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Accurate prediction of $\dot{V}O_{2max}$ in cycle ergometry

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ABSTRACT

STORER, T. W., J. A. DAVIS, and V. J. CAIOZZO. Accurate prediction of $\dot{V}O_{2max}$ in cycle ergometry. *Med. Sci. Sports Exerc.*, Vol. 22, No. 5, pp. 704–712, 1990. Numerous equations exist for predicting $\dot{V}O_{2max}$ from the duration (an analog of maximal work rate, $\dot{W}_{max}$) of a treadmill graded exercise test (GXT). Since a similar equation for cycle ergometry (CE) was not available, we saw the need to develop such an equation, hypothesizing that CE $\dot{V}O_{2max}$ could be accurately predicted due to its more direct relationship with $\dot{W}$. Thus, healthy, sedentary males ($N = 115$) and females ($N = 116$), aged 20–70 yr, were given a 15 $W \cdot min^{-1}$ CE GXT. The following multiple linear regression equations which predict $\dot{V}O_{2max}$ ($ml \cdot min^{-1}$) from the independent variables of $\dot{W}_{max}$ (W), body weight (kg), and age (yr) were derived from our subjects:

Males: $Y = 10.51\,(W) + 6.35\,(kg) - 10.49\,(yr) + 519.3\ ml \cdot min^{-1}$;
$R = 0.939$, $SEE = 212\ ml \cdot min^{-1}$.

Females: $Y = 9.39\,(W) + 7.7\,(kg) - 5.88\,(yr) + 136.7\ ml \cdot min^{-1}$;
$R = 0.932$, $SEE = 147\ ml \cdot min^{-1}$

Using the 95% confidence limits as examples of worst case errors, our equations predict $\dot{V}O_{2max}$ to within 10% of its true value. Internal (double cross-validation) and external cross-validation analyses yielded r values ranging between 0.920 and 0.950 for the male and female regression equations. These results indicate that use of the equations generated in this study for a 15 $W \cdot min^{-1}$ CE GXT provides accurate estimates of $\dot{V}O_{2max}$.

WORK RATE, FUNCTIONAL CAPACITY, PREDICTION EQUATIONS

The evaluation of exercise tolerance is important in assessing cardiopulmonary health status or in identifying the potential for endurance performance. An important index of exercise tolerance is the amount of oxygen that can be taken up by the working muscles during maximal exercise (31). Typically, a graded exercise test (GXT) performed on a treadmill or cycle ergometer is used to determine this important parameter of aerobic function. Ideally, the GXT includes measurements of ventilation and gas exchange so that maximal oxygen uptake ($\dot{V}O_{2max}$) can be determined directly. However, the assessment of $\dot{V}O_{2max}$ during a GXT is technically difficult and time consuming and involves expensive equipment. In 1973, Bruce et al. (8) introduced an equation to predict $\dot{V}O_{2max}$ based on duration of exercise on the Bruce treadmill protocol. The rationale for this approach is that, in normal subjects, $\dot{V}O_2$ is linearly related to work rate and work rate is linearly related to test duration. Hence, $\dot{V}O_2$ is linearly related to test duration. This equation, with its relatively low standard error of estimate, is widely used today. Other investigators (6,15,16,26,27) have also developed equations which predict $\dot{V}O_{2max}$ from treadmill test duration.

From a physiological perspective, it is preferable to predict $\dot{V}O_{2max}$ from a maximal work rate instead of test duration since $\dot{V}O_2$ is directly linked to work rate but is only indirectly linked to test duration through work rate. However, work rates can neither easily nor accurately be determined for treadmill exercise. This may explain the widespread use of test duration instead of maximal work rate to predict $\dot{V}O_{2max}$ from this testing mode. Unlike the treadmill, cycle ergometers provide easily and accurately quantifiable work rates (21,33) and yield $\dot{V}O_2$ values at submaximal work rates that are less variable than those obtained from treadmill exercise (5, p. 338). Both of these factors suggest that

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the estimation of $\dot{V}O_{2max}$ from maximal work rate may be improved for cycle ergometer exercise when compared to treadmill exercise.

At present, estimates of $\dot{V}O_{2max}$ using cycle ergometry are made from submaximal test data which usually employ the linear relationship between a series of submaximal work rates and the corresponding heart rates (4,29). This requires an extrapolation of the heart rate vs work rate regression line to the maximal heart rate (usually age-predicted). This heart rate is then used to predict a maximal work rate. Finally, the *predicted* maximal work rate is used to predict $\dot{V}O_{2max}$. Correction factors, some of which were derived empirically (5, p. 349), may be used to adjust the predicted $\dot{V}O_{2max}$ value for the effects of age, gender, and/or body size (2,4,5). Although these tests may be attractive in terms of their ease of administration and lack of required maximal effort, they have been shown to have relatively poor predictive accuracy (10–27% error) with high standard errors of estimate (10,28).

