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Research article

Validity of a Newly-Designed Rectilinear Stepping Ergometer Submaximal Exercise Test to Assess Cardiorespiratory Fitness

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Abstract
The maximum oxygen uptake ($\dot{V}O_2max$), determined from graded maximal or submaximal exercise tests, is used to classify the cardiorespiratory fitness level of individuals. The purpose of this study was to examine the validity and reliability of the YMCA submaximal exercise test protocol performed on a newly-designed rectilinear stepping ergometer (RSE) that used up and down reciprocating vertical motion in place of conventional circular motion and giving precise measurement of workload, to determine $\dot{V}O_2max$ in young healthy male adults. Thirty-two young healthy male adults (32 males; age range: 20 - 35 years; height: 1.75 ± 0.05 m; weight: 67.5 ± 8.6 kg) firstly participated in a maximal-effort graded exercise test using a cycle ergometer (CE) to directly obtain measured $\dot{V}O_2max$. Subjects then completed the progressive multistage test on the RSE beginning at 50W and including additional stages of 70, 90, 110, 130, and 150W, and the RSE YMCA submaximal test consisting of a workload increase every 3 minutes until the termination criterion was reached. A metabolic equation was derived from the RSE multistage exercise test to predict oxygen consumption ($\dot{V}O_2$) from power output (W) during the submaximal exercise test ($\dot{V}O_2(mL \cdot min^{-1}) = 12.4 \times W(watts) + 3.5\ mL \cdot kg^{-1} \cdot min^{-1} \times M + 160 mL \cdot min^{-1}$, R^2= 0.91, standard error of the estimate (SEE) = $134.8 mL \cdot min^{-1}$). A high correlation was observed between the RSE YMCA estimated $\dot{V}O_2max$ and the CE measured $\dot{V}O_2max$ (r=0.87). The mean difference between estimated and measured $\dot{V}O_2max$ was 2.5 $mL \cdot kg^{-1} \cdot min^{-1}$, with an SEE of 3.55 $mL \cdot kg^{-1} \cdot min^{-1}$. The data suggest that the RSE YMCA submaximal exercise test is valid for predicting $\dot{V}O_2max$ in young healthy male adults. The findings show that the rectilinear stepping exercise is an effective submaximal exercise for predicting $\dot{V}O_2max$. The newly-designed RSE may be potentially further developed as an alternative ergometer for assessing cardiorespiratory fitness and the promotion of personalized health interventions for health care professionals.

Key words: Maximum oxygen uptake, metabolic equation, rectilinear reciprocating motion, constant power output.

Introduction

Exercise physiologists suggest that direct measurement of maximal oxygen uptake ($\dot{V}O_2max$) during graded maximal exercise is the criterion measure of cardiorespiratory fitness (Heyward, 2013). Nonetheless, this method requires expensive equipment and experienced personnel and many individuals are not able to meet the criteria for maximal exertion because of fatigue, low motivation, or physical limitations (Herda et al., 2014; Noonan et al., 2000). The submaximal exercise test estimates a person's aerobic capacity based on the assumption that a linear relationship exists between oxygen uptake ($\dot{V}O_2$) and heart rate (HR) within a certain range of HR (Heyward, 2013). Compared with maximal exercise testing, a submaximal exercise test is safer and more appropriate in public health institutions and clinical practice when assessing cardiorespiratory fitness of individuals (Herda et al., 2014; American College of Sports Medicine, 2013).

The use of traditional modes of testing in the prediction of $\dot{V}O_2max$, such as with a treadmill or cycle ergometer (CE), may prove to be limited in some populations, including elderly people or deconditioned individuals (Siconolfi et al., 1982). To enable exercise testing across a greater range of population groups, tests with some new modalities of ergometers have been designed. In a study presented by Billinger et al. (2012), the YMCA submaximal cycling protocol was adapted for use with the NuStep T5xr recumbent stepper and used to estimate VO_2peak in healthy adults (r = 0.91; SEE = 4.09 $mL \cdot kg^{-1} \cdot min^{-1}$). With the popularity and continued interest in step aerobic training, the researchers provided a relatively more accurate estimate of $\dot{V}O_2max$ for young women (20–25 years) who used this device for aerobic training (r = 0.57; SEE = $5.3 mL \cdot kg^{-1} \cdot min^{-1}$) as compared to estimates for their untrained counterparts (r = 0.00; SEE = 6.7 $mL \cdot kg^{-1} \cdot min^{-1}$) (Roy et al., 2004). Paré et al. (1993) validated the prediction of VO_2peak from a submaximal exercise test performed by paraplegics on a wheelchair ergometer (r = 0.83; SEE = $0.19 L \cdot min^{-1}$) and observed the linear relationship between $\dot{V}O_2$ and power output (W) ($\dot{V}O_2$= 0.79+0.02 W; r = 0.80, SEE = $0.22 L \cdot min^{-1}$). The design of these different modalities of exercise devices provides the publics and health professionals with alternative exercise modes and methods for assessing cardiorespiratory fitness.

