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Original Research

Use of Heart Rate Index to Predict Oxygen Uptake – A Validation Study

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ABSTRACT

International Journal of Exercise Science 13(7): 1705-1717, 2020. An equation that uses heart rate index (HRI) defined as HR/HRrest to predict oxygen uptake (VO_2) in METs (e.g., METs = 6 × HRI – 5) has been developed retrospectively from aggregate data of 60 published studies. However, the prediction error of this model as used by an individual has not been established. Therefore, the purpose of this study was to examine the predictive validity of the HRI equation by comparing submaximal and maximal VO_2 predicted by the equation (VO_2-Pred) with that measured by indirect calorimetry (VO_2-Meas). Sixty healthy adults (age 20.5 ± 2.4 yr., body mass 69.4 ± 13.4 kg, height 1.7 ± 0.1 m) underwent a VO_2max test and an experimental trial consisting of a 15-min resting measurement and three successive 10-min treadmill exercise bouts performed at 40%, 60% and 80% of VO_2max. VO_2 and HR were recorded during both the submaximal and maximal exercises and used to obtain VO_2-Pred and VO_2-Meas for each intensity and for VO_2max. Validation was carried out by paired t-test, regression analysis, and Bland-Altman plots. A modest but significant ($p < 0.05$) correlation was observed between VO_2-Meas and VO_2-Pred at 40% ($r = 0.58$), 60% ($r = 0.53$), and 80% of VO_2max ($r = 0.56$) and at VO_2max ($r = 0.50$). No differences between VO_2-Pred and VO_2-Meas were found at 40% (5.53 ± 1.21 vs. 5.28 ± 0.98 METs, respectively) of VO_2max, but VO_2-Pred was higher ($p < 0.05$) than VO_2-Meas at 60% (8.42 ± 1.77 vs. 7.96 ± 1.39 METs, respectively) and 80% (10.79 ± 2.13 vs. 10.29 ± 1.81 METs, respectively) of VO_2max. In contrast, VO_2-Pred was lower ($p < 0.05$) than VO_2-Meas at VO_2max (12.32 ± 2.30 vs. 13.38 ± 2.24 METs, respectively). Standard errors of the estimate were 0.81, 1.20, 1.54, and 1.97 METs at 40%, 60%, 80% of VO_2max and at VO_2max, respectively. These results suggest that further investigation aimed to establish the accuracy of using HRI to predict VO_2 is warranted.

KEY WORDS: Validity, prediction accuracy, metabolic equivalent, submaximal exercise, maximal oxygen uptake

INTRODUCTION

Using heart rate (HR) to estimate energy expenditure and maximal oxygen uptake (VO_{2max}) has been extensively investigated on the basis of the well-known linear relationship between HR and oxygen uptake (VO_2) (8, 30). The method is, however, subject to the limitation that HR-VO_2 relationship can be affected by factors such as age, sex, fitness, exercise modality, and environmental conditions (1, 3, 22). In attempting to mitigate the effect of these variables, the use of HR index (HRI), which is equal to a given HR divided by resting HR (HR_{rest}) has been purposed (19, 25, 26, 28, 29). It is considered that this HR-based ratio scale that includes HR_{rest} can potentially remove the need for individual calibration often required for tracking daily activity using HR (26, 28). Recently, HRI has been shown to correlate with levels of habitual physical activity in adults (27).

The utility of HRI was further examined in a retrospective study that extracted the data from 60 published studies to explore the relationship between various HR measures and VO_2 under both submaximal and maximal conditions (28). In this study, Wicks et al. (28) developed a prediction equation that uses HRI as an independent variable to estimate mass-specific VO_2 or MET: METs = 6 × HRI – 5, where a MET equals 3.5 ml·kg^{-1}·min^{-1} of VO_2 (2). As the dataset includes diverse populations, different modes of exercise, and both submaximal and maximal data, the authors claimed that the equation has the potential to allow for inter-individual comparisons without individual calibration (28). An equation that involves HR_{net} (i.e., HR – HR_{rest}) was also evaluated in the same study. However, the authors found that the model that involves HR_{net} (i.e., METs = 0.09 × HRI + 1) could underestimate VO_2 especially in endurance-trained individuals with higher levels of VO_{2max} (28). Given that the HRI equation was developed based off aggregate analysis, this study could not determine its prediction accuracy when applied on an individual basis. Interestingly, in a study that attempted to cross-validate this predictive model among a group of college-aged men, Haller et al. (13) found that the equation significantly underestimated VO_{2max} by an average of 5.1 ml·kg^{-1}·min^{-1}.

