A method of determining anaerobic threshold from percutaneous oxygen saturation

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The anaerobic threshold (AT) is the point of the aerobic-to-anaerobic metabolic switch. Despite the many clinical applications of AT, this measurement requires sophisticated equipment and skills. Here, we investigated a simple measurement method for AT using percutaneous oxygen saturation (SpO₂) and pulse rate (PR) with a pulse oximeter in a study of exercise stress on healthy volunteers. Twenty individuals (ten men and ten women) were included in the study. Various respiratory parameters, including AT, were measured using conventional analytical methods. The SpO₂ threshold (ST) was calculated using the SpO₂-Slope method. The mean ± standard deviations SpO₂ at ST was 97.8% ± 0.3% in men and 99.0 ± 0.3% in women. The concordance and interchangeability between ST and various five different types of AT, the ventilatory equivalent for oxygen (VE/VO₂_AT), V-Slope (V-Slope_AT), ventilatory equivalent (VE_AT), respiratory exchange ratio (R_AT), and partial pressure of end-tidal oxygen (PETO₂_AT) were generally high, with positive correlation coefficients in the range of [0.68–0.80]. These findings suggest that the SpO₂-Slope method with a pulse oximeter may be a useful and simple method to determine AT compared to conventional methods.

Regular physical activity at an appropriate level is necessary to maintain health. Previous studies have shown that individuals with a higher level of physical endurance have a healthier life, extended longevity, and lower mortality and that exercise improves cardiac function. The anaerobic threshold (AT) is defined as the point at which the metabolism switches from aerobic to anaerobic. Exercising at the AT could prevent cardiovascular diseases and metabolic syndrome and contribute to the maintenance and improvement of health. Exercising at AT is also used in sports training as it can help improve the athletes’ competitiveness.

In the exercise above AT, glycolysis is accelerated, resulting in lactate accumulation and acidosis. Lactate is buffered by bicarbonate to produce CO₂. This results in respiratory gas changes, such as increased alveolar CO₂ emissions relative to oxygen uptake. Consequently, the best-known methods of AT measurement are expiratory gas analysis and blood lactic acid quantification. Expiratory gas analysis is a widely used noninvasive method in medicine and sports. However, it requires an expensive expiratory gas analyzer and a trained technician. This method can determine five different types of AT, the ventilatory equivalent for oxygen (VE/VO₂_AT), V-Slope (V-Slope_AT), ventilatory equivalent (VE_AT), respiratory exchange ratio (R_AT), and partial pressure of end-tidal oxygen (PETO₂_AT) of which the VE/VO₂-AT and V-Slope-AT are the most widely used. It has been reported that during exercise loading, VE/VO₂, R, and PETO₂ movements flex upward at AT, the slope of the VCO₂–VO₂ relationship increases rapidly, and VE increases excretion. As new, simple, accurate, and noninvasive methods of AT measurement are desirable, methods using the partial pressure of carbon dioxide (PaCO₂), lactic acid in sweat, systolic blood pressure, and heart rate (HR) have been developed. However, none of them has been able to provide a practical alternative to expiratory gas analysis.

Pulse oximetry is widely used in clinical practice as it provides a noninvasive method of measuring percutaneous oxygen saturation (SpO₂), which reflects arterial oxygen pressure (PaO₂). SpO₂ during exercise is used in both clinical and research settings for many purposes, including the evaluation of the severity of cardiac functional impairment, the confirmation of the efficacy of exercise therapy, the assessment of the need for oxygen supplementation, and the evaluation of the oxygenation level of hemoglobin in arterial blood. SpO₂ is generally

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measured with pulse oximetry in the fingers, earlobes, or forehead. Notably, its accuracy is greatly affected by peripheral hypoperfusion and body movements, which hamper pulse wave detection\(^{29,30}\).

