ORIGINAL ARTICLE

Development of nonexercise prediction models of maximal oxygen uptake in healthy Japanese young men

**Kiyoshi Sanada · Taishi Midorikawa ·
Tomohiro Yasuda · Charles F. Kearns ·
Takashi Abe**

Abstract The present study developed nonexercise models for predicting maximal oxygen uptake ($\dot{V}O_{2max}$) using skeletal muscle (SM) mass and cardiac dimensions and to investigate the validity of these equations in healthy Japanese young men. Sixty healthy Japanese men were randomly separated into two groups: 40 in the development group and 20 in the validation group. $\dot{V}O_{2max}$ during treadmill running was measured using an automated breath-by-breath mass spectrometry system. Left ventricular internal dimensions at end-diastole (LVIDD) and at end-systole (LVIDS) were measured using M-mode ultrasound with a 2.5 MHz transducer. Stroke volume (SV) was calculated based on the Pombo rule. SM mass was predicted by B-mode ultrasound muscle thickness. Correlations were observed between $\dot{V}O_{2max}$ and predicted thigh ($r = 0.74$, $P < 0.001$) and lower leg SM mass ($r = 0.55$, $P < 0.001$). Furthermore, there were correlations between $\dot{V}O_{2max}$ and LVIDD ($r = 0.74$, $P < 0.001$) and SV ($r = 0.72$, $P < 0.001$). Stepwise regression analysis was applied to thigh SM mass and SV for prediction of $\dot{V}O_{2max}$ in the development group, and these parameters were closely correlated with absolute measured $\dot{V}O_{2max}$ ($R^2 = 0.72$, $P < 0.001$) by multiple regression analysis. When the $\dot{V}O_{2max}$ prediction equations were applied to the validation group, significant correlations were also observed between the measured and predicted $\dot{V}O_{2max}$ ($R^2 = 0.83$, $P < 0.001$). These results suggested that nonexercise prediction of $\dot{V}O_{2max}$ using thigh SM mass and cardiac dimension is a valid method to predict $\dot{V}O_{2max}$ in young Japanese adults.

Keywords Cardiorespiratory fitness · Cardiac dimensions · Skeletal muscle mass · Ultrasound

Introduction

Maximal oxygen uptake ($\dot{V}O_{2max}$) is an important parameter related to cardiorespiratory fitness and quantifying training. $\dot{V}O_{2max}$ is used for quantifying training intensity for aerobic exercise prescription, evaluating the effects of aerobic exercise programs, and classifying individuals for health risks (American College of Sports Medicine 1995). Typically, a maximum graded exercise test performed on a treadmill or cycle ergometer is used to determine $\dot{V}O_{2max}$. However, this measurement method requires an extensive laboratory, specialized technicians, and considerable subject motivation.

A number of submaximal exercise tests have been developed to estimate $\dot{V}O_{2max}$, based on heart rate during submaximal exercise (Astrand and Ryhming 1954; Cooper 1968; Fox 1973; McArdle et al. 1972; Ryhming 1953; Siconolfi et al. 1982). At present, estimation of maximal heart rate (e.g., the 220 minus age) is most commonly used to estimate $\dot{V}O_{2max}$ using the $\dot{V}O_2$–heart rate relationship during submaximal exercise. However, type of exercise, fitness level, gender,

K. Sanada (✉)
Consolidated Research Institute for Advanced
Science and Medical Care, Waseda University,
513 Wasedatsurumaki-cho, Shinjuku-ku,
Tokyo 162-0041, Japan
e-mail: sanada@waseda.jp

K. Sanada · T. Midorikawa · T. Yasuda ·
C. F. Kearns · T. Abe
Tokyo Metropolitan University, 1-1, Minami-Ohsawa,
Hachioji, Tokyo 192-0397, Japan

body composition and age influence maximal heart rate. One standard deviation from the average of the maximal heart rate of the same-age subjects is ±10 beat min^{-1}, and day-to-day heart rate validation averages ±5 beat min^{-1}. This limitation indicates that $\dot{V}O_{2max}$ predicted from maximal/submaximal heart rate falls within 10–20% of the value for a given subject (McArdle 2001). Nonexercise prediction models of $\dot{V}O_{2max}$ use for anthropometry or physical activity (Davis et al. 2002; Fairbarn et al. 1994; Heil et al. 1995; Jackson et al. 1990; Jones et al. 1985; Matthews et al. 1999; Rosen et al. 1998). However, these methods fail to predict $\dot{V}O_{2max}$ in certain subjects (Kolkhorst and Dolgener 1994; Malek et al. 2004; Whaley et al. 1995).

