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ORIGINAL RESEARCH

Prediction of males' physical work capacity in various simulated altitudes using an incremental cycle ergometer exercise test at sea level

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Abstract

Standard approach to predict the decrease in physical fitness that will occur following a transition to a higher altitude is unavailable. Therefore, the study aimed to design simple mathematical models to predict submaximal exercise performance in various altitude environments, using a simple physical work capacity test conducted at sea level involving >200 subjects. After splitting the subjects' data in a ratio of 7:3, we used 70% of the data for regression model development and employed 30% for cross-validation testing. All subjects performed submaximal exercise tests using a cycle ergometer at artificial altitudes of 2000 m, 3000 m, 4000 m, 5000 m, and at sea level. We applied simple regression analysis to create a predictive model with the statistical significance set at the level of <5%. There were 233 subjects involved in this study. The coefficient of determination of our regression model was 40–58%, and the standard error of estimation was 14.96–17.27 watts. The cross-validation of our regression model was 8–10%. Among the regression models developed, the one applied to an artificial altitude of 5000 m was 17%, and the regression model applied to an artificial altitude below 4000 m had no issues in generalization since the cross-validation was less than 10%. However, the regression model applied to an artificial altitude of 5000 m had a cross-validity of 17%; therefore, it should be used with caution.

Keywords

High altitude; Hypoxia; Physical work capacity; Exercise performance; Estimation; Prediction; Regression

1. Introduction

It is established that temporary exposure to high altitude causes a decrease in physical work capacity [1]. In addition, exposure of low-altitude dwellers to high-altitude environments positively improves metabolic and cardiac responses, triggering an improvement in physical athletic performance [2]. Therefore, hypoxic training is a suitable choice for pre-adaptation to a high-altitude environment [3, 4]. In addition to high-altitude climbers, the athletes of endurance events also use hypoxic training to improve their performance [5–8].

Sinex and Chapman [9] suggested methods of general hypoxic training for athletes and demonstrated that there are differences in individual responses to hypoxic training. Therefore, individual reaction characteristics should be considered to improve physical exercise ability in a high-altitude environment. Based on the extent of change in physical exercise ability in a high-altitude environment, the exercise training goal could be customised for pre-acclimatization. For instance, if an athlete targets to climb Mt. Mont Blanc at (an altitude of 4807 m), a physical fitness test needs to be taken. If the test predicts that the physical work capacity would decrease by 20% at an altitude of 5000 m, participating in an exercise program that improves physical work capacity by 20% before climbing would be advantageous. However, there is no standard approach to predict the decrease in physical fitness that will occur in a high-altitude environment.

In general, measuring athletic ability and fitness level is the most accurate. However, when direct measurement is not feasible, a method for predicting the capacity of exercise or physical fitness level using simple test results or biological information is applied. We reviewed previous studies that predicted fitness levels to identify methods for predicting maximum exercise capacity using only the age of the subject [9, 10], or a simple physical fitness test [11, 12], and predicting the anaerobic threshold using a simple physical fitness test [13].

However, very few studies have predicted exercise ability and fitness levels in high-altitude environments. Most of the previous studies predict the onset of acute mountain sickness [14–16]. Moreover, the exercise tolerance (% HRmax) in a high-altitude environment (3500 m) has also been predicted using the results of a step test conducted in a low-altitude condition (600 m) [17]. However, very few studies have predicted

TABLE 1. The subject's age distribution.

Range of age	Simulated altitude[1]							
	2000 m		3000 m		4000 m		5000 m	
	Frequency	Ratio (%)	Frequency	Ratio (%)	Frequency	Ratio (%)	Frequency	Ratio (%)
10–19	7	5.9	7	5.9	7	5.9	18	8.9
20–29	110	93.2	111	93.3	110	93.2	151	74.4
30–39	1	0.8	1	0.8	1	0.8	9	4.4
40–49	0	0.0	0	0.0	0	0	11	5.4
50–59	0	0.0	0	0.0	0	0	11	5.4
Over 60	0	0.0	0	0.0	0	0	3	1.5
Total	118	100.0	119	100.0	118	100	203	100.0

[1] *Simulated altitude is a normobaric hypoxic environment.*

TABLE 2. The sample size and age of subjects were included in the data analysis.

