Original Research

Prediction of Maximal Oxygen Consumption from Rating of Perceived Exertion (RPE) using a Modified Total-body Recumbent Stepper

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ABSTRACT

International Journal of Exercise Science 8(4): 414-424, 2015. Exercise training is crucial to improve cardiovascular health and quality of life in people with spinal cord injuries (SCI). A key limitation is the lack of validated submaximal tests to evaluate and predict cardiovascular fitness in this population. The purpose of this study was to validate a submaximal test to predict maximal oxygen consumption for individuals with SCI. Ten able-bodied participants and two individuals with SCI completed a rating of perceived exertion (RPE)-based submaximal oxygen consumption test and a graded maximal oxygen consumption test on a NuStep T4 recumbent stepper. Prediction of VO_2max from an RPE-based protocol is feasible and can produce reliable predicted VO_2max values in the able bodied population. This study is a proof of concept to the implementation of a submaximal test protocol using a total body recumbent stepper to predict VO2max in able-bodied individuals. Additionally, this study shows evidence of feasibility of performing this test in SCI individuals.

KEY WORDS: VO_{2max}, submaximal test, graded exercise test

INTRODUCTION

The most accurate measurement of cardiovascular fitness in healthy individuals is through the measurement of oxygen consumption at an individual's maximal work rate (VO_2max). VO_2max is commonly used for exercise prescription as this variable gives the health professional an objective measurement of the cardiovascular fitness of an individual (9, 21, 22, 24, 25). However, maximal effort tests cannot be done without the use of expensive equipment (typically not found in clinics or fitness facilities), are time consuming, and usually need to be conducted with medical supervision.

Tests estimating VO_2max from submaximal levels of work are commonly used to estimate the VO_2max of healthy populations because they are typically more affordable, do not require the patients to exercise at maximal levels of exertion, and are safer for special populations (21, 22). The most accurate submaximal tests to predict VO_2max are performed with a treadmill and estimate VO_2max values with a combination of heart rate and work load. In some clinical populations, especially those with a motor disability, such as spinal cord injury, the use of a treadmill or bicycle ergometer and their validated exercise tests is simply not possible. In this case, other modalities of submaximal exercise protocols using arm crank ergometers have been developed (1, 2, 7, 18, 27, 28). However, the small and easily exhaustible muscles of the upper body often do not adequately stress the cardiovascular system, resulting in lower VO_2max values (12, 14).

In a study comparing cardiovascular responses between able-bodied individuals and individuals with SCI, Higuchi, Kitamura, Kawashima, Nakazawa, Iwaya and Yamasaki (17) found that passive walking resulted in similar values for VO_2max, pulmonary ventilation, and heart rate in individuals with spinal cord injury (SCI) when compared to able-bodied participants. Therefore, even passive use of the muscles of the lower body may increase an individual's cardiovascular response to exercise. A total body recumbent stepper could potentially elicit the same cardiovascular responses to exercise as passive walking. Maximal tests using a total body recumbent stepper have been established for both able-bodied individuals (5) and individuals with stroke (6).

Another limitation of most current validated submaximal protocols to predict VO_2max is that they are based on heart rate (HR) values (3, 4, 13, 25, 26) as it has been reported that as intensity of exercise increases, HR increases for the most part, in a linear fashion. However, HR is not an accurate measurement of exercise intensity in individuals with sympathetic impairments as seen in SCI or individuals taking β blockers. Recently, studies have found VO_2max may be also predicted from the overall rating of perceived exertion (RPE) in healthy and clinical populations (10). Further, Al-Rahamneh and Eston (1) reported that a submaximal exercise protocol using an arm crank ergometer and RPE to estimate VO_2max in individuals with SCI show high correlation with the directly measured values from a maximal test. Since RPE may be a more reliable indicator of cardiovascular stress in individuals with SCI than HR, the current study will attempt to establish a submaximal protocol based off RPE using a total body recumbent stepper.

METHODS

Participants
Ten healthy neurologically intact and 2 SCI individuals were invited to participate in this proof of concept, pilot study. The study took place at The Frazier Rehab Institute in Louisville, KY. Each participant performed a graded exercise test (GXT) on a total body recumbent stepper (NuStep T4 ergometer, Ann Arbor, MI) to measure VO_2max and a submaximal test to estimate VO_2max. The tests were separated by at least 48 hours and at most one week. Participants were asked to not perform any moderate or heavy exercise 12 hours prior to the test. Each test was conducted on the same total body recumbent stepper. The seat position was set so the subject had a slight bend in their knee at full extension. Arm handles

were positioned to allow full extension without leaning forward in the seat.

