

Research Paper

Contribution of Body Mass Index Stratification for the Prediction of Maximal Oxygen Uptake

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Abstract

The purpose of this study was to investigate whether modeling within separate body mass index (BMI) stratifications improves the accuracy of maximal oxygen uptake (VO_{2max}) prediction compared to a model developed regardless of adults' BMIs. A total of 250 Taiwanese adults (total group, TOG) aged 22–64 years participated in this study, and were stratified into a normal group (NOG: 135), an overweight group (OVG: 69), and an obesity group (OBG: 46), according to the BMI classification recommended by the Taiwan Ministry of Health and Welfare. VO_{2max} was directly measured on an electromagnetic bicycle ergometer. Using the participant's heart rate in the 3-min incremental step-in-place test and demographic parameters, VO_{2max} prediction models established for four groups were TOG model, NOG model, OVG model, and OBG model, respectively. Compared with the TOG model, the OVG and OBG models had higher coefficients of determination and lower standard error of estimates (SEEs), or %SEEs. The validities of the NOG ($r = 0.780$), OVG ($r = 0.776$), and OBG ($r = 0.791$) models for BMI subgroups increased by 1.79%, 4.64%, and 8.22% respectively, and the reliabilities (NOG model: ICC = 0.755; OVG model: ICC = 0.765; OBG model: ICC = 0.779) increased by 3.18%, 3.27%, and 9.63%, respectively. These results suggested using separate models established in BMI stratifications can effectively improve the prediction of VO_{2max} .

Key words: VO_{2max} ; 3-min incremental step-in-place; prediction model; BMI

Introduction

Obesity is a risk factor for various chronic diseases, including hypertension, cardiovascular disease (CVD), diabetes, and kidney disease [1–7], with CVD being the leading cause of death worldwide [8]. Body mass index (BMI) is a standardized index calculated by dividing body weight (in kg) by height squared (in m^2) and is used by the World Health Organization (WHO) to measure a person's degree of obesity: underweight, normal weight, overweight, and obese. BMI can be calculated

easily and quickly and is therefore the most commonly used anthropometric indicator in research and clinical practice to assess obesity in the general population [4, 9, 10]. Past studies have shown that overweight or obesity, described as higher BMI, is a major risk factor for cardiovascular disease in the general population [1, 2, 11]. Reducing body weight to within the normal range has a positive effect on blood pressure and lipid levels, which are effective in reducing cardiovascular morbidity and all-cause

mortality [12–15]. The BMI thresholds for diagnosing obesity vary across different populations. Based on the association between various health conditions and BMI, WHO established, for European and North American populations, a normal BMI of 18.5–24.9 kg/m²; in contrast, a BMI of 25–29.9 kg/m² is defined as overweight, and a BMI of 30 kg/m² and above is defined as obese [3, 12, 16]. However, using 30 kg/m² as the BMI threshold for diagnosing obesity is too high for Asian populations and tends to underestimate health risks [17]. Therefore, the Taiwan Ministry of Health and Welfare defines BMI of greater than or equal to 27 kg/m² as obese, according to local population characteristics; A BMI between 24 kg/m² and 27 kg/m² is considered overweight, normal weight is defined as 18.5 ≤ BMI < 24 kg/m², and BMI below 18.5 kg/m² indicates underweight [17, 18].

Cardiorespiratory fitness (CRF) is an important indicator to assess cardiovascular health status in adults with different BMI levels [19, 20], and measuring CRF levels can predict the risk of future cardiovascular disease and all-cause mortality. Previous studies have shown a significant negative correlation between BMI and CRF in normal weight, overweight, and obese individuals, and adults with higher BMI levels typically have lower CRF levels [21, 22]. The most direct and accurate measure of CRF is incremental cardiopulmonary exercise testing (CPET) on a treadmill or bicycle ergometer. In CPET, the plateau in VO₂ reached by the participant at exhaustion represents the maximum upper limit of CRF [23]. Therefore, maximal oxygen uptake (VO_{2max}) is the best indicator of CRF levels in adults with various BMIs [24, 25]. However, this approach has several drawbacks. Direct measurement of VO_{2max} requires expensive laboratory equipment, the participants must exercise until exhaustion, which is time-consuming, and maximum physical effort tends to increase the risk of adverse cardiovascular events in adults with higher BMI levels [20]. Therefore, it is essential to explore low-risk and effective submaximal exercise solutions to indirectly measure VO_{2max} in adults with various BMIs.

Many scholars have proposed various submaximal exercise protocols in the past to predict VO_{2max} [26–29], and most of them developed VO_{2max} prediction formulas using age, sex, body mass, BMI, percent body fat (PBF), heart rate (HR), or distance to assess the CRF levels of adults with various BMIs using overall data. The most common field test is the 20-meter shuttle run test. It is simple, easy to administer, and convenient for simultaneous testing of multiple individuals [30]. However, it requires a large space and is susceptible to environmental factors (rain, snow, etc.). To reduce the time and space

costs of CRF testing, many studies have developed different step-up tests, such as the Young Men's Christian Association (YMCA), Queen's College, and Harvard Step tests, which require participants to continuously step onto and off a box of 20 to 50 cm height for three to five minutes [24, 31–34]. However, in the most widely used 3-minute YMCA step test study, many scholars found that adults with higher BMIs were unable to complete the exercise test at standard intensity [35, 36], and they were prone to falling during the process of stepping onto and off the box. Therefore, an alternative to step-up tests, namely the 3 min incremental step-in-place (3MISP) test, has recently been proposed. Taking into account individual differences, the 3MISP test uses the midline between the middle of the anterior superior iliac spine and the patella as the target for knee elevation during stepping, without a step-up box, so it is safer and easier to complete than step-up tests. The prediction formula established by combining the exercise HR during the 3MISP test with demographic parameters can predict the VO_{2max} of healthy adults with relative accuracy [29, 37].

However, using the same prediction formula for adults with different BMIs may affect the accuracy of VO_{2max} estimation. Previous studies have found that the traditional approach to modeling VO_{2max} using overall data may overestimate VO_{2max} in individuals with low fitness levels and underestimate VO_{2max} in individuals with high fitness levels [28, 38–42]. This overestimation or underestimation of VO_{2max} may be due to individual differences in participants, especially their degrees of obesity. To investigate whether modeling within separate BMI stratifications improves the accuracy of VO_{2max} prediction compared to a model developed regardless of adults' BMIs, this study stratified all participants (i.e., the total group, TOG) into three groups: the normal group (NOG), the overweight group (OVG), and the obesity group (OBG), according to the BMI classification criteria established by the Taiwan Ministry of Health and Welfare [17, 18]. Then corresponding VO_{2max} prediction models were developed for each group. The effectiveness of the BMI stratified models was also compared with that of the VO_{2max} prediction model constructed using the TOG. In this study, it was hypothesized that the prediction models established within separate BMI stratifications (NOG, OVG, and OBG) would result in better VO_{2max} estimation than TOG model developed regardless of adults' BMIs.

Materials and methods

Study design

All participants (i.e., TOG) were stratified into three groups: NOG ($18.5 \leq \text{BMI} < 24 \text{ kg/m}^2$), OVG ($24 \leq \text{BMI} < 27 \text{ kg/m}^2$), and OBG ($\text{BMI} \geq 27 \text{ kg/m}^2$), according to the BMI classification criteria established by the Taiwan Ministry of Health and Welfare [17, 18]. Each participant completed the $\text{VO}_{2\text{max}}$ and 3MISP tests. $\text{VO}_{2\text{max}}$ was measured directly using an electromagnetic bicycle ergometer (Excalibur Sport Ergometer, Lode BV, the Netherlands). Chest strap heart rate sensors (Polar H10, Polar Electro Oy, Finland) were used to measure the heart rate response of participants during the $\text{VO}_{2\text{max}}$ and 3MISP tests. $\text{VO}_{2\text{max}}$ prediction models (i.e., the TOG, NOG, OVG, and OBG models, respectively) were developed for the TOG, NOG, OVG, and OBG by multivariate linear regression analysis. The validities and reliabilities of these prediction models were validated with the Pearson's correlation coefficient and intraclass correlation coefficient (ICC).