$\dot{V}O_{2max}$ is associated with central and peripheral factors. Central factors include pulmonary diffusing capacity, cardiac output [stroke volume (SV) times heart rate], and oxygen-carrying capacity of the blood (Bassett and Howley 2000), of which SV can be evaluated from cardiac dimensions (Pombo et al. 1971). The relationship between cardiac dimensions using echocardiography and $\dot{V}O_{2max}$ is reported (Osborne et al. 1992; Saito and Matushita 2004; Yamazaki et al. 2000), however, there is no imfomation on the prediction of $\dot{V}O_{2max}$ using both central and peripheral factors. Peripheral factors include skeletal muscle (SM) characteristics, such as SM mass. The absolute quantity of muscle mass activated during exercise is an important factor in achieving a high $\dot{V}O_{2max}$. Ultrasound-derived prediction equations are capable of taking measurements in the field and are valid in predicting total and regional SM mass in both men and women (Sanada et al. 2005). We hypothesized that if central and peripheral factors of SV and SM mass were included in a prediction model of $\dot{V}O_{2max}$, the accuracy may be improved. The purpose of this study was to develop a nonexercise model to predict $\dot{V}O_{2max}$ using cardiac dimensions and SM mass, and to investigate the validity of these equations in Japanese young adults.

Methods

Sixty healthy young Japanese men were separated randomly into two groups: 40 in the development group and 20 in the validation group (Table 1). They participated in college club activities, such as football, swimming, track and field, karate, and engaged in continuous aerobic exercise for at least one session per week for a minimum of 1 h per session. All subjects were physically active but were not specially trained athletes. The purpose, procedures, and risks of the study were explained to each subject prior to inclusion,

Table 1 Physical characteristics of the subjects

Variable	Development[a] (n = 40)	Varidation[a] (n = 20)
Age (years)	21.1 ± 2.3	21.6 ± 3.1
Body mass (kg)	60.9 ± 6.9	62.3 ± 7.3
Body fat (%)	15.1 ± 2.1	14.9 ± 2.5
PA-R	5.8 ± 1.7	5.9 ± 1.6
Physical activity (kJ day^{-1})	1,219 ± 586	1,153 ± 407
Total energy expenditure (kJ day^{-1})	9,099 ± 1,110	8,937 ± 870
Walk steps (steps day^{-1})	9,367 ± 2,945	9,250 ± 3,546
$\dot{V}O_{2max}$, (ml kg^{-1}min^{-1})	58.6 ± 7.3	59.2 ± 7.4

[a] Mean ± standard diviation

and all subjects gave their written informed consent prior to participation in the study. The Tokyo Metropolitan University Departmental Ethical Commission approved this study.

Physical activity

All participants wore a uniaxial accelerometer (Lifecorder; Suzuken, Nagoya, Japan) on the left side of the body for 24 h, except when sleeping and showering. Each subject was tested over 7 days, and the per-day mean number of steps (steps day^{-1}), physical activity (kJ day^{-1}), and physical intensity (kJ steps^{-1} day^{-1}) were recorded. The NASA/JSC physical activity scale (PA-R), a questionnaire, was used to survey the subject's physical activity.

