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Can VO_{2max} be accurately estimated using exercise-duration based prediction equations and a nomogram?

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Abstract

Study aim: The purpose of this study was to examine a large cohort of young Canadian adults to determine if exercise time from a maximal Bruce Treadmill Protocol could accurately predict measured VO_{2max} values by inputting the total exercise time into prediction equations and a nomogram.
Materials and methods: 550 kinesiology undergraduate student (280 male and 270 female) participants, with a mean body mass (BM) of 72.08 ± 15.05 kg, mean age of 21.16 ± 1.26 years old and mean height of 171.95 ± 10.25 cm completed a maximal graded exercise test to obtain their VO_{2max} (measured). Predicted VO_{2max} was calculated with various equations using the variable of total exercise test time. Linear regression models were created to determine how well the predicted VO_{2max} values compared to the measured values.
Results: Across all VO_{2max} calculation methods, males obtained higher VO_{2max} values on both the measured (49.89 ± 9.21 mL/kg/min) and predicted values (46.04–55.40 mL/kg/min) and exercised for a longer duration of time (14.33 minutes) compared to females (40.89 ± 7.50 mL/kg/min, 38.87–48.36 mL/kg/min, 11.92 minutes). Classifications and percentile rankings were created using each measured and predicted method.
Conclusions: The Healthy Persons Equation [6], Healthy Men and Women Equation [2], Active and Sedentary Women/Men Equations [10, 22] and nomogram [13] cannot accurately predict VO_{2max} in healthy young adults, with R^2 values between 0.38–0.50. The Healthy Persons Equation [6] was found to very closely mimic the seven-category classifications determined from the measured CPET VO_{2max} values.

Keywords: Aerobic capacity – Normative-reference values – Estimated VO_{2max} – Classifications – Maximal oxygen uptake

Introduction

VO_{2max} provides an indication of aerobic power and cardiorespiratory fitness, and is a strong predictor of health and disease [5, 15, 20]. Specifically, cardiorespiratory fitness has been shown to be a more powerful predictor of cardiovascular disease risk than other traditional risk factors (such as smoking, hypertension, high cholesterol and type two diabetes) [18, 23]. Low VO_{2max} values are often associated with the development of cardiovascular disease risk factors and all-cause mortality [5, 14, 15]. By definition, VO_{2max} is the product of maximal cardiac output and the arterial-venous difference [17], the greatest rate that the body can use oxygen, and the point where an increase in workload does not increase oxygen uptake [4]. Accurate and reliable measurement of VO_{2max} provides a key method in determining health status [15, 20].

Using computerized instrumentation on a metabolic cart is known to be the best indicator for determining aerobic power and assessing cardiorespiratory fitness, requiring a maximal exercise test collecting expired O_2 and CO_2 in a breath by breath analysis [7, 11, 15]. The Bruce Treadmill Protocol is one of the most commonly used maximal exercise test protocols, consisting of seven, three-minute stages which increase in both speed and grade [22, 25]. The main disadvantage of assessing cardiorespiratory fitness with computerized systems is the cost of equipment, time needed to properly sanitize equipment, and the need for a competent investigator throughout the test [20]. Submaximal exercise tests attempt to combat the limitations of maximal tests by having participants exercise at a lower workload and/or duration without the involvement

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of a metabolic cart. However, the sources of variability in operating at a lower capacity may lead to error with submaximal prediction. This includes the variability in submaximal heart rate (HR) at the same work rate on different days, the variability in age-predicted HR_{max}, and the break in linearity of HR and O_2 as maximum is approached, as some individuals may have larger VO_2 increases than HR increases as they approach their maximum [3].

A lower-cost technique to evaluate VO_{2max} uses prediction equations, still allowing the individual to exercise to maximal capacity, but not requiring indirect calorimetry with O_2 and CO_2 analysis [2, 10, 22]. There are various equations used to predict cardiorespiratory fitness which use variables from the test (treadmill speed, treadmill grade, duration of test, workload) and/or individual characteristics (age, sex, body mass, height, physical activity level) [11, 16]. Several equations using a combination of both total exercise test time and individual characteristics for predicting VO_{2max} from treadmill performance have been created [2, 6, 10, 22]. The present study assessed the Healthy Persons [6], Healthy Men and Women (at the higher, lower and average range) [2], Active and Sedentary Women (for females only) [22], and Active and Sedentary Men (for males only) [10] equations to estimate VO_{2max} values based on total test time. These equations stem from the idea that VO_{2max} is highly correlated with duration of exercise in maximal multistage incremental protocols, in addition to modifying equations based on sex, physical activity levels, health status, and age (all factors which impact VO_{2max}) [6]. Total exercise time has also been used on a nomogram in order to predict VO_{2max} [13]. The main limitation with this nomogram is the upper-limit for exercise time of 16 minutes. Participants who exercise beyond 16 minutes can only be estimated to have a VO_{2max} of greater than 55mL/kg/min or 51mL/kg/min for males and females, respectively [13]. As the cost of a metabolic cart is high and testing requires a skilled investigator, these aforementioned equations and nomograms have attempted to predict maximal aerobic power and cardiorespiratory fitness using only the total exercise time from the Bruce Treadmill Protocol.