Participants

A total of 250 healthy Taiwanese adults (124 males, 126 females) aged 22 to 64 years completed this study. None of the participants had medical histories of chronic diseases such as cardiovascular, skeletal or muscular diseases that might affect their ability to complete the exercise tests. The participants were divided according to the BMI classification criteria established by the Taiwan Ministry of Health and Welfare [17, 18], and the NOG, OVG, and OBG had 135, 69, and 46 participants, respectively. This study was approved by the Institutional Review Board of the Industrial Technology Research Institute (Hsinchu, Taiwan). All participants provided informed consent forms prior to participation in the experiment. And all experiments were conducted in accordance with relevant guidelines and regulations, i.e., the principles of the Declaration of Helsinki guidelines. In this study, the body weights and PBF of all participants were measured by body composition analyzer (InBody® 570, Biospace, Inc., Seoul, Korea), and BMI was calculated by dividing the participant's body weight (in kg) by the square of his/her height (in m^2).

Maximal graded exercise test

$\text{VO}_{2\text{max}}$ was measured directly using the maximal graded exercise test (GXT) on a standard electromagnetic bicycle ergometer (Excalibur Sport Ergometer, Lode BV, the Netherlands). The initial workload was 25 W, followed by a progressive increase in resistance of 15 W every 2 minutes until

the participant could no longer achieve the required pedaling frequency of 70 revolutions per minute [29]. During the GXT, participants wore a chest strap heart rate sensor throughout the exercise to monitor their heart rate and used the Borg Rating of Perceived Exertion (RPE) Scale (6–20) to rate their exertion [43]. Simultaneously, $\text{VO}_{2\text{max}}$ was obtained and the respiratory exchange ratio (RER) of each participant was monitored with a cardiopulmonary exercise testing system (Vmax Encore 29 System, VIASYS Healthcare Inc., Yorba Linda, CA, USA). In this study, participants were considered to have achieved $\text{VO}_{2\text{max}}$ if they met three of the following conditions: the participant's maximum heart rate reached more than ninety percent of the age-based maximum heart rate ($220 - \text{age}$); the RER was greater than or equal to 1.10; the increase in oxygen consumption began to plateau as the load continued to increase; and the RPE was greater than or equal to 18 [28, 29].

3-min incremental step-in-place test

The 3MISP test began with a stepping frequency of 80 steps per minute (SPM) and then increased by 16 SPM every 30 seconds for 3 minutes. The heart rate response was recorded at the beginning of the exercise (HR0), at the first (HR1), second (HR2), and third (HR3) minutes into the exercise, and at the first minute after the end of the exercise (HR4). Participants were required to wear a heart rate sensor for monitoring of their heart rate response during the 3MISP test. The midpoint between the anterior superior iliac spine and the patella was measured and marked with colored tape as the height of knee elevation during stepping. Once the test began, the participant had to step to the tempo of a metronome, and each knee had to be raised to the indicated height. If the participant could not achieve the required knee height or keep up with the metronome for 30 seconds, then the 3MISP test was stopped and the data were excluded from the analysis [37].

Statistical analysis

Multivariate analysis of variance was used to compare the differences in physical characteristics between the TOG, NOG, OVG and OBG, followed by the Bonferroni post-hoc test. The relationship between actual $\text{VO}_{2\text{max}}$ measurements and other measurements in different BMI subgroups was evaluated, and the $\text{VO}_{2\text{max}}$ predictive validity of the TOG, NOG, OVG and OBG models in each group was assessed by calculating the Pearson's correlation coefficients (r). Absolute r values between 0.00 and 0.10, between 0.10 and 0.39, between 0.40 and 0.69, between 0.70 and 0.89, and between 0.90 and 1.00 are indicative of negligible, weak, moderate, strong, and very strong

correlations, respectively [44]. Four VO_{2max} prediction models (i.e., the TOG, NOG, OVG, and OBG models) were developed by multiple stepwise regression analysis (training and verification sets were classified at 7:3 ratio), using the heart rate during the 3MISP test, age, sex (female = 0; male = 1), and body composition. The linearity, normality of residuals, and homoscedasticity assumptions of each model were checked using scatterplots, Shapiro-Wilk test/histograms of standardized residuals, and residual plots, respectively. We calculated variance inflation factor (VIF) to test the multi-collinearity of the datasets. Multivariate coefficients of determination (R^2), standard error of estimate (SEE), %SEE, mean absolute error (MAE), and root mean squared error (RMSE) were used to analyze and compare the fit and accuracy of the TOG, NOG, OVG, and OBG models. Cross-validation analysis for each model was performed by the predicted residual error sum of squares (PRESS) statistical method [28, 29]. The predictive reliability of these models for VO_{2max} in different BMI subgroups was validated by calculating ICCs (two-way mixed models; absolute agreement). For the ICC values, < 0.5 is regarded as poor, 0.5–0.75 as moderate, 0.75–0.9 as good, and > 0.90 as excellent reliability [45]. Paired sample t-tests and Bland-Altman plots were used to compare the differences between the actual VO_{2max} measurements and the VO_{2max} estimates for each BMI subgroups [46]. p less than 0.05 was considered to be statistically significant. All data in this study were analyzed in SPSS (version 22.0, IBM Corp., USA).

Results

The descriptive characteristics of the subjects

Table 1 presents the descriptive characteristics of the participants in the TOG, NOG, OVG, and OBG. The results of the multivariate analysis of variance showed that there were significant differences in BMI, PBF, and VO_{2max} among the TOG, NOG, OVG, and OBG (all $p < 0.001$). According to the post-hoc results, VO_{2max} values were higher in the TOG, NOG, and OVG than in the OBG by 4.10 ($p = 0.002$), 5.32 ($p < 0.001$), and 4.45 $mL \cdot kg^{-1} \cdot min^{-1}$ ($p = 0.006$), respectively.

Correlation between the VO_{2max} and independent variables

Table 2 presents the Pearson's correlation coefficients between the actual VO_{2max} measurements and independent variables in the TOG, NOG, OVG, and OBG. The results showed that, in the TOG and NOG, age (TOG: $r = -0.259$, NOG: $r = -0.270$), PBF (TOG: $r = -0.697$, NOG: $r = -0.712$), and HR0 (TOG: $r = -0.454$, NOG: $r = -0.501$) were significantly negatively

correlated with VO_{2max} (all $p < 0.01$). In addition, positive correlation was found between sex (female = 0, male = 1) and both $\Delta HR3-HR4$ and VO_{2max} (TOG, sex: $r = 0.461$, $\Delta HR3-HR4$: $r = 0.573$; NOG, sex: $r = 0.542$, $\Delta HR3-HR4$: $r = 0.543$; all $p < 0.01$). In the OVG, there was negative correlation between age and VO_{2max} ($r = -0.330$, $p = 0.006$) but positive correlation between sex and both $\Delta HR3-HR4$ and VO_{2max} (sex: $r = 0.639$, $\Delta HR3-HR4$: $r = 0.539$, both $p < 0.01$). In the OBG, there was negative correlation between age ($r = -0.294$, $p = 0.048$), PBF ($r = -0.760$, $p < 0.01$), HR4 ($r = -0.684$, $p < 0.01$) and VO_{2max} .