$\dot{V}O_{2max}$

$\dot{V}O_2$ during treadmill running was measured using an automated breath-by-breath mass spectrometry system (Aeromonitor AE-280S, Minato Medical Science, Tokyo, Japan). The subjects warmed up at 180 or 190 m min^{-1} at fixed 0° grade for 5 min. The treadmill speed increased at a rate of 10 m min^{-1} for each successive 1 min of running until fatigue, defined as the speed at which the subject could no longer continue to keep up with the treadmill. $\dot{V}O_2$ and the respiratory gas exchange ratio were measured every 30 s. Heart rate was also measured every 30 s during exercise using a monitor (Vantage XL, Polar Electro, Kempele, Finland). The range of perceived exertion (RPE) was expressed every 1 min. $\dot{V}O_{2max}$ was recorded as the highest value of $\dot{V}O_2$ for 30 s during each exercise test. The following criteria were used to establish that maximum effort had been achieved: $\dot{V}O_{2max}$ appeared as a plateau in $\dot{V}O_2$ despite an increase in treadmill speed (increased $\dot{V}O_2$ within 150 ml min^{-1}), maximum heart rate within ±11 beats min^{-1} of the age-predicted

maximum (220 minus age), and a maximum respiratory exchange ratio above 1.15 (Howley et al. 1995).

Cardiac dimensions

Left ventricular echocardiograms were obtained by an experienced technician, with subjects in the resting state and in the left lateral decubitus position. The left ventricle was observed in the two-dimension long-axis plane with a 2.5 MHz transducer. M-mode recording were derived from a cursor line crossing the left ventricle below the tips of the mitral valve leaflets. Left ventricular internal dimension at end-diastole (LVIDD) and left ventricular internal dimension at end-systole (LVIDS) were mesured, and the SV was calculated according to Pombo et al. (1971); $SV = LVIDD^3 – LVIDS^3$. The inter-observer differences in LVIDD and LVIDS (analysis of five separate M-mode scans in five male subjects) were 2.0 ± 1.4 and $1.9 \pm 1.9\%$, respectively, and the intra-observer differences in LVIDD and LVIDS (comparisons of the same images in five male subjects analyzed by two observers) were 2.4 ± 0.8 and $3.0 \pm 1.4\%$, respectively.

Skeletal muscle mass

Muscle thickness (MTH) determined by B-mode ultrasound was measured at nine sites from the anterior and posterior surfaces of the body (Abe et al. 1994): lateral forearm, anterior and posterior upper arm, abdomen, subscapula, anterior and posterior thigh, and anterior and posterior lower leg. Ultrasonographic evaluation of the MTH was performed using a real-time linear electronic scanner with a 5-MHz scanning head (SSD-500, Aloka, Tokyo, Japan). The scanning head with water-soluble transmission gel provided acoustic contact without depression of the skin surface and placed perpendicular to the tissue interface under the marked sites. The MTHs were measured directly and were determined as the distance from the adipose tissue–muscle interface to the muscle–bone interface. Total and regional SM mass were estimated using the equations of Sanada et al. (2006). The MTHs were converted to mass units in kilograms by ultrasound-derived prediction equations using site-matched MTH × height, which calculated the arm, trunk, thigh, and lower leg SM mass.

Fat free mass

Fat free mass (FFM) was estimated from body density using the subcutaneous fat measurements from B-mode ultrasound (Abe et al. 1994). The body density

estimated by nine sites subcutaneous fat layer (the measurement sites described in Ultrasound MTH and measurements). The SE of the estimate of body density using ultrasound equations is ~0.006 gm l^{-1} (–2.5% body fat) for men and women. Body fat percentage was calculated from the body density using the equation of Brozek et al. (1963). FFM was the difference between body mass and fat mass.

Statistical analysis

Measured and calculated values are expressed as means ± standard deviation (SD). Student's t test was used for comparison of variables between the development and validation groups. Pearson's product correlations were calculated between the prediction variables (anthropometric measurements, physical activity, cardiac dimensions, and total and regional SM mass) and $\dot{V}O_{2max}$. Stepwise multiple regression analyses were performed for these prediction variables and $\dot{V}O_{2max}$. The prediction equations obtained from the model-development group were then validated in the cross-validation group using the Bland and Altman approach (Bland and Altman 1986). The alpha level for testing significance was set at $P < 0.05$. All statistical analyses were completed using Stat View v5.0 for Windows (SYS Institute).