In addition to these different exercise modalities, rectilinear reciprocating motion is seldom used as a regular exercising modality compared with circular reciprocating motion, such as cycle ergometer. When using a rotary crank mechanism, the force application, however, is not constant throughout the pedal-crank revolution (Ratel et al., 2004). Ericson and Nisell (1988) showed that the tangential force (perpendicular to the crank) exertion was maximal when the position of the crank was approximately horizontal (90 degree crank angle), and the tangential

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force was minimal at two points, known as the top dead center (0 degree crank angle) and bottom dead center (180 degree crank angle) (Chen et al., 1997; 2001; Ericson and Nisell, 1988; Patterson and Moreno, 1990). Moreover, Ericson and Nisell (1988) found that the tangential force was the only mechanically efficient force while the centrifugal force (perpendicular to the tangential force and running alongside the crank) did not contribute to the end mechanical efficiency. Optimum mechanical efficiency was reached if the centrifugal force equaled zero, implying that the sum of forces was directed tangentially and acted in the same instantaneous direction as the pedal moves (Ericson and Nisell, 1988). Therefore, a mechanism of only linear vertical motion of the pedals will overcome the dead centers and be mechanically efficient because the vertical force is nearly the only tangential force and it is entirely in the direction of the pedal's movement. Since some individuals are unfamiliar with cycling exercise, a rectilinear stepping motion using only linear vertical motion of the lower extremities, may provide a simple and alternative mode of exercise for them. In addition, Miller et al. (2001) suggested that a stepper cycle powered by a reciprocating vertical motion was applicable for people with cognitive, orthopedic, and neuromuscular conditions as it reduced the required range of movement of the lower limb joints when compared to a conventional bicycle. Moreover, many different types of stepping activities, including using various types of step ergometers, were found to be beneficial to knee muscle strengthening and rehabilitation programmes (Willett et al., 2010).

Our research team designed a new rectilinear stepping ergometer (RSE) that was based on a spinning bike and used up and down reciprocating vertical motion of the lower extremities in place of conventional circular motion. The purpose of this study was to examine the validity and reliability of the YMCA submaximal exercise test protocol for determining $\dot{V}O_2$max in young healthy male adults using the RSE. We hypothesized that the RSE YMCA submaximal exercise test would be a valid test for determining $\dot{V}O_2$max.

Table 1. Physical characteristics of the subjects (n = 32).

Variable	Means (±SD)
Age (years)	27.0 (3.4)
Height (m)	1.75 (.05)
Weight (kg)	67.5 (8.6)
Body Mass Index (BMI)	22.2 (2.3)
Rest HR(bpm)	64 (7)

Methods

Subjects

Thirty-two healthy males (n = 32; Age range: 20 - 35 years; Height: 1.75 ± 0.05 m; Weight: 67.5 ± 8.6 kg) were recruited to participate in this study. Subjects' age and physical characteristics are presented in Table 1. All subjects were screened and free from major cardiovascular risk, orthopedic and metabolic diseases. All procedures in this study were approved by our local ethics committee. Before testing, all subjects were asked to sign a written institutionally approved informed consent and they were informed of the benefits and risks of the study prior to signing the document. The subjects performed a CE maximal exercise test and an RSE submaximal exercise test to test the validity of the RSE for predicting $\dot{V}O_2max$. Reliability testing consisted of two paired test-retest sessions separated by no more than 4 days. All tests were separated by at least 48 hours and completed within 3 weeks. Before each test, subjects were asked to avoid alcohol and any heavy exercise for at least 6 hours. Subjects were familiar with the CE, but not all were familiar with RSE and every subject had an opportunity to practice the rectilinear stepping movement pattern and step cadence for approximately 15 minutes with no load prior to the RSE exercise test.