Without the use of a metabolic cart and the associated equipment, an individual would be able to perform a Bruce protocol on a treadmill simply by manually adjusting the speed and grade on the treadmill, exercising to maximal capacity, and using the total exercise time in a prediction equation. To the authors knowledge, investigators have not used time-based equations and nomograms to predict VO_{2max} and compare these values to those obtained with computerized instrumentation on a metabolic cart on a large cohort of young Canadian adults. Therefore, the purpose of this study was to use a large sample of young Canadian adults to determine if the exercise time from a maximal Bruce Treadmill Protocol could accurately predict the measured VO_{2max} value garnered from computerized instrumentation on a metabolic cart, by inputting the total exercise time into prediction equations and a nomogram.

Material and methods

Participants

A total of 605 volunteers completed a maximal graded exercise test with a metabolic cart using the Bruce treadmill protocol. Data collection occurred across ten semesters, over a twelve-year period (from Fall 2011 to Fall 2022). All participants were enrolled in an exercise physiology laboratory course at a Canadian University. Participants had varying levels of athletic ability and fitness status (ranging from sedentary to recreationally active to varsity athletes) gleaned from the completion of the Get Active Questionnaire [1] or Physical Activity Readiness Questionnaire [24]. All subjects signed institutionally cleared Research Ethics Board consent forms. Following exclusions (described below in Statistical Analyses), data from 550 participants [280 male (50.09%) and 270 female (49.91%)], with a mean body mass (BM) of 72.08 ± 15.05 kg (80.90 ± 13.65 kg males, 62.94 ± 10.20 kg females), mean age of 21.16 ± 1.26 years old (21.31 ± 1.29 years males, 20.00 ± 1.21 years females) and mean height of 171.95 ± 10.25 cm (178.97 ± 7.82 cm males, 164.67 ± 6.83 cm females) were analyzed.

Protocol

VO_{2max} measurements were collected using computerized instrumentation with metabolic and respiratory equipment (COSMED Quark Cardio Pulmonary Exercise Testing [CPET] with associated Software). Exercise testing was completed on a Trackmaster Treadmill using the Bruce Maximal Treadmill Protocol, which consisted of seven stages, each with a duration of three minutes. Speed and grade increased from stages one through seven (1.7mph/10%, 2.5mph/12%, 3.4mph/14%, 4.2mph/16%, 5.0mph/18%, 5.5mph/20%, 6.0mph/22%). Prior to testing, participant weight (in kg) and height (in cm) were obtained using a digital scale and stadiometer (Model 130500KL). Participant name, sex, height, weight, and date of birth were inputted into the CPET system. The participant was fitted with the HR monitoring device, mask and headpiece compatible with the system, and an overhead harness for safety. A warm-up consisted of 3 minutes of walking at 1.7 mph and 0% grade; after which, the participant was instructed not to hold onto the treadmill bars at any point during the test and were verbally encouraged to continue exercising as the workload increased. The test was terminated when the participant could no longer continue or if several of the subjective (i.e., rating of perceived exertion between 17–20, appearance of exhaustion) and objective (i.e., respiratory exchange ratio of ≥1.1–1.15, achievement of age-predicted heart rate HR_{max} or within 10 beats per minute of HR_{max}, a plateau in HR despite an increase in workload and a plateau in VO_2 despite an increase in workload) indicators were met [13]. Following the termination of the test, subjects walked for a minimum of five minutes at a grade of 0% and self-selected speed to cool down. Test times were inputted into the Healthy Persons [6], Healthy Men and Women (at the higher, lower and average range) [2], Active and Sedentary Women (for females only) [22], and Active and Sedentary Men (for males only) [10] equations to estimate VO_{2max} values based on total test time. The equation used for each method are displayed in Table 1. Nomogram values were determined using test time in minutes [13], after all test times were rounded to the nearest 30 second increment, in order to predict VO_{2max} on the male or female nomograms (as seen in Appendix A).

Statistical analyses

Before proceeding with data analysis, data were removed for reasons including those who withdrew consent from sharing their test scores (36 participants), erroneous data (17 participants), and age (2 participants [aged 39 and 52]). These participants were not representative of the studied population. Outliers identified in the raw data set were included in the statistical analyses, as long as they were not considered to be erroneous due to data entry error.

Statistical analyses were completed using the IBM Statistical Package for the Social Sciences (SPSS) software (version 29). Shapiro-Wilk tests for normality were performed and showed that the distributions departed significantly from normality. Therefore, non-parametric tests were used. Descriptive statistics and an independent samples Mann-Whitney U t-test were conducted to compare the means and determine statistical significance (p <0.05) between the sexes for each of the dependent variables. Nonparametric Wilcoxon paired samples t-tests were performed on males and females separately to compare the CPET software to each of the predicted methods. Multiple linear regressions were used to generate a VO_{2max} regression model using each of the time-based equations and the nomogram as predictor variables independently. The relative accuracy of the VO_{2max} model was evaluated based on the computed Coefficient of Determination (R^2).