Results

Correlations were observed between $\dot{V}O_{2max}$ and predicted thigh ($r = 0.74$, $P < 0.001$) and lower leg SM mass ($r = 0.55$, $P < 0.001$) in the development group (Table 2). Furthermore, there were correlations between $\dot{V}O_{2max}$ and LVIDD ($r = 0.74$, $P < 0.001$) and SV ($r = 0.72$, $P < 0.001$, Table 3). A correlation was observed between SV and thigh SM mass ($r = 0.50$, $P < 0.01$). There were correlations between $\dot{V}O_{2max}$ and body mass, PA-R, and total energy expenditure

Table 2 Lower body muscle thickness and estimated SM mass, and correlation coefficients between $\dot{V}O_{2max}$ and muscle thickness or SM mass in the development group

Variable	Development[a] (n = 40)	r value	P value
Total SM mass (kg)	23.1 ± 3.4	0.78	< 0.001
Arm SM mass (kg)	2.4 ± 0.7	0.36	< 0.05
Trunk SM mass (kg)	11.4 ± 3.8	0.25	NS
Thigh SM mass (kg)	9.1 ± 1.1	0.74	< 0.001
Lower leg SM mass (kg)	2.4 ± 0.4	0.55	< 0.001

[a] Mean ± standard diviation

SM skeletal muscle

Table 3 Cardiac dimensions using M-mode ultrasound, and correlation coefficients between $\dot{V}O_{2max}$ and cardiac dimensions

Variable	Development[a] $(n = 40)$	r value	P value
LVIDD (mm)	45.9 ± 4.3	0.74	< 0.001
LVIDS (mm)	30.8 ± 4.0	0.62	< 0.001
Stroke volume (ml)	68.5 ± 17.8	0.72	< 0.001

[a] Mean ± standard diviation; *LVIDD* left ventricular internal dimension at end-diastole; *LVIDS* left ventricular internal dimension at end-systole

($P <$ 0.001, Table 4). Moreover, Stepwise regression analysis was applied to the predicted thigh SM mass and SV to predict $\dot{V}O_{2max}$ in the development group, and the values were closely correlated with absolute measured $\dot{V}O_{2max}$ ($n = 40$, $R^2 = 0.72$, $P < 0.001$, SEE = 0.39 l min^{-1}).

When the $\dot{V}O_{2max}$ prediction equations were applied to the validation group, correlations were also observed between the predicted and measured $\dot{V}O_{2max}$ ($n = 20$, $R^2 = 0.83$, $P < 0.001$, Fig. 1a). There was not any bias in prediction of $\dot{V}O_{2max}$ for the validation group (Fig. 1b). The predicted $\dot{V}O_{2max}$ in the validation group was 3.70 ± 0.61 l min^{-1} and was not significantly different from the measured $\dot{V}O_{2max}$ of 3.66 ± 0.55 l min^{-1} (Table 5).

## Discussion

Several indirect methods of estimating $\dot{V}O_{2max}$ based on heart rate responses to submaximal exercise have been developed (Astrand and Ryhming 1954; Cooper

Table 4 Correlation coefficients between $\dot{V}O_{2max}$ and physical characteristics in the development group and non-exercise prediction equations of $\dot{V}O_{2max}$ using stepwise regression analysisin the development group

Variable	r value	P value
Age (years)	–0.04	NS
Body mass (kg)	0.66	< 0.001
Body fat (%)	–0.12	NS
PA-R	0.59	< 0.001
Physical activity (kJday^{-1})	0.19	NS
Total energy expenditure (kJday^{-1})	0.56	< 0.001
Walk steps (steps day^{-1})	0.06	NS
Prediction equatios (l min^{-1})	R^2	SEE (l min^{-1})
One variable	0.55	0.49
$\dot{V}O_{2max} = 0.367 \times$ Thigh SM mass + 0.217		
Two variables	0.72	0.39
$\dot{V}O_{2max} = 0.253 \times$ Thigh SM mass + 0.015 × SV + 0.248		