Figure 1. Rectilinear Stepping Ergometer (RSE).

Instrumentation

The rectilinear stepping ergometer (RSE) (Figure 1) used for the present study was designed by members of the Research Center for Information Technology of Sports and Health. A high-accuracy pressure and displacement sensor were respectively mounted on the pedals and the rectilinear motion guiding unit, to accurately measure the force and speed in the vertical direction. It is simple for giving direct measurement of power output on the RSE by multiplying the measured force by speed (power = force × speed). An electric generator braking system was connected to the rectilinear motion guiding unit through a gear transmission unit. The vertical motion of pedals was transformed into the circular motion of the gears through a rectilinear motion guiding unit and actuated the rotation of the generator rotor to produce the brake power through a gear transmission unit. Braking power ranged from 30 up to 400 watts. The resistance of RSE could be instantly adjusted through the change of exciting current of the electric generator, which kept a constant power output (accuracy ± 1.5 watts) with a stepping cadence over a range of 80 -120 steps per minute. When instant power output exceeded the target value, the exciting current decreased to lower the resistance and the instant power output decreased simultaneously. Conversely, the exciting current was increased when the instant power output was under the target value. This has been found to be important during submaximal exercise testing because stepping cadence fluctuates and maintaining constant power allows subjects to reach a steady heart rate during each stage of the test (Herda et al., 2014; Billinger et al., 2012). The pedal stroke length of circular crank pedals cannot be adjusted, but the pedal stroke length of the RSE could be changed through an adjustable limit switch to fit the user's leg and stroke pattern, allowing short or long strokes. The height of the saddle and the handles could be adjusted manually for maximum comfort.

Procedures

Maximum cycle ergometer exercise test

Subjects participated in a cycle ergometer graded maximal exercise test, which consisted of a 4-minute warm-up phase of pedaling with no load, followed by a progressive phase with workload increments of 25 W every minute (Maud et al., 1995). Subjects were required to maintain the cadence at fixed 60 rpm throughout the test. The test was terminated when at least three of the following criteria were achieved: (a) the subject reached volitional fatigue and requested to end the test (b) achievement of an age-predicted maximal HR (220-age) (c) a plateau in oxygen consumption with increasing workload (d) the subject was unable to maintain the cadence (e) a respiratory exchange ratio (RER) greater than 1.10.

Figure 2. RSE Multistage Exercise Test.

RSE multistage exercise test

Before using the submaximal exercise test to predict $\dot{V}O_2$max, a metabolic equation describing the relationship between oxygen consumption ($\dot{V}O_2$) and power output (W) adapted for RSE was needed to be developed to predict $\dot{V}O_2$ from W. Subjects were asked to perform a progressive multistage exercise test and maintain the cadence at $100\ \text{steps} \cdot \text{min}^{-1}$ throughout the test (Figure 2). After a 3 minutes warm-up with an initial workload of 30W, the test began at 50 W and included additional stages of 70, 90, 110, 130, and 150 W. Steady rate $\dot{V}O_2$ at each stage was recorded, which occurred when the absolute difference in oxygen consumption between two successive minutes after 3 min of the current stage did not exceed 50 $\text{mL} \cdot \text{min}^{-1}$, and the mean of those two minutes was used as the steady rate value. After reaching a steady state, the workload was increased to the next stage until the subjects reached 85% of the age-predicted maximal HR (220 - age) or finished the 150 W stage. On completion of the progressive multistage exercise test, a metabolic equation to predict $\dot{V}O_2$ from W using the RSE was developed using linear regression analysis.

Table 2. YMCA protocol adapted for the RSE.

