Real-Time Monitoring System to Evaluate Exercise Load, Hypoxic Load, and Safety in a Normobaric Hypoxic room

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***Abstract*— One way to increase the effectiveness of exercise is to use a normobaric hypoxic environment. However, exercise in a normobaric hypoxic environment is not always safe to non-athletes because the safety and influences are still unclear. Therefore, in this study, 24 non-athlete subjects aged 20–39 and 40–59 years were subjected to the analysis of a 15-min exercise load test on a self-propelled treadmill at three different oxygen concentrations (16%, 18%, and 20%) to determine the safe oxygen concentration of normobaric hypoxic exercise in non-athletes and to select and validate the indicators to be measured for the development of a real-time monitoring system. The measurement indicators were electrocardiogram, heart rate (HR), blood pressure, arterial oxygen saturation (SpO_2), the product of the HR and systolic blood pressure and treadmill velocity. The experimental results showed that normobaric hypoxic was sufficiently effective and safe at an oxygen concentration of 16% in both age groups of 20–39 years and 40–59 years. In addition, HR and SpO_2 were shown to be indices that can evaluate exercise load and hypoxic load in real-time. These results suggest that non-athletes can safely perform normobaric hypoxic exercise and that increased use by non-athletes may lead to improved health.**

I. Introduction

The use of hypoxic environments has been attracting attention as a method to enhance the effectiveness of exercise [1]. When an exercise is performed in a hypoxic environment, the oxygen carrying capacity to the muscles is improved through increasing hemoglobin concentration and number of red blood cells in the blood [2]. Additionally, exercising under a hypoxic environment is considered to be an effective therapy for people with low physical fitness, obesity, etc., because it can be expected to have sufficient effects even when the exercise load is low compared to exercising in a normal oxygen environment [3][4]. The use of hypoxic environments has been attempted in the field of sports such as high-altitude training. In the past, live high/train high, which involves going to high altitudes to train, was often used, and training was often conducted in a hypobaric hypoxic environment. Hypobaric hypoxic can cause headaches and dizziness, which are typical symptoms of altitude sickness and results in difficulty in maintaining body conditioning. To overcome these problems, live high/train low, in which people live at high altitudes and train at low altitudes, has become the mainstream [5]. However, because most time is spent in a hypoxic environment, all people, except competitive athletes, cannot easily and safely benefit from the hypoxic environment. Therefore, a method of training in a normobaric hypoxic room (hypoxic room) at a low altitude under normal pressure is attracting attention. In addition to lower risks of headaches and dizziness under normobaric pressure as compared to those experienced in high altitudes, a hypoxic room allows users to set the oxygen concentration based on their individual needs, making it safer than training at high altitudes [5]. However, the response of non-athletes to the exercise load under a normobaric hypoxic environment is estimated to vary widely among individuals, unlike competitive athletes who routinely undergo cardiopulmonary load exercise. In particular, hypoxic exercise is expected to cause an increase in heart rate (HR) and a decrease in arterial oxygen saturation (SpO_2) in people with low physical fitness, and the possibility of altitude sickness symptoms, such as headache, dizziness, and nausea, cannot be denied. If there is sufficient safety knowledge for non-athletes, they can benefit from the effects of exercise in a hypoxic environment. However, to date, there have been a limited number of studies that have investigated the safety of normobaric hypoxic exercise for non-athletes. Therefore, the development of a system to determine the appropriate oxygen concentration and to evaluate the exercise load and hypoxic load by measuring biological indices such as HR and SpO_2 in real time can enable many people, including non-athletes, to safely exercise in a hypoxic environment and improve their health.

Accordingly, this study aims to determine the safe oxygen concentration for normobaric hypoxic environment exercise and to select indices to be measured for exercise loading and real-time monitoring of hypoxic loading. A total of 40 subjects aged 20–39 and 40–59 years were subjected to exercise load tests using a self-propelled treadmill set up in a hypoxic room at three different oxygen concentrations (20%, 18% [equivalent to 1,000 m altitude], and 16% [equivalent to 2,000 m altitude]).