While there are numerous cycle ergometer GXT protocols in the literature, a frequently used protocol consists of the work rate increasing 15 $W \cdot min^{-1}$ (23, 34). However, an equation for estimating $\dot{V}O_{2max}$ does not exist for this cycle ergometer GXT protocol. Hence, it was the purpose of this study to develop an equation which would predict $\dot{V}O_{2max}$ using the maximal work rate achieved during a standard cycle ergometer graded exercise test as the principal prediction variable. These equations could then be used to assess cardiopulmonary functional capacity when direct measurement of $\dot{V}O_2$ is not feasible and/or to provide normal standards against which a measured $\dot{V}O_{2max}$ could be evaluated.

METHODS

In order to characterize the cardiopulmonary responses to cycle ergometer exercise, 115 males and 116 females, aged 20–70 yr, underwent graded exercise testing. These sedentary, nonsmoking, and apparently healthy subjects were recruited in a manner that resulted in approximately 20 subjects per gender in the following age decades: 20–29, 30–39, 40–49, 50–59, and 60–69 yr. A subject was considered sedentary if he or she did not exercise more than once per week in any activity designed to develop cardiopulmonary fitness (1). To be considered a nonsmoker, subjects must not have smoked for the past 15 yr. Subjects were taking no medications and were free from cardiovascular and/or pulmonary disease at the time of the study. Subject characteristics are displayed in Table 1.

TABLE 1. Subject characteristics and distribution by test site.

	Males				Females			
Test Site	*N*	Age (yr)	Weight (kg)	Height (cm)	*N*	Age (yr)	Weight (kg)	Height (cm)
ECC								
$\bar{X}$	34	42.4	80.4	175.8	54	41.7	64.8	162.1
± SD		16.7	17.0	7.4		15.2	11.3	6.1
Range		20–67	49–132	161–194		20–67	45–101	150–175
UCI								
$\bar{X}$	81	42.5	83.4	179.8	62	46.6	62.7	166.0
± SD		14.8	10.7	7.0		13.2	10.6	6.5
Range		20–69	58–120	163–196		20–70	41–94	144–188
P		>0.05	>0.05	<0.05		>0.05	>0.05	<0.05
Total								
$\bar{X}$	115	42.5	82.5	178.8	116	44.3	63.7	164.4
± SD		14.8	12.9	7.3		14.3	10.9	6.6
Range		20–69	49–132	161–196		20–70	41–101	144–188

ECC = El Camino College; UCI = University of California, Irvine.

All subjects were recruited and tested at two institutions: El Camino College (ECC) in Torrance, CA, and the University of California at Irvine (UCI). A third institution, Harbor-UCLA Medical Center (H-UCLA), served as a reference site in order to ensure that the cardiopulmonary data collected at ECC and UCI were not different. The H-UCLA data collection system has been previously described and validated (7). Prior to the start of the present investigation, 15 subjects (nine from ECC and six from UCI) performed incremental cycle ergometer exercise tests both at their own institution and at the reference laboratory. There was good agreement between values for maximal oxygen uptake ($\dot{V}O_{2max}$) at each test site and the reference site. Paired *t*-tests revealed no significant differences ($P > 0.05$) between mean $\dot{V}O_{2max}$ values obtained at H-UCLA (2.60 $l \cdot min^{-2}$) and at ECC (2.67 $l \cdot min^{-1}$); $t = 2.44$. Similarly, no significant differences were observed between the mean $\dot{V}O_{2max}$ values measured at H-UCLA (2.89 $l \cdot min^{-1}$) and at UCI (2.95 $l \cdot min^{-1}$); $t = 1.93$. The correlation coefficients for $\dot{V}O_{2max}$ between H-UCLA and the two test sites were $r = 0.97$ (ECC) and $r = 0.96$ (UCI).

After giving their informed consent and completing routine screening tests (e.g., resting 12-lead ECG and blood pressure), subjects cycled for 4 min at 0 W. Thereafter, the cycle ergometer work rate increased in 15-$W \cdot min^{-1}$ increments until the subject reached his or her limit of tolerance. The pedal rate was maintained at 60 rpm throughout the test as confirmed by a pedal revolution counter. Subjects were verbally encouraged by test administrators to provide a true maximal effort. A Monark ergometer was used at each test site to provide the work rates. The ergometers were calibrated at 1-wk intervals.

Pulmonary ventilation and gas exchange were measured either breath-by-breath with an on-line data acquisition system (Exertrend, Alpha Technologies, Laguna Hills, CA) or at 30-s intervals using a semi-automated, mixing chamber system (9). The Exertrend system exployed a turbine volume transducer (13) for the measurement of expired minute ventilation ($\dot{V}_E$). A continuous sample of expired gas, drawn from the mouthpiece, was transported via heated sampling lines to electronic gas analyzers for the measurement of oxygen (O_2) and carbon dioxide (CO_2) concentrations (Applied Electrochemistry S3-A, Sunnyvale, CA, and Beckman LB-2, Fullerton, CA, respectively). The computer of this system sampled each breath for its volume and O_2 and CO_2 concentrations at the rate of 50 Hz. After time alignment, the ventilation and gas exchange data were cross-multiplied to yield oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and the respiratory exchange ratio (R). The gas analyzers were calibrated before each test with gases of known concentration. The turbine volume transducer was calibrated each day with a calibration syringe. The breath-by-breath data were averaged and displayed over 30-s intervals to correspond with the data format of the semi-automated system.

