mask causes health problem such as breathlessness (feeling of fatigue) and inhibition of exhaust heat in summer (heat stroke), and it is becoming a problem. Various studies have been conducted on the effects of wearing a mask on the human body, the increase in lung load during respiration, the suppression of airflow diffusion in exhaled breath (KASAHARA et al., 2004, Hamada et al. 2021, Bao-guo Yao et al. 2019), the decrease in workability caused by the increase in CO_2 intake (MIMURA et al., 2018) and etc (UEKI et al., 2020; Anindita et al., 2020) are stated. Figure 1 shows the surface temperature with and without wearing a mask. In a room with a temperature of 23 ºC, wearing a mask for 15 minutes increased the skin surface temperature from the mouth to the neck by about 1 ºC. From this, when wearing a mask, it is considered that some exhaled breath is retained in the mask, and at the same time, there are concerns about problems such as an increase in CO_2 intake and a decrease in heat loss. To resolve these problems, we establish a new indoor environment control method in this paper. To this end, we first elucidate the characteristics of expiration and inspiration while wearing a mask. By quantitatively examining their respiratory characteristics while wearing a mask, we clarified the maintenance index of indoor thermal environments in terms of heat balance in the human body.

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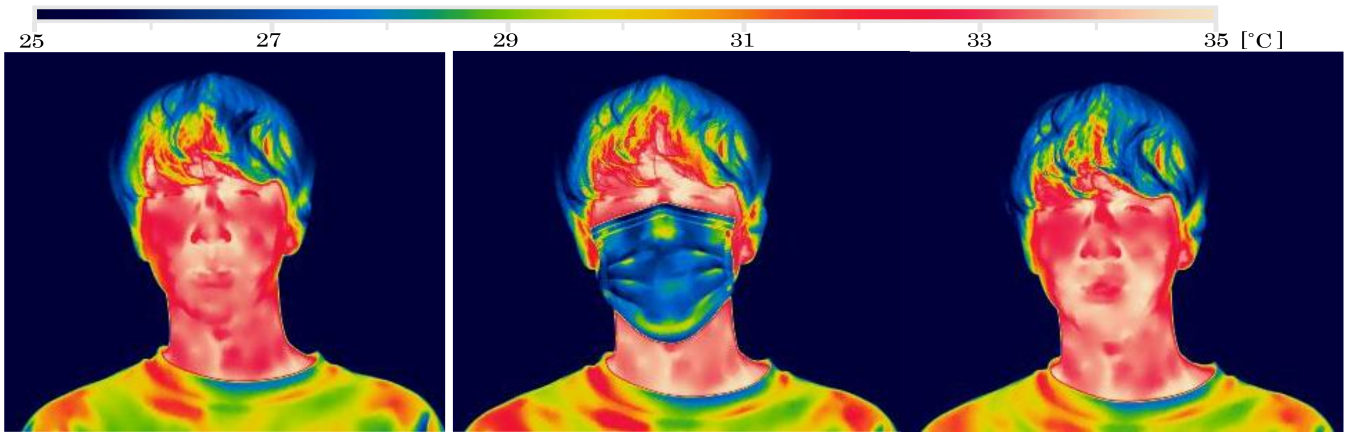


(a) Non-wear (b) Wearing (c) After wearing

Figure 1 Surface temperature ((a) is the skin surface temperature before wearing a mask, (b) is the surface temperature when wearing a mask for 15 minutes in a room with a temperature of 23 ºC, (c) is the skin surface temperature when the mask is removed immediately after (b)).

WORK EFFICIENCY WHEN WEARING A MASK

1. Experimental Methods

The experiments were conducted on the effect on work efficiency when wearing a mask. 35 university students were examined for simple work efficiency depending on wearing and non-wearing masks. Subjects performed simple work (Japanese text typing) for 40 minutes at home (shown in Figure 2) controlled in a constant environment (room temperature: 24~26ºC, humidity: 40~60%). In the experiment, the difference in work achievement rate depending on wearing and non-wearing a mask was divided into two groups as shown in Table 1, and the experiment is performed according to the procedure shown in Fig. 3.