Previous studies have found that \(\text{SpO}_2\) declines during incremental exercise\(^{26,30–32}\). In athletes, the value of the inflexion point at which \(\text{SpO}_2\) suddenly declines during exercise is reportedly associated with \(\text{AT}\)\(^{33}\). During incremental exercise, there are two inflection points at which the \(\text{SpO}_2\) declines before \(\text{AT}\). The time to the second decrease in \(\text{SpO}_2\) and the time before \(\text{AT}\) is reached are closely correlated\(^{34}\). However, \(\text{SpO}_2\) fluctuations during exercise are inconsistent and complex\(^{34}\). Visual determination of the inflexion point at which \(\text{SpO}_2\) suddenly starts to decline requires significant experience and knowledge of \(\text{SpO}_2\) from the investigator. Hence, a method to automatically determine \(\text{AT}\) using \(\text{SpO}_2\) and pulse rate (PR) with only a pulse oximeter, a noninvasive and simple device that does not require expiratory gas analysis or even HR monitor, would greatly contribute to improving the health and performance of more people from optimal intensity exercise using \(\text{AT}\).

In this study, we developed a method to calculate \(\text{AT}\) automatically from \(\text{SpO}_2\) and PR data obtained with pulse oximetry and investigated its validity as an alternative method for \(\text{AT}\) measurement.

### Results

The demographic data of the subjects are shown in Table 1. The mean age of the participants was 37.0 ± 2.1 years (25–57 years). Their mean body mass index (BMI) was 21.2 ± 0.4 kg/m\(^2\) (17.7–25.5 kg/m\(^2\)). Figure 1 shows a scatter plot of the PR and HR of all subjects. There was a strong correlation between PR and HR from rest through cardiopulmonary exercise testing (CPX) \((r = 0.995, p < 0.001)\). \(\text{SpO}_2\) and PR during cardiopulmonary exercise testing decrease at some point with increasing exercise intensity. Figure 2a shows representative \(\text{SpO}_2\) and PR time series data during cardiopulmonary exercise testing. \(\text{SpO}_2\) decreased from a certain point with increasing intensity.

### Table 1.

Characteristics of the participants. Values are presented as mean ± SE. BMI body mass index, SE standard error.

| Parameter | Unit   | Values        | Min | Max |
|-----------|--------|---------------|-----|-----|
| Number    | n      | 20 (Male 10, Female 10) | --  | --  |
| Age       | years  | 37.9 ± 2.1    | 25  | 57  |
| Height    | cm     | 163.6 ± 1.7   | 152.7 | 178.3 |
| Weight    | kg     | 56.9 ± 1.9    | 46.3 | 74.6 |
| BMI       | kg/m\(^2\) | 21.2 ± 0.4 | 17.8 | 25.5 |

![Figure 1. Relationship between pulse rate and heart rate. The data is from the rest to the end of loading. The pulse rate was measured with a pulse oximeter, and the heart rate was measured with a heart rate monitor. The correlation was investigated by calculating Pearson’s correlation coefficient (r) and the p-value. Bpm beats per minute, HR heart rate, PR pulse rate, \(\text{SpO}_2\) percutaneous oxygen saturation.](image)
PR, although the behavior was not constant. Figure 2b shows SpO2 values at the SpO2 threshold (ST). In all subjects, SpO2 at ST appeared within the SpO2 reference range (96%-100%). Table 2 shows the PR, oxygen consumption (VO2), and Load at different AT values and ST. For VE/VO2_AT, R_AT, and PETO2_AT, indeterminate AT data were treated as missing data. The final analysis included 19 subjects for VE/VO2_AT and R_AT and 14 subjects for PETO2_AT. The mean PR was 132.2 ± 3.1 at V-Slope_AT, 133.0 ± 2.8 at VE/VO2_AT, 129.5 ± 3.1 at R_AT, 135.4 ± 4.0 at PETO2_AT, 129.7 ± 3.3 at VE_AT, and 127.8 ± 2.9 at ST. The VO2 was 1408.6 ± 64.3 at V-Slope_AT, 1427.4 ± 74.4 at VE/VO2_AT, 1364.8 ± 80.2 at R_AT, 1398.5 ± 79.4 at PETO2_AT, 1366.4 ± 69.0 at VE_AT, and 1328.8 ± 44.6 at ST. Each individual’s PR, oxygen consumption (VO2), and each AT and ST for Load are detailed in Supplementary Tables S1, S2, and S3.