	Stage Ⅰ 50 Watts			
	HR<80	**HR 80-89**	**HR 90-100**	**HR>100**
Stage Ⅱ	150 Watts	125 Watts	100 Watts	75 Watts
StageⅢ	175 Watts	150 Watts	125 Watts	100 Watts
StageⅣ	200 Watts	175 Watts	150 Watts	125 Watts

RSE submaximal exercise test

After completing the CE maximal exercise test, subjects were asked to perform a YMCA submaximal exercise test on the RSE. They were required to maintain the cadence at $100\ \text{steps} \cdot \text{min}^{-1}$ throughout the test. The YMCA protocol (Table 2) adapted for the RSE started with an initial workload at 50 W and the resistance was increased every 3 minutes according to the protocol (Table 2) until one of the following criteria was achieved: (a) volitional fatigue (b) 85% of the age-predicted maximal HR (220 - age) (c) submaximal test was completed. Each stage lasted 3 minutes and an extra minute was added to obtain the steady-state HR if HR varied by more than $5\ \text{beats} \cdot \text{min}^{-1}$ between the second and third minutes of each stage. If the variation was within $5\ \text{beats} \cdot \text{min}^{-1}$, the steady-state HR of the current stage was recorded and subjects were asked to progress to the next stage. The test assumed a linear relationship between HR and workload at 110 - 150 $\text{beats} \cdot \text{min}^{-1}$ HR range (Golding et al., 1989). HR collected from the last two stages of the test and the respective workload calculation were used to draw a straight line between workload (x - axis) and HR (y - axis) and the line extended to the subject's age-predicted maximal HR (220 - age) to calculate the corresponding maximal working capacity (W_{peak}). $\dot{V}O_2$max was subsequently calculated using the RSE metabolic equation which was developed previously.

Data collection

Data collection was performed at the Research Center for Information Technology of Sports and Health. The cycle ergometer and RSE exercise test were conducted separately on a Monark cycle ergometer (Monark 839E, Sweden) and the RSE invented by members of the Research Center for Information Technology of Sports and Health. The seat and handle heights/positions of both sets of equipment were adjusted according to each subject's comfort. A metabolic measurement system (MedGraphics VO2000, UK) was used to measure and analyze oxygen uptake through collection of expired gases during the tests. Subjects wore a nose clip and expired through a two-way rebreathing valve connected to the metabolic cart. HR was continuously monitored throughout each exercise testing session using a Polar HR monitor (Polar Electro, Finland). All equipment was calibrated precisely before testing according to the manufacturer's recommendations.

Statistical analysis

The arithmetic mean and standard deviation were used for descriptive statistics. Pearson correlation coefficient (r) was used to determine the relationship between the CE $\dot{V}O_2max$ test and the RSE YMCA submaximal test and a Bland-Altman plot was constructed to determine the level of agreement between the CE measured $\dot{V}O_2max$ and RSE YMCA estimated $\dot{V}O_2max$. The standard error of the estimate($SEE = S_y\sqrt{(1-r^2)}$) was calculated to estimate the accuracy of the RSE YMCA estimated $\dot{V}O_2max$ and CE measured $\dot{V}O_2max$. The mean difference of the prediction was calculated by subtracting the RSE YMCA $\dot{V}O_2max$ test result from the CE $\dot{V}O_2max$ test result. Paired t test was used to examine for a significant difference between the two test results. To determine the test-retest reliability for each testing protocol, the intra-class correlation coefficients (ICC) were calculated for the CE maximal testing and RSE submaximal testing protocols. Regression analysis was used to develop the equation to predict oxygen uptake ($\dot{V}O_2$) from power output (W).

Results

All subjects' individual data points and a regression line of measured oxygen uptake ($\dot{V}O_2$) on power output (W) from the RSE multistage test are presented (Figure 3). The linear equation (A) was represented to calculate $\dot{V}O_2$ from W for the RSE test and a high correlation was observed between the two variables ($R^2 = 0.88$):

$$\dot{V}O_2(\mathrm{mL}\cdot min^{-1}) = 12.4 \times W(\text{watts}) + 351\ \mathrm{mL}\cdot min^{-1} \quad \text{(A)}$$
$$(R^2 = 0.88,\ SEE = 155.5\ \mathrm{mL}\cdot \mathrm{min}^{-1})$$

Similarly to the ACSM leg ergometry metabolic equation (Heyward, 2013), after factoring in an estimation of resting metabolism per kg of body weight (M) the additional unloaded stepping $\dot{V}O_2$ was approximately 160 $\mathrm{mL}\cdot\mathrm{min}^{-1}$, the final equation (B) was developed and then used for predicting $\dot{V}O_2$ from a submaximal power output (W).