Simulated altitude[1] (m)	n	Age (yrs)	Height (cm)	Weight (kg)
2000	118	23.5 ± 2.1	176.4 ± 5.2	73.8 ± 10.4
3000	119	23.5 ± 2.1	176.4 ± 5.2	73.6 ± 10.1
4000	118	23.5 ± 2.1	176.4 ± 5.2	73.8 ± 10.0
5000	203	27.4 ± 10.0	174.7 ± 6.2	71.1 ± 9.9

[1] *Simulated altitude is a normobaric hypoxic environment.*

fitness levels in various altitude environments. The reason is that it is environmentally and technically very difficult to measure physical fitness in various high-altitude environments.

Therefore, the purpose of this study was to create simple mathematical models to predict submaximal exercise performance in various altitude environments using the results of a simple physical work capacity test conducted at sea level with more than 200 subjects.

2. Methods

2.1 Participants

The participants were recruited into the study after obtaining informed consent. We presented the subject's age distribution in Table 1. Each subject performed a submaximal exercise test in four artificial hypoxic and sea level environments and only the data from subjects who completed all measurements required for analysis were used (Table 2).

2.2 Research Design

The study subjects were equally into four teams. In addition, we set the measurement order of each team to eliminate systematic errors due to the measurement order. In addition, we removed the training effect by setting the interval between individual tests to more than two days. The measurement sequences for each team are listed in Table 3.

All subjects participating in the experiment underwent incremental submaximal exercise tests at artificial altitudes of 2000 m, 3000 m, 4000 m, 5000 m, and at sea level. We performed an incremental submaximal exercise test using a cycle ergometer (Combi 75XLII, Konami Corporation, Tokyo, Japan) and ramp protocol [9].

TABLE 3. Randomized measurement sequence.

Team[1]	Sample size	Measurement sequence
A	59	2000 m–3000 m–4000 m–5000 m
B	57	3000 m–4000 m–5000 m–2000 m
C	58	4000 m–5000 m–2000 m–3000 m
D	59	5000 m–2000 m–3000 m–4000 m

[1] *The team name is defined to distinguish the measurement sequence and is unrelated to the data-analysis process.*

2.3 Measurement of Physique

We measured the height and weight of all subjects using Inbody 3.0 (Inbody, Seoul, Korea), between 8 and 9 AM. The subjects fasted for at least four hours before the measurement. We instructed the subjects to wear light clothing for the measurements. And we pressed the measurement button after confirming that the subject was standing on the measuring board with bare feet and holding the measuring electrodes in both hands. We instructed the subjects to remove all metal accessories they had for accurate measurements.

2.4 Physical Work Capacity Test

The age and sex of the subjects were entered into the cycle ergometer. Then, the cycle ergometer calculated the subject's target heart rate (75% HRmax) according to Miyashita's formula (HRmax = 209 − 0.69 × age) [9]. Next, the subject attached a heart rate sensor connected to the cycle ergometer to the earlobe and started the measurement. After beginning the measurement, the subject pedaled the cycle ergometer at a constant speed of 50 rpm. Subsequently, the exercise load was

TABLE 4. Sample size after applying Bernoulli's trials (7:3).

Purpose of use	Simulated altitude[1]			
	2000 m	3000 m	4000 m	5000 m
Development of regression model (70%)	83	83	83	142
Cross-validation test (30%)	35	36	35	61

[1] *Simulated altitude is a normobaric hypoxic environment.*

increased every 1 minute, and the measurement was automatically terminated when the subject's heart rate reached the target heart rate (75% HRmax). After the measurement, the examiner recorded the subject's exercise load (watt) corresponding to 75% HRmax.

We performed all tests in an environmental hypoxic chamber (Submersible Systems Technology, Huntington Beach, CA, USA). Each subject was acclimatized in the hypoxic chamber for 30 min for each test before exercise tests were performed [2]. A constant temperature (23 ± 2 °C) and humidity (50 ± 2%) were maintained in the chamber during the test.

2.5 Data Analysis

2.5.1 Sample size calculation

The G*Power program (ver. 3.1.9.7, Heinrich-Heine-Universität Düsseldorf Univ., Düsseldorf, Germany) was used for power analysis to estimate the appropriate sample size. We calculated the sample size based on the study by Burtscher *et al.* [17]. We queried by entering 40 for the total sample size, 3 for the number of predictors, and 0.5, for the observed coefficient of determination (R^2). As a result, the coefficient of determination of the research hypothesis was calculated to be 0.443. Subsequently, we entered the statistical significance level as 0.05, statistical power as 0.9, and the number of predictors as 4, and obtained the result for the total sample size of 32 subjects. Since this study did not pose a severe risk to the subjects and considering that the submaximal fitness test was simple, 233 males aged 18–68 years were recruited as subjects to increase the statistical power of the results of this study which was 0.9 or higher.