Multivariate regression models for predicting VO_{2max}

Table 3 presents the multivariate regression models for predicting VO_{2max} in the TOG, NOG, OVG, and OBG. The VIFs for the TOG (1.036-2.642), NOG (1.101-2.019), OVG (1.017-1.112), and OBG (1.158-1.510) models were all less than 10 (Table 3), indicating that there was no multi-collinearity among the predictor parameters of each model [47]. Figure 1 shows the percentage changes in R^2 (Figure 1A), SEE (Figure 1B), and %SEE (Figure 1C) for the NOG, OVG, and OBG models developed within separate BMI stratifications compared with the TOG model including age, sex, PBF, BMI, HR0, and $\Delta HR3-HR4$. The results showed that, compared with the TOG model ($R^2 = 0.637$, SEE = 4.382 $mL \cdot kg^{-1} \cdot min^{-1}$, %SEE = 12.84%), the NOG model showed a 2.20% higher R^2 (0.651), a 0.44% higher SEE (4.401 $mL \cdot kg^{-1} \cdot min^{-1}$), and a 2.27% lower %SEE (12.55%); R^2 (0.668) was higher by 4.87%, SEE (4.041 $mL \cdot kg^{-1} \cdot min^{-1}$) was lower by 7.77%, and %SEE (11.71%) was lower by 8.80% for the OVG model; R^2 (0.750) was higher by 17.74%, SEE (3.353 $mL \cdot kg^{-1} \cdot min^{-1}$) was lower by 23.47%, and %SEE (11.39%) was lower by 11.27% for the OBG model. The cross-validation results of the PRESS method suggested that TOG, NOG, OVG, and OBG models had high cross-validities (ΔR^2 : 0.01 to 0.014; ΔSEE : 0.043 to 0.193 $mL \cdot kg^{-1} \cdot min^{-1}$).

Testing model assumptions

Linear regression assumptions (linearity, normality of residuals, and homoscedasticity) of TOG, NOG, OVG, and OBG models were all satisfied in this study. Figure 2 described the linear relationship between the measured VO_{2max} and the independent variables with the scatter plots. The results of the Shapiro-Wilk test indicated that the residuals within the TOG ($p = 0.840$), NOG ($p = 0.055$), OVG ($p = 0.455$), and OBG ($p = 0.922$) models were normally distributed. Histograms of the standardized residuals were also plotted to evaluate normality of residuals and to check whether there were outliers in each

model (Figure 3). It could be found that standardized residuals of the TOG, NOG, OVG, and OBG models all followed normal distribution, and there were no outliers in their histograms. Homoscedasticity was tested using the scatter plots of the standardized residuals against regression standardized predicted value for each model. As shown in Figure 4, the residual plots of models were randomly scattered around the zero horizontal line, suggesting that the TOG, NOG, OVG, and OBG models all fulfilled the homoscedasticity assumption.

Prediction accuracy of the regression model

The prediction accuracy of the TOG, NOG, OVG, and OBG models in the BMI subgroups was checked using performance metrics such as MAE and RMSE

(Table 4). The MAEs and RMSEs of the TOG model (NOG: MAE = 3.79 mL·kg⁻¹·min⁻¹, RMSE = 4.53 mL·kg⁻¹·min⁻¹; OVG: MAE = 3.58 mL·kg⁻¹·min⁻¹, RMSE = 4.30 mL·kg⁻¹·min⁻¹; OBG: MAE = 3.32 mL·kg⁻¹·min⁻¹, RMSE = 3.99 mL·kg⁻¹·min⁻¹) for the BMI subgroups were all higher than those of NOG model (MAE: 3.72 mL·kg⁻¹·min⁻¹, RMSE: 4.44 mL·kg⁻¹·min⁻¹), OVG model (MAE: 3.16 mL·kg⁻¹·min⁻¹, RMSE: 3.98 mL·kg⁻¹·min⁻¹), and OBG model (MAE: 2.70 mL·kg⁻¹·min⁻¹, RMSE: 3.18 mL·kg⁻¹·min⁻¹). These results indicated that the regression models developed within separate BMI stratifications would result in better prediction accuracy than TOG model.

Table 1. The descriptive characteristics of the subjects.

	TOG (N = 250)	NOG (N = 135)	OVG (N = 69)	OBG (N = 46)	p	Range
Age (years)	43.3 ± 10.0	42.8 ± 10.1	45.6 ± 10.2	41.5 ± 9.2	0.132	22.0–64.0
Male (N)	124	49	43	32		
Female (N)	126	86	26	14		
Height (cm)	166.1 ± 8.2 ^d	164.2 ± 8.2 ^d	167.2 ± 7.5	170.0 ± 7.4 ^{ab}	<0.001	150.0–188.0
Body mass (kg)	67.4 ± 12.9 ^{bd}	59.5 ± 8.2 ^{acd}	70.8 ± 7.3 ^{bd}	85.4 ± 10.1 ^{abc}	<0.001	43.5–123.9
BMI (kg/m ²)	24.2 ± 3.3 ^{bcd}	21.9 ± 1.7 ^{acd}	25.3 ± 0.9 ^{abd}	29.5 ± 2.4 ^{abc}	<0.001	18.5–37.8
PBF (%)	26.2 ± 7.0 ^d	24.3 ± 6.3 ^d	26.3 ± 6.8 ^d	31.5 ± 6.4 ^{abc}	<0.001	9.2–44.1
VO _{2max} (mL·kg ⁻¹ ·min ⁻¹)	33.9 ± 7.2 ^d	35.1 ± 7.3 ^d	34.2 ± 6.8 ^d	29.8 ± 6.1 ^{abc}	<0.001	18.8–52.0
HR0 (bpm)	83 ± 11	83 ± 12	82 ± 11	86 ± 11	0.212	57–109
HR4 (bpm)	129 ± 17	129 ± 17	127 ± 19	133 ± 16	0.242	83–161
ΔHR3-HR4 (bpm)	28 ± 9	29 ± 9	28 ± 10	25 ± 7	0.056	9–56

TOG, total group. NOG, normal group. OVG, overweight group. OBG, obesity group. PBF, percent body fat. BMI, body mass index. HR0, heart rate at the start of the 3MISP test. HR4, heart rate at the first minute after the 3MISP test. ΔHR3-HR4, the difference in heart rate between the third minute into the 3MISP test and the first minute after the test. Values are presented as the mean ± standard deviation. ^a Significantly different from the TOG, *p* < 0.05. ^b Significantly different from the NOG, *p* < 0.05. ^c Significantly different from the OVG, *p* < 0.05. ^d Significantly different from the OBG.

Table 2. Pearson’s correlation coefficients between VO_{2max} and independent variables in each group.

Groups	Variables	VO _{2max}	Age	Sex	PBF	HR0	HR4
TOG	Age (years)	-0.259**					
	Sex (female = 0, male = 1)	0.461**	0.001				
	PBF (%)	-0.697**	0.174**	-0.457**			
	HR0 (bpm)	-0.454**	-0.004	-0.184**	0.414**		
	HR4 (bpm)	-0.452**	-0.092	-0.262**	0.407**	0.631**	
	ΔHR3-HR4 (bpm)	0.573**	-0.180**	0.200**	-0.411**	-0.451**	-0.616**
NOG	Age (years)	-0.270**					
	Sex (female = 0, male = 1)	0.542**	-0.006				
	PBF (%)	-0.712**	0.246**	-0.593**			
	HR0 (bpm)	-0.501**	0.074	-0.192*	0.451**		
	HR4 (bpm)	-0.427**	0.023	-0.262**	0.407**	0.613**	
	ΔHR3-HR4 (bpm)	0.543**	-0.196*	0.264**	-0.419**	-0.457**	-0.597**
OVG	Age (years)	-0.330**					
	Sex (female = 0, male = 1)	0.639**	-0.025				
	PBF (%)	-0.537**	0.129	-0.732**			
	HR0 (bpm)	-0.308**	-0.145	-0.170	0.308**		
	HR4 (bpm)	-0.352**	-0.219	-0.220	0.317**	0.721**	
	ΔHR3-HR4 (bpm)	0.539**	-0.179	0.164	-0.216	-0.398**	-0.629**
OBG	Age (years)	-0.294*					
	Sex (female = 0, male = 1)	0.554**	-0.004				
	PBF (%)	-0.760**	0.234	-0.557**			
	HR0 (bpm)	-0.470**	0.067	-0.299*	0.468**		
	HR4 (bpm)	-0.684**	-0.134	-0.511**	0.551**	0.507**	
	ΔHR3-HR4 (bpm)	0.655**	-0.221	0.435**	-0.596**	-0.515**	-0.633**

TOG, total group. NOG, normal group. OVG, overweight group. OBG, obesity group. PBF, percent body fat. HR0, heart rate at the start of the 3MISP test. HR4, heart rate at first minute after the 3MISP test. ΔHR3-HR4, the difference in heart rate between the third minute into the 3MISP test and the first minute after the test. * *p* < 0.05; ** *p* < 0.01.