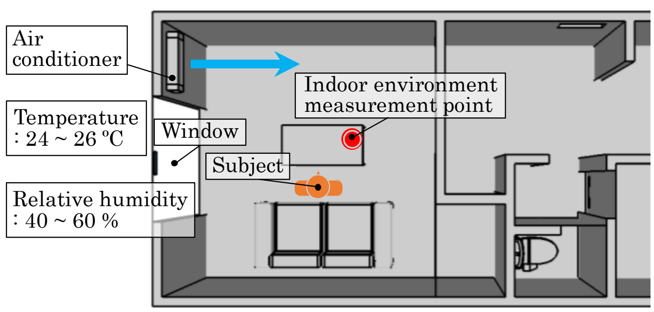


Figure 2 Room conditions for the experiment.

Table 1. Consideration case

Group	First half work	Second half work
A	Wearing a mask	Non-wear a mask
B	Non-wear a mask	Wearing a mask

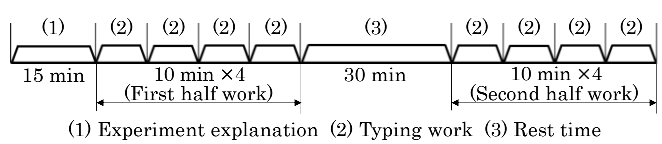
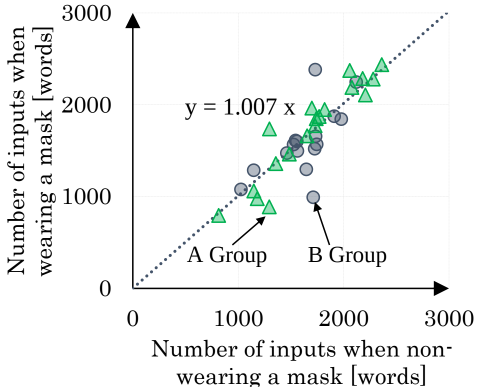


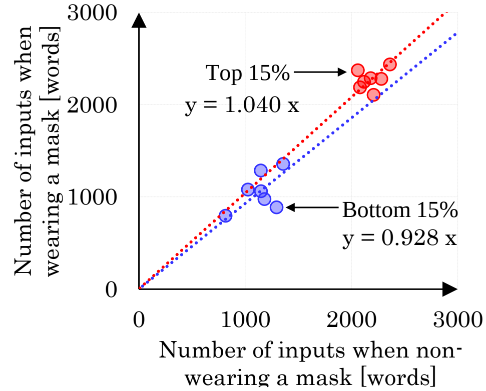
Figure 3 Experimental procedure.

2. Experimental Results

Figure 4 (a) shows the number of characters entered by all subjects with and without masks, (b) shows the results of the top 15% and the bottom 15%of the total number of input characters. According to Figure 4 (a), the simple work efficiency when wearing a mask tended to increase by 0.7% on average, and there was no difference between wearing and non-wearing a mask. But according to Figure 4 (b), the subjects with the bottom 15% of the number of input characters had a decrease in simple work efficiency of about 7.2% due to wearing the mask. From these results, there is concern that wearing a mask may affect the reduced efficiency of simple work. We think that additional consideration (Increase the number of subjects, Change the content of simple works, etc.) is needed regarding the effect of wearing a mask on work efficiency.



(a) Comparison of all subjects



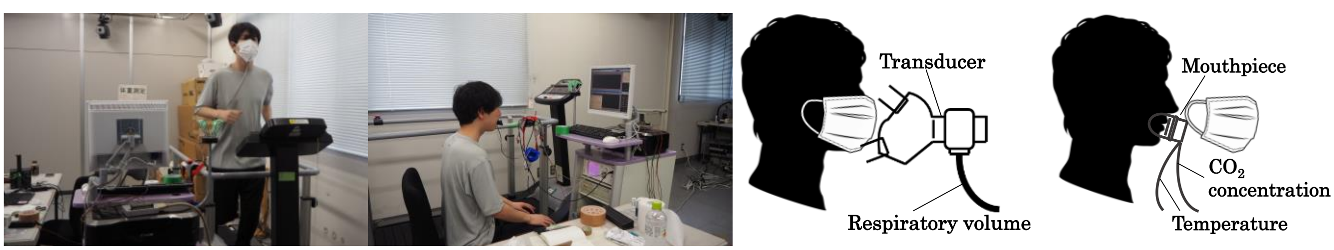
(b) Comparison of top and bottom

Figure 4 Number of imputs when wearing or non-wearing amask.