Table 3 shows the analysis of concordance, interchangeability, and correlation between ST and different AT values. The mean difference between PR at ST and that at R_AT and VE_AT (95% CI lower bound/upper bound) was −1.5 (−6.6/3.7) and −1.9 (−6.5/2.8), respectively, whereas the mean differences between PR at ST and that at V-Slope_AT, VE/VO2_AT, and PETO2_AT were −4.3 (−8.4/−0.3), −5.3 (−9.2/−1.4), and −4.6 (−9.2/−0.02), respectively. Addition errors were observed because the 95% CI did not include 0. The 20% relative error rate between ST and different AT values exceeded 95% in all cases, confirming the high interchangeability of the two sets of measurement results. The correlation coefficients were 0.68–0.80, indicating a positive correlation between the two sets of measurement results. The VO2 values also exhibited high interchangeability and a positive correlation between those at ST and those at different AT values. However, the mean differences with the values at V-Slope_AT, VE/VO2_AT, and PETO2_AT were −79.8 (−157.5/−2.2), −111.5 (−190.5/−32.6), and −87.5 (−168.5/−6.4), respectively. Addition errors were also observed for these findings. W values also showed high interchangeability and a positive correlation, with addition errors observed, between ST and VE/VO2_AT and between ST and PETO2_AT of 8.9 (−15.8/−2.0) and −7.2 (−14.2/−0.2), respectively.

Figure 2. (a) Representative SpO2 and PR time series data during cardiopulmonary exercise testing. SpO2 percutaneous oxygen saturation, PR pulse rate, Bpm beats per minute. (b) Distribution of SpO2 corresponding to ST. SpO2 was distributed in the range of 97–100%. SpO2 percutaneous oxygen saturation, ST percutaneous oxygen saturation threshold.
are two inflexion points at which \( \text{SpO}_2 \) decreases before AT. Additionally, the time until the second decrease in \( \text{SpO}_2 \) and AT. Had the method described in this study been used, Martín-Escudero et al. showed high correlation and agreement with \( \text{SpO}_2 \)-Slope method to obtain AT from the two parameters, \( \text{SpO}_2 \), PR, and many other.

It has been well established from arterial blood gas measurements that arterial oxygen partial pressure decreases during incremental exercise\(^{35,36} \). \( \text{SpO}_2 \) measured with pulse oximetry reflects arterial blood oxygen saturation, which is associated with arterial oxygen partial pressure. In recent years, \( \text{SpO}_2 \) has also been reported to decrease during incremental exercise\(^{37} \). In light of this observation, Nikooie et al. reported that the inflexion point from the two parameters of \( \text{SpO}_2 \) and PR. Since this approach does not require any special skills, experience, or knowledge, it offers a simpler method of AT measurement than conventional expiratory gas analysis.