Table 3. Multiple regression models predicting VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$) in the TOG, NOG, OVG, and OBG.

Models	Variables	B	β	p	VIF	R ²	SEE	%SEE	R ² p	SEE _p
TOG model	Constant	52.991		<0.001		0.637	4.382	12.84	0.623	4.550
	Age (years)	-0.092	-0.123	0.010	1.036					
	Sex (female = 0, male = 1)	5.213	0.366	<0.001	2.222					
	PBF (%)	-0.300	-0.288	<0.001	2.642					
	BMI (kg/m^2)	-0.352	-0.160	0.017	2.066					
	HR0 (bpm)	-0.085	-0.135	0.018	1.488					
NOG model	$\Delta HR3-HR4$ (bpm)	0.213	0.264	<0.001	1.406					
	Constant	53.695		<0.001		0.651	4.401	12.55	0.637	4.444
	Age (years)	-0.093	-0.132	0.050	1.101					
	Sex (female = 0, male = 1)	3.668	0.250	0.002	1.532					
	PBF (%)	-0.447	-0.385	<0.001	2.019					
	HR0 (bpm)	-0.131	-0.208	0.006	1.401					
OVG model	$\Delta HR3-HR4$ (bpm)	0.178	0.201	0.006	1.310					
	Constant	29.888		<0.001		0.668	4.041	11.71	0.661	4.234
	Age (years)	-0.167	-0.260	0.005	1.017					
	Sex (female = 0, male = 1)	7.640	0.551	<0.001	1.112					
OBG model	$\Delta HR3-HR4$ (bpm)	0.268	0.371	<0.001	1.094					
	Constant	77.740		<0.001		0.750	3.353	11.39	0.740	3.291
	Age (years)	-0.208	-0.318	0.004	1.158					
	PBF (%)	-0.426	-0.405	0.002	1.510					
	HR4 (bpm)	-0.197	-0.477	<0.001	1.368					

PBF, percent body fat. BMI, body mass index. HR0, heart rate at the start of the 3MISP test. HR4, heart rate at first minute after the 3MISP test. $\Delta HR3-HR4$, the difference in heart rate between the third minute into the 3MISP test and the first minute after the test. B, unstandardized regression weights. β , standardized regression weights. SEE, standard error of estimate. %SEE, SEE/mean of measured $VO_{2max} \times 100$. R²p, PRESS squared multiple correlation coefficient; SEE_p, PRESS standard error of estimate.

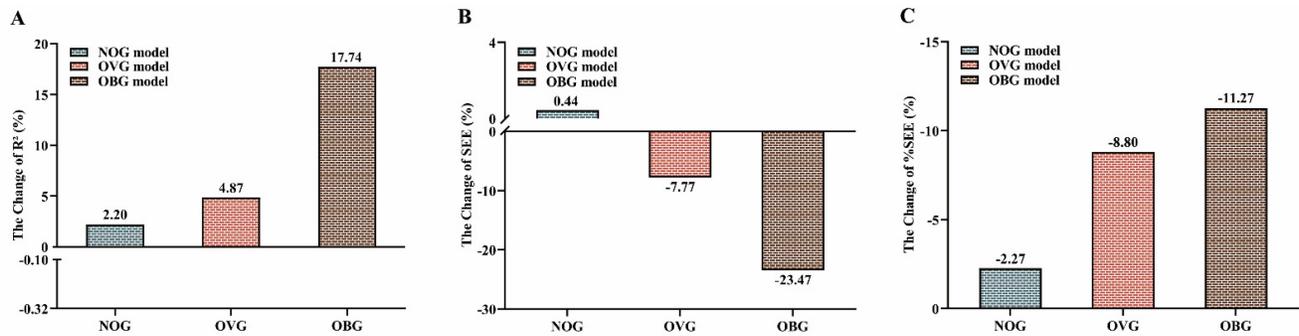


Figure 1. Percentage changes in R² (A), SEE (B), and %SEE (C) of the NOG, OVG, and OBG models compared with the TOG model. NOG, normal group. OVG, overweight group. OBG, obesity group. SEE, standard error of estimate. %SEE, SEE/mean of measured $VO_{2max} \times 100$.

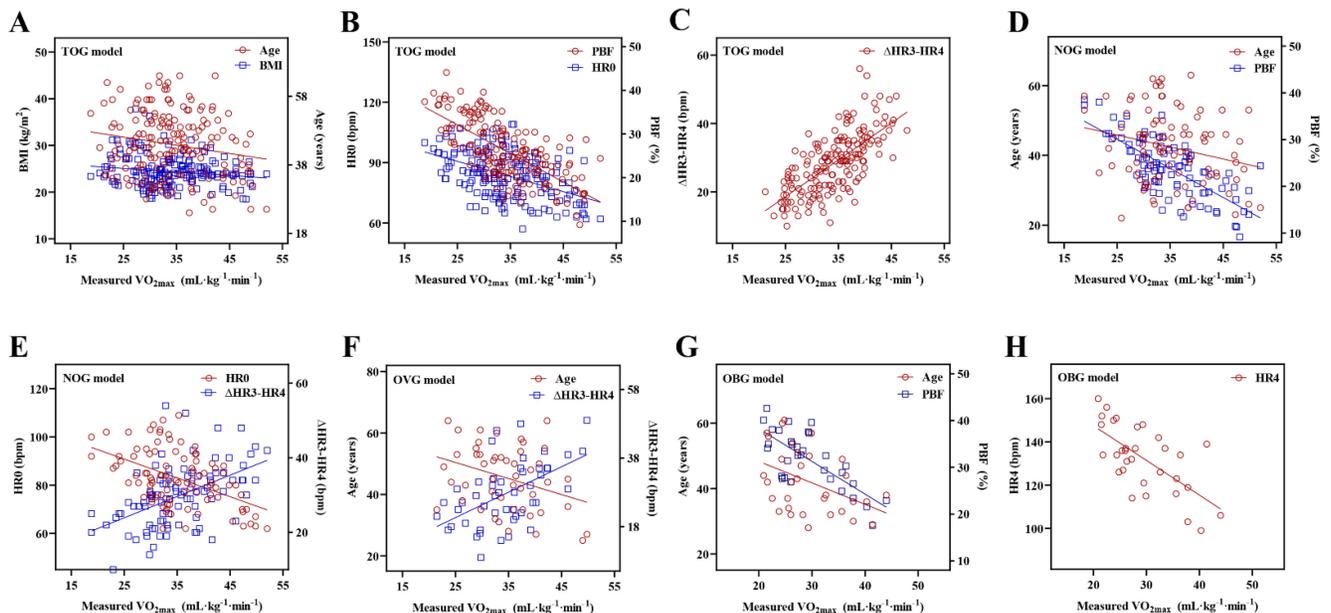


Figure 2. Scatter plots between the measured VO_{2max} and the independent variables within the TOG (A-C), NOG (D-E), OVG (F), and OBG (G-H) models.