With the semi-automated system, inspired minute ventilation ($\dot{V}_I$) was measured with a Parkinson-Cowan dry gas spirometer fitted with an optical encoder. A digital panel meter displayed these ventilation measurements. Expired ventilation was determined from $\dot{V}_I$ using the Haldane transformation (12). The expired air was directed into a 5-l mixing chamber. Samples of this expired air were analyzed for their fractional concentrations of O_2 ($F\bar{E}_{O_2}$) and CO_2 ($F\bar{E}_{CO_2}$). Gas analyzers, identical to those used at ECC, were used for these analyses and were calibrated before each test with gases of known concentrations. Inspired ventilation, $F\bar{E}_{O_2}$, and $F\bar{E}_{CO_2}$ were entered manually every 30 s into a personal computer. Standard equations were used to calculate $\dot{V}O_2$, $\dot{V}CO_2$, and R. In both equipment configurations, $\dot{V}O_{2max}$ and maximal work rate ($\dot{W}_{max}$) were determined for a complete 30-s collection interval at maximal exercise.

Throughout each test, the ECG was monitored continuously by use of the CM5 lead placement. Electrocardiograms were recorded during the last 10 s of each minute. Blood pressures were taken every 3 min throughout the test.

While test duration (an analog of $\dot{W}_{max}$) is known to be well correlated with $\dot{V}O_{2max}$, the age (3), body weight (5, p. 321; 33), and gender (2,3) of subjects are also associated with $\dot{V}O_{2max}$. Hence, multiple linear regression, using $\dot{V}O_{2max}$ ($ml \cdot min^{-1}$) as the dependent variable and $\dot{W}_{max}$ (W), body weight (kg), and age (yr) as independent variables, was used to generate gender-specific equations for prediction of $\dot{V}O_{2max}$. Similarly, a gender-independent equation, utilizing the entire sample of 231 male and female subjects, was developed for the purpose of comparison with other equations in the literature. Each independent variable was tested for its significance as a predictor of the dependent variable (24, pp. 66–72).

The regression equations were validated using both internal and external (independent) cross-validation procedures. The internal cross-validation was performed using the double cross-validation procedure described by Kerlinger and Pedhazur (24, p. 284). Briefly, this method required the original sample to be divided randomly into two groups. e.g., A and B. A prediction equation was then derived from each of the subgroups. Following this, the equation developed from the A subgroup was applied to the B subgroup in order to predict the dependent variable ($\dot{V}O_{2max}$ in this case) for the B subgroup; the predicted value was then compared to the measured value obtained on the B subgroup using simple regression analysis. This procedure was repeated by applying the prediction equation developed from the B subgroup to the A subgroup and once again correlating the predicted value with the measured value. The equations are valid if the two simple correlation coefficients (r) are similar (24, p. 284). A second comparison was made between the multiple correlation coefficients (R) of the two entire samples (males and females) and the R values of their respective subgroups. In this latter analysis, a shrinkage formula was applied to the calculated R in order to correct for sampling bias (30, p. 11). This correction was small (about 0.04 of an R unit) for our data because of our large sample size and the small number of independent variables. Again, if the R values are similar, the equations developed from the entire samples are considered valid (24, p. 284).

The external cross-validation consisted of applying the male and female regression equations found in this study to an independent sample of 36 subjects (26 males, 10 females). The mean ± SD age (yr), weight (kg), $\dot{V}O_{2max}$ ($ml \cdot min^{-1}$), and $\dot{W}_{max}$ (W) for the 26 male subjects were 37.4 ± 9.3 yr, 85.6 ± 17.4 kg, 2762 ± 643 $ml \cdot min^{-1}$, and 200.5 ± 41.9 W, respectively, and were 26.1 ± 10.4 yr, 60.5 ± 9.8 kg, 2153 ± 493 $ml \cdot min^{-1}$, and 169.1 ± 35.5 W, respectively, for the ten female subjects. Fifteen of the cross-validation subjects were studied 2 yr after the main study was completed using a calibrated Monark cycle ergometer (model 868) following the same test protocol and using the Exertrend breath-by-breath system previously described. The remaining 21 subjects had been tested 9 yr earlier, in duplicate, using this same protocol on a Godart electrically braked cycle ergometer. Oxygen uptake, $\dot{V}CO_2$, and R were determined from measurements of minute ventilation and O_2 and CO_2 concentrations in the expired air using a breath-by-breath system previously described (11). Nine of the 21 subjects tested 9 yr earlier were re-evaluated, in duplicate, after 9 wk of endurance training.

As with the subjects of the present study, the cross-validation subjects were sedentary nonsmokers and were apparently healthy. They gave their informed consent and completed the same screening tests.

Stepwise multiple linear regression equations were

TABLE 2. Values at maximal exercise by test site for the males, females, and males plus females.