| Variables (n)                  | V-Slope_AT (20) | VE/VO\(_2\)_AT (19) | R_AT (19) | PETO\(_2\)_AT (14) | VE_AT (20) |
|-------------------------------|-----------------|-----------------------|-----------|--------------------|------------|
| Pulse rate (bpm)              | Average difference (d) (95% CI Lower/Upper) | -4.3 (-8.4/0.3) | -5.3 (-9.2/-1.4) | -1.5 (-6.6/3.7) | -4.6 (-9.2/-0.02) | -1.9 (-6.5/2.8) |
| ±20% relative error (%)       | 95              | 100                   | 100       | 100                | 100        |
| Correlation coefficient (r) (p-value) | 0.79 (<0.01) | 0.80 (<0.01) | 0.68 (<0.01) | 0.84 (<0.01) | 0.75 (<0.01) |
| VO\(_2\) (ml/min)             | Average difference (d) (95% CI Lower/Upper) | -79.8 (-157.5/-2.2) | -111.5 (-190.5/-32.6) | -40.6 (-133.8/52.6) | -87.5 (-168.5/-6.4) | -37.7 (-122.9/47.6) |
| ±20% relative error (%)       | 90              | 89                    | 89        | 93                 | 90         |
| Correlation coefficient (r) (p-value) | 0.83 (<0.01) | 0.92 (<0.01) | 0.89 (<0.01) | 0.91 (<0.01) | 0.83 (<0.01) |
| Load (watt)                   | Average difference (d) (95% CI Lower/Upper) | -6.5 (-13.0/0.1) | -8.9 (-15.8/-2.0) | -2.7 (-10.9/5.5) | -7.2 (-14.2/-0.2) | -2.7 (-10.0/4.6) |
| ±20% relative error (%)       | 90              | 89                    | 74        | 93                 | 80         |
| Correlation coefficient (r) (p-value) | 0.80 (<0.01) | 0.89 (<0.01) | 0.84 (<0.01) | 0.86 (<0.01) | 0.74 (<0.01) |

Table 3. Consistency, compatibility, and correlation of ST and AT. Bpm beats per minute, VO\(_2\) oxygen consumption, V-Slope V-Slope, VE/VO\(_2\) oxygen ventilatory equivalent, R gas exchange ratio, PETO\(_2\) end-tidal oxygen concentration, VE ventilation, CI confidence interval, r correlation coefficient, AT anaerobic threshold, ST percutaneous oxygen saturation threshold.

**Discussion**

In this study, we investigated whether the automatic calculation of AT at ST using pulse oximetry was a valid alternative to the conventional method of AT measurement with expiratory gas analysis. Our results confirmed the validity of the \( \text{SpO}_2 \)-Slope method for determining AT from the two parameters of \( \text{SpO}_2 \) and PR with a high degree of accuracy. The superiority of the \( \text{SpO}_2 \)-Slope method lies in its ability to automatically calculate ST as the inflexion point from the two parameters of \( \text{SpO}_2 \) and PR. Therefore, our method to calculate AT automatically from \( \text{SpO}_2 \) and PR data obtained by pulse oximetry can potentially be a noninvasive and simple alternative method of measuring AT. For \( \text{SpO}_2 \) and PR measurements, a new medical wrist-worn device has been shown to be sufficiently accurate, reliable, and consistent compared to medical pulse oximeters, with no side effects\(^{35} \). In the future, our method could be extended to wearable devices to continuously measure \( \text{SpO}_2 \) and PR in daily life, which could contribute to not only improving health and performance by providing optimal exercise intensity but also detecting cardiovascular diseases.

The \( \text{SpO}_2 \) at ST, which reflects AT, was ≥ 96% in all our study subjects, with a mean value of 97.8% ± 0.3% in men and 99.0% ± 0.3% in women. All the subjects in the study of Martin-Escudero et al. were female athletes with...
Exercise-induced arterial hypoxemia, defined as a drop in $\text{SpO}_2$ of $-4\%$ or more in comparison with the resting exercise, sleep cycle, or other aspects of their daily lives during the three days preceding the experiment; to avoid the use of different types of exercise, (3) the measurements of $\text{SpO}_2$ at different sites, (4) multiracial with differences are affected by (1) expanding the range of subjects to include elderly, sick patients, and competitive athletes, (2) breath gas analysis and HR measurements. Further studies are required to verify whether these measurements are less affected by body movement, may enable more accurate measurement of AT from $\text{SpO}_2$ and PR in the future.

In our study, we confirmed that PR measured by pulse oximetry and HR measured by the reliable HR sensor showed a high correlation. This did not change even when HR exceeded 155 bpm (Fig. 1). As a result, there was no adverse effect of exercise, and the decrease in $\text{SpO}_2$ was likely small. A fingertip sensor was used for $\text{SpO}_2$ measurements both in our study and in other studies, in which $\text{SpO}_2$ measured with pulse oximetry decreased before AT. In light of factors such as body movement, the use of sensing at the ears or forehead, which are less affected by body movement, may enable more accurate measurement of AT from $\text{SpO}_2$ and PR in the future.