RESPIRATORY CHARACTERISTICS WHEN WEARING A MASK

1. Experimental Methods

The subject experiments was conducted to understand the effect of wearing a mask on the expiratory and inspiratory characteristics (flow rate, temperature, CO_2 concentration) of the occupants. Figure 5 shows the outline of the experiment, Table 2 shows the experimental conditions, and Figure 6 shows the experimental procedure. While keeping the indoor conditions constant (23 °C, 55 %RH, 600 ppm (CO_2)), the experiment was conducted in a total of 4 cases with and without masks at sitting and running operation. In each case, the measurement was performed in a total of two stages (the respiratory flow rate was measured in the first stage, and the CO_2 concentration and temperature were measured in the second stage), and analysis was performed for 10 seconds when the values remained stable.



(a) Experimental scenery (b) Measuring method

Figure 5 Experiment outline.

Table 2. Experimental conditions

Indoor Environment	23 °C, 55 %RH, 600 ppm (CO_2)
Running Speed	8 km/h
Clothes	Short sleeve T-shirt, Long pants
Casing	Case 1: Non-wear (Sitting), Case 2: Non-wear (Running), Case 3: Wearing a mask (Sitting), Case 4: Wearing a mask (Running)

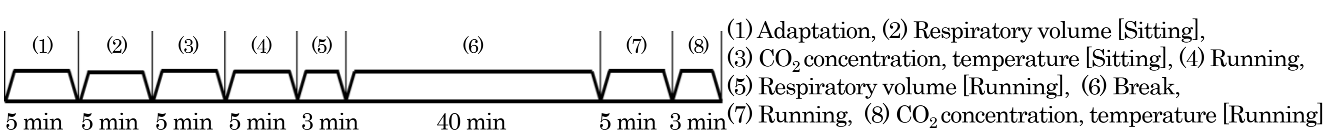
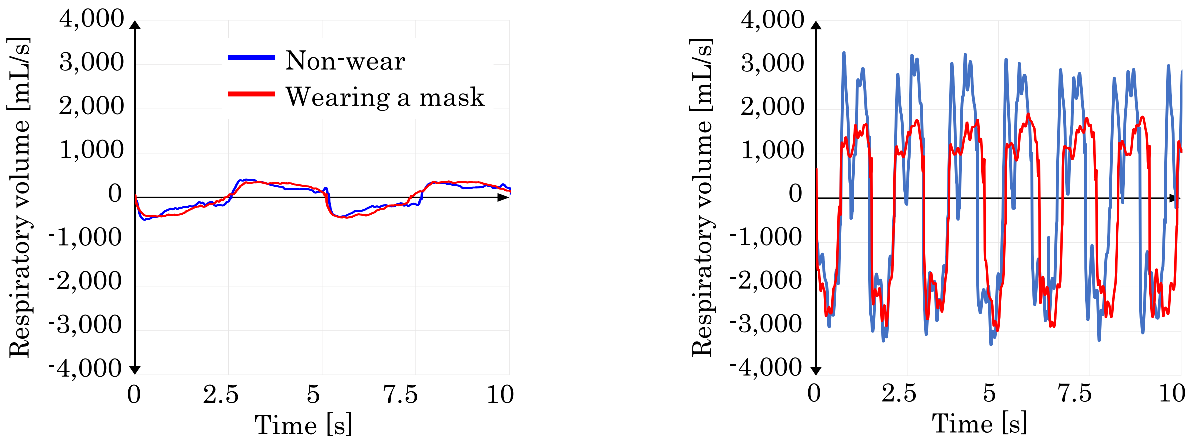


Figure 6 Experimental procedure.

2. Experimental Results

Respiratory Volume. Figure 7 shows the experimental results of respiratory volume. When wearing a mask, it was confirmed that the numerical value fluctuated in a minute time due to the influence of ventilation resistance. It was also confirmed that although the instantaneous respiratory volume fluctuated depending with or without a mask was worn, wearing the mask had no significant effect on the respiratory volume. It is considered that this is because the ventilation resistance of the mask is supplemented by the load on the lungs. In addition, it was confirmed that running increased the respiratory volume by about 6 times.