PA-R physical activity scale; *SEE* standard estimation error; *SV* stroke volume
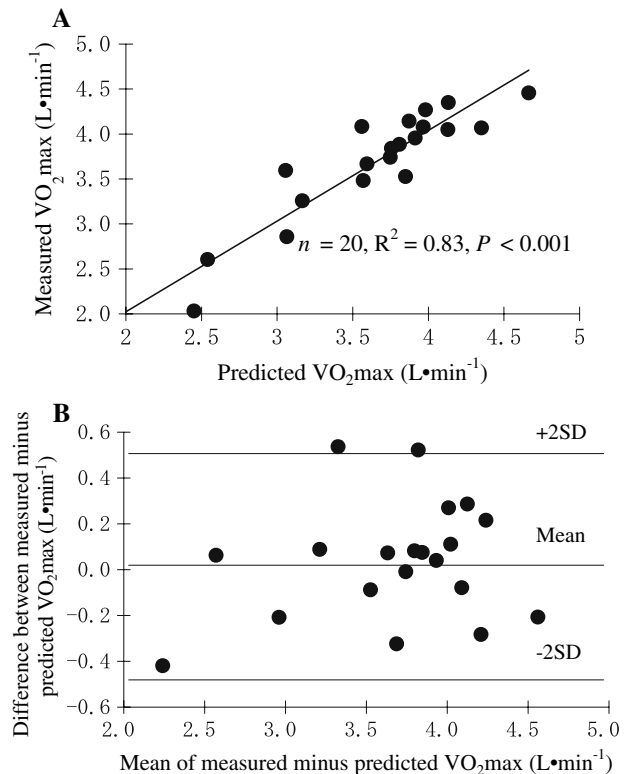
Fig. 1 Relationship between the measured and predicted absolute $\dot{V}O_{2max}$ values in the validation group (**a**), and Bland–Altman analysis of the validation group (**b**). Differences between the measured and predicted $\dot{V}O_{2max}$ values plotted against the measured and predicted $\dot{V}O_{2max}$ values

1968; Fox 1973; McArdle et al. 1972; Ryhming 1953; Siconolfi et al. 1982). These methods show good prediction accuracy, with high R^2 value, low SEE, and SEE% of the measured value. Siconolfi et al. (1982) reported $R^2 = 0.73$, SEE of 0.36 l min^{-1}, and SEE% of 14% using their multiple regression equation during submaximal cycle ergometry exercise; $\dot{V}O_{2max} = 0.348 \dot{V}O_2$ of Astrand–Ryhming test –0.035 × age. Fox et al. (1973) also reported a prediction equation based on linear regression analysis relating $\dot{V}O_{2max}$ to submaximal heart rate during the fifth minute of bicycle exercise at 150 W. Their regression equation, R^2, SEE, and SEE% were: $\dot{V}O_{2max} = 19.26 \times$ submaximal heart rate at 150 W + 6,300; 0.58; 0.246 l min^{-1}; 7.8% of the measured value. In a field study using walk-run performance, SEE% of predicted $\dot{V}O_{2max}$ from submaximal tests averaged about 8–10% of the measured value (McArdle 2001). The SEE and SEE% values of the nonexercise prediction model in the present study (two variables) were 0.39 l min^{-1} and 10.5% of the measured value (Table 4), respectively, and were similar to the SEE and SEE% reported for exercise-based prediction models.

Table 5 Comparison of non-exercise prediction of $\dot{V}O_{2max}$ in the present and previous studies in the validation group