Percentile rankings and a seven-category classification system were established for calculated CPET software VO_{2max} (mL/kg/min), total exercise time (minutes), each individual prediction equation VO_{2max} (mL/kg/min), and the nomogram VO_{2max} (mL/kg/min) for both males and females independently. To create performance classifications, the range in the raw data scores and their associated Z-scores were calculated using Microsoft Excel. The process used a modification of the methods used by Zupan et al. [26], similar to that used by Duquette & Adam [8] and Duquette et al. [9]. The range was divided by seven to generate seven classifications: elite, excellent, above average, average, below average, fair and poor. Each classification was separated by equal raw data scores and Z-score increments. For example, the Z-score range for female total exercise time was 6.37 (–2.72 to 3.65), so each of the seven performance classifications were separated by 0.91 SDs. This value corresponded to equal raw data score categories of 1.80 minutes (range of 12.60 minutes was divided by 7). For example, 1.80 minutes was subtracted from the highest VO_{2max} score recorded (19.15 minutes – 1.80 minutes) to create an 'elite' classification of >17.35 minutes. Likewise, 1.80 minutes was subtracted from 17.35 minutes to yield an 'excellent' classification of 15.55 minutes – 17.35 minutes. The same process was utilized for the remainder of the classifications. In comparison, male total exercise time values had a Z-score range of 5.72 (–2.85–2.87) and each classification was separated by 0.82 SDs, corresponding to raw data score categories of 1.96 minutes (since the range of 13.75 minutes was divided by 7). For example, 1.96 minutes was subtracted from the highest total exercise time (21.23 minutes – 1.96 minutes) to create an 'elite' classification of >19.27 minutes. Similarly, 1.96 minutes was subtracted from 19.27 minutes to create an 'excellent' classification of 17.31 minutes

Table 1. Equations used to predict VO_{2max} from total CPET time

Equation	VO_{2max} (mL/kg/min) =
Healthy Persons [6]	6.7–2.82 (male = 1, female = 2) + 0.056 (time in seconds)
Healthy Men and Women [2]	3.814 (time in minutes) – 3.938 ± 4.68
Active and Sedentary Women [22]	(4.38 x time in minutes) – 3.9
Active and Sedentary Men [10]	14.76 – (1.379 × time in minutes) + (0.451 × time in $minutes^2$) – (0.012 x time in $minutes^3$)

CPET= cardiopulmonary exercise test.

– 19.27 minutes. The same process was used to yield all seven categories. The same procedure was utilized to create performance classifications for the measured CPET, predicted equations and nomogram VO_{2max}.

Results

The independent samples Mann-Whitney U t-test revealed statistically significant differences between the sexes for measured and predicted VO_{2max} values ($p < 0.001$). Measured and predicted VO_{2max} means, standard deviations, maximum and minimum values are presented in Table 2. Across all VO_{2max} methods, males obtained higher VO_{2max} values across both the measured (49.89 ± 9.21 mL/kg/min) and predicted (46.04–55.40 mL/kg/min) methods and exercised for a longer duration of time (14.33 ± 2.40 minutes) compared to females (40.89 ± 7.50 mL/kg/min, 38.87–48.36 mL/kg/min, 11.92 ± 1.97 minutes), respectively. Percentile rankings, ranging from the 5th to 95th percentiles for female and male VO_{2max} data, are presented in Tables 3 and 4, respectively. Female and male performance classifications with seven categories ranging from poor to elite were constructed, and may be found in Table 5. Linear regression equations were created comparing the CPET VO_{2max} values to the total exercise test time, predicted equations VO_{2max} values and nomogram VO_{2max} values independently (shown in Figure 1 and 2 for females and males, respectively). When comparing measured values to prediction equations and a nomogram, the R^2 values

Table 2. Maximal oxygen uptake in Healthy Young Canadian Adults VO_{2max} based on different assessment methods

VO_{2max} Method of assessment	Sex	N	Mean ± SD	Minimum	Maximum
CPET Software (mL/kg/min)	Males	280	49.89 ± 9.20	22.22	82.58
	Females	270	40.90 ± 7.50	22.91	66.41
	Total	550	45.48 ± 9.53	22.22	82.58
Total Exercise Time (mins)	Males	280	14.33 ± 2.40	7.48	21.23
	Females	270	11.92 ± 1.97	6.55	19.15
	Total	550	12.96 ± 2.51	6.55	21.23
Nomogram (mL/kg/min) [13]	Males	280	48.96 ± 5.60	30.00	55.00
	Females	270	38.87 ± 5.70	23.00	51.00
	Total	550	44.01 ± 7.57	23.00	55.00
Healthy Persons Equation (mL/kg/min) [6]	Males	280	52.02 ± 8.04	29.02	75.22
	Females	270	41.16 ± 6.61	23.07	65.40
	Total	550	46.70 ± 9.16	23.07	75.22
Healthy Men and Women Equation: (–) Lower Range (mL/kg/min) [2]	Males	280	46.04 ± 9.15	19.92	72.37
	Females	270	36.89 ± 7.50	16.36	64.42
	Total	550	41.55 ± 9.54	16.36	72.37
Healthy Men and Women Equation: (+) Higher Range (mL/kg/min) [2]	Males	280	55.40 ± 9.15	29.28	81.72
	Females	270	46.25 ± 7.50	25.72	73.78
	Total	550	50.91 ± 9.54	25.72	81.72
Healthy Men and Women Equation: Average (mL/kg/min) [2]	Males	280	50.72 ± 9.15	24.60	77.05
	Females	270	41.57 ± 7.50	21.04	69.10
	Total	550	46.23 ± 9.54	21.04	77.05
Active and Sedentary Women [22] and Men (mL/kg/min) [10]	Males	280	51.89 ± 9.35	24.66	73.93
	Females	270	48.36 ± 8.61	24.78	79.97
	Total	550	51.89 ± 9.35	24.66	79.97

*Note: Calculations were made rounding to the closest two decimal places. CPET= cardiopulmonary exercise test.