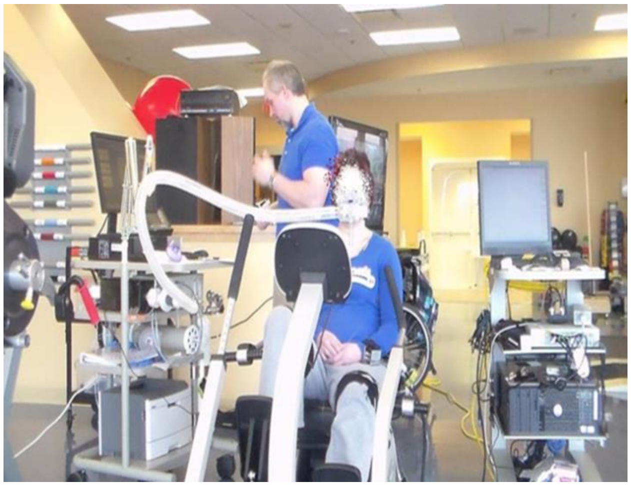

Figure 1. Recording of resting values prior to VO2 max protocol in a participant with SCI using a NuStep T4 ergometer.

Protocol

Oxygen consumption was analyzed with a Parvo Medic TrueOne 2400 (Sandy, UT). Analysis of the oxygen and carbon dioxide composition of the expired air occurred every 10 seconds. The cart was calibrated with a 3-liter syringe for flowmeter calibration and the ambient air for gas calibration at least 30 minutes before testing as recommended by the manufacturer's guidelines. Heart rate was recorded using a Polar heart rate monitor as well as by 3-lead EKG. Rating of perceived exertion was recorded using the Borg 6-20 scale, which was explained to each participant using standardized instructions (8). Any questions the participant had were answered to ensure full understanding. All variables such as gas consumption, respiratory exchange ratio, heart rate, V_E, power output, and time were not visible to the participant during the test.

VO_{2max} Test Protocol: Participants warmed up for two minutes at a resistance of 1 and at 115 steps per minute (SPM) consistent with previously developed exercise test protocols (5, 6). After the two minute warm up, the participants immediately began the test at a resistance of 4. Every two minutes, the resistance was increased until exhaustion. 20 seconds before the end of each stage, the participants were asked to report their RPE. Blood pressure and heart rate were measured before warm up, immediately after the test, and 5 minutes posttest. The test was terminated when 1) the subject reports subjective fatigue and stops the test despite verbal encouragement and 2) the subject is no longer able to keep the SPM at or above 115 for able bodied participants and 80 for SCI participants.

Submaximal Test Protocol: Participants warmed up for two minutes at a resistance of 1 and at 115 SPM for able bodied participants and 80 SPM for SCI participants . This intensity was chosen based on a previously validated protocol for individuals with stroke (6). The participants were then asked to complete 5 two minute stages at RPEs of 9, 11, 13, 15, and 17. Every 30 seconds participants were asked their RPE. If their RPE was anything other than the RPE assigned for that stage, resistance was adjusted. Watts and HR were also taken every 30 seconds. Blood pressure and heart rate were measured before warm up, immediately after the test, and 5 minutes posttest. Participants were instructed to cool down at a resistance of 1 and at their own pace for two minutes after blood pressure and heart rate were taken immediately posttest.

Statistical Analysis

The VO_2 data from the submaximal test were modeled with a linear mixed effects model. Two models were evaluated, one having RPE as the only fixed effect (RPE Only) and one having RPE and wattage (RPE + Watts) as fixed effects. In both of these models, random effects for the intercept and RPE were included; a wattage random effect did not statistically improve the fit of the model to the data (ANOVA, p = .13). From these two models, estimates of the intercept, RPE, and wattage fixed effects were generated with 95% confidence intervals.