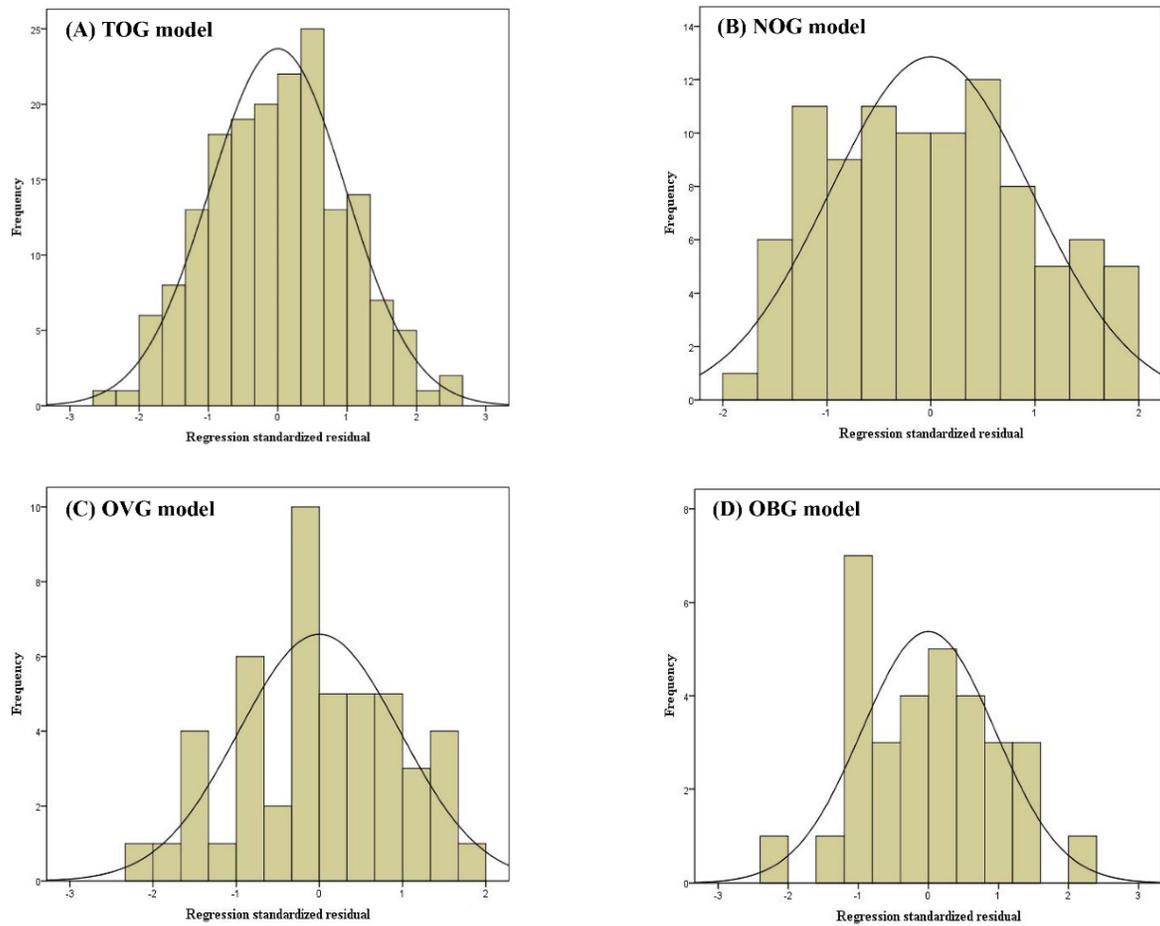


Figure 3. Histograms of standardized residuals for the TOG (A), NOG (B), OVG (C), and OBG (D) models.

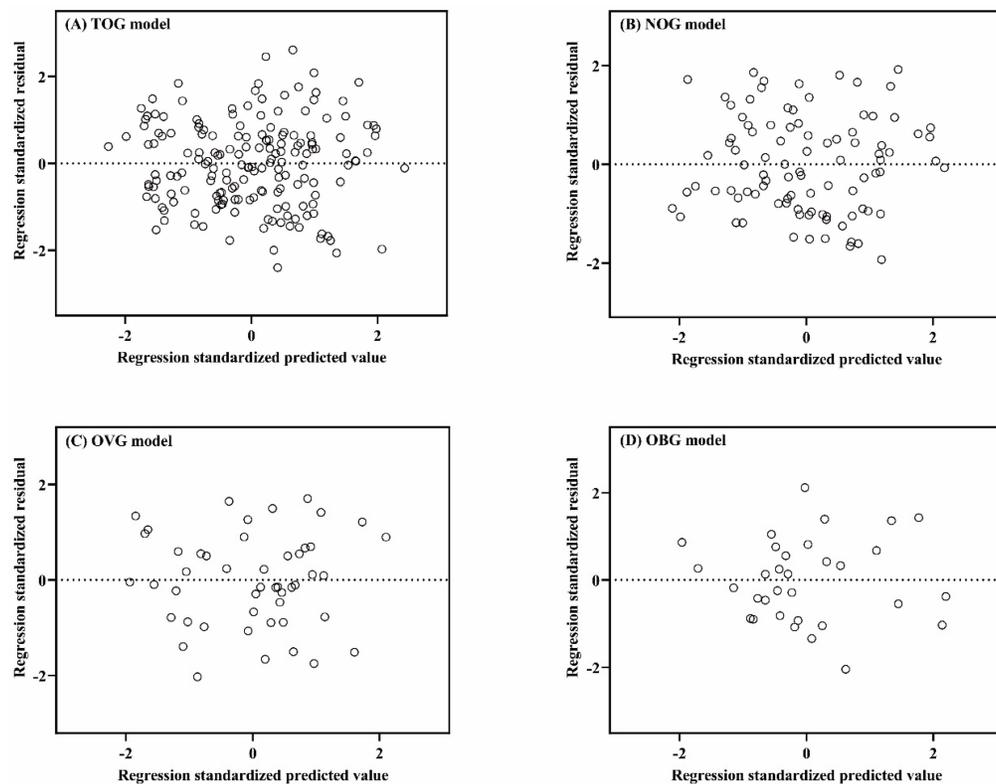


Figure 4. Scatter plots of the standardized residuals against regression standardized predicted value for the TOG (A), NOG (B), OVG (C), and OBG (D) models.

Table 4. Prediction accuracy of the regression model in the NOG, OVG, and OBG.

	NOG		OVG		OBG	
	TOG model	NOG model	TOG model	OVG model	TOG model	OBG model
MAE	3.79	3.72	3.58	3.16	3.32	2.70
RMSE	4.53	4.44	4.30	3.98	3.99	3.18

MAE, mean absolute error. RMSE, root mean squared error.

Comparison between actual VO_{2max} measurements and VO_{2max} estimates

Figure 5A presents the differences between actual VO_{2max} measurements and VO_{2max} estimates by the TOG model in the NOG, OVG, and OBG. Figure 5B shows the differences between the actual VO_{2max} measurements and the VO_{2max} values predicted by the NOG model, OVG model, and OBG model for different BMI subgroups. The results showed a significant difference between the measured VO_{2max} and the VO_{2max} predicted by the TOG model in the OBG (29.80 ± 6.12 mL \cdot kg⁻¹ min⁻¹ vs. 30.96 ± 5.80 mL \cdot kg⁻¹ min⁻¹, $p = 0.049$). In the NOG, OVG, and OBG, there were no statistically significant differences between the actual VO_{2max} measurements and the VO_{2max} values predicted by the NOG model, OVG model, and OBG model, respectively (NOG: 35.12 ± 7.26 mL \cdot kg⁻¹ min⁻¹ vs. 34.52 ± 6.05 mL \cdot kg⁻¹ min⁻¹; OVG: 34.25 ± 6.84 mL \cdot kg⁻¹ min⁻¹ vs. 34.58 ± 5.38 mL \cdot kg⁻¹ min⁻¹; OBG: 29.80 ± 6.12 mL \cdot kg⁻¹ min⁻¹ vs. 29.42 ± 5.65 mL \cdot kg⁻¹ min⁻¹; all $p > 0.05$).