Table 3. Percentile rankings for females

Percentiles	CPET software VO_{2max} (mL/kg/min)	Total exercise time (mins)	Nomogram VO_{2max} (mL/kg/min) [13]	Healthy Persons Equation VO_{2max} (mL/kg/min) [6]	Healthy Men and Women Equation Lower Limit VO_{2max} (mL/kg/min) [2]	Healthy Men and Women Equation Upper Limit VO_{2max} (mL/kg/min) [2]	Healthy Men and Women Equation Average VO_{2max} (mL/kg/min) [2]	Active and Sedentary Equation VO_{2max} (mL/kg/min) [22]
5	28.05	9.11	30.55	32.01	26.51	35.87	31.19	36.45
10	31.85	9.80	33.00	33.99	28.76	38.12	33.44	39.02
15	33.26	10.07	33.00	34.91	29.81	39.17	34.49	40.24
20	33.80	10.35	35.00	35.84	30.86	40.22	35.54	41.43
25	35.62	10.56	35.00	36.54	31.66	41.02	36.34	42.36
30	37.33	10.82	36.00	37.45	32.65	42.01	37.33	43.50
35	38.45	11.05	36.00	38.19	33.53	42.89	38.21	44.50
40	39.04	11.17	36.00	38.66	33.99	43.35	38.67	45.03
45	39.77	11.34	38.00	39.30	34.66	44.02	39.34	45.80
50	40.34	11.58	38.00	40.04	35.56	44.92	40.24	46.83
55	41.05	11.97	39.00	41.27	37.02	46.38	41.70	48.51
60	42.34	12.21	39.00	42.2	37.98	47.34	42.66	49.62
65	43.50	12.65	41.00	43.56	39.63	48.99	44.31	51.51
70	44.57	12.83	42.00	44.22	40.33	49.69	45.01	52.31
75	45.54	13.12	42.00	45.21	41.42	50.78	46.10	53.56
80	46.89	13.52	44.00	46.57	42.98	52.34	47.66	55.36
85	48.88	13.96	45.00	48.12	44.65	54.01	49.33	57.27
90	50.70	14.44	47.00	50.01	46.48	55.84	51.16	59.38
95	54.16	15.40	50.00	52.88	50.14	59.50	54.82	63.58

*Note: Percentile rankings were calculated by rounding to the closest two decimal places. CPET= cardiopulmonary exercise test.

Table 4. Percentile rankings for males

Percentiles	CPET Software VO_{2max} (mL/kg/min)	Total exercise time (mins)	Nomogram VO_{2max} (mL/kg/min) [13]	Healthy Persons Equation VO_{2max} (mL/kg/min) [6]	Healthy Men and Women Equation Lower Limit VO_{2max} (mL/kg/min) [2]	Healthy Men and Women Equation Upper Limit VO_{2max} (mL/kg/min) [2]	Healthy Men and Women Equation Average VO_{2max} (mL/kg/min) [2]	Active and Sedentary Equation VO_{2max} (mL/kg/min) [10]
5	34.95	10.55	38.00	39.33	31.62	40.98	36.30	36.32
10	38.61	11.58	42.00	42.80	35.56	44.92	40.24	40.65
15	41.45	12.12	43.00	44.59	37.59	46.95	42.27	42.92
20	43.28	12.48	45.00	45.84	39.01	48.37	43.69	44.50
25	44.71	12.67	45.00	46.44	39.69	49.05	44.37	45.27
30	45.74	12.88	46.00	47.18	40.53	49.89	45.21	46.21
35	46.91	13.27	47.00	48.47	42.00	51.36	46.68	47.84
40	47.72	13.57	47.00	49.48	43.15	52.51	47.83	49.12
45	48.26	13.98	48.00	50.88	44.74	54.10	49.42	50.88
50	49.28	14.41	50.00	52.29	46.33	55.69	51.01	52.62
55	50.10	14.71	50.00	53.33	47.51	56.87	52.19	53.90
60	51.21	15.10	52.00	54.62	48.97	58.33	53.65	55.45
65	52.26	15.24	52.00	55.09	49.52	58.88	54.20	56.03
70	53.47	15.39	54.00	55.60	50.09	59.45	54.77	56.63
75	54.75	15.78	55.00	56.91	51.58	60.94	56.26	58.16
80	56.01	15.98	55.00	57.58	52.34	61.70	57.02	58.94
85	58.09	16.41	55.00	59.02	53.98	63.34	58.66	60.56
90	60.70	17.09	55.00	61.31	56.57	65.93	61.25	63.02
95	66.04	18.97	55.00	67.52	63.77	73.13	68.45	69.01

*Note: Percentile rankings were calculated by rounding to the closest two decimal places. CPET= cardiopulmonary exercise test.