This study had several limitations. First, as the subjects were healthy adult volunteers, the results may not be applicable to elderly people and patients with diseases requiring exercise rehabilitation or to highly trained competitive athletes. Second, the exercise in this study was performed on a bicycle ergometer. Therefore, it is not known whether similar results would be obtained from exercise on a treadmill or steps. Third, in this experiment, we measured $\text{SpO}_2$ and PR at a fingertip. However, other sites may enable more sensitive $\text{SpO}_2$ and PR measurements that are unaffected by body movements during exercise. Forth, the subjects who participated in this experiment were only Japanese. Fawzy et al. have reported higher rates of potential hypoxemia undetected by pulse oximetry in Asian, black, and Hispanic patients compared to non-Hispanic white patients. Therefore, it is necessary to keep in mind that racial bias could exist in pulse oximetry measurements due to skin pigmentation.

In summary, this is the first study to show that the ST calculated using the $\text{SpO}_2$-Slope method from $\text{SpO}_2$ and PR results during exercise testing exhibits high concordance, interchangeability, and correlation with AT values measured with expiratory gas analysis. Our results suggested that the $\text{SpO}_2$-Slope method may be a valid simple, inexpensive, and accurate method of AT measurement. The simplicity, low cost, and high accuracy of this technique of AT measurement decrease both the burden on the subject and the analysis cost. As such, this approach has the potential to make major contributions in areas including the prevention and improvement of metabolic syndrome, exercise therapy for respiratory and cardiac rehabilitation, and the extension of healthy longevity as an index for building endurance in improving sports competitiveness.

**Methods**

**Study design.** This study was approved in advance by the FANCL Corporation. Clinical Research Ethics Review Board (C2021-006, approval date of April 30, 2021) and conducted at the FANCL Corporation Research Institute in May and June 2021. The experiments complied with the Declaration of Helsinki (adopted in 1964, revised for the 7th time at the Fortaleza General Meeting in 2013) and the Ethical Guidelines for Medical and Biological Research Involving Human Subjects (December 22, 2014, partly revised February 28, 2017). Care was always taken to protect the subjects’ human rights. The study participants were provided with a full written explanation of the study purpose and its content, as well as the voluntary nature of their participation. Participants gave both their informed consent for study participation and for the publication of their images/data in an online open-access publication. The UMIN clinical trial registration system number for this study was UMIN000044183. It was registered with UMIN on 12/05/2021 and last updated on 17/11/2021 (https://center6.umin.ac.jp/cgi-open-bin/ctr/ctr.cgi?function=brows&action=brows&receptno=R000050457&type=summary&language=J).

**Study subjects.** This clinical trial included ten men and ten women. The selection criteria of the study were as follows: healthy men and women aged between 20 and 65 years with a BMI of 18.5–30 kg/m². The exclusion criteria were as follows: (1) serious liver, gastrointestinal, kidney, or heart disease; (2) participation in a long-term interventional study of food or medicinal product either at enrollment or during the study (including planned participation); (3) intention to become pregnant during the study period, pregnancy (including possible pregnancy), or lactation; (4) COVID-19 infection or close contact with an infected person; (5) exercise-induced arrhythmia, exercise-induced anaphylaxis, or other exercise-induced condition or motor disorder; (6) considered unsuitable for study participation for any other reasons by a study investigator. After consent had been obtained, the subjects’ date of birth, age, current medical history (treatment, medication), exercise habits, smoking, and alcohol consumption were analyzed.