Validity and reliability of models for predicting VO_{2max}

Figure 6 presents the relationships between the actual VO_{2max} measurements in the NOG (Figure 6A), OVG (Figure 6B), and OBG (Figure 6C) and the VO_{2max} values predicted by the TOG, NOG, OVG, and OBG models, respectively. Figure 7A, B presents the validity analysis (r) and reliability analysis (ICC) of these four models for predicting VO_{2max} in different BMI subgroups. Figure 7B indicates that the NOG ($r = 0.794$, ICC = 0.779, both $p < 0.001$), OVG ($r = 0.812$, ICC = 0.790, both $p < 0.001$), and OBG ($r = 0.856$, ICC = 0.854, both $p < 0.001$) models had good validity and reliability in predicting VO_{2max} for each BMI subgroups^{44,45}. Compared with the predictive validity and reliability of the TOG model for VO_{2max} in different BMI subgroups (NOG: $r = 0.780$, ICC = 0.755; OVG: $r = 0.776$, ICC = 0.765; OBG: $r = 0.791$, ICC = 0.779; all $p < 0.001$; Figure 7A), the NOG, OVG, and OBG models improved the predictive validities of VO_{2max} in the NOG, OVG, and OBG by 1.79%, 4.64%, and 8.22%, and the reliabilities by 3.18%, 3.27%, and 9.63%, respectively (Figure 7C).

Bland–Altman analysis of VO_{2max} measured and predicted

Figure 8 presents Bland–Altman Plots including

the linear regression between the difference and average of predicted and measured VO_{2max} in BMI subgroups. The results of Shapiro–Wilk test suggested that the residues were evenly distributed among the different VO_{2max} values in the NOG (TOG model: $p = 0.148$; NOG model: $p = 0.17$), OVG (TOG model: $p = 0.966$; OVG model: $p = 0.652$), and OBG (TOG model: $p = 0.672$; OBG model: $p = 0.645$). The mean difference between the VO_{2max} values predicted by the TOG model and the actual VO_{2max} measurement values in the NOG and OVG were -0.05 mL \cdot kg⁻¹ min⁻¹ ($p = 0.893$) and 0.06 mL \cdot kg⁻¹ min⁻¹ ($p = 0.911$), respectively, and the 95% limits of agreement (LoA) were -8.96 to 8.86 mL \cdot kg⁻¹ min⁻¹ and -8.43 to 8.54 mL \cdot kg⁻¹ min⁻¹, respectively (Figure 8A, B). In the OBG, there was a significant difference between the VO_{2max} values predicted by the TOG model and the actual VO_{2max} measurements (mean differences = 1.15 mL \cdot kg⁻¹ min⁻¹, $p = 0.049$), with a 95% LoA of -6.42 to 8.73 mL \cdot kg⁻¹ min⁻¹ (Figure 8C). There were no significant differences between the actual VO_{2max} measurements and those predicted respectively by the NOG, OVG, and OBG models in each BMI subgroup (all mean differences from -0.59 to 0.33 mL \cdot kg⁻¹ min⁻¹, $p > 0.05$), and the corresponding % LoA in the NOG, OVG, and OBG were -9.26 to 8.07 mL \cdot kg⁻¹ min⁻¹, -7.50 to 8.16 mL \cdot kg⁻¹ min⁻¹, and -6.65 to 5.89 mL \cdot kg⁻¹ min⁻¹, respectively (Figure 8D–F).

Discussion

In the past, many studies have used the overall data from adults with various BMIs to establish a VO_{2max} prediction formula with a considerable degree of reliability and validity, and they also supported the application of submaximal exercise to assess CRF [24, 25, 29, 48, 49]. However, overestimation or underestimation of VO_{2max} by the prediction formula has been found in some studies based on submaximal exercise. This phenomenon may be due to individual differences, especially in specific groups, such as those with high or low levels of physical fitness [28, 37, 42]. However, few studies have further investigated this phenomenon. Further investigation based on key factors is particularly important for analyzing the causal relationship between it and the predictivity of VO_{2max} . The WHO recommends the use of BMI classification to assess the degree of obesity in the general population, overweight or obesity increases the risk of cardiovascular disease [1, 11, 12].

The correlation between BMI and CRF is significantly negative, and adults with higher BMI usually have lower CRF levels [21, 22].

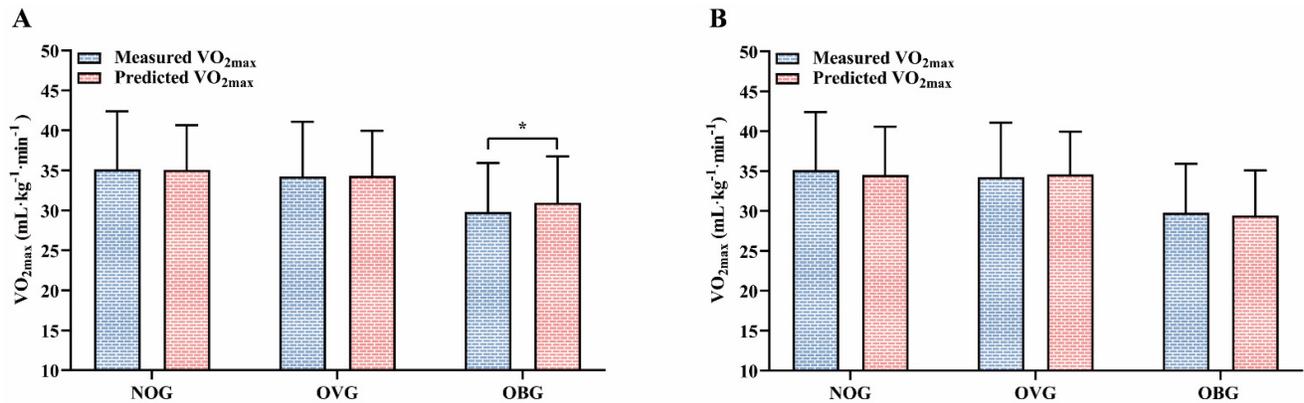


Figure 5. (A) Differences between the measured VO_{2max} and the VO_{2max} predicted by the TOG model in the NOG, OVG, and OBG. **(B)** Differences between the measured VO_{2max} and the VO_{2max} predicted by the NOG model, OVG model, and OBG model in the NOG, OVG, and OBG. NOG, normal group. OVG, overweight group. OBG, obesity group. * Significant difference between the measured and predicted VO_{2max} ($p < 0.05$).

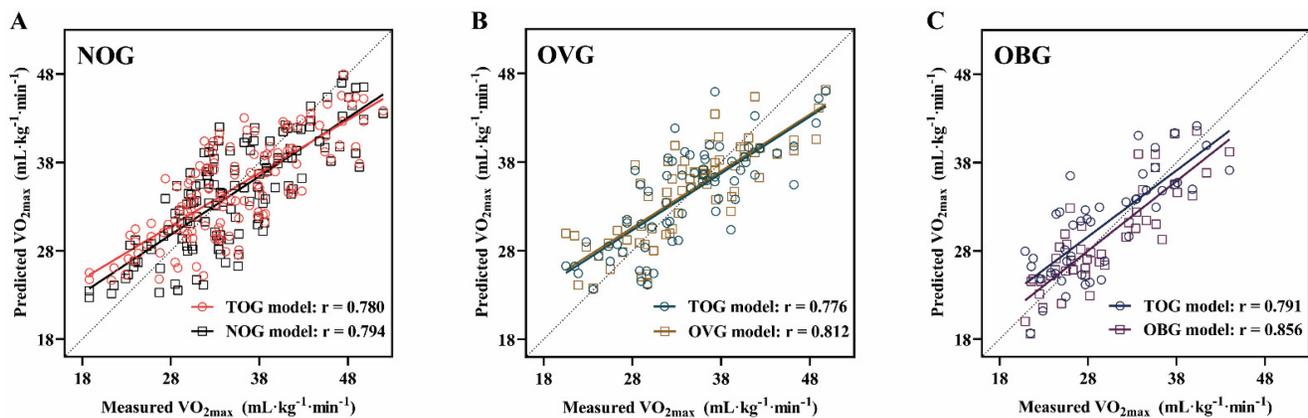


Figure 6. The relationships between the measured VO_{2max} and the VO_{2max} predicted by the TOG, NOG, OVG, and OBG models for the NOG **(A)**, OVG **(B)**, and OBG **(C)**. TOG, total group. NOG, normal group. OVG, overweight group. OBG, obesity group.