Predictions of VO_2max were generated from these models using the linear fixed effects equations and the best linear unbiased predictors (BLUP) of the random effects (23). For the RPE Only model, maximal VO_2 was predicted at an RPE of 20 to correspond with the maximal test protocol. For the RPE + Watts model, the average wattage at RPE = 20 varies from subject to subject and is not known, since the submaximal test terminates at RPE = 17. To address this problem, a second linear mixed effects model was fit in which average wattage was predicted as a linear function of RPE, with intercept and RPE random effects. Average wattage at RPE = 20 was predicted from this model, and this predicted average wattage was used to predict maximal VO_2 at RPE = 20 in RPE + Watts model. To evaluate the association between predicted and observed VO_2max, Pearson's correlation coefficient and Lin's concordance correlation coefficient (19) were calculated.

The RPE Only and RPE + Watts models were fit for the full submaximal data (RPE from 9 to 17) and on two subsets of the data – RPE from 9 to 15 and RPE from 9 to 13 – in order to determine if the submaximal test could be terminated at an RPE lower than 17 and still accurately predict maximal VO_2. Predictions from these models were generated as described above, and Pearson and Lin coefficients calculated between observed and predicted maximal VO_2 were calculated. All analyses were conducted in the open-source R software environment.

RESULTS

Ten able-bodied participants (5 male, 5 female) participated in the submaximal and maximal oxygen consumption tests (Table 1). The average age was 28 and ages ranged from 20 to 37 years. The average RPE recorded at the end of the maximal test was 19.4 (SD = 0.70) with a minimum of 18. Average respiratory exchange ratio at peak RPE was 1.17 (±0.08). Average heart rate was 180.28 (9.70) beats per minute. Average wattage of the participants at maximal RPE was 244.5 W (69.48) and average wattage ranged from 147 W to 382.5 W.

Linear prediction equations were built from the fixed effects estimates generated by the linear mixed effects model (Table 2). Predictably, VO_2 increased with RPE and wattage, although the rate at which VO_2 increased with RPE varied substantially based on the subset of the data used. In the RPE Only model, the magnitude by which predicted VO_2 increased for every one unit increase in RPE ranged from 1.58 in the RPE 9-13 subset of the data to 2.00 in the full (RPE 9-17) data. In the RPE + Watts model, the magnitude by which predicted VO_2 increased for every one unit increase in RPE ranged from 0.50 in the full data to 0.63 in RPE 9-15 subset. Estimated fixed effects

Table 1. Able-bodied subject characteristics and values obtained during the last stage of the stepper protocol with a maximal reported effort.

Subject	Age	Sex	Weight (Kg)	Height (cm)	Maximum reported RPE	RER	HR	Watts	Resistance
1	26	F	67.1	162.6	20	1.29	196	147	7
2	24	M	104.3	175.3	19	1.17	173	382	9
3	24	F	65.8	174.6	18	1.19	176	230	9
4	37	M	102.1	177.8	20	1.19	192	251	8
5	20	M	72.6	180.3	19	1.21	186	274	10
6	29	F	67.1	160.0	20	1.29	185	166	8
7	30	M	83.0	175.3	19	1.16	166	294	9
8	24	M	74.8	172.7	20	1.13	183	263	8
9	29	M	96.2	185.4	20	1.04	169	259	10
10	37	F	65.5	175.3	19	1.07	176	176	8
Summary mean (sd)									
M	27 (6.0)	6	88.8 (13.9)	177.8 (4.5)	19.5 (0.5)	1.15 (0.06)	178.3(10.2)	287.4 (49.0)	9 (0.89)
F	29 (5.7)	4	66.4 (0.8)	168.1 (8.0)	19.2 (1.0)	1.21 (0.11)	183.3(9.4)	180.1 (35.7)	8 (0.82)
All	28 (5.6)	10	79.8 (15.5)	173.9 (7.6)	19.4 (0.7)	1.17 (0.08)	180.3 (9.7)	244.5 (69.5)	8.6 (0.97)

coefficients for RPE were reduced in the RPE + Watts model due to the inclusion of the wattage fixed effect. Predicted VO_2 increased by between 0.10 to 0.11 for every 1 W increase.

The equations for predicting maximal VO_2 are based on the fixed effects in Table 2 and the best linear unbiased predictions (BLUPs) of the random effects for each subject. The random effects represent subject-specific deviations from the population-level intercept and slope fixed effects. BLUP estimates of the random effects are generated for each subject, providing the prediction equation for the

Table 2. Estimates of fixed effects coefficients from RPE Only and RPE + Watts models. Values are point estimate (95% confidence interval).