Test Site		Males $\dot{W}_{max}$ (W)	Males $\dot{V}O_{2max}$ (ml·min^{-1})	Males HR_{max} (bpm)	Males R_{term}		Females $\dot{W}_{max}$ (W)	Females $\dot{V}O_{2max}$ (ml·min^{-1})	Females HR_{max} (bpm)	Females R_{term}
ECC	$\bar{X}$ =	208.0	2780.9	176.9	1.25		139.8	1668.4	176.0	1.28
	SD =	35.9	592.6	14.0	0.09		32.2	397.9	15.6	0.10
N = 34	MIN =	147.0	1694.0	152.0	1.06	N = 54	58.0	772.0	140.0	1.00
	MAX =	279.0	3829.0	202.0	1.38		221.0	2704.0	200.0	1.52
UCI	$\bar{X}$ =	206.8	2770.4	174.0	1.21		126.6	1563.1	168.6	1.26
	SD =	43.5	618.4	19.3	0.07		29.0	386.7	17.4	0.10
N = 81	MIN =	103.0	1411.0	126.0	1.02	N = 62	59.0	818.0	132.0	1.04
	MAX =	294.0	4162.0	210.0	1.49		206.0	2614.0	204.0	1.44
	P =	>0.05	>0.05	>0.05	>0.05		<0.05	>0.05	<0.05	>0.05
Total	$\bar{X}$ =	207.1	2773.5	174.7	1.24		132.7	1612.1	171.7	1.27
	SD =	41.2	608.3	18.0	0.09		31.1	393.8	17.0	0.10
N = 115	MIN =	103.0	1411.0	126.0	1.02	N = 116	58.0	772.0	132.0	1.00
	MAX =	294.0	4162.0	210.0	1.49		221.0	2704.0	204.0	1.52
Total,	$\bar{X}$ =	169.8	2190.3	173.2	1.25					
Males	SD =	52.1	774.4	17.6	0.09					
and	MIN =	58.0	772.0	126.0	1.00					
Females	MAX =	294.0	4162.0	210.0	1.52					
N = 231										

ECC = El Camino College; UCI = University of California, Irvine.

TABLE 3. Equations for prediction of $\dot{V}O_{2max}$ (ml·min^{-1}).

Equation Number	Sample	Independent Variables	Coefficient	Constant	R	SEE (ml·min^{-1})
1	Males	$\dot{W}_{max}$ (W)	10.51	519.3	0.94	212.0
	N = 115	Body weight (kg)	6.35			
		Age (yr)	−10.49			
2	Females	$\dot{W}_{max}$ (W)	9.39	136.0	0.93	145.0
	N = 116	Body weight (kg)	7.71			
		Age (yr)	−5.88			
3	Males and	$\dot{W}_{max}$ (W)	10.22	403.4	0.97	187.0
	females	Body weight (kg)	7.15			
	N = 231	Age (yr)	−7.91			
		Gender*	−252.2			

* Gender coefficient is 0 for males and 1 for females.

generated using the Statistical Programs for the Social Sciences (SPSS-X). The ability of the equations developed from the present study to predict $\dot{V}O_{2max}$ in the cross-validation samples was assessed by Pearson Product-Moment correlation coefficients and by standard errors of estimate (SEE). Possible significant differences between the means of measured vs predicted $\dot{V}O_{2max}$ in the external cross-validation study were examined by a dependent *t*-test. The $P < 0.05$ level was chosen to indicate statistical significance.

RESULTS

Values at maximal exercise for $\dot{W}$ (W), $\dot{V}O_2$ (ml·min^{-1}), HR (bpm), and R_{term} (the respiratory exchange ratio, i.e., $\dot{V}CO_2/\dot{V}O_2$, at termination of exercise) are presented in Table 2. Evidence for the achievement of $\dot{V}O_{2max}$ included a) R_{term} in excess of 1.00 (cf. 25) and b) attainment of age-predicted HR_{max}. None of the 231 subjects had an R_{term} less than 1.00; the mean ± SD value was 1.25 ± 0.09. The mean difference between measured HR_{max} and that predicted as 220 minus age for the 231 subjects was 2.8 bpm. This is well within the ±10 bpm SEE reported for the relationship between maximal heart rate and age (18).

Stepwise multiple linear regression, with $\dot{V}O_{2max}$ (ml·min^{-1}) as the dependent variable vs the independent variables of $\dot{W}_{max}$ (W), body weight (kg), and age (yr), was used to generate equations specific for each gender and one equation independent of gender. These equations, along with their multiple correlation coefficients (R) and SEE, are presented in Table 3. Each independent variable in all three equations was a significant predictor of the dependent variable. The *F*-test for the increment in R^2 resulting from the addition of each independent variable to the equation was significant at $P < 0.05$ (24). Thus, while $\dot{W}_{max}$ was selected as the first predictor variable in these equations (accounting for 84.1%, 81.7%, and 91.6% of the common variance in the male, female, and gender-independent equations, respectively), statistically significant contributions to the prediction of $\dot{V}O_{2max}$ were made with the addition of body weight and age.