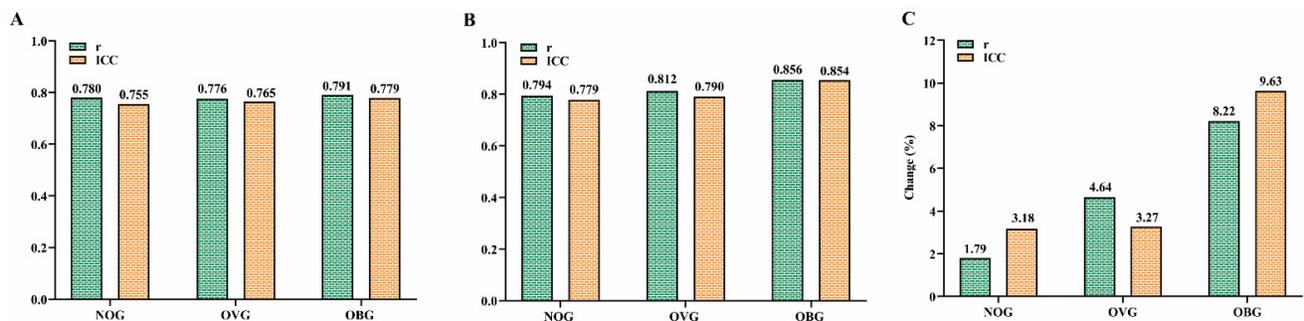


Figure 7. (A) The predictive validity (r) and reliability (ICC) of VO_{2max} in the TOG model for the NOG, OVG, and OBG. **(B)** The predictive validity (r) and reliability (ICC) of VO_{2max} in the NOG, OVG, and OBG models for the NOG, OVG, and OBG respectively. **(C)** Compared with the predictive validity (r) and reliability (ICC) of the TOG model for VO_{2max} in different BMI subgroups, the percentage changes in predictive validity (r) and reliability (ICC) of the NOG, OVG, and OBG models for VO_{2max} in each BMI subgroup. ICC, intraclass correlation coefficient. NOG, normal group. OVG, overweight group. OBG, obesity group.

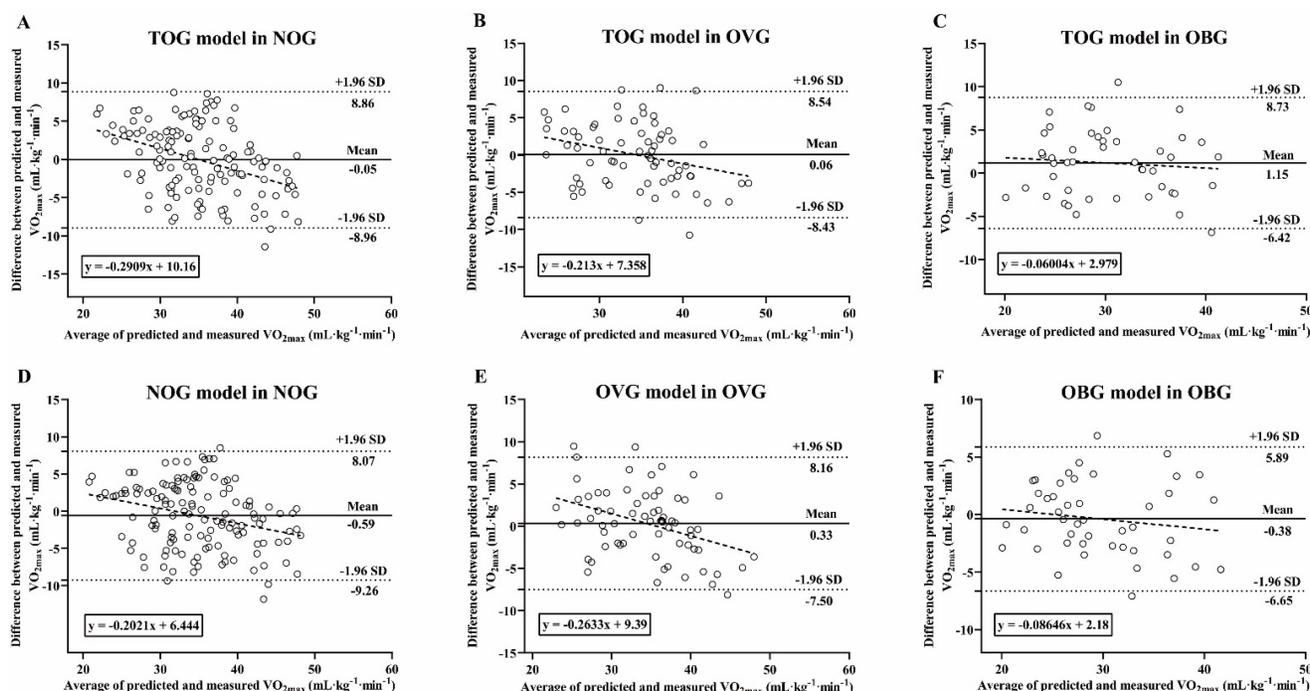


Figure 8. The differences between the predicted and measured VO_{2max} values were presented in Bland–Altman Plots, and the dotted line represents the regression line: **(A)** TOG model in NOG; **(B)** TOG model in OVG; **(C)** TOG model in OBG; **(D)** NOG model in NOG; **(E)** OVG model in OVG; **(F)** OBG model in OBG. TOG, total group. NOG, normal group. OVG, overweight group. OBG, obesity group.

Therefore, in this study, the TOG was stratified into three groups (i.e., NOG: $18.5 \leq \text{BMI} < 24 \text{ kg/m}^2$, OVG: $24 \leq \text{BMI} < 27 \text{ kg/m}^2$, OBG: $\text{BMI} \geq 27 \text{ kg/m}^2$) according to the BMI classification criteria established by the Taiwan Ministry of Health and Welfare [17, 18], and corresponding VO_{2max} prediction models (i.e., the NOG, OVG, and OBG models) were developed for each BMI subgroup and compared in terms of validity and reliability with the TOG model. The results of this study supported our original hypothesis, modeling after stratification by BMI increased R^2 and decreased %SEEs for the prediction of VO_{2max} in the NOG, OVG and OBG. In addition, this study also demonstrated that establishing separate prediction models within BMI stratifications can further improve the predictive validity and reliability of VO_{2max} for each BMI subgroup, as well as the agreement between the measured and predicted VO_{2max} . The accuracy of VO_{2max} prediction will be affected if the same prediction model is used for adults with various BMIs. Therefore, using separate prediction models developed within BMI stratifications is recommended for VO_{2max} estimation. Members of the general public can use the corresponding VO_{2max} prediction model to assess their own CRF levels with reference to the appropriate BMI subgroups (i.e., NOG, OVG, or OBG), which can provide a basis for the development or adjustment of later exercise programs.

The models for predicting VO_{2max} in the TOG, NOG, OVG, and OBG were developed by the

multiple stepwise regression analysis. Eventually, the independent variables selected for the TOG model were age, sex, PBF, BMI, HR0, and $\Delta\text{HR3-HR4}$; The independent variables selected for the NOG model were age, sex, PBF, HR0, and $\Delta\text{HR3-HR4}$; The independent variables selected for the OVG model were age, sex, and $\Delta\text{HR3-HR4}$; The independent variables selected for the OBG model were age, PBF, and HR4. Each of the independent variables (i.e., age, sex, PBF, BMI, and 3MISP-HR) used in this study was significantly related from VO_{2max} (Table 2), which is consistent with previous studies indicating that age, sex, physical characteristics (PBF or BMI), and HR are important predictors of VO_{2max} [28, 29, 31, 37, 41, 51]. In particular, heart rate is a physiological indicator of cardiac and circulatory system function. Previous studies have shown a linear relationship between exercise heart rate and VO_{2max} during the 3MISP test [29, 37], and the results of this study supported this view. In this study, HR0 and HR4 during the 3MISP test were negatively correlated with VO_{2max} , and $\Delta\text{HR3-HR4}$ was positively correlated with VO_{2max} in the NOG, OVG and OBG, as well as in the TOG (Table 2). Studies by Matsuo et al. [28] and Chung et al. [37] also reported that heart rate at the beginning of, during, and after exercise were significantly and negatively correlated with VO_{2max} , and the decrease in heart rate after exercise was positively correlated with VO_{2max} . Clearly, heart rate is an important factor in predicting VO_{2max} . By continuously monitoring the

heart rate response during the 3MISP test, we can objectively understand the load on the participant's body during exercise [19], and improve the accuracy of VO_{2max} prediction models in different BMI subgroups.