**Experimental methods.** The subjects were instructed to make no major changes to their normal diet, exercise, sleep cycle, or other aspects of their daily lives during the three days preceding the experiment; to avoid a severe drop from the basal value of $98.07\% \pm 0.616$ to $93.7\% \pm 1.65\%$ before. This finding may correspond to exercise-induced arterial hypoxemia, defined as a drop in $\text{SpO}_2$ of $-4\%$ or more in comparison with the resting value. According to Dominelli et al., many studies have identified a decrease in $\text{PaO}_2$ corresponding to EIAH, even at submaximal exercise. Other studies, however, have not identified the presence of EIAH in women at a load of $60\% \text{VO}_2_{\text{max}}$, at which AT may occur. This finding suggests that the magnitude of the decrease in $\text{SpO}_2$ may vary widely between individuals, affecting the analysis of our data.

The accuracy of $\text{SpO}_2$ values measured with pulse oximetry also depends on the measurement devices. Because $\text{SpO}_2$ measurements during exercise are affected by body movements and hypoperfusion, this study used a medical device that has been verified to produce highly accurate results even when the body is moving, and perfusion is low. In addition, discrepancies between HR and PR also occur in conditions of body movement and hypoperfusion. An older study reported that HR deviates from PR when HR exceeds 155 beats/min (bpm). In our study, we confirmed that PR measured by pulse oximetry and HR measured by the reliable HR sensor showed a high correlation. This did not change even when HR exceeded 155 bpm (Fig. 1). As a result, there was no adverse effect of exercise, and the decrease in $\text{SpO}_2$ was likely small. A fingertip sensor was used for $\text{SpO}_2$ measurements both in our study and in other studies, in which $\text{SpO}_2$ measured with pulse oximetry decreased before AT. In light of factors such as body movement, the use of sensing at the ears or forehead, which are less affected by body movement, may enable more accurate measurement of AT from $\text{SpO}_2$ and PR in the future.
vigorously exercise, alcohol consumption, and binge eating and drinking during the day preceding the experiment; and to consume their evening meals by 10 p.m. on the evening before the experiment with avoidance of excessively fatty food. The experiment was conducted in the morning after the subjects had fasted (with the exception of fluid intake) since the previous evening. On the day of the test, the subjects consumed a designated food 3 h before and subsequently ate and drank nothing but water until the test was conducted. The designated food was a Lime and Grapefruit Flavor Calorie Mate Gel (Otsuka Pharmaceutical, Japan) with a nutritional content of 200 kcal, including 8.2 g protein, 4.4 g fat, 33.2 g carbohydrate, and salt equivalence of 0.11 g. Before the test, their height, weight, body fat percentage, blood pressure, and pulse rate were measured.

**Study parameters.** An online expiratory gas analyzer (AE300S, Minato Medical Science, Tokyo, Japan) was used to measure VO₂, carbon dioxide emission (VCO₂), ventilation (VE), gas exchange ratio (R = VCO₂/VO₂), oxygen ventilatory equivalent (VE/VO₂), carbon dioxide ventilatory equivalent (VE/VCO₂), end-tidal oxygen concentration (PETO₂), and end-tidal carbon dioxide concentration (PETCO₂) in expiratory gases sampled using the mixing chamber method. HR was measured with a heart rate sensor (T31 Heart Rate Sensor N, POLAR, Japan) attached to the chest. Simultaneously, SpO₂ and pulse rate (PR) were measured with pulse oximetry (NellcorTM N-BSJ, Covidien Japan) via a sensor (Nelcor Sensor DS100A, Covidien Japan) attached to the index finger of the left hand as Fig. 3a. Expiratory gas parameters and HR were measured every 20 s, while SpO₂ and PR were measured every 4 s, with the mean values of every five measurements (20-s mean values) used as the measured values. Data from the final minute of the warm-up until the end of the test were used in the analysis.