The correlation coefficients and the corresponding SEE for the measured vs predicted $\dot{V}O_{2max}$ values were 0.94 and 196 ml·min^{-1} for the males, 0.93 and 134 ml·min^{-1} for the females, and 0.97 and 194 ml·min^{-1} for the gender-independent equations, respectively. Displayed in Figure 1 are the individual data points for predicted $\dot{V}O_{2max}$ from the gender-specific equations (males in Panel a and females in Panel b) and the gender-independent equation (males plus females in Panel c), with the corresponding values for measured $\dot{V}O_{2max}$.

The results of the internal, double cross-validation analysis of the male gender-specific equation yielded r

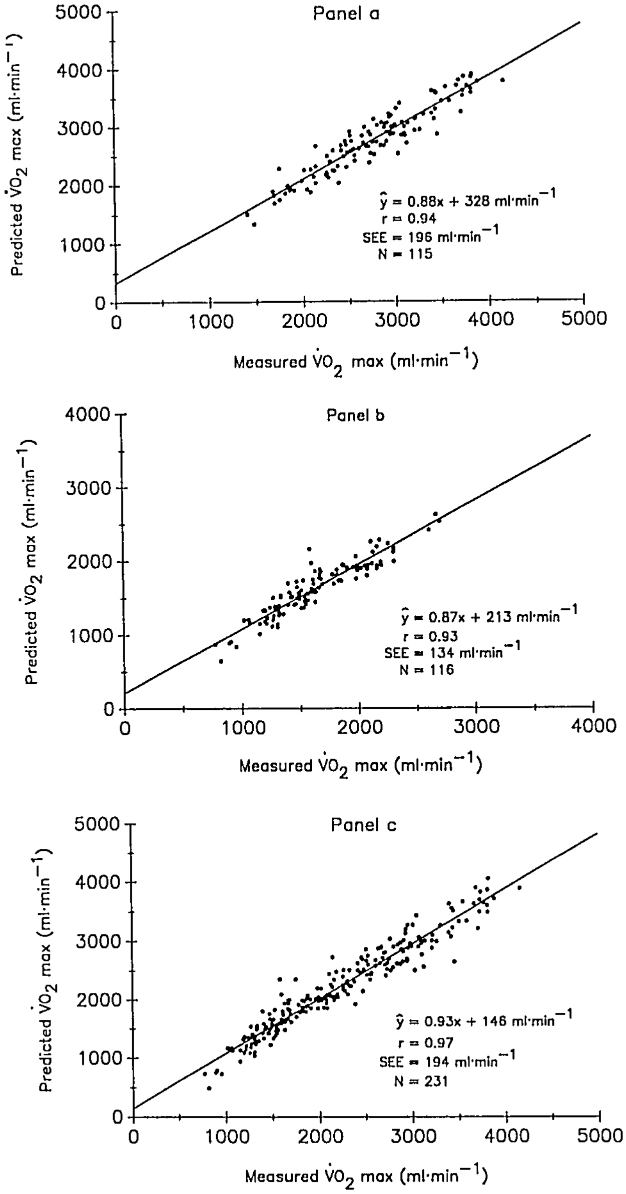

Figure 1—Individual data points for comparison of predicted $\dot{V}O_{2max}$ to measured $\dot{V}O_{2max}$. Panel a: data points for all 115 male subjects. Panel b: data points for all 116 female subjects. Panel c: data points for all 231 male plus female subjects. Equations used to predict $\dot{V}O_{2max}$ in Panels a, b, and c correspond to equations 1, 2, and 3, respectively, as reported in Table 3.

values between 0.937 and 0.942, with SEE between 186 ml·min^{-1} and 209 ml·min^{-1}. The multiple correlation coefficients generated in this analysis were 0.943 and 0.938; after correction for shrinkage (30), they were 0.939 and 0.934. For the female gender-specific equation, the r values were between 0.920 and 0.937, with SEE between 122 ml·min^{-1} and 159 ml·min^{-1}. The multiple correlation coefficients were 0.928 and 0.936; after correction for shrinkage, they were 0.924 and 0.943.

Application of the gender-specific equations developed in this study to the 36 external cross-validation subjects is depicted in Figure 2. The correlation coefficient between the predicted $\dot{V}O_{2max}$ and the measured $\dot{V}O_{2max}$ was 0.95, with a SEE of 176 ml·min^{-1}. The difference between the mean values for the measured $\dot{V}O_{2max}$ and the predicted $\dot{V}O_{2max}$ (20 ml·min^{-1}, −0.8%) was not statistically significant.

To further evaluate the utility of these equations (generated and cross-validated on sedentary subjects), we applied the male gender-specific equation to nine of the male external cross-validation subjects. Although previously sedentary, these nine men had undergone 9 wk of cycle ergometer endurance exercise training, improving $\dot{V}O_{2max}$, on average, by 25% (11). Figure 3 illustrates that these nine subjects remained on essentially the same regression line (similar slopes and y-intercepts) but, predictably, moved further up that same line as a result of their improved functional capacity. Statistical comparison of the two slopes (14) revealed a nonsignificant *t*-ratio of −0.9.