The results of this study indicated that the TOG model including age, sex, PBF, BMI, and 3MISP-HR (i.e., HR0, $\Delta HR3$ -HR4) overestimated VO_{2max} in the OBG (Figure 5A), which is consistent with previous studies reporting that the VO_{2max} prediction formula using the overall data will overestimate VO_{2max} in individuals with low fitness levels and underestimate it in individuals with high fitness levels [28, 38–42]. This overestimation of VO_{2max} in individuals with low fitness levels may increase the risk of adverse cardiovascular events. To improve the accuracy of VO_{2max} estimation and reduce the estimation error, in this study, all subjects were stratified into three groups (i.e., NOG, OVG, and OBG) according to the BMI classification criteria established by the Taiwan Ministry of Health and Welfare, and corresponding VO_{2max} estimation models (i.e., NOG, OVG, and OBG models) were developed for each BMI subgroup. The results of this study showed that the explained amount (R^2) of VO_{2max} in the NOG, OVG, and OBG models increased by 2.20–17.74%, SEE changed by 0.44–23.47%, and %SEE decreased by 2.27–11.27% (Figure 1) as compared with the TOG model, and their MAEs and RMSEs were all lower (Table 4) in BMI groups. The predicted values of VO_{2max} in the NOG, OVG, and OBG models were not significantly different from the actual VO_{2max} measurements of each BMI subgroup (Figure 5B). These results imply significant differences in CRF levels among adults with different BMIs (Table 1), which may affect the accuracy of VO_{2max} prediction if the same prediction model is used. In contrast, developing separate prediction models within BMI stratifications can effectively improve the predictivity of VO_{2max} and reduce the error.

To further evaluate the validities and reliabilities of the VO_{2max} prediction models based on BMI subgroups, this study employed the Pearson's correlation coefficient and ICC statistical methods for the NOG, OVG, and OBG models [44, 45] and compared the predictive validities and reliabilities of VO_{2max} in the NOG, OVG, and OBG with the TOG model constructed using the TOG. The results of this study showed that the validities of NOG, OVG, and OBG models increased by 1.79–8.22%, and the reliabilities increased by 3.18–9.63% comparing to the TOG model for BMI subgroups (Figure 7). In previous studies, many scholars have developed feasible VO_{2max} prediction models regardless of an individual's BMI. They also found that these

prediction models overestimated VO_{2max} in individuals with low fitness levels and underestimated VO_{2max} in those with high fitness levels [38–40, 42]. The results of this study indicated that developing separate VO_{2max} prediction model within BMI stratifications can significantly improve the predictive validity and reliability of VO_{2max} in adults with various BMIs.

The Bland–Altman plot is one of the most suitable statistical methods for assessing the agreement between two quantitative measures [46, 50], and many previous studies have applied this method to analyze the agreement between direct and indirect measures (i.e., VO_{2max} prediction models) of VO_{2max} [28, 29, 37, 52], with considerable success. Therefore, in this study, Bland–Altman analysis was used to evaluate and compare the agreement between the methods for predicting VO_{2max} in the NOG, OVG, and OBG with the TOG model and direct measurement of VO_{2max} , as well as the agreement between establishing separate VO_{2max} prediction models (i.e., the NOG, OVG, and OBG models) within BMI stratifications and direct VO_{2max} measurement. The results of this study showed that the 95% LoAs between the VO_{2max} values predicted by the TOG model and the actual VO_{2max} measurements in the NOG, OVG and OBG were larger than those of the VO_{2max} prediction models developed within separate BMI stratifications (i.e., the NOG, OVG, and OBG models) for each BMI subgroup (Figure 8). Moreover, in OBG, the mean difference between the actual measured VO_{2max} values and those predicted by the TOG model was significant ($1.15 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, $p = 0.049$; Figure 8C), while no significant differences were found between the actual measured VO_{2max} values and those predicted by the OBG model (Figure 8F). These results implied higher agreement between the method of predicting VO_{2max} for each BMI subgroup by developing BMI stratified models and the direct VO_{2max} measurement method than that of a model established regardless of adults' BMIs. Therefore, to improve the accuracy of VO_{2max} prediction, it is recommended that corresponding prediction models be developed within separate BMI stratifications for predicting VO_{2max} in adults with various BMI levels.

In summary, the BMI stratification approach for VO_{2max} prediction proposed in this study achieved good results, and similar approaches need to be further explored, especially when applied to other demographics, such as older adults and patients. This will help to improve the accuracy of CRF assessment and practical application in fitness/rehabilitation.

Limitations and suggestions

There are certain limitations in this study. First, our subjects are healthy adults aged 20-64 years, so we cannot know the stability of using the model in this study to predict VO_{2max} in children, adolescents, elders, or individuals with diseases. Second, the BMI stratification in this study is carried out according to the BMI classification criteria established by the Taiwan Ministry of Health and Welfare, thus the stratification models may not be suitable for other racial groups. Future research should increase the diversity of samples to verify the applicability of our prediction models to the wider population. Finally, this study is a cross-sectional rather than a longitudinal study, so causal inference cannot be made. Further follow-up studies are needed in the future.

Conclusions

In this study, we have developed relatively accurate prediction models for estimating VO_{2max} in healthy adults with various BMIs, and the general public can use the corresponding VO_{2max} prediction model to assess their CRF levels with reference to their BMI classification subgroup (i.e., NOG, OVG, or OBG), which can provide a basis for the development or adjustment of their exercise training programs. The traditional approach of building a VO_{2max} prediction model regardless of an individual's BMI, i.e., using the same prediction formula for adults with different BMIs, will affect the accuracy of VO_{2max} estimation. Establishing separate VO_{2max} prediction models within BMI stratifications can further reduce the SEE or %SEE values of BMI subgroups, improving both the predictive validity and the reliability, as well as the agreement between the measured and predicted VO_{2max} . These results indicated that BMI can be regarded as a basis for the stratification, and it is recommended to use BMI stratified models for VO_{2max} prediction.

Abbreviations

VO_{2max} : maximal oxygen uptake; BMI: body mass index; TOG: total group; NOG: normal group; OVG: overweight group; OBG: obesity group; SEE: standard error of estimate; CVD: cardiovascular disease; WHO: World Health Organization; CRF: Cardiorespiratory fitness; CPET: cardiopulmonary exercise testing; PBF: percent body fat; HR: heart rate; YMCA: Young Men's Christian Association; 3MISP: 3 min incremental step-in-place; HR0: heart rate at the start of the 3MISP test; HR4: heart rate at first minute after the 3MISP test; $\Delta HR3-HR4$: the difference in heart rate between the third minute into the 3MISP

test and the first minute after the test; ICC: intraclass correlation coefficient; GXT: graded exercise test; RPE: rating of perceived exertion; RER: respiratory exchange ratio; SPM: steps per minute.

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Author Contributions

F.L., C.-S.H., and W.-S.C.C. designed the study. F.L., C.-P.Y., C.-A.H., C.-Y.W., H.-C.Y., and Y.-S.C. carried out the experiments. F.L., C.-S.H., and C.-P.Y. analyzed the data. F.L. and C.-S.H. prepared the figure and tables and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors have declared that no competing interest exists.

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