2.5.2 Statistical Analysis

We used age, height, weight, and physical work capacity at sea level as independent variables to predict physical work capacity at each artificial altitude. A multiple regression analysis (stepwise method) was used to develop a regression model. In addition, we checked linearity, continuity, normality of residuals, independence of residuals, homogeneity of residual variance, multicollinearity, and outliers to create an accurate regression model. We set the statistical significance level to less than 5%.

2.5.3 Division of Data (Bernoulli trials)

We split the final data in a ratio of 7:3 using Bernoulli's trial. Subsequently, we used 70% of the data for regression model development and 30% of the data for cross-validation tests (Table 4).

2.5.4 Outliers

We defined an outlier as a value with an absolute value of three or more standardized residuals. We repeated the analysis after removing outliers found during the regression analysis. The status of the outliers removed is presented in Table 5. The proportion of outliers removed during the development of each regression model was less than 2.4%.

2.5.5 Cross-Validation Test

We checked the cross-validation of our predictive model by using 30% of the total data. We calculated the predicted values of the cross-validation data by using the regression equation developed in this study. We then calculated the mean absolute percentage error (MAPE) using the residuals between the predicted and measured values, as in Eqn. 1 [18]. In addition, we calculated the standard error of the estimation using Eqn. 2 [12].

$$MAPE\ (\%) = \frac{\sum \left| \frac{Watt_{real} - Watt_{pred.}}{Watt_{real}} \right| \times 100}{N} \tag{1}$$

The *MAPE* is the mean absolute percentage error (%), where $Watt_{real}$ is the actual measured value of physical work capacity at 75% HRmax and $Watt_{pred.}$ is the predicted value of physical work capacity at 75% HRmax. The "*N*" is the sample size.

$$SEE\ (watt) = \sqrt{\frac{\sum (Watt_{real} - Watt_{pred.})^2}{n-2}} \tag{2}$$

SEE is the standard error of estimate (watt). $Watt_{real}$ is the actual measured value of physical work capacity at 75% HRmax and $Watt_{pred.}$ is the predicted value of physical work capacity at 75% HRmax. The "*n*" is the sample size.

3. Results

3.1 Descriptive Statistics of Physical Work Capacity in Each Hypoxic Condition

Table 5 presents the descriptive statistics, the amount of change, and the coefficient of variation for the physical work capacity measured in each artificial altitude environment.

The decrease in physical work capacity at 75% HRmax above 4000 m artificial altitude was greater than that below 4000 m artificial altitude. In addition, considering the coefficient of variation between the artificial altitudes, the relative variance of the artificial altitude above 4000 m was greater than that of the artificial altitude below 3000 m (Table 6).

TABLE 5. The ratio of outliers.

Number of outliers	Simulated altitude[1]			
	2000 m	3000 m	4000 m	5000 m
Count of outliers	2	2	2	3
Ratio of outliers	2.4%	2.4%	2.4%	2.1%

[1]*Simulated altitude is a normobaric hypoxic environment.*

TABLE 6. Descriptive statistics of physical work capacity at 75% HRmax for each simulated altitude.

Variables	Simulated altitude[1]			
	2000 m	3000 m	4000 m	5000 m
PWC75% HRmax (watt)	151.90 ± 23.88	141.69 ± 20.87	132.11 ± 22.13	105.12 ± 23.22
Δ%	−4.32	−8.71	−16.37	−31.14
CV (%)	15.7	14.7	16.8	22.0

PWC75% HRmax: physical work capacity at 75% HRmax; Δ%: change rate from sea level; CV: coefficient of variation; [1]*Simulated altitude is a normobaric hypoxic environment.*

TABLE 7. Coefficient of determination (R^2) for each regression model.