$$\dot{V}O_2(\mathrm{mL}\cdot min^{-1}) = 12.4 \times W(\text{watts}) + 3.5\ \mathrm{mL}\cdot kg^{-1}\cdot min^{-1} \times \mathrm{M} + 160\mathrm{mL}\cdot min^{-1} \quad \text{(B)}$$
$$(R^2 = 0.91,\ SEE = 134.8\ \mathrm{mL}\cdot \mathrm{min}^{-1})$$

Mean and standard deviation values for the two exercise test (CE maximal and RSE submaximal exercise test) variables are reported (Table 3). The mean difference between two variables was 2.5 $\mathrm{mL}\cdot\mathrm{kg}^{-1}\cdot\mathrm{min}^{-1}$. A paired t test revealed no significant difference between CE $\dot{V}O_2max$ and RSE YMCA $\dot{V}O_2max$ ($p < 0.01$). Pearson's correlation coefficient between the RSE YMCA submaximal exercise test for estimated $\dot{V}O_2max$ and CE maximal exercise test for measured $\dot{V}O_2max$ ($r = 0.87$, Figure 4) indicated a strong relationship between the two tests for assessing cardiorespiratory fitness in young healthy male adults, and the standard error of the estimate (SEE) was 3.55 $\mathrm{mL}\cdot\mathrm{kg}^{-1}\cdot\mathrm{min}^{-1}$. The Bland-Altman plot (Figure 5) presents the agreement between CE $\dot{V}O_2max$ and RSE YMCA $\dot{V}O_2max$. The bias for two $\dot{V}O_2max$ values was 2.5$\mathrm{mL}\cdot\mathrm{kg}^{-1}\cdot\mathrm{min}^{-1}$, with limits of agreement of -4.3 $\mathrm{mL}\cdot\mathrm{kg}^{-1}\cdot\mathrm{min}^{-1}$ and 9.3 $\mathrm{mL}\cdot\mathrm{kg}^{-1}\cdot\mathrm{min}^{-1}$. High test-retest reliabilities were found for both the CE maximal exercise test (ICC = 0.91) and the RSE submaximal exercise test (ICC = 0.92).

Table 3. Measured CE (cycle ergometer) and estimated $\dot{V}O_2max$ (maximum oxygen consumption, $mL\cdot kg^{-1}\cdot min^{-1}$) from the RSE (rectilinear stepping ergometer) YMCA submaximal test (n = 32).

Test	Range	Means (±SD)
CE $\dot{V}O_2max$	28.6-56.5	41.8 (7.2)
RSE YMCA $\dot{V}O_2max$	29.3-57.7	44.3 (6.1)

Discussion

Since laboratory direct measurement of $\dot{V}O_2max$ is expensive, time-consuming and requires well-trained personnel, submaximal exercise testing is a more practical and efficient way in clinical practice when assessing cardiorespiratory fitness. The prediction of $\dot{V}O_2max$ using

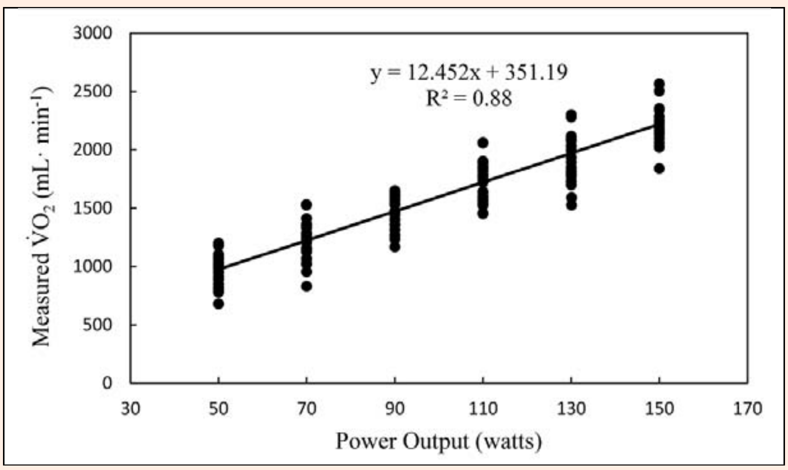

Figure 3. Relationships between measured $\dot{V}O_2$ and power output (W) through RSE multistage exercise test