Data Subset	RPE Only		RPE + Watts		
	Intercept	RPE	Intercept	RPE	Wattage
RPE 9 – 17 (Full)	-4.99 (-9.25, -0.72)	2.00 (1.57, 2.42)	-1.99 (-3.69, -0.29)	0.50 (0.20, 0.81)	0.11 (0.09, 0.13)
RPE 9 - 15	-3.91 (-8.05, 0.21)	1.90 (1.46, 2.35)	-1.85 (-3.87, 0.16)	0.63 (0.31, 0.95)	0.10 (0.08, 0.12)
RPE 9 -13	-0.62 (-4.81, 3.56)	1.58 (1.13, 2.04)	-0.61 (-3.57, 2.35)	0.52 (0.18, 0.86)	0.10 (0.08, 0.12)

given subject. For example, for the full data (RPE 9-17), the prediction equations for a subject from the RPE Only and RPE + Watts models, respectively, were

Predicted VO_2 = $(-4.99 + BLUP_I) + (2.00 + BLUP_{RPE})*RPE$

Predicted VO_2 = $(-1.99 + BLUP_I) + (0.50 + BLUP_{RPE})*RPE + 0.11*Wattage$

where $BLUP_I$ is the BLUP estimate of the intercept random effect and $BLUP_{RPE}$ is the BLUP estimate of the RPE random effect; there was no random effect for the wattage fixed effect. Prediction equations for the two subsets of the data (RPE 9-15, RPE 9-13) were constructed similarly.

Predicted maximal VO_2 from the full data (RPE 9-17) correlated well with observed maximal VO_2, with Pearson coefficients 0.86 and 0.88 for and Lin coefficients of 0.81 and 0.83 for the RPE Only and RPE + Watts models, respectively (Table 2, Figure 2). The Pearson and Lin coefficients were reduced for predictions from the RPE 9-15 subset of the data, although the association between maximal VO_2 predicted from the RPE 9-15 subset and observed maximal VO_2 was significant, as the 95% confidence intervals for the Pearson and Lin coefficient excluded zero. Predicted maximal VO_2 from the RPE 9-13 subset of the data was not significantly correlated with observed VO_2.

Confidence intervals for the predicted maximal VO_2 were generated based on the estimated residual standard errors from each mixed effects model – 2.09 for the RPE Only model on the full data (RPE 9-17) and 1.12 for the RPE + Watts model on the full data. Six of the ten 95% confidence intervals for maximal VO_2 predicted from the RPE Only model contained the observed maximal VO_2, and 5 of ten for the RPE + Watts model (Figure 3). Further, six of the ten maximal VO_2 predicted from the RPE Only model were within 10% of the