II. Materials and Methods

A. Subjects

Healthy non-athletes with no cardiovascular or respiratory disease aged between 20–39 and 40–59 were selected as the subjects of this experiment. The target number of research subjects for each age group was 20. The number of male or female subjects was adjusted to more than a quarter of all subjects, and the number of subjects with body mass index (BMI) <22 or BMI ≥22 was adjusted to more than a quarter of all subjects. In the selection of subjects, a checklist was used to confirm that the selection criteria were met by the research physician in charge of the study, who specializes in diabetes and endocrine/metabolic diseases.

B. Experimental procedure

In this study, we constructed a system to measure bioindicators in a hypoxic room to verify exercise load, hypoxic load, and safety in the hypoxic environment. We conducted an exercise load test using a self-propelled treadmill (Matrix S-Drive, Johnson Health Tech, Tokyo, Japan), at three different oxygen concentrations (20%, 18%, and 16%) under observation by a physician. The exercise load tests at each oxygen concentration were performed at least 24 h apart. There was no upper limit to the interval between exercise sessions.
In the exercise load test, the subjects were observed for 5 min in a resting chair sitting position under a set oxygen concentration environment, and the research physician checked if the exercise load was possible. Then, using a self-propelled treadmill with an inclination angle of 7°, the subjects walked for 15 min while ensuring that their double product (DP: the product of the HR and systolic blood pressure) did not exceed 25,000. Finally, the subjects were observed in a resting chair sitting position outside the hypoxic environment for at least 5 min. Fig. 1 shows the exercise load test. The exercise load test was stopped when any of the following discontinuance criteria were met:

- If the oxygen saturation falls below 85% during exercise
- If the DP is greater than 25,000 during exercise
- When the medical staff judges that it is difficult to continue the exercise load

The hypoxic environment was set up using a hypoxic generator (YHS-C10, Hypotec, Tokyo, Japan). Electrocardiogram (ECG) was measured from typical lead II using an electrocardiogram (BSM-3400, Nihon Kohden, Tokyo, Japan). Blood pressure (BP) was measured from the subject's right upper arm using a sphygmomanometer (TM-2590N, A&D, Tokyo, Japan). SpO_2 was measured from the subject's right earlobe using an ear clip sensor (MLT332, ADInstruments, Otago, New Zealand). The pulse signal corresponding to the rotation speed of the treadmill was measured using a length counter (CT1-3:10A, Line Seiki, Tokyo, Japan). ECG, SpO_2, and pulse signal were collected using an eight-channel biological amplifier (PL3508, ADInstruments, Otago, New Zealand) and recorded using LabChart Pro (ver. 8.1.17, ADInstruments, Otago, New Zealand). HR was continuously calculated from the R-wave intervals of the ECG using LabChart Pro. The treadmill velocity (Velocity) was continuously calculated from the pulse signal using LabChart Pro. BP data were recorded using TMMate (ver. 1.07, A&D, Tokyo, Japan). ECG, HR, SpO_2, and Velocity were recorded in real time during the entire exercise load test. BP was manually measured seven times: before entering the hypoxic room, 5 min after entering the hypoxic room and resting chair sitting position, standing on the treadmill, 5 min after starting to walk, 10 min after starting to walk, 15 min after starting to walk, and 5 min after finishing the resting chair sitting position outside the hypoxic room. BP measurements during walking were taken while standing still on the treadmill and were not included in the walking time.

Fig. 1 Exercise load test in a hypoxic room.

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Clinical Research Ethics Committee of Kumamoto University Hospital.

III. Data and Statistical Analysis

A. Subjects Selection and Analysis Epoch

None of the subjects were dropped out of the experiment considering the discontinuance criteria. However, subjects whose measurement data contained a lot of noise were excluded, hence, the number of subjects for the final analysis was 24. The final attributes of the participants in this experiment are listed in Table I. The values in the table are the mean ± standard deviation.

The measured data analyzed for each epoch are shown in Table II.