Table 5. VO_{2max} classifications for females and males

Classifications	CPET software VO_{2max} (mL/kg/min)	Total exercise time (mins)	Nomogram VO_{2max} (mL/kg/min) [13]	Healthy Persons Equation VO_{2max} (mL/kg/min) [6]	Healthy Men and Women Equation Lower Limit VO_{2max} (mL/kg/min) [2]	Healthy Men and Women Equation Upper Limit VO_{2max} (mL/kg/min) [2]	Healthy Men and Women Equation Average VO_{2max} (mL/kg/min) [2]	Active and Sedentary Equation VO_{2max} (mL/kg/min) [22] [10]
Females								
Elite	>60.20	>17.35	>46.99	>59.35	>57.55	>66.91	>62.23	>72.10
Excellent	53.99–60.20	15.55–17.35	43.00–46.99	53.30–59.35	50.68–57.55	60.04–66.91	55.36–62.23	64.22–72.10
Above average	47.78–53.98	13.75–15.54	39.00–42.99	47.25–53.29	43.81–50.67	53.17–60.03	48.49–55.35	56.34–64.21
Average	41.57–47.78	11.95–13.74	35.00–38.99	41.2–47.24	36.94–43.80	46.30–53.16	41.62–48.48	48.46–56.33
Below average	35.36–41.56	10.15–11.94	31.00–34.99	35.15–41.19	30.07–36.93	39.43–46.29	34.75–41.61	40.58–48.45
Fair	29.15–35.35	8.35–10.14	27.00–30.99	29.1–35.14	23.2–30.06	32.56–39.42	27.88–34.74	32.70–40.57
Poor	<29.15	<8.35	<27.00	<29.10	<23.2	<32.56	<27.88	<32.70
Males								
Elite	>73.96	>19.27	>51.43	>68.62	>64.88	>74.24	>69.56	>66.90
Excellent	65.34–73.96	17.31–19.27	47.86–51.43	62.02–68.62	57.39–64.88	66.75–74.24	62.07–69.56	59.86–66.90
Above average	56.72–65.33	15.35–17.30	44.29–47.85	55.42–62.01	49.90–57.38	59.26–66.74	54.58–62.06	52.82–59.85
Average	48.1–56.71	13.39–15.34	40.72–44.28	48.82–55.41	42.41–49.89	51.77–59.25	47.09–54.57	45.78–52.81
Below average	39.48–48.09	11.43–13.38	37.15–40.71	42.22–48.81	34.92–42.40	44.28–51.76	39.6–47.08	38.74–45.77
Fair	30.86–39.47	9.47–11.42	33.58–37.14	35.62–42.21	27.43–34.91	36.79–44.27	32.11–39.59	31.70–38.73
Poor	<30.86	<9.47	<33.58	<35.62	<27.43	<36.79	<32.11	<31.70

*Note: Classifications were calculated by rounding to the closest whole number value. CPET= cardiopulmonary exercise test.

Table 6. Coefficient of determination (R^2) between CPET VO_{2max} and predicted methods

VO_{2max} method of assessment	Females	Males
Total exercise time	0.4888	0.4610
Nomogram [13]	0.4773	0.3857
Healthy Persons Equation [6]	0.5033	0.4596
Healthy Men and Women Equation: (–) Lower range [2]	0.5016	0.4610
Healthy Men and Women Equation: (+) Higher range [2]	0.5016	0.4610
Healthy Men and Women Equation: Average [2]	0.5016	0.4610
Active and Sedentary Women [22] and Men [10]	0.5016	0.4536