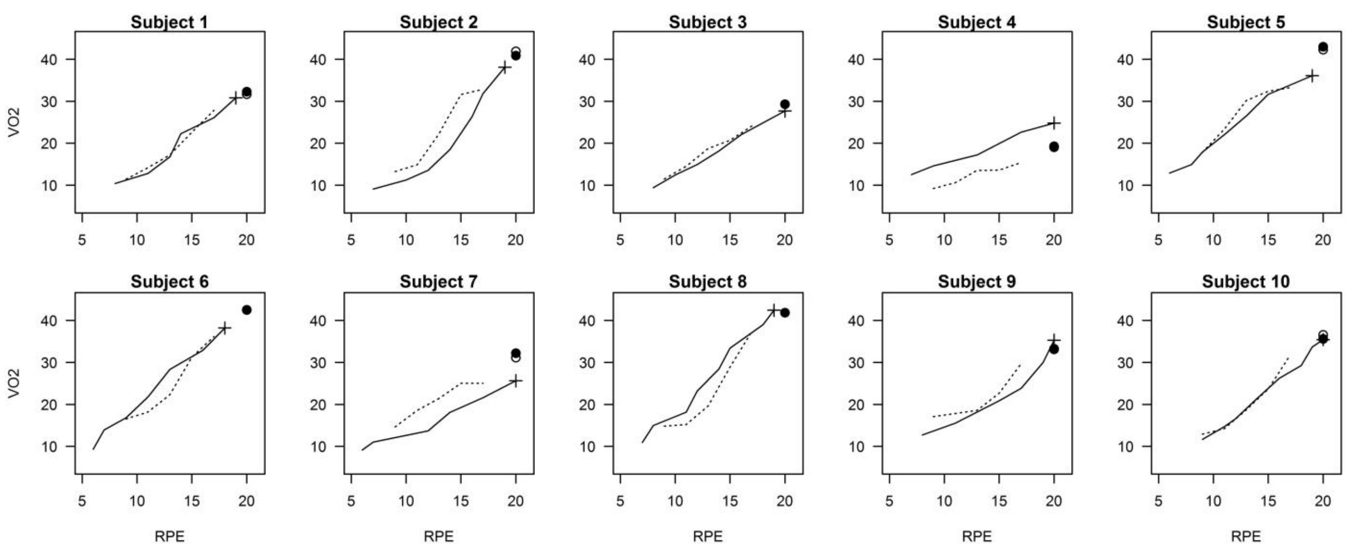

Figure 2. Plot of VO2 from the max (solid lines) and submaximal (dotted lines) test protocols by subject. Observed maximal VO2 are marked by +, and predicted maximal VO2 are marked by solid (RPE Only) and open (RPE + Watts) dots.

Table 3. Maximal VO2, observed from the maximal test and predicted by the submaximal test for the RPE Only and RPE + Watts models for three subsets of the data, with summary statistics and measures of association. Estimated Pearson correlation coefficients and Lin concordance correlation coefficients are provided with 95% confidence intervals.

Participant	Observed	RPE 9-17		RPE 9-15		RPE 9-13	
		RPE-Only	RPE + Watts	RPE-Only	RPE + Watts	RPE Only	RPE + Watts
1	30.8	32.3	31.7	29.9	29.7	26.7	28.3
2	38.1	40.9	41.9	40.6	43.5	34.4	35.2
3	27.7	29.3	29.3	29.1	28.6	29.4	28.5
4	24.8	19.1	19.3	19.4	18.7	20.3	20.7
5	36.1	43.0	42.3	47.1	47.2	48.6	48.2
6	38.2	42.5	42.5	40.7	39.0	33.6	30.1
7	25.6	32.2	31.2	35.0	33.2	33.6	34.4
8	42.4	41.8	41.8	36.7	37.3	28.7	29.1
9	35.3	33.1	33.2	30.9	30.9	26.6	26.9
10	35.4	35.6	36.6	31.6	32.8	28.2	28.8
Mean (SD)	33.4 (5.9)	35.0 (7.5)	35.0 (7.6)	34.1 (7.2)	34.1 (8.1)	31.0 (0.2)	31.0 (7.2)
Correlation	-	0.86 (0.49, 0.97)	0.88 (0.57, 0.97)	0.65 (0.04, 0.91)	0.71 (0.14, 0.92)	0.33 (-0.37, 0.80)	0.30 (-0.41, 0.78)
Concordance	-	0.81 (0.47, 0.94)	0.83 (0.53, 0.95)	0.63 (0.08, 0.88)	0.67 (0.18, 0.89)	0.30 (-0.31, 0.74)	0.27 (-0.34, 0.72)

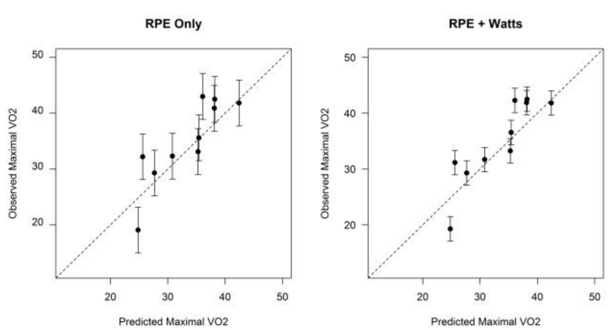

Figure 3. Scatterplots of observed vs. predicted maximal VO2, with predictions from the RPE Only (left panel) and RPE + Watts (right panel) models. Dashed line represents observed = predicted.

observed values, and six of ten for the RPE + Watts model. Predicted maximal VO_2 slightly and non-significantly overestimated observed maximal VO_2, by an average of 1.5 (95% CI = [-9.2, 6.1]) for the RPE Only model and by an average of 1.5 (-8.6, 5.6) for the RPW + Watts model. Prediction accuracy and confidence interval coverage of the models fit to subsets of the data (RPE 9-15 and RPE 9-17) were not considered due to the reduced correlation between observed and predicted maximal VO_2 (Table 3).