**Cardiopulmonary exercise testing method.** Cardiopulmonary exercise testing (CPX) was conducted by means of a Ramp Test using an ergometer (Corival cpet, Kyokko Bussan, Japan) as Fig. 3b (Participants gave both their informed consent for study participation and for the publication of their images/data in an online open-access publication.). After 2 min at rest, the subject engaged in a 5-min warm-up at 50 W and 120 rpm, after which the exercise load was increased by 10 W/min until the subject reached one of the conditions for halting the test. These conditions include any of the following: (1) the subject was unable to continue exercise at 120 rpm due to leg fatigue; (2) the subject’s heart rate during the exercise exceeded 85% of the predicted maximum heart rate (220 – age in years), or (3) the investigator decided that the test should be halted. The saddle was adjusted so that the subject’s knees were slightly bent when the pedals were at their lowest point.

**Determination of AT.** AT determination with expiratory gas analysis was conducted by doctors and physiotherapists involved in the CPX. Following the criteria adopted by Wasserman et al., five different ATs were measured: V-Slope_AT (defined as the point at which the VO₂–VCO₂ relationship with increasing exercise intensity increased to ≥45°); VE/VO₂_AT (defined as the point at which VE/VO₂ started to increase with no increase in VE/VCO₂); R_AT (defined as the point at which R started to increase); PETO₂_AT (defined as the point at which PETO₂ started to increase with no increase in PETCO₂); and VE_AT (defined as the point at which VCO₂ started to increase in proportion to VO₂). Graphs were produced using VO₂ as the independent variable for V-Slope_AT and PR as the independent variable for the other methods. The PR and load corresponding to VO₂ of V-Slope_AT were calculated with linear regression. For the other four methods, the VO₂ and load corresponding to the PR of AT were calculated with linear regression.

**Automatic determination of AT using SpO₂ and PR with a pulse oximeter.** SpO₂ and PR during the CPX were measured using a pulse oximeter. Figure 4 shows the SpO₂_Slope method for creating the SpO₂...
threshold (ST). We calculated the dividing point that minimized the residual sum of squares when the pulse oximetry measurements were divided into two regression lines at a bifurcation on the 2nd-order regression curve. This regression curve was obtained when PR was designated as the independent variable and SpO2/PR as the dependent variable. Of the two points between this dividing point, the one with the higher PR was chosen as ST. The VO2 and load corresponding to PR at ST were calculated with linear regression. SpO2 of PR at ST was designated as ST_SpO2.

Statistical analysis. We used the following tests to investigate the concordance, interchangeability, and correlation between the exercise intensity (PR, VO2, load) at AT, determined using the five different expiratory gas analysis methods, and at ST, determined with the SpO2-Slope method. Concordance was investigated by calculating the 95% confidence interval (95% CI) of the mean difference between the two measured values (d). If this CI included 0, then the concordance was considered high. If it did not include 0, an addition error was considered to be present. Interchangeability was investigated by calculating the difference between the mean measurement (a) and measurement (b) for each subject. The error was calculated as a proportion of the difference to the mean (relative error) (b/a × 100). If the proportion of data for which the relative error was ±20% (20% relative error rate) exceeded 75%, the two methods were considered interchangeable. The correlation was investigated by calculating Pearson’s correlation coefficient (r) and the p-value. If 0.4 < |r| ≤ 0.7, the parameters were considered correlated. If 0.7 < |r| ≤ 1.0, they were considered strongly correlated. JMP® 14.1.0 statistical software (SAS Institute Inc.) was used for statistical analysis.

Data availability
All data from these studies are contained within this manuscript or are available from the corresponding author upon reasonable request. Source data are provided in this paper.

Received: 20 July 2022; Accepted: 14 November 2022
Published online: 22 November 2022

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Acknowledgements
We would like to thank all the participants and everyone involved in this study and in the writing of this paper.
Author contributions
Conceptualization, methodology, and exercise tests were conducted by M.A. Data analysis was performed by K.U., Y.N., D.I., K.F., M.T., and Y.M. Y.I performed the statistical analysis and created the figures. The original draft was prepared by M.A. and Y.I. Review and editing were performed by M.A. K.U., Y.N., D.I., K.F., M.T., Y.M., and K.U. supervised the entire process. All authors have read and agreed to the published version of the manuscript.

Funding
This study was funded by a research grant from FANCL Corporation.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-022-24271-w.

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