Items	Model No.	Simulated altitude[1]			
		2000 m	3000 m	4000 m	5000 m
R^2					
	Model 1	0.578	0.493	0.398	0.468
	Model 2	-	-	-	0.495
Adjusted R^2					
	Model 1	0.573	0.486	0.391	0.464
	Model 2	-	-	-	0.487

[1]*Simulated altitude is a normobaric hypoxic environment; Model No.; Regression model number.*

3.2 Development of Regression Models to Estimate Physical Work Capacity in Hypoxic Environments

3.2.1 Determination of the Regression Models

In this study, we applied multiple regression analysis (stepwise method) with age, height, weight, and physical work ability at sea level as independent variables. As a result, there was only one independent variable in each regression model below the artificial altitude of 4000 m: the physical work capacity at sea level. In contrast, there were two regression models at an artificial altitude of 5000 m. In one of the regression models, only physical work capacity at sea level was an independent variable, whereas, in the other, height and physical work capacity at sea level were independent variables. By comparing the two regression models, we confirmed that the coefficient of determination (R^2) increased by only 2.7%, even when height was added as an independent variable in the regression model. Therefore, we concluded that it was not efficient to include height as an independent variable.

Therefore, we used only the physical work capacity at sea level as the independent variable for each regression model.

The coefficient of determination (R^2) of the simple regression models using only the physical work capacity at sea level as an independent variable was 0.398–0.578 (Table 7).

3.2.2 Linearity

We constructed a scatter plot to check the linearity between the independent and dependent variables (Fig. 1) and confirmed that each regression model had linearity between independent and dependent variables.

3.2.3 Independence of Residuals

We calculated the Durbin-Watson index to confirm the independence of the residuals. Since the Durbin-Watson index of each regression model was close to 2, we concluded that each regression model was independent of the residuals (Table 8).

3.2.4 *F*-test for Each Regression Model

We carried out F-test to confirm the significance of the regression model which confirmed that the null hypothesis "the regression coefficient of the independent variable is 0" was rejected in each regression model. Hence, each regression model was found to be statistically significant (Table 9).

3.2.5 The Goodness of Fit for Each Regression Model

We calculated MAPE to confirm the goodness of fit of each regression model. The MAPE range of each regression model was 0.08~0.14%, and the MAPE range in the cross-validation test was 8.09~17.0%. In particular, the MAPE at an artificial