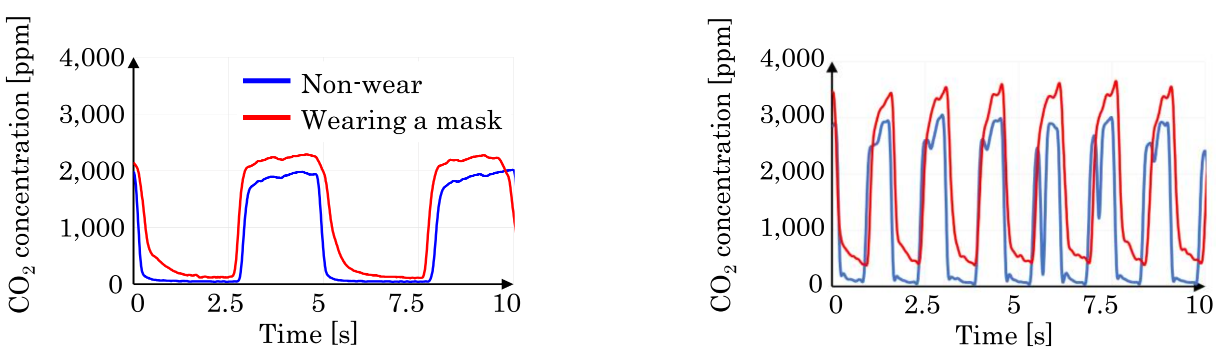


(a) Sitting (b) Running

Figure 7 Experimental results of respiratory volume [mL/s].

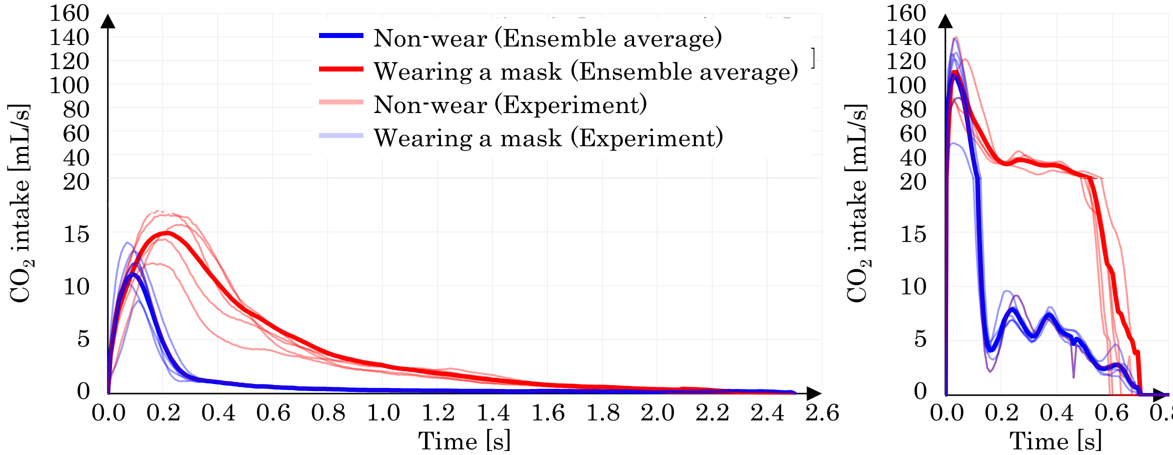
CO_2 Intake. Figure 8 shows the experimental results of CO_2 concentration during exhalation and inspiration. It was confirmed that when the mask was worn, the CO_2 concentration during exhalation and inspiration increased in both the maximum and minimum values because of the retention of exhaled air in the mask. In addition, it was confirmed that running increased the CO_2 concentration by about 1.5 times.

Subsequently, the CO_2 intake per breath was calculated from the integrated value of the respiratory flow rate and the CO_2 concentration (Fig. 9). The difference between with and without a mask was remarkable. The CO_2 intakes per a minute in the sitting were 32.6 L/min (Case 1: Non-wear a mask), 112.1 L/min (Case 3: Wear a mask). In addition, the CO_2 intakes per a minute in the running were 434.7 L/min (Case 2: Non-wear a mask), and 947.3 L/min nn(Case 4: Wear a mask). From this result, it was confirmed the CO_2 intake per a minute wearing a mask increased 3.4 times at sittinng and 2.2 times at running. Since the respiratory volume is the same regardless of with or without a mask is worn, it is considered that the increase in CO_2 concentration greatly contributes to these results. Therefore, it was quantitatively confirmed that wearing a mask increased CO_2 intake.