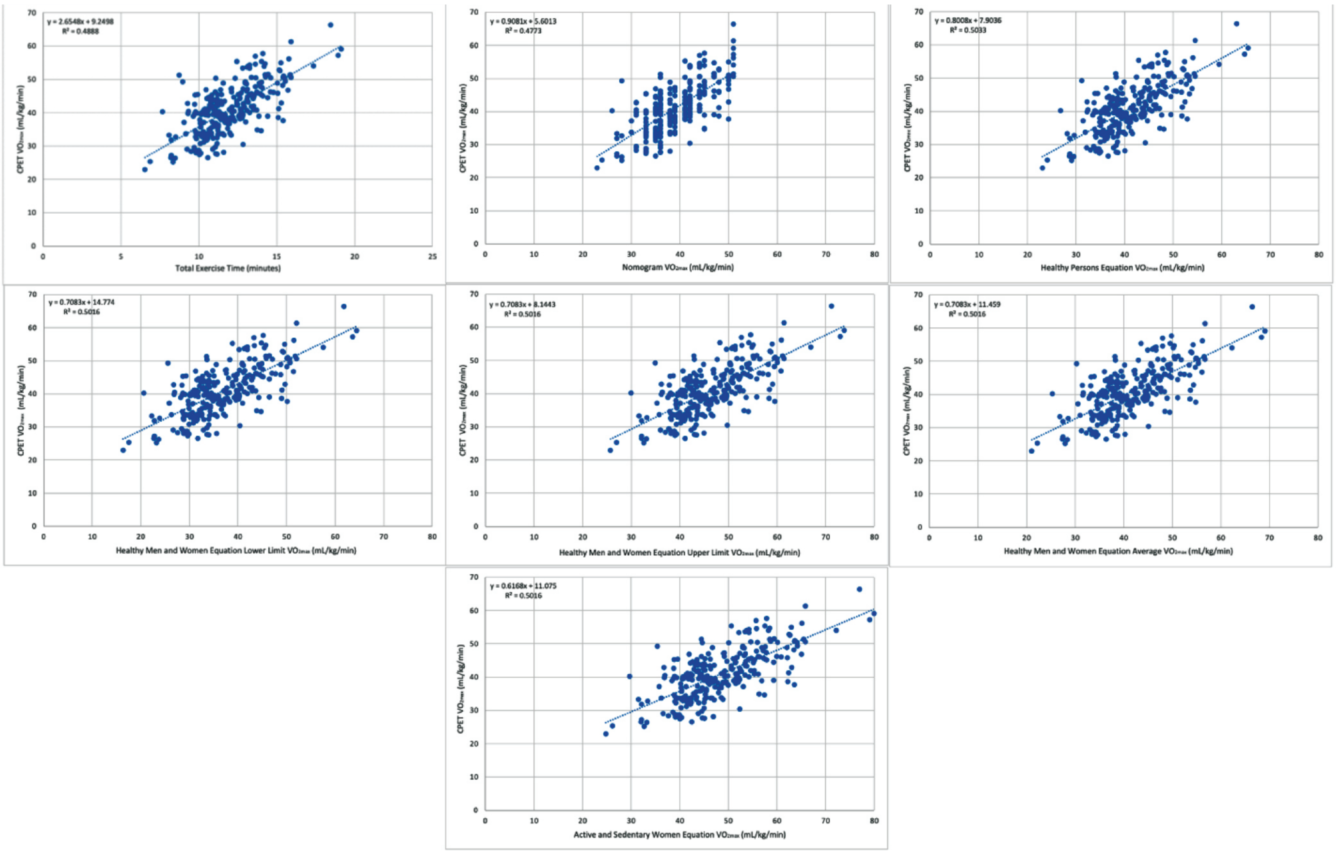


Figure 1. Female linear regression analysis for measured VO_{2max} from CPET Software and predicted methods: total exercise time (top left), nomogram [13] (top center), Healthy Persons Equation [6] (top right), Healthy Men and Women Equation: lower limit) [2] (middle left), Healthy Men and Women Equation: upper limit) [2] (middle center), Healthy Men and Women Equation: average [2] (middle right) and Active and Sedentary Women [22] (bottom center).

ranged from 0.48–0.50 for females and 0.39–0.46 for males, and are presented in Table 6, Figure 1 and 2.

Discussion

The main objective of this study was to assess whether VO_{2max} values estimated through predictive methods (several equations and a nomogram) using the exercise test time during a maximal test matched measured VO_{2max} values using metabolic equipment during that same maximal test. VO_{2max} is often estimated using predicted methods because they are more cost effective, quicker, and easier, and they do not require highly-trained personnel [19]. Limited research has been placed on the use of time-based prediction methods (i.e., equations and nomograms) when compared to measured VO_{2max} results. In the current study, all of the prediction equations [2, 6, 22] accounted for approximately the same amount of predictive power in the female VO_{2max} values (R^2 = 0.50); while