B. HR • SpO_2 • Velocity Data

As in the previous study, the measured HR, SpO_2, and Velocity were analyzed using the average of the data obtained during the 1 min before the end of the epoch [6]. Previous studies have shown that obese individuals start with 40%–60% of their heart rate reserve (*HRR*) and a gradual increase of the exercise intensity (*EI*) [7]. In addition, to increase maximal oxygen uptake, the *EI* should be 50%–70% of the *HRR* [7]. Based on these recommendations, in this experiment, we set the target HR (HR_{tgt}) when *EI* was 60% of the *HRR*. HR_{tgt} was calculated by the Karvonen method using (1) [8][9]. *HRR* and HR_{max} were calculated using (2) and (3), respectively [5]. HR_{rest} in (2) is the average value for each age group in epoch 1. *age* in (3) is the average age of each age group.

$$HR_{tgt} = HRR \times EI + HR_{rest}, \quad (1)$$
$$HRR = HR_{max} - HR_{rest}, \quad (2)$$
$$HR_{max} = 220 - age\,. \quad (3)$$

Table. I List of subjects for analysis

Gender / age group	Number of Subjects	Age [years]	Height [cm]	Weight [kg]	BMI [kg/m^2]
M / 20–39 y	8	21.8±0.66	171.9±5.0	59.5±8.7	20.1±2.0
F / 20–39 y	6	29.8±7.0	156.3±5.4	54.6±8.5	22.4±3.6
M / 40–59 y	3	49.7±7.4	173.3±1.9	74.7±2.1	24.9±0.83
F / 40–59 y	7	47.1±4.8	160.1±3.7	60.3±9.3	23.6±4.4
all / 20–59 y	24	34.5±12	163.8±8.4	59.4±10	22.1±3.7

Table. II Analysis epochs

Epoch number	contents
Epoch1	Resting chair sitting position in the hypoxic room for 5 minutes
Epoch2	0–5 minutes after starting to walk
Epoch3	5–10 minutes after starting to walk
Epoch4	10–15 minutes after starting to walk
Epoch5	Resting chair sitting position outside the hypoxic room for 5 minutes

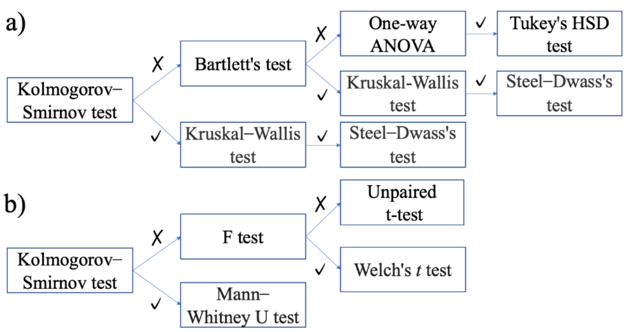

Fig. 2 Flowchart of statistical tests. ✓ in the figure indicates P < 0.05 and ✗ indicates P ≥ 0.05. a) Statistical test in pattern 1. b) Statistical test in pattern 2.

Two patterns of statistical tests were performed using the mean values of the measured data during the last 1 min of epoch 4 [10][11]. Pattern 1 is a comparison within age groups using each oxygen concentration as a group. Pattern 2 is a comparison between age groups at the same oxygen concentration with each oxygen concentration as a group. Statistical tests were conducted according to the flowchart in Fig. 2a for Pattern 1 and Fig. 2b for Pattern 2. The significance level was set at 0.05.

IV. Results

Fig. 3 shows the trend of the mean values of HR, SpO_2, and Velocity per epoch for all subjects.

A. HR

Fig. 3a shows that the HR increases with the duration of walking in all oxygen concentrations. The results of the one-way analysis of variance (One-way ANOVA) in pattern 1 and unpaired t-test in pattern 2 showed no significant difference in oxygen concentration or age (P > 0.05).