(a) Sitting (b) Running

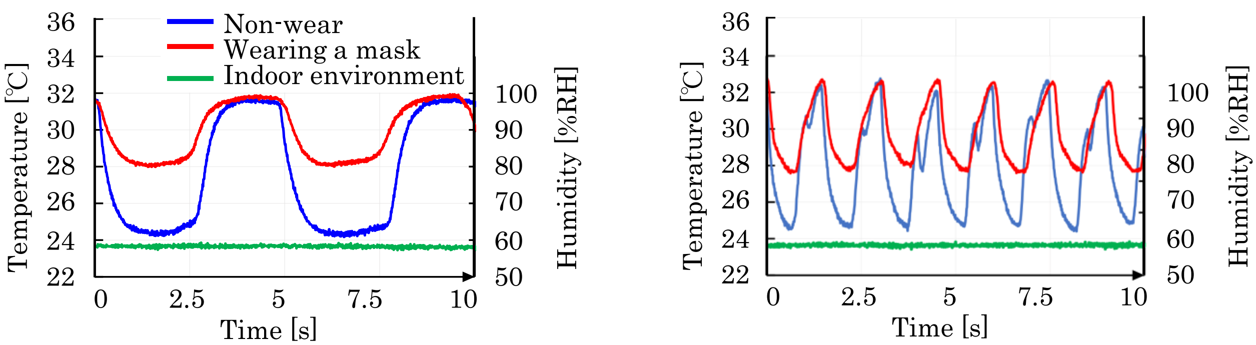
Figure 8 Experimental results of CO_2 concentration [ppm].



(a) Sitting (b) Running

Figure 9 Experimental results of CO_2 intake with one breath [mL/s].

Heat Balance. Figure 10 shows the experimental results of expiratory/inspiratory temperature and relative humidity. From these results, it was confirmed that the intake air temperature increased significantly when the mask was worn. From this result, it is guessed that when the mask was worn, exhaled air remained in the mask, and the exhaled air temperature rose by inhaling part of the air during inspiration. Since the respiratory volume is the same regardless of with or without a mask (shown in Figure 7), there is concern that wearing a mask disturbs heat loss from breathing.



(a) Sitting (b) Running

Figure 10 Experimental results of expiratory/inspiratory temperature and humidity [°C, %RH].

Next, the heat loss due to respiration wearing a mask was calculated from the experimental results shown in Figure 10. The heat loss due to respiration was guessed by calculating the relative humidity of exhalation and inspiration by the law of similarity with temperature (shown in Table 3). The formula for calculating heat loss via respiration defined by J.B. Cain et al., given by Eqs. (1) and (2), is used for the calculation.

$$\dot{Q}_{convection,lungs} = \dot{m}_{air,lungs} \cdot C_{p,air} \cdot (T_{exhale} - T_{ambient}) \quad (1)$$

$$\dot{Q}_{latent,lungs} = \dot{m}_{air,lungs} \cdot h_{fg} \cdot (X_{exhale} - X_{ambient}) \quad (2)$$

where $\dot{Q}_{convection,\,lungs}$ is a sensible heat loss [W], $\dot{Q}_{latent,\,lungs}$ is a latent heat loss [W], $\dot{m}_{air,\,lungs}$ is a inspratory volume [kg/s], $\dot{C}_{p,\,air}$ is a air specific heat (1.005 [kg/(kg·K)]), h_{fg} is a enthalpy of vaporization [kJ/kg], T_{exhale} is a expiratory temperature [K], $T_{ambient}$ is a ambient air temperature [K], X_{exhale} is a expiratory absolute humidity [kg/kg(DA)], $X_{ambient}$ is a ambient air absolute humidity [kg/kg(DA)].

Table 3. Respiratory heat loss

Case	Respiratory heat loss [W]
Case 1: Non-wear (Sitting)	9.7
Case 2: Non-wear (Running)	61.9
Case 3: Wearing a mask (Sitting)	5.7
Case 4: Wearing a mask (Running)	34.1

Wearing a mask reduced respiratory heat loss by 4.0 W at sitting and 27.8 W running. Considering the convective heat transfer coefficientof the human body (TANABE., 1995), to maintain comfort even when wearing a mask, it is necessary to lower the room temperature by 1~2 ºC according to the metabolic rate of the occupants.

DISCUSSION

In this study, we conducted experiments on voluntary subjects in order to understand the respiratory characteristics when wearing a mask. From the results of the experiment, the characteristics of respiratory volume, CO_2 concentration, and temperature/humidity when wearing a mask were confirmed.