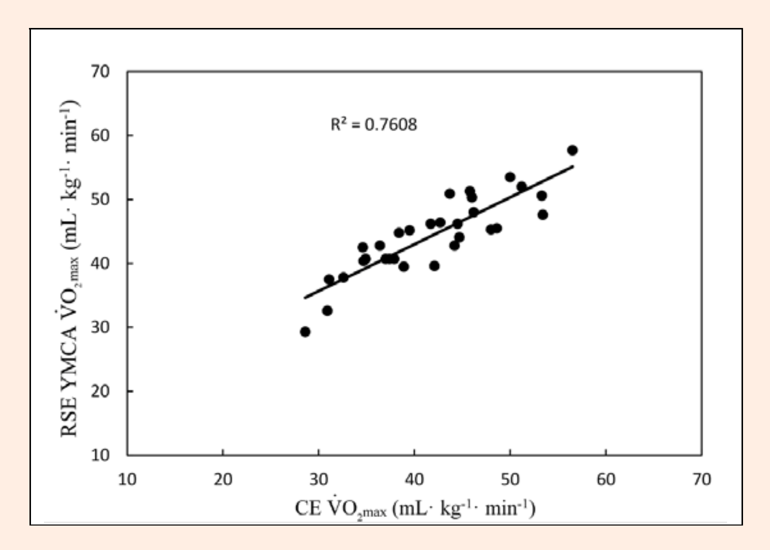

Figure 4. CE measured $\dot{V}O_2$max versus RSE YMCA estimated $\dot{V}O_2$max. Pearson correlation is represented.

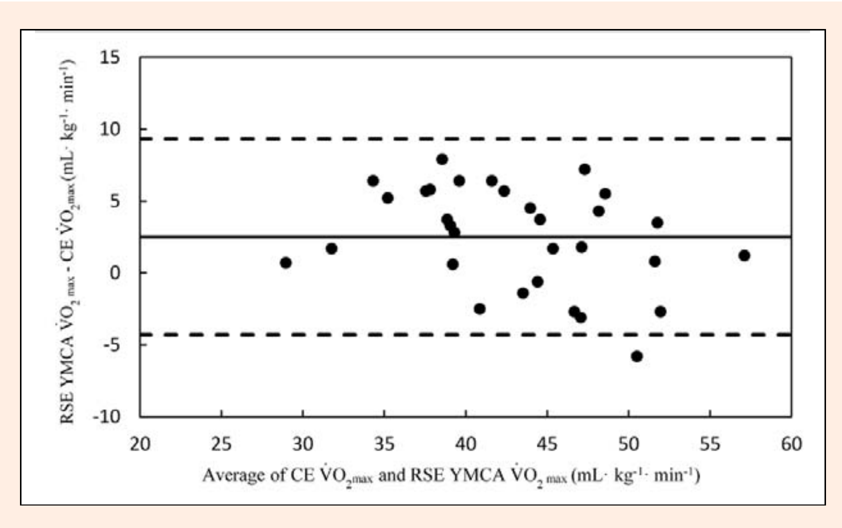

Figure 5. Bland-Altman plot of CE measured $\dot{V}O_2$max and RSE YMCA estimated $\dot{V}O_2$max

submaximal testing is more appropriate in certain venues such as fitness centers, rehabilitation clinics, and assisted living facilities (Billinger et al., 2012), where maximal testing is not feasible. In this study, we designed a rectilinear stepping ergometer (RSE) as a new modality of exercise device for assessing cardiorespiratory fitness and our findings suggested that the YMCA submaximal exercise test protocol performed on the RSE could accurately predict $\dot{V}O_2$max in young healthy male adults. The study potentially provides the publics and health care professionals a new and alternative modality of exercise to assess cardiorespiratory fitness.

Our findings suggested that the RSE YMCA submaximal exercise test was valid and feasible for estimating $\dot{V}O_2$max in young healthy male adults. The RSE YMCA submaximal exercise test was strongly correlated with the CE maximal exercise test for assessing $\dot{V}O_2$max ($r = 0.87$) and the mean difference between the two tests was 2.5 $mL \cdot kg^{-1} \cdot min^{-1}$, which was not significantly different ($p < 0.01$). The SEE reflects the accuracy of the estimate, a lower SEE value indicating a greater accuracy of the predicted result. In our study, the SEE of 3.55 $mL \cdot kg^{-1} \cdot min^{-1}$ was close to 1 metabolic equivalent (1 MET = 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$) and considered appropriate for predicting $\dot{V}O_2$max (Heyward, 2013). Furthermore, as illustrated in Figure 5, the limits of agreement presented that both upper and lower limit were below the recommended 10 $mL \cdot kg^{-1} \cdot min^{-1}$ (Heyward, 2013), which reflects a good predictive capability.