B. SpO_2

Fig. 3b shows that as the oxygen concentration decreases and the SpO_2 also decreases. The lowest value among all subjects was 86%, however, the physician confirmed that there was no problem in continuing the exercise. The results of the Steel-Dwass's test for Pattern 1 in the 20–39 and 20–59 age groups showed no significant difference between the oxygen concentrations of 20% and 18% (P > 0.05). In addition, the results of Tukey's HSD test for pattern 1 in 40–59 age groups showed no significant difference between 20% and 18% oxygen concentration (P > 0.05). However, for each age group, the value at 16% was significantly lower than those at 20% and 18% oxygen concentrations (P < 0.05). The results of the unpaired t-test in pattern 2 show that the SpO_2 values of 40–59 years old at 20% oxygen concentration were significantly lower than those of 20–39 years old (P < 0.05).

C. Velocity

Fig. 3c shows that the Velocity was highest when the oxygen concentration was 20%. However, the results of the One-way ANOVA in patterns 1 and unpaired t-test in pattern 2 of Velocity did not show any significant differences in oxygen concentration or age (P > 0.05).

V. Discussion

A. HR

The result that there is no significant difference in HR between each oxygen concentration is consistent with previous studies in which exercise load tests were conducted in environments with of 20% and 15% O_2 [12]. Therefore, exercise under hypoxic conditions is not expected to produce a significant difference in HR compared to exercise under normoxic conditions. By setting HR_{tgt} using age and HR_{rest} even under hypoxic environments, it is possible to appropriately evaluate the exercise load tailored to an individual as in a previous study [9], in which HR_{tgt} was set under a normoxic environment. Furthermore, as HR during exercise can be easily measured, it is thought that setting the upper and lower limits of HR_{tgt} will allow real-time evaluation of whether the load is appropriate or not [9].

B. SpO_2

The SpO_2 level at resting epoch 1 in all age groups, at 18% and 16% O_2, is approximately 2% lower than the SpO_2 at 20% O_2. This result, which shows a decrease in SpO_2 at rest under a normobaric hypoxic environment, is consistent with previous studies [6][12]. In a previous study [6], a 15 min rest period was provided, and an oxygen concentration of 13% decreased the SpO_2 level by approximately 20% compared to an oxygen concentration of 20%. Moreover, in another previous study [12], a 30 min rest period was provided, and a 15% oxygen concentration decreased the SpO_2 level by approximately 7% compared to a 20% oxygen concentration. Therefore, the difference in the degree of decrease from previous studies is thought to be due to differences in the duration of the resting state and oxygen concentration. The SpO_2 level during exercise under normobaric normoxic conditions for each age group decreased by a maximum of only approximately 2% compared to the epoch 1 values. On the other hand, the SpO_2 level during exercise under normobaric hypoxic conditions decreased by a maximum of approximately 9% compared to the epoch 1 values. These results are similar to those of previous studies in which exercise load tests were performed at an oxygen concentration of 15% [12], implying that SpO_2 is an effective indicator that can be used to assess hypoxic loads. The results of the statical test for both the 20–39 and 40–59 age groups showed significant differences not only between the oxygen concentrations of 20% and 16%, but also between those of 18% and 16%. These results suggest that an oxygen concentration of 16% during exercise may be sufficient to obtain the effects of a normobaric hypoxic environment in both age groups. However, in both age groups, the subjects whose SpO_2 levels decreased to nearly 85% during exercise at an oxygen concentration of 16% may have a high sensitivity to normobaric hypoxic environments. For these subjects, it would be safer to perform exercise at an oxygen concentration of 18% rather than 16% because the SpO_2 does not decrease excessively. Thus, the safe value of oxygen concentration can be determined from the susceptibility of the subject's SpO_2 levels to exercise. In addition, according to the results of this experiment, safety can be evaluated in real-time by maintaining the value of SpO_2 to 85% or higher during exercise in a normobaric hypoxic environment.

C. Velocity

In this experiment, the Velocity ranged from 3–5 km/h, but it was well above HR_{tgt}; therefore, a walking Velocity of 3–5 km/h was considered sufficient. This Velocity can be achieved even by those who are physically weak or obese [4]. However, the treadmill used in this experiment was a self-propelled type with an inclination angle of 7°. If the treadmill was a motorized treadmill, then the Velocity could be increased.