No variation in the respiratory volume due to wearing a mask was confirmed during both resting and running phases. This indicates that the ventilation resistance generated by wearing a mask is compensated by the additional load on the lungs. In addition, it was confirmed that exercise increased the respiratory volume approximately by a factor of six. The rate of increase in respiratory volume during exercise in this study is close to the result of ICRP Pub 71. It has been reported that the fitness center where occupants exercise has a very high COVID-19 infection rate (Serina Chang et al., 2020), and it is considered that the increase in respiratory volume during exercise has an effect. Based on these, when exercising, wearing a mask is required more than at rest. However, while wearing a mask, the increase in CO_2 concentration was 1,500 ppm during resting and 5,700 ppm during exercise. From this result, the increase in CO_2 intake due to wearing a mask became a problem. Typically, the indoor CO_2 concentration is recognized as a bad environment at 2,000 ppm and the allowable concentration of indoor pollution at 5,000 ppm (Azuma, 2018). Wearing a mask raises the CO_2 concentration in inspiration, and there is a risk that it will be equivalent to the concentration conditions in this adverse environment. In addition, the CO_2 intakes per minute were 32.6 L/min when resting without a mask, 112.1 L/min when resting while wearing a mask, 434.7 L/min when exercising without a mask, and 947.3 L/min when exercising while wearing a mask (shown in Figure 11). Compared to resting without a mask, when exercising with a mask, CO_2 intake increased 29.1 times, which was confirmed to be a very dangerous situation. On the other hands, during rest, the heat loss per breath was observed to be 9.7 W while not wearing a mask and 5.7 W while wearing a mask, exhibiting a decrease of 4.0 W. During exercise, the heat loss per breath was observed to be 61.9 W while not wearing a mask and 34.1 W while wearing a mask, exhibiting a decrease of 27.8 W (shown in Figure 12). In this paper, we proposed a new indoor temperature control standard that takes into account the convective heat transfer coefficient of the human body.

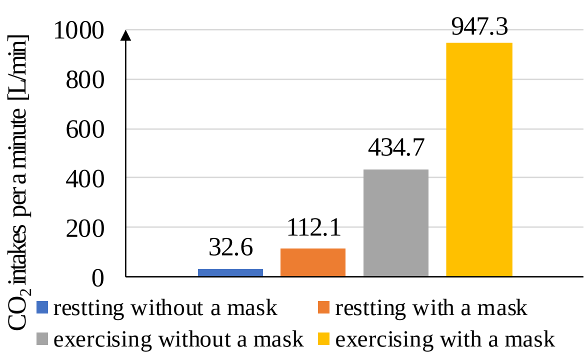


Figure 11 CO_2 intakes per a minute

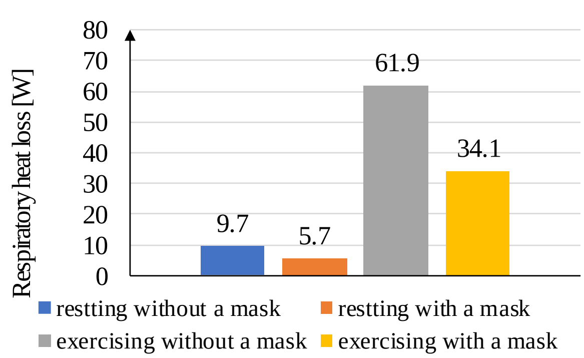


Figure 12 Respiratory heat loss

CONCLUSION

In this study, we conducted a subject experiment on the affect of simple work eficiency and the expiratory/inspiratory characteristics when wearing a mask and obtained the following findings.

(1) The subjects with the bottom 15% of the work achievement rate had a decrease in work efficiency of about 7.2% due to wearing the mask.

(2) Respiratory volume does not change with wearing a mask.

(3) When wearing a mask, CO_2 intake per a minute increases 3.4 times sitting and 2.2 times running.

(4) When wearing a mask, the heat loss of breathing decreases by 4.0 W sitting and 27.8 W running.

(5) In order to maintain the comfort of the human body wearing a mask, it is necessary to lower the room temperature by 1~2 ºC according to the metabolic rate of the occupants.

For the thermal comfort of the human body, we proposed a theoretical solution when wearing a mask. It was confirmed that wearing a mask prevented heat loss from respiration, but it is thought that this problem can be solved by controlling the room temperature to a low temperature. On the other hands, CO_2 intake increased significantly even when the outside air was kept at a low concentration, suggesting the danger of wearing a mask. However, further studies are needed regarding the effects on the human body and performance.

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