	$\dot{V}O_{2max}$[a] (ml kg^{-1}min^{-1})	Difference from the measured value (P value)	Correlation coefficients between the measured and predicted $\dot{V}O_{2max}$ (R^2 value)	Significance of the correlations (P value)	SEE (ml kg^{-1}min^{-1})
Measured value	3.70 ± 0.61				
Fairbarn et al. (1994)	3.69 ± 0.24	NS	0.12	NS	2.08
Jackson et al. (1990)	3.20 ± 0.40	$P < 0.001$	0.66	$P < 0.001$	0.69
Whaley et al. (1995)	3.34 ± 0.43	$P < 0.001$	0.65	$P < 0.001$	0.67
Heil et al. (1995)	3.23 ± 0.38	$P < 0.001$	0.68	$P < 0.001$	0.70
Matthews et al. (1999)	3.34 ± 0.34	$P < 0.001$	0.61	$P < 0.001$	0.88
Davis et al. (2002)	2.96 ± 0.17	$P < 0.001$	0.37	$P < 0.01$	1.96
Present study (two variables)	3.66 ± 0.55	NS	0.83	$P < 0.001$	0.39

[a] Mean ± standard diviation

Nonexercise tests have been developed based on body composition, including percent of body fat or body mass index, and physical activity determined by a questionnaire method (NASA/JSC physical activity scale; PA-R, Table 5). Excluding the report of Fairbarn et al. (1994), most of the nonexercise prediction models described lower results than the measured $\dot{V}O_{2max}$. Kolkhorst and Dolgener (1994) also reported that the nonexercise prediction model using the equations of Jackson et al. (1990) significantly underestimated aerobic capacity in college students with high $\dot{V}O_{2max}$. Malek et al. (2004) developed a nonexercise model of $\dot{V}O_{2max}$ using exercise duration and intensity based on a self-questionnaire in aerobically trained women. They reported R^2, SEE, and SEE% values of 0.58, 0.26 l min^{-1}, and 10%, respectively. Although they suggested that the prediction equation is a valid method, their study used six predictors and no statistical selection, such as stepwise regression analysis, was performed. In contrast to previous nonexercise prediction models, the predicted $\dot{V}O_{2max}$ (validation group) was not significantly different from the measured $\dot{V}O_{2max}$, and the derivation of the nonexercise prediction models resulted in a validity coefficient of $R^2 = 0.83$ and SEE of 0.39 l min^{-1} (Fig. 1).

It is of interest how the central and peripheral factors contribute to the $\dot{V}O_{2max}$. In the present study, the R^2 value of the estimated SV was similar to the thigh SM mass, with values of 0.52 and 0.55, respectively. The sum of these values was >1.00 because the variables interact with each other ($R^2 = 0.25$, $P < 0.05$). The R^2 value in the development group was 0.72 (Table 4), and the remaining 28% variation may be associated with other peripheral factors (e.g. peripheral diffusion gradients) or pulmonary diffusing capacity (Bassett and Howley 2000). Although $\dot{V}O_{2max}$ is limited by cardiac output, i.e., the oxygen-delivery capacity, the MRI-measured lower body SM mass was correlated with $\dot{V}O_{2max}$ during running ($R^2 = 0.90$),

independent of body or fat-free body mass (Sanada et al. 2005). SM mass is an important determinant of exercise capacity in patients with chronic heart failure (Cicoira et al. 2001; Lang et al. 1997). Lang et al. (1997) reported that there was a significant linear correlation between leg lean mass measured by dual-energy X-ray absorptiometry and $\dot{V}O_{2max}$ ($R^2 = 0.47$, $P < 0.001$) in stable ambulatory patients with heart failure. This R^2 value was similar to that in healthy subjects in the present study. On the other hand, the left ventricular dimension also closely correlated with $\dot{V}O_{2max}$ in a cross-sectional study in 142 men ($R^2 = 0.64$, $P < 0.001$) and in a meta-analysis in 762 men ($R^2 = 0.52$, $P < 0.001$) (Osborne et al. 1992). The R^2 value was similar to the value in the present study. Osborne et al. (1992) noted that the LVIDD was correlated with $\dot{V}O_{2max}$ ($R^2 = 0.71$, $P < 0.001$), but not the LVIDS. The observations of Takahashi et al. (2003) support these results. Osborne et al. (1992) explained these findings by noting that endurance training involves high-intensity exercise bouts in which left ventricular cardiac output and SV are increased for up to several hours per day. These results suggest that the thigh SM mass and cardiac dimensions are important determinants of $\dot{V}O_{2max}$ in healthy young men.

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