Two participants with SCI completed the submaximal and maximal oxygen consumption tests. Both were male and age 28. One subject had as thoracic 3 motor and sensory complete SCIby the American Spinal Injury Impairment Scale (20) (AIS A, T3 SCI) and achieved RPE 20 during the maximal test with RER of 1.09 and wattage of 120W at resistance 9. The other subject

Table 4. VO2 and wattages from submaximal and maximal tests of two SCI participants.

	Reported RPE	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
T3 AIS A SCI Participant	Submaximal VO2				10.0		10.5		12.4		14.4		17.7			
	VO2 max		5.9		8.4			10.7		10.3			13.9		18.0	22.9
	Submaximal watts				58.5		60.0		72.0		83.8		93.5			
	Maximal watts		45.0		51.0			56.0		65.5			81.5		106.5	120.0
T4 AIS C SCI Participant	Submaximal VO2				12.2		12.5		15.3		17.5		20.3			
	VO2 max	11.9				15.3		17.1				22.9				18.1
	Submaximal watts				62.8		70.5		77		89.5		113			
	Maximal watts	60				85		94				99.5				117

had a thoracic 4-6 motor incomplete SCI (AIS C, T4-6 SCI) and achieved RPE 20 during the maximal test with RER of 1.25 and wattage of 117W at resistance 7. The VO_2 and wattage from their submaximal and maximal tests are in Table 4. The protocols were similar to the able-bodied protocol, except that participants had to maintain a cadence of 80. Legs of both of the SCI participants were stabilized and strapped with bilateral leg stabilizers (NuStep Inc., Ann Arbor, MI).

DISCUSSION

Cardiovascular fitness tests provide fitness and health care professionals with valid information to make decisions regarding health management and to prescribe exercise interventions in both healthy and clinical populations. The primary purpose of performing a submaximal graded test is to estimate cardiovascular fitness by predicting VO_2max without the burden of testing to exhaustion. Several submaximal tests have been validated for different populations (16, 29) showing strong correlation with actual VO2 max values (3, 4, 13). This study is presenting a novel submaximal approach to estimate cardiovascular fitness using a total-body recumbent stepper exercise using RPE. This is in agreement with previous studies on RPE and VO_2max prediction in individuals with spinal cord injury (1, 2, 11, 15).

Predictions of maximal VO_2 from the RPE + Watts model were better correlated with observed maximal VO_2 than predictions from the RPE only model (0.88 vs. 0.86). However, the improvement in correlation by including wattage was small and statistically non-significant ($p = .89$), indicating that the predictions from the two models were essentially equivalently associated with observed maximal VO_2. Further, predictions from the RPE + Watts model require that wattage at RPE = 20 be predicted from a separate model, and that this predicted wattage at RPE = 20 be used to predict maximal VO_2. Calculating this predicted wattage at RPE = 20 is not only burdensome but also carries additional error into the prediction of maximal VO_2.

The effect of this additional prediction error on the correlation between observed and predicted VO_2 is not readily apparent. As such, we recommend the use of the RPE Only model in generating predictions of maximal VO_2 from the submaximal test protocol.

The predictions from the linear mixed effects model are closely related to weighted averages of the predictions made by a linear regression model for all participants and separate linear regression models for each subject. The weights comprising this weighted average are proportional to the sizes of the random effects variances and the residual variance. For the RPE Only model, the variance of the intercept and RPE random effects were 25.2 and 0.3 respectively. The residual variance for the RPE Only model was 4.4, so that the intercept random effect was the primary source of variation. Because of this, the predictions from the random effects model were more closely related to predictions from separate linear regressions for each subject than to predictions from a single regression fit to all participants. Therefore, a clinician conducting the submaximal test on a single patient can predict maximal VO_2 by a simple linear regression of VO2 onto the RPE recorded during the submaximal test. This and the small sample size may limit the ability to generalize the findings.

The results of this study show that VO2max can be estimated using a submaximal graded exercise test when extrapolated to RPE 20. There is a strong correlation between predicted and actual VO2 max values in healthy able-bodied individuals. Additionally, this study is a proof of a concept of the feasibility to perform this protocol in individuals with SCI. These findings have important clinical implications in assessing cardiovascular fitness and maximal aerobic capacity in populations in which HR is not a reliable mean for prediction or when maximal exercise test is not feasible.

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