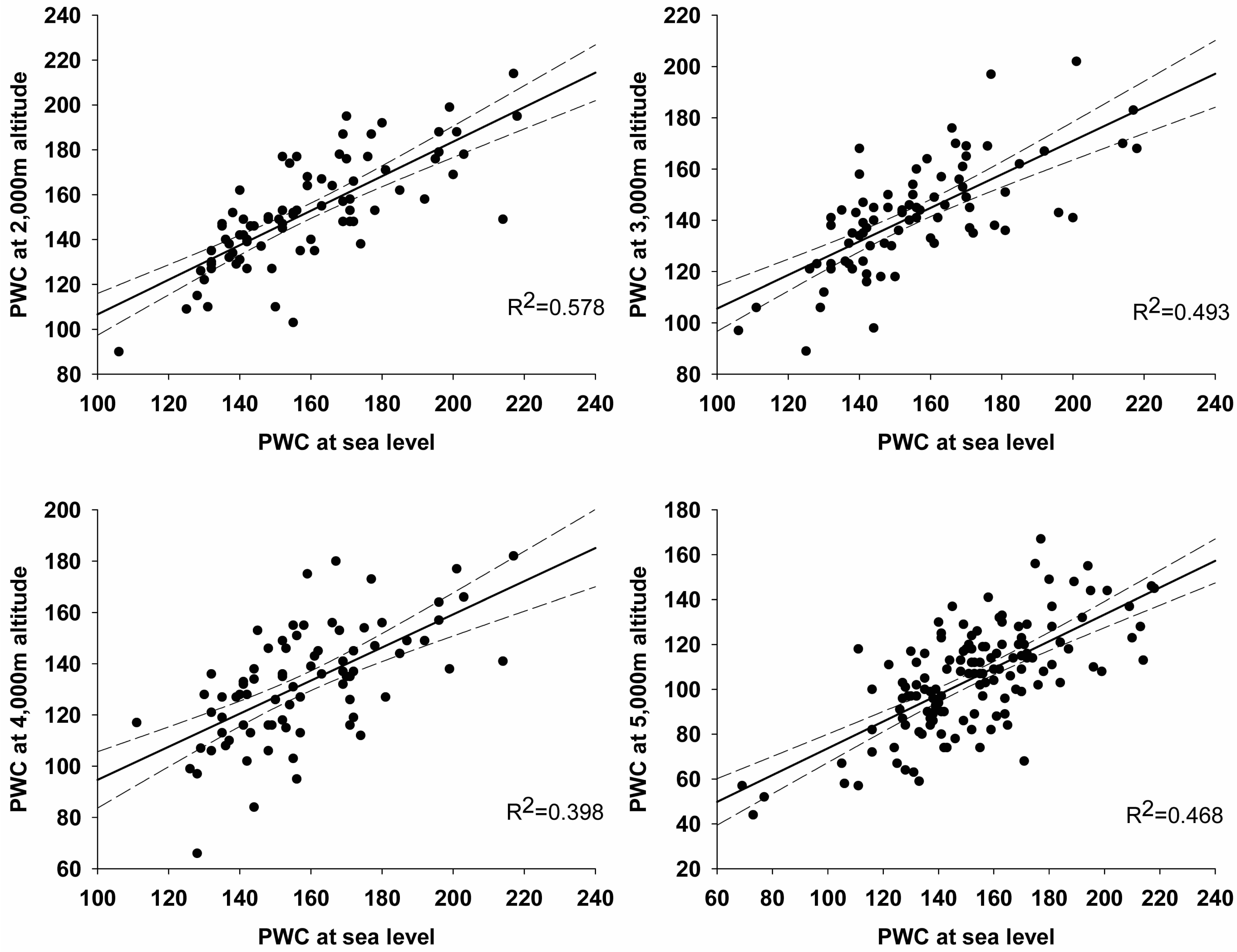

FIGURE 1. Scatter plot. PWC: physical work capacity.

TABLE 8. Durbin-Watson index.

Simulated altitude[1]	2000 m	3000 m	4000 m	5000 m
Durbin-Watson index	2.232	2.418	2.138	2.151

[1] *Simulated altitude is a normobaric hypoxic environment.*

TABLE 9. *F*-test and significance values for each regression model.

Variables	Simulated altitude[1]			
	2000 m	3000 m	4000 m	5000 m
F-value	108.296	76.759	52.288	120.371
Significant	0.000	0.000	0.000	0.000

[1] *Simulated altitude is a normobaric hypoxic environment.*

altitude of 4000 m or less was approximately 10%, whereas the MAPE at an artificial altitude of 5000 m was 17.0% (Table 10).

3.2.6 Normality of Residuals for Each Regression Model

We conducted the Shapiro-Wilk test to confirm the normality of the residuals of each regression model and confirmed that the residuals of each regression model were normal (Table 11).

3.2.7 Regression Equations to Estimate Physical Work Capacity at Each Simulated Altitude

In Table 12, we present the regression models that predict the physical work capacity at each artificial altitude, along with the standard error of estimation.

TABLE 10. Standard error of estimation and the mean absolute percentage error for each regression model.

Variables	Tasks	Simulated altitude[1]			
		2000 m	3000 m	4000 m	5000 m
Mean of PWC75% HRmax (watt)					
	Development regression model	151.90	141.69	132.11	105.12
	Cross-validation test	154.29	150.36	129.34	110.52
SEE (watt)					
	Development regression model	15.61	14.96	17.27	17.00
	Cross-validation test	16.51	17.51	15.70	22.00
MAPE (%)					
	Development regression model	0.08	0.08	0.11	0.14
	Cross-validation test	8.09	8.82	10.20	17.00

PWC75% HRmax: physical work capacity at 75% HRmax; SEE: standard error of estimation; MAPE: mean absolute percentage error; [1]Simulated altitude is a normobaric hypoxic environment.

TABLE 11. Results of normality test for each regression model.

Items	Simulated altitude[1]			
	2000 m	3000 m	4000 m	5000 m
Shapiro-Wilk's statistics	0.977	0.992	0.992	0.984
Significant	0.149	0.921	0.894	0.589

[1]Simulated altitude is a normobaric hypoxic environment.

TABLE 12. Regression equations.

Simulated altitude[1]	Regression equations	SEE
2000 m	$y = 29.740 + 0.769x$	±15.610
3000 m	$y = 40.145 + 0.654x$	±14.957
4000 m	$y = 30.067 + 0.646x$	±17.272
5000 m	$y = 14.000 + 0.597x$	±17.004

y: Physical work capacity at 75% HRmax at each simulated altitude; x: physical work capacity at 75% HRmax at sea level; SEE: standard error of estimation; [1]Simulated altitude is a normobaric hypoxic environment.