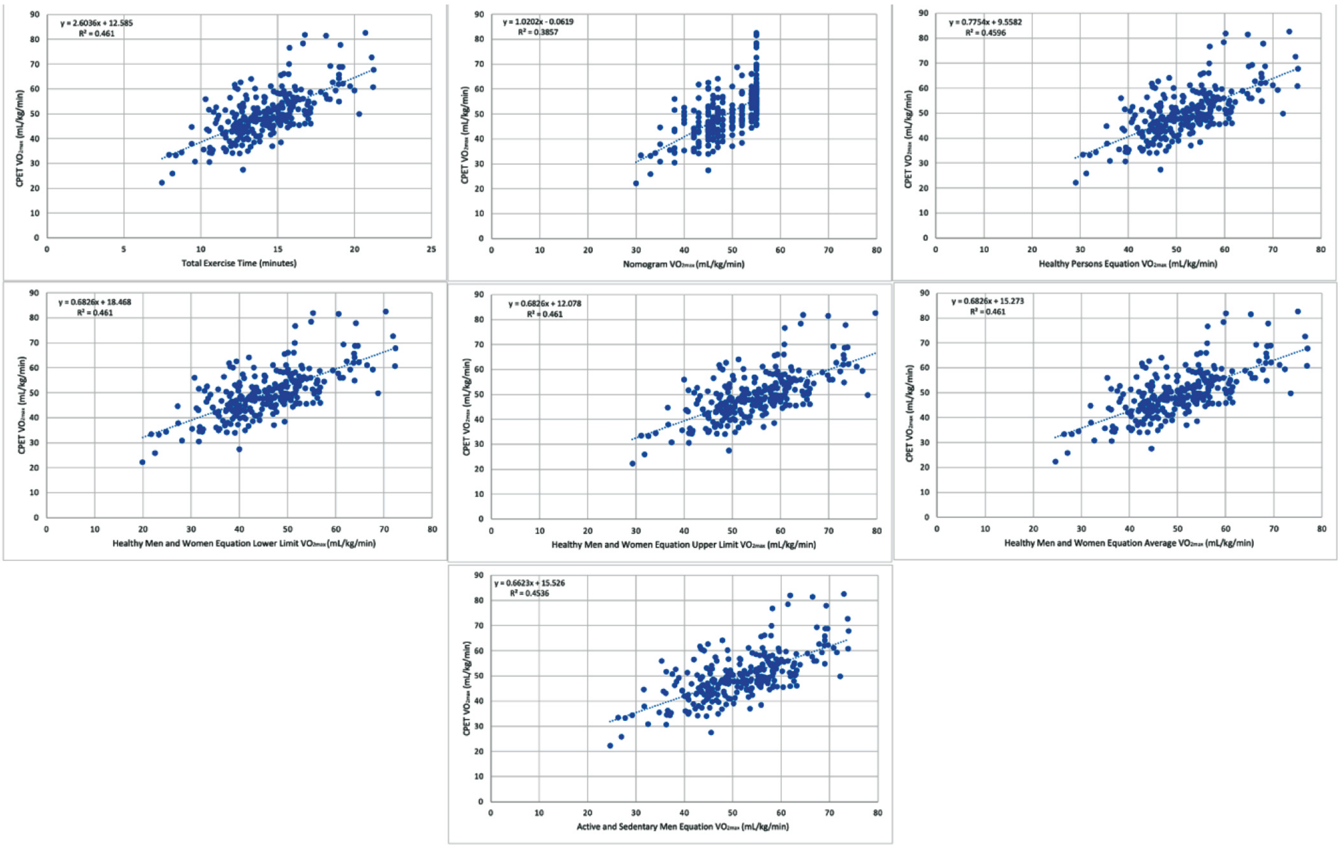


Figure 2. Male linear regression analysis for measured VO_{2max} from CPET Software and predicted methods: total exercise time (top left), nomogram [13] (top center), Healthy Persons Equation [6] (top right), Healthy Men and Women Equation: lower limit [2] (middle left), Healthy Men and Women equation: upper limit) [2] (middle center), Healthy Men and Women Equation: average [2] (middle right) and Active and Sedentary Men [10] (bottom center)

the lowest amount of predictive power was shown when using the nomogram [13] to predict VO_{2max} ($R^2 = 0.48$). For males, the Healthy Persons [6] and Healthy Men and Women Equations [2] best predicted the VO_{2max} values ($R^2 = 0.46$), while the nomogram [13] was the worst at predicting the measured VO_{2max} ($R^2 = 0.39$).

The limitation of using the nomogram comes from the time restriction. Any participants who lasted longer than 16 minutes during the Bruce protocol had an estimated VO_{2max} of 51 mL/kg/min for females and 55 mL/kg/min for males. In the current study, a ceiling effect for 25.36% of the male participants and 2.96% of the female participants occurred, making this predictive method less valid, especially for aerobically trained males. The classifications for VO_{2max} using the nomogram are significantly skewed in the higher ranked classifications for both males and females. For females, a participant with a VO_{2max} value of >46.99 mL/kg/min was ranked as elite compared to >60.20 mL/kg/min as measured through the CPET metabolic system (an underestimation of 13.21 mL/kg/min). The difference was even greater in males, as a participant with a VO_{2max} value of >51.43 mL/kg/min is ranked as elite compared to >73.96 mL/kg/min as measured through the CPET metabolic system (an underestimation of 22.53 mL/kg/min). This aligns with the current research that VO_{2max} tends to be underestimated with the use of prediction methods for aerobically trained individuals [16]. This underestimation tends to be exacerbated when using prediction equations that only use physical characteristics (such as age, BM, and/or sex) [16]. Malek et al. [16] suggested that changing the y-intercept of equations that only use physical characteristics could decrease this underestimation in aerobically trained athletes, however, doing so on the entire current population was not feasible, since not all participants in the current study were aerobically trained like those in Malek et al. [16].

In comparison to using age, sex and body mass index (BMI), treadmill grade and speed (which typically correspond to time) has been shown to be a more effective factor in predicting VO_{2max} in a maximal graded exercise test [12]. However, the need for including age as a predictor variable when estimating VO_{2max} across a large range of ages is well established [12]. The Healthy Persons Equation [6] was derived from mostly (72%) older (>45 years of age) male subjects, and about half (45%)

of the female subjects were >45 years of age [6]. This may account for the high variability between the Healthy Persons Equation [6] and the present study, with R^2 values of 0.50 and 0.46 for females and males, respectively. The lower value for males may come from a higher percentage of older adults used in the creation of the regression equation compared to the present study (average age of 21.31 ± 1.29 years old for males). Interestingly, when comparing the seven classifications for the Healthy Persons Equation [6] for females, the categories did not differ greater than 0.85 mL/kg/min from the measured CPET VO_{2max} values. The high level of congruence between the measured and predicted values suggests that general classifications may be made using the Healthy Persons Equation [6]. Additionally, in the percentile rankings using the Healthy Persons Equation [6] for females, CPET VO_{2max} did not differ more than 0.92 mL/kg/min between the 25th and 90th percentile. Similar results were displayed using the same equation in males in the middle range classifications (from below average to above average), with deviations no greater than 3.32mL/kg/min. In the percentile rankings for males using this equation, VO_{2max} did not differ more than 3.41 mL/kg/min between the 25th and 90th percentile (yet was still 2.49 mL/kg/min greater than the female deviations).

Looking at the classifications as a whole, five out of the six equations estimated the elite, excellent and above average categories to be lower than they were measured during CPET, while five of the six equations estimated the poor, fair and below average categories to be higher than measured during CPET for males. This trend did not occur in the female classifications as the equations equally over – and under-estimated the VO_{2max} at both the above-average and below-average categories when compared to the measured CPET values. The Healthy Men and Women Equation at the upper limit showed the greatest overestimation of VO_{2max}, deviating by a maximum of 7.12 mL/kg/min and 7.82 mL/kg/min across all percentiles for both males and females, respectively.

The Active and Sedentary Women equation [22] used a small sample size that combined both active (n = 20) and sedentary individuals (n = 29). Combining these two groups could account for differences in VO_{2max}, as a higher state of aerobic training can account for greater VO_{2max} values [15]. A young adult female population was used to create the Active and Sedentary Women equation (mean age of 27 years old) [21]. When testing this equation in middle-aged males (aged 33–55 years old), well matched for fitness with the females, there was a high degree of similarity [21]. Pollock et al. [21] therefore suggested that fitness, rather than sex or age, is more important when creating regression equations to account for population specificity. Similarly, when cross validation was used to compare prediction equations that primarily used physical factors (age, height, weight, sex), without the use of an exercise test using aerobically trained males and females, 16 out of the 18 equations assessed to estimate VO_{2max} displayed some population specificity as it related to the subjects' level of aerobic fitness [16]. Seventeen of the 18 equations significantly ($P < 0.006$) underestimated measured VO_{2max}, ranging from 2.9–18.4 mL/kg/min for males and 2.3–16.7 mL/kg/min for females [16]. The same trend of underestimation occurred with equations that also used a leisure time score (rating of physical fitness) [16], once again showing that level of fitness *is* an important variable when creating VO_{2max} regression equations.