A limitation of this study is the small number of subjects investigated. In order to reliably understand the variation of biological indices of exercise in normobaric hypoxic environments, it is necessary to analyze the data of a much larger number of subjects.

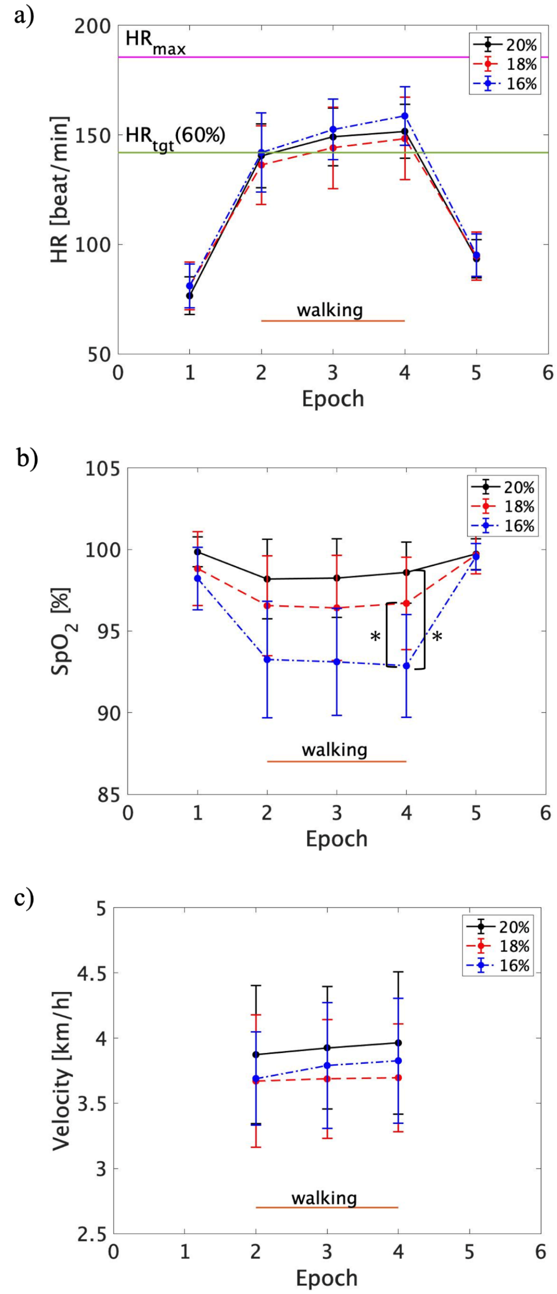

Fig. 3 Mean values of HR, SpO_2, and Velocity per epoch for all subjects. The error bars indicate standard deviation, the HR_{max} line indicates HR_{max}, the HR_{tgt} (60%) line indicates HR_{tgt} when *EI* is set to 60%, and the walking line indicates the epoch during walking. *$P < 0.05$ between 20%,18%, and 16% O_2. a) Changes in the mean values of HR, b) changes in the mean values of SpO_2, and c) changes in the mean values of Velocity

VI. Conclusions

In this study, 24 non-athlete subjects aged 20–39 years and 40–59 years were subjected to an exercise load test in which they walked on a self-propelled treadmill for 15 min at three different oxygen concentrations (20%, 18%, and 16%). The experiments were conducted to verify the exercise load, hypoxic load, and safety. The results demonstrated that HR and SpO_2 are effective indicators to evaluate exercise load and hypoxic load in real time. Normobaric hypoxic exercise was shown to be effective when performed at an oxygen concentration of 16% for participants in both age groups. Further, it was shown that to achieve HR_{tgt} at 60% EI on a self-propelled treadmill with an inclination angle of 7°, it is necessary to walk at a speed of approximately 3–5 km/h, which is achievable even for physically weak individuals. Moreover, a SpO_2 level greater than 85% during exercise was considered safe. The results of this study indicate that real-time monitoring of exercise and hypoxic loads during normobaric hypoxic exercise is possible and can be performed safely by non-athletes.

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