4. Discussion

This study aimed to create simple mathematical models to predict submaximal exercise performance in various altitude environments using the results of a simple physical work capacity test conducted at sea level. In our study, we used only physical work capacity at sea level as the independent variable of the regression model at each artificial altitude. Previous studies [19, 20] reported that physical work capacity decreased with increasing age; therefore, we expected age to be a significant independent variable. However, the statistical analysis showed that age was not a significant independent variable in any regression model. Therefore, we concluded that there was no relationship between the decrease in physical work capacity with increasing age and the reduction in physical work capacity in the high-altitude environment.

The MAPE of each regression model applied to an artificial altitude of ≤4000 m was ≤10%. According to previous studies [18, 21–23], "the estimation result is valid if the estimation error of physical strength is within 10%". Therefore, most of the regression models we developed had no issues with the validity of the estimates. However, the MAPE of the regression model applied to the artificial altitude of 5000 m was 17.0% which indicated a large estimation error. Similarly, Nelson *et al.* [18] suggest that estimating methods with a MAPE greater than 10% should be cautiously used. The MAPE of the regression model applied to an artificial altitude of 4000 m was 10.2%. It is unclear why the estimation error was large at an artificial altitude of 4000 m or higher. Considering the CV in Table 5, the relative variance of the measured values above 4000 m was larger than the relative variance of the measured values below 4000 m. In general, if the variance is large, the estimation error of the linear equation is also large. The large dispersion of physical fitness measurements at altitudes above 4000 m may be due to significant differences in responses between individuals in a high-altitude environment [1]. In similar previous studies, Buskirk [24] demonstrated that individual conditions, such as acute mountain sickness, pulmonary hypertension, and edema, and one's work capacity could be problematic at high altitudes. Imray *et al.* [25] reported that acute mountain sickness occurs rapidly at altitudes above 3000 m. Additionally, Honigman *et al.* [26] reported that acute mountain sickness is more frequent in younger, unhealthy individuals, those living at sea level, having a history of acute mountain sickness, and having underlying lung problems. Therefore, to estimate exercise ability at an altitude of ≥4000 m, individual differences may be significant due to various reasons.

By checking the primary assumptions in the regression analysis developed in this study, we confirmed that all basic assumptions of the regression analysis were satisfied. The coefficient of determination of our regression model was in the range of 0.398–0.578. These values are slightly smaller than 0.6, the coefficient of determination of the regression model developed by Burtscher *et al.* [17]. However, our result was larger than the coefficient of determination (0.297–0.520) calculated using the correlation coefficient (0.545–0.721) suggested by Gibson *et al.* [27].

Burtscher *et al.* [17] created a regression model to predict exercise tolerance at 3500 m altitude using the results of the step test at an altitude of 600 m and additional independent variables. Gibson *et al.* [27] compared a 6-minute treadmill walking test conducted in a hypoxic chamber (simulated altitude of 3400 m) with a 6-minute outdoor walking test performed at an actual altitude of 3400 m (Cuzco, Peru). However, we created regression models to predict physical work capacity in environments with various altitudes using only simple physical fitness measurement results at sea level as an independent variable. Therefore, our regression models have a performance similar to that of previous studies, although it is a more straightforward method compared to previous studies.

5. Conclusions

The method of predicting submaximal exercise capacity in various high-altitude environments with submaximal exercise performance measured at sea level has an explanatory power of approximately 40–58% and an estimation error of 8–17%. Among the regression models we developed, the regression model applied to an artificial altitude below 4000 m had no problem with generalization because the cross-validation was less than 10%. However, the regression model applied to an artificial altitude of 5000 m had a cross-validity of 17%; therefore, it should be used with caution. This method we've created will be able to tell someone in advance how much their physical work capacity will decrease in the high-altitude environment when they want to travel to high altitude.

ABBREVIATIONS

MAPE, mean absolute percentage error; SEE, standard error of estimation; CV, coefficient of variation; PWC, physical work capacity.

AUTHOR CONTRIBUTIONS

SSN and HYP—designed the research study; drafted the manuscript. HYP and JWK—performed experiments. SSN—analyzed the data. SSN, HYP, and JWK—discussed the results. All authors contributed to the editorial changes in the manuscript. All authors have read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was conducted according to the Helsinki Declaration's guidelines and approved by the local ethics committee of Kyunghee University (KHSIRB 2015-024). Also, informed consent was obtained from all subjects involved in the study.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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