Although the mean difference between CE $\dot{V}O_2$max and RSE YMCA $\dot{V}O_2$max was no more than 3 $mL \cdot kg^{-1} \cdot min^{-1}$, we found that the RSE YMCA submaximal exercise test did overpredict $\dot{V}O_2$max, which was 2.5 $mL \cdot kg^{-1} \cdot min^{-1}$ higher than CE measured $\dot{V}O_2$max. A previous cross-validated study by Beekley et al. (2004) reported the validity of the CE YMCA test against the maximal exercise test of CE and treadmill (TM). They found a moderately high significant correlation between TM $\dot{V}O_2$max and predicted $\dot{V}O_2$max from the CE YMCA test ($r = 0.77$, $p < 0.05$), with a mean difference between the two variables of 1.84 $mL \cdot kg^{-1} \cdot min^{-1}$, indicating that the current CE YMCA submaximal test appeared to be effective in predicting TM $\dot{V}O_2$max rather than CE $\dot{V}O_2$max. Beekley et al. (2004) suggested some factors that may have led to a prediction error between the TM measured $\dot{V}O_2$max and the CE YMCA predicted $\dot{V}O_2$max, including the sex of the subjects, differences in exercise modalities, and only partial linearity between the power output (W) and heart rate (HR) in the YMCA protocol.

In our study, the prediction difference between the two exercise tests may be attributed to several factors. First, the RSE metabolic equation was developed based on the relationship between actual $\dot{V}O_2$ and W and we used this equation to predict $\dot{V}O_2$ from W during the submaximal test. The slope of our developed equation was 12.4 $mL \cdot watt^{-1} \cdot min^{-1}$, which was slightly higher than the slope of the current ACSM leg ergometer metabolic equation (10.8 $mL \cdot watt^{-1} \cdot min^{-1}$) (Heyward, 2013). This increase of slope could be explained by the use of different exercise modalities and may result in a higher value for the RSE estimated $\dot{V}O_2$max. Lang et al. (1992) mentioned that the intercept of the metabolic equation, including a resting metabolism estimation and an tra $\dot{V}O_2$, could be another important source of prediction error. Second, the YMCA submaximal test was based on the assumption that the linear relationship existed between W and HR (Golding et al., 1989). However, several studies have mentioned that this linearity existed only at certain heart rates (Beekley et al., 2004; Golding et al., 1989; Lang et al., 1992). As described in the Y's way to Physical Fitness (Golding et al., 1989), at low heart rates, many external stimuli, such as talking, laughter, and nervousness, could affect the heart rate. Also, when exercise intensity exceeded the gas exchange threshold (GET), the relationship was no longer linear (Jamnick et al., 2016; Londeree et al., 1997). Thus, in our study, this nonlinearity may result in an overprediction of $\dot{V}O_2$max. In addition, the exercise modality could have a crucial influence on prediction difference. Despite both the CE and RSE belonging to lower-extremity exercise, the muscle groups mobilized in these two exercises are different and this may be an important factor in prediction accuracy.

To our knowledge, our study is the first to study exercise testing using a rectilinear reciprocating motion. We chose to study this rectilinear stepping exercise modality for several reasons. First, compared with traditional circular motion, the up and down rectilinear motion overcomes the mechanical dead centers, known as the "dead spots" in some studies (Chen et al., 1997; Chen et al., 2001). Chen et al. (1997) described the "dead spots" at 0 and 180 degree of crank arm position in cycling with functional electrical stimulation (FES), basically the transition point between knee extension and flexion during the cyclical movement of the leg. Other researchers have reported that, under a stable cycling status, the cycling speed decreased more violently at the mechanical "dead spots" angle at which points the stimulated muscle has minimal amount of torque output (Chen et al., 2001). Moreover, Ericson and Nisell (1988) suggested that in rotary crank mechanism, the optimum mechanical efficiency was reached if the centrifugal force equaled zero, implying that the sum of forces was directed tangentially and acted in its entirety in the direction as the pedal moves. Therefore, we suggest that such a rectilinear reciprocating motion of RSE is mechanically efficient because the vertical force is nearly the only tangential force and it is entirely in the direction of the pedal's movement. Second, since some individuals are unfamiliar with cycling exercise (American College of Sports Medicine, 2013), the RSE maybe more simple for them to use. A short-stroke stepping pattern of the RSE may be applicable for those who cannot perform large scale leg movement, such as elderly people or individuals with knee injury. Additionally, RSE is a lower-limb exercise modality, and lower-limb dominant exercise training improves flow-mediated vasodilation (FMD) in the lower extremities for patients with chronic heart failure (CHF) (Kobayashi, et al., 2003).