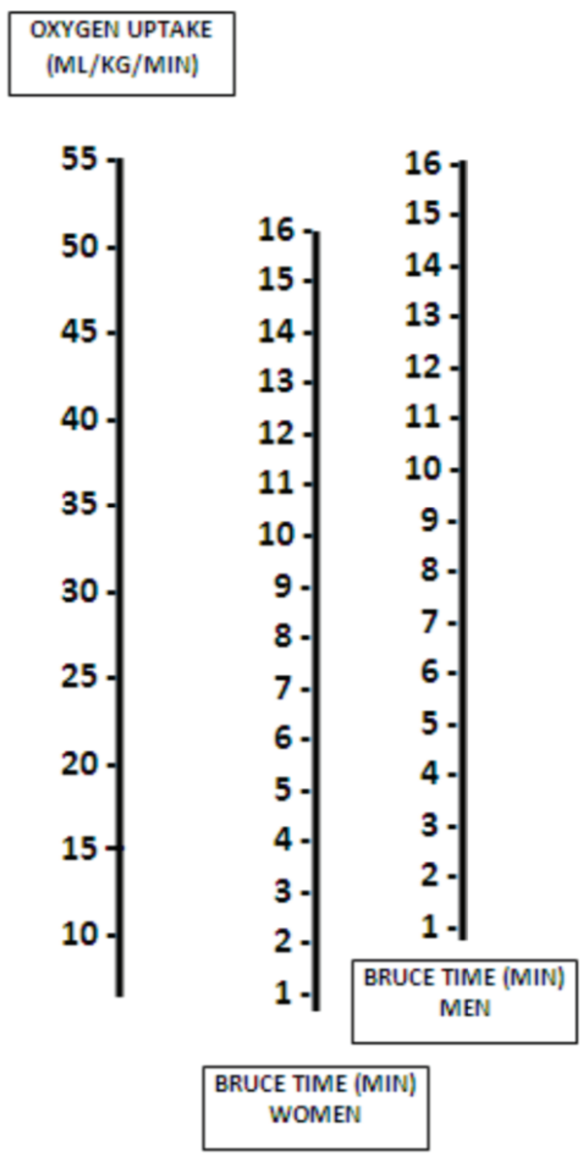
In Foster et al.'s [10] Active and Sedentary Men Equation (for males), a nonlinear (cubic) regression model was created in attempt to increase the applicability to a wider population range. The use of the cubic model stemmed from the relatively large increments that occur from one stage to the next in the Bruce protocol (i.e., the uncertainty to walk or run in stages three and four) [10]. In addition, a larger validation sample size (n = 200) of males were used with a broad spectrum of age (mean = 48.1 ± 16.3 years old), clinical conditions (symptomatic angina, post myocardial revascularization surgery, outpatient cardiac rehabilitation program) and level of fitness (77% of sample was trained) [10]. The low coefficient of determination between the present study and the Active and Sedentary Men Equation [10] ($R^2 = 0.45$), may be explained by the use of individuals with clinical conditions compared to the present study which only used a healthy population, as clinical conditions can negatively impact VO_{2max} [15].

A maximal graded exercise test with a metabolic cart measuring respiratory gases is a common way to measure VO_{2max}, but due to time and cost limitations, there still remains an interest in the use of regression equations to predict VO_{2max}. Regression equations in specific populations which combine age, body size, sex, physical fitness along with exercise test variables may be most effective in predicting VO_{2max}. Future research should focus on the development and cross validation of equations with specific populations using variables that affect VO_{2max} to investigate if there is a more significant relationship in prediction equations and measured VO_{2max}. This will assist in determining if there is always a need for metabolic equipment in collecting VO_{2max} data.

This study's main purpose was to determine if the exercise time from a maximal Bruce Treadmill Protocol could be used to accurately predict the measured VO_{2max} garnered from the computerized instrumentation on a metabolic cart. Our results indicated that the Healthy Persons Equation [6], Healthy Men and Women Equation (at the lower, higher and average range) [2], Active and Sedentary Women Equation [22], Active and Sedentary Men Equation [10] and nomogram [13] while performing the Bruce protocol cannot accurately predict VO_{2max} in healthy young adults with R^2 values between 0.38–0.50, leaving at least half of the variance unexplained by the models. The male and female nomograms [13] had the least amount of predictive power out of all of the methods used to predict the measured $VO_{2max.}$ The Healthy Persons Equation [6] was found to very closely mimic the seven-category classifications determined from the measured CPET VO_{2max} values. Overall, a metabolic cart collecting concentrations of expired gases in a maximal graded exercise test to measure VO_{2max} should still be used to obtain accurate and reliable values.

Appendix A

Nomogram for a Bruce Protocol VO_{2max} treadmill test used by plotting the participant's exercise time (in minutes) and drawing a horizontal line to obtain VO_{2max} (mL/kg/min) (modified from Heyward, 2010).



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