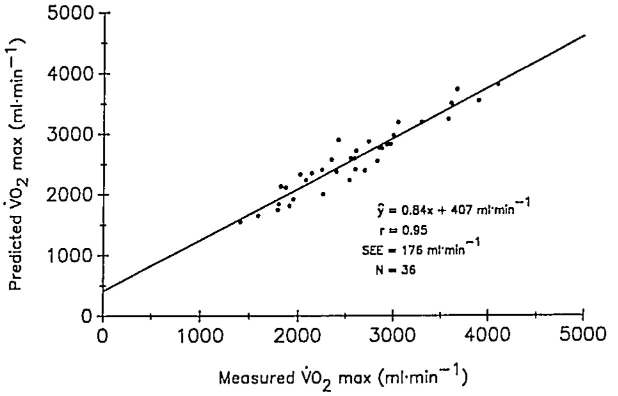

Figure 2—Individual data points for 36 cross-validation subjects (26 males and 10 females) for comparison of predicted $\dot{V}O_{2max}$ to measured $\dot{V}O_{2max}$. The gender-specific equations (equation 1 or 2 in Table 3) were used to estimate $\dot{V}O_{2max}$.

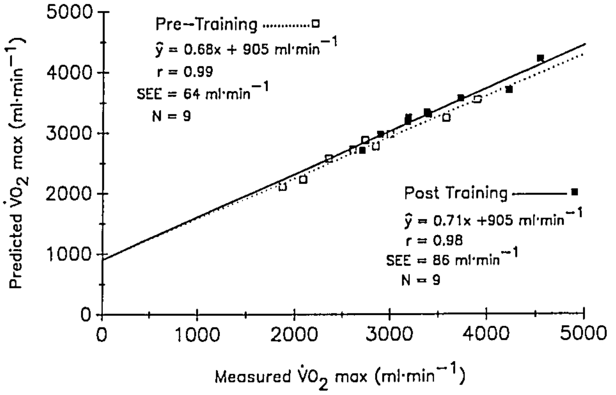

Figure 3—Comparison of predicted vs measured $\dot{V}O_{2max}$ in nine male subjects before and after 9 wk of endurance exercise training. The slopes of the two regression lines were not significantly different, suggesting that the male gender-specific equation is insensitive to improved cardiorespiratory fitness consequent to endurance exercise training.

DISCUSSION

The principal finding of the present study is that $\dot{V}O_{2max}$ can be accurately predicted from a cycle ergometer graded exercise test. This is indicated by the high correlations and low standard errors of estimate of our equations. The accuracy of these equations can be examined by computing the worst-case errors, i.e., the errors that would be obtained if we assumed that the true value was at the lower or upper 95% confidence limit (CL). For example, our male gender-specific equation predicts a $\dot{V}O_{2max}$ of 2774 ml·min^{-1} for our average male subject who had a $\dot{W}_{max}$ of 207.1 W, weighed 82.5 kg, and was 42.5 yr of age. As the SEE for this equation is 212 ml·min^{-1}, the lower and upper 95% confidence limits of predicted $\dot{V}O_{2max}$ for our male subjects are 2354 ml·min^{-1} and 3194 ml·min^{-1}, respectively. The accuracy of this prediction is then defined as

$$\frac{\text{SEE}}{\text{lower 95\% CL value}} \times 100 \text{ and } \frac{\text{SEE}}{\text{upper 95\% CL value}} \times 100.$$

For our sample of male subjects, the accuracy is 9.0% and 6.6% at the lower and upper 95% CL, respectively. For our sample of female subjects, the accuracy is 10.9% and 7.6% at the lower and upper 95% CL, respectively. Our gender-independent equation yields accuracies of prediction at the lower and upper 95% confidence limits of 7.8% and 5.9%, respectively, for the males and 15.1% and 9.4% for the females. Hence, our equations, on average, predict $\dot{V}O_{2max}$ to within 10% of its true value for 95 out of every 100 subjects. As a comparison, we computed the accuracy of the Bruce et al. (8) general equation using this technique and obtained values of 10.4% and 7.3% for the males and 14.7% and 9.3% for the females at the lower and upper 95% CL, respectively. Hence, our gender-specific equations and the gender-independent equation of Bruce et al. (8) yield similar results.