Another advantage of RSE is that a constant power output is ensured with stepping cadence fluctuating over certain ranges. The exciting current of the electric generator instantaneously changes to adjust the resistance based on the *proportion integration differentiation* (PID) control principle, to inversely change the increase or decrease of power output (W) caused by the fluctuation of stepping cadence. When instant power output exceeds the target value, the exciting current needs to decrease to lower the resistance, so the instant power output decreases simultaneously. Conversely, the exciting current will be increased when the instant power output is under the target value. Thus, the constant power output is maintained during the exercise test. This is crucial for standardizing the workload across all subjects and maintaining constant power allows subjects to reach a steady state HR (within 5 $beats \cdot min^{-1}$) during submaximal exercise test (Billinger et al., 2012; Herda et al., 2014).

The results presented in this study are limited to a relatively small sample size (n = 32) of male subjects. The validity of the RSE YMCA submaximal exercise test for estimating $\dot{V}O_2$max needs to be confirmed in a wider sample including females and subjects of different ages and physical condition. In addition, the RSE metabolic equation should be revised by considering gender and stepping cadence as determinants of $\dot{V}O_2$ and its validity requires testing on a larger variety of populations. Another limitation of the present study is that the volunteers we recruited had a predetermined positive attitude toward the study and physical activity. Subjects unaccustomed to the exercise on the RSE may reach volitional fatigue more quickly due to leg muscle fatigue similar to that of a cycle ergometer, affecting the prediction accuracy of $\dot{V}O_2$max.

There is a need for further research to improve accuracy in the prediction of $\dot{V}O_2$max from the RSE submaximal exercise test with a larger variety of populations, and to examine the validity of the RSE graded maximal exercise test in determining $\dot{V}O_2$max. Furthermore, research into the biomechanical advantages and efficiency of energy expenditure from this novel exercise modality would also be of value.

Conclusion

A rectilinear stepping exercise modality was presented in this study and the results indicated that the RSE submaximal exercise test was valid and reliable for estimating $\dot{V}O_2$max in young healthy male adults. Since submaximal exercise test is more practical in assessing cardiorespiratory fitness without expense, risk, and hard effort, the result of this study will provide the rectilinear stepping exercise as an effective submaximal exercise mode for predicting $\dot{V}O_2$max for the publics. The RSE designed for this study may be potentially developed as a new and alternative ergometer to assess cardiorespiratory fitness and could be used in the future by healthcare professionals to promote personalized health interventions.

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Key points

- The rectilinear stepping exercise is a simple modality of exercise, which requires only up and down movements of the legs. It overcomes the mechanical dead centers of circular motion and is mechanically efficient. It is potentially applicable to a large group of populations.
- The RSE gives an accurate measurement of power output and ensures a constant power output independent of stepping cadence.
- The RSE submaximal exercise test is valid and feasible for estimating $\dot{V}O_2$max in young healthy male adults compared with the CE maximal exercise test.
- The rectilinear stepping exercise is an effective submaximal exercise mode for predicting $\dot{V}O_2$max. The RSE designed for this study may be potentially developed as a new and alternative ergometer to assess cardiorespiratory fitness and could be used in the future by healthcare professionals to promote personalized health interventions.

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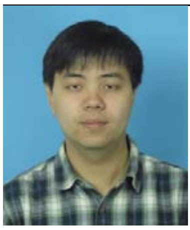

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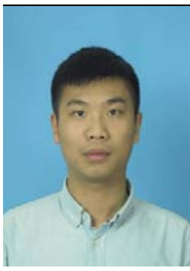

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