The demonstrated accuracy of our equations is due primarily to the high correlation between $\dot{V}O_{2max}$ and $\dot{W}_{max}$. Bruce et al. (8) demonstrated that maximal time on the treadmill (analogous to $\dot{W}_{max}$) was the first variable selected in their stepwise multiple regression analysis for prediction of $\dot{V}O_{2max}$ (in units of ml·kg^{-1}·min^{-1}). Time on the treadmill accounted for 82% of the common variance in their study. Similarly, $\dot{W}_{max}$ (W) was the first variable chosen to predict $\dot{V}O_{2max}$ for both the males and the females of the present study (Table 4). To facilitate a more direct comparison of our data to that of Bruce et al. (8), we pooled our male and female subjects to generate a gender-independent equation. Once again, $\dot{W}_{max}$ was the first variable chosen in the stepwise multiple regression procedure, accounting for 92% of the common variance (Table 4). The larger coefficient of determination (R^2) demonstrated in the present study suggests that $\dot{V}O_{2max}$ is more closely related to $\dot{W}_{max}$ in cycle ergometry than in treadmill test duration, which itself is highly correlated to treadmill work rate. The problem with treadmill test duration is that two people can accomplish the same maximal time on the treadmill, but one may have a higher measured $\dot{V}O_{2max}$ than the other because the former is less efficient in performing maximal treadmill exercise (19). Because the efficiency of cycle ergometry is virtually the same for everyone, two people that reach the same $\dot{W}_{max}$ should have the same $\dot{V}O_{2max}$, assuming that their capacity to perform anaerobic work during maximal graded exercise testing is similar.

TABLE 4. Comparison of multiple regression statistics for equations generated in the present study and for the Bruce et al. (8) gender-independent equation.

Equation Number and Sample	Variable	Step Entered	R	R^2	Increment in R^2
1 Males, present study	$\dot{W}_{max}$ (W)	1	0.917	0.841	
	Age (yr)	2	0.931	0.866	0.025
	Weight (kg)	3	0.939	0.882	0.016
2 Females, present study	$\dot{W}_{max}$ (W)	1	0.904	0.817	
	Age (yr)	2	0.919	0.845	0.028
	Weight (kg)	3	0.932	0.868	0.023
3 Males and females, present study	$\dot{W}_{max}$ (W)	1	0.957	0.916	
	Age (yr)	2	0.963	0.927	0.011
	Weight (kg)	3	0.966	0.933	0.006
	Gender	4	0.971	0.943	0.015
Bruce et al., males and females	Duration (min)	1	0.907	0.822	
	Gender	2	0.920	0.846	0.023
	Age (yr)	3	0.923	0.852	0.006
	Weight (kg)	4	0.925	0.855	0.003

We chose to develop separate equations for males and females rather than pool their data and thus obtain a gender-independent multiple regression equation with a coefficient for gender. It has been well established that $\dot{V}O_{2max}$ is lower in females if expressed in absolute terms (ml·min^{-1}). While Bruce et al. (8) reported gender as the second variable selected for inclusion in their prediction of $\dot{V}O_{2max}$, analysis of our pooled data for men and women (Table 4) revealed that gender was the last variable added to the equation, entering after both weight and age. Gender did, however, significantly increase the magnitude of R^2 as displayed in Table 4.

While the absolute $\dot{V}O_2$ (l·min^{-1}) for treadmill exercise at a given work rate is substantially affected by body weight, such is not the case in cycle ergometer exercise since the body weight is supported by the seat. However, Wasserman and Whipp (33) have reported that $\dot{V}O_2$ is influenced by the subject's body weight even in this weight-supported exercise due to the differences in the O_2 cost of moving the legs; for any given work rate, they found that the $\dot{V}O_2$ was 5.8 ml·min^{-1} higher for each additional kilogram of body weight. In our male and female subjects, body weight was a significant predictor of $\dot{V}O_{2max}$, entering the regression equation at step 2 for the females and at step 3 for the males. When the male and female data were pooled, body weight was the second independent variable which entered the equation, significantly increasing R^2.

The maximal $\dot{V}O_2$ declines with age due to a number of potential factors including decreases in lean body mass and reductions in maximal exercise values for cardiac output, pulmonary ventilation, and pulmonary diffusing capacity (5, pp. 385–386). While these changes should have been accounted for by decreases in maximal work rate, age remained a significant predictor of $\dot{V}O_{2max}$ in our equations, entering the equation at the third (last) step for the women and at the second step for men. Age entered the Bruce et al. equation at the third step and was categorized with weight as an insignificant predictor of $\dot{V}O_{2max}$ (8). The small increment in R^2 resulting from the addition of age to our gender-independent equation was, however, statistically significant.

Table 5 contains a comparison of predictor variables, correlation coefficients, and SEE between the present study and other investigations using maximal treadmill or cycle ergometer protocols. When several equations were presented by other studies, the equation which yielded the highest R and the lowest SEE was selected for comparison. It is apparent from Table 5 that the equations of the present study yield high multiple correlation coefficients and low SEE.

The double cross-validation procedure is the most rigorous method for validating regression equations (24, p. 284). Validity is established when this procedure yields high simple correlation coefficients between the true value and the predicted value for the dependent variable in subgroups of the original sample and when these high correlations are similar. The correlation coefficients (r) obtained from this procedure were 0.937 and 0.942 for the males and 0.920 and 0.937 for the females, thus verifying that the original regression equations derived from the entire male and the entire female samples are valid. Furthermore, the R values generated in the double cross-validation procedure were also high and quite similar to the R values obtained from the regression analyses using all the male and all the female subjects. Thus, our gender-specific equations are generalizable and should provide valid estimates of $\dot{V}O_{2max}$ in other subject samples which have characteristics similar to our sample of subjects.

Application of the gender-specific equations developed in this study to the 26 male and ten female independent (i.e., external) cross-validation subjects produced a validity coefficient of $r = 0.95$, with a SEE of 176 $ml \cdot min^{-1}$. Figure 2 illustrates this relationship. An added feature of the present validation sample is that 21 of the male subjects were tested 9 yr earlier, in duplicate, using an entirely different equipment configuration but with the same cycle ergometer protocol. It would seem apparent, therefore, that experimenter or equipment specificity has little impact on the utility of these equations.

Nine of the 21 sedentary male subjects tested 9 yr earlier underwent 9 wk of endurance exercise training, which improved their $\dot{V}O_{2max}$, on average, by 25%. As revealed in Figure 3, the accuracy of prediction was not affected by improved cardiorespiratory fitness; the slopes, y-intercepts, and SEE are nearly identical. The mean difference between the actual and predicted $\dot{V}O_{2max}$ before training was −0.5% (−43 $ml \cdot min^{-1}$). After training, the mean difference was −2.4% (−110 $ml \cdot min^{-1}$). Neither difference was statistically significant, although there was a trend toward underprediction. These results suggest that the equations generated in this study may also be used to estimate $\dot{V}O_{2max}$ in a more active population. This observation was also made by Bruce et al. (8) and Froelicher et al. (20). Both groups of investigators were unable to demonstrate significant differences in predicting $\dot{V}O_{2max}$ from treadmill duration as a function of habitual level of activity.

While there are many positive aspects in utilizing the prediction equations generated in this study, this indirect approach does result in the loss of diagnostic data that would have been available had ventilation and gas exchange been measured. Failure to make these measurements throughout an exercise test reduces the possibility of detecting other important parameters of aerobic function, e.g., the anaerobic threshold (34). Additionally, Hansen et al. (22) have recently demonstrated that patients with cardiovascular disease have a $\dot{V}O_2$ vs work rate slope during incremental exercise which is significantly lower than predicted. Thus, use of prediction equations which include maximal work rate as a

TABLE 5. Comparison of prediction variables, correlation coefficients (R or r), and SEE between regression equations found in the literature and those found in the present study for the prediction of $\dot{V}O_{2max}$.

Study	*N*	Work Device	Variables*	R or r	SEE ($ml \cdot min^{-1}$)	SEE ($ml \cdot kg^{-1} \cdot min^{-1}$)
Present study, 1989	M = 115	CE	$\dot{W}$, WT, Age	0.939	212	2.57
	F = 116				145	2.28
Bruce et al., 1973 (8)	M = 138	TM	D, G, Age, HT, Activity	0.926	245	3.12
	F = 157					
Jones et al., 1985 (23)	M = 50	CE	G, Age, WT, HT	0.881	441	5.63
	F = 50					
Town and Golding, 1977 (32)	M = 20	TM	Age, HR, WT, %Grade	0.838	330	4.08
Froelicher et al., 1975 (20)	M = 77	TM	D	0.870	368	4.71
Fox, 1973 (17)	M = 87	CE	HR at 150 W	0.760	246	3.39

* $\dot{W}$ = work rate; WT = body weight; G = gender; D = Duration of test; Activity = habitual level of physical activity; HT = height; %Grade = treadmill percent grade.

predictor variable would overestimate the true $\dot{V}O_{2max}$ of these patients. It is apparent, therefore, that one must consider the relative advantages and disadvantages in using indirect vs direct methods for the assessment of $\dot{V}O_{2max}$. When the constraints of equipment, time, expense, and technical assistance prohibit the direct measurement of $\dot{V}O_2$, use of accurate prediction equations such as the ones generated in the present study provides an attractive alternative. However, caution is advised if these equations are used in subjects with known or suspected cardiovascular disease.

CONCLUSIONS

We have generated equations to predict $\dot{V}O_{2max}$ that have high correlation coefficients, low standard errors of estimate, and levels of accuracy which allow prediction of $\dot{V}O_{2max}$ to within 10% of its true value in 95 out of every 100 subjects. These equations have been validated with rigorous internal and external validation procedures, including an independent sample of subjects, some of whom were tested 9 yr earlier with an equipment configuration different from that used to test the study sample. Results of the internal cross-validation study suggest that our equations are generalizable. Further proof of the generalizability of our equations was demonstrated in our external cross-validation study. Additionally, our male gender-specific equation appears to be insensitive to the effects of endurance exercise training. For those practitioners who prefer cycle ergometry as the exercise test mode, use of the equations generated in this study provides accurate estimates of $\dot{V}O_{2max}$ for the assessment of cardiopulmonary functional capacity and/or normal standards against which a measured $\dot{V}O_{2max}$ may be evaluated. Our equations may be specific, however, to the GXT protocol we used, i.e., a 15 $W \cdot min^{-1}$ increase in work rate. For practitioners who test young and fit subjects, the 15 $W \cdot min^{-1}$ GXT protocol results in lengthy test durations. These subjects should be evaluated using protocols employing larger work rate increments, e.g., 30 $W \cdot min^{-1}$. It will then be necessary to validate the present equations for these different protocols.

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