Using the HRI equation that involves only two simple measurements, resting HR and activity HR (either submaximal or maximal), to assess both energy expenditure and cardiorespiratory fitness can be attractive to clinicians and fitness professionals. However, evidence concerning its predictive validity remains both scarce and inconsistent. Hence, the present investigation was designed to cross-validate the HRI equation proposed by Wicks et al. (28) by employing both submaximal and maximal exercise protocols. We hypothesized that VO_2 predicted from the HRI equation would be comparable to VO_2 measured by indirect calorimetry regardless of exercise intensity.

METHODS

Participants

Sixty healthy young adults including 28 males and 32 females participated in this study. These participants were healthy, free of any orthopedic injury, and have not taken any medications, anabolic steroids, or nutritional supplements known to affect exercise performance as revealed by their responses to a medical and physical activity questionnaire. The sample size was determined by the G*Power software program (version 3.0.10) using the data reported by Haller et al. (13). In this study, effect sizes ranged from 0.37 to 0.92 for the three treadmill protocols employed, which indicated that a largest sample size needed to achieve an 80% power at 0.05 is 60. 20% of these participants were involved in varsity sports such as baseball, basketball, field hockey, soccer, swimming, and track/cross-country, whereas the remaining participants were considered physically active but did not participate in an organized training program for more than three months. Participants were informed of the purpose and testing procedures of the study and each gave their written consent to participate. All experimental procedures were evaluated and approved by the Institutional Review Board for Human Subjects Experimentation. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (21). The physical and physiological characteristics of participants are presented in Table 1.

Table 1. Physical and physiological characteristics of subjects.

Variables	Men (n = 28)	Women (n = 32)	Both Sexes (n = 60)
Age (yr.)	20.5 ± 1.6	20.5 ± 2.9	20.5 ± 2.4
Body mass (kg)	79.46 ± 11.82	60.54 ± 6.91	69.37 ± 13.40
Height (m)	1.79 ± 0.10	1.65 ± 0.06	1.72 ± 0.10
% Fat	12.94 ± 5.91	25.02 ± 5.10	19.38 ± 8.16
VO_{2rest} (ml·kg^{-1}·min^{-1})	3.81 ± 0.65	3.58 ± 0.41	3.68 ± 0.54
VO_{2max} (ml·kg^{-1}·min^{-1})	51.71 ± 6.95	42.58 ± 6.06	46.84 ± 7.91
VO_{2max} (l·min^{-1})	3.95 ± 0.96	2.57 ± 0.41	3.21 ± 1.00
HR_{rest} (beats·min^{-1})	64.51 ± 6.26	74.4 ± 10.50	69.78 ± 10.07
HR_{max} (beats·min^{-1})	197.75 ± 7.03	197.00 ± 6.18	197.68 ± 6.13
HRI_{max}	3.09 ± 0.28	2.71 ± 0.37	2.89 ± 0.38
RER_{max}	1.16 ± 0.07	1.12 ± 0.07	1.14 ± 0.07
V_{Emax} (l·min^{-1})	131.46 ± 23.44	87.11 ± 15.53	107.81 ± 29.60

Data are means ± SD. VO_2: oxygen uptake; HR: heart rate; HRI: heart rate index defined as HR/HR_{rest}; RER: respiratory exchange ratio; V_{Emax}: maximal expiratory ventilation.

Protocol

Design: Each participant completed a familiarization session, a VO_{2max} test, and an experimental trial on three separate days. Participants' body mass and body composition were determined during the familiarization session. During VO_2max tests, participants performed an incremental exercise on a treadmill until volitional exhaustion. The experimental trial consisted of a 15-min resting period and three successive 10-min treadmill exercise bouts performed at 40%, 60% and 80% of VO_2max in an ascending order, respectively. VO_2 and HR were measured continuously during both the rest and exercise periods. Data from these measurements allowed for predicting VO_2 from HRI using the equation developed by Wicks et al. (28): METs = 6 × HRI – 5. The predicted VO_2 values were then compared with VO_2 directly measured by indirect calorimetry at submaximal and maximal levels.

Both the VO_{2max} tests and the experimental trials were conducted in a 3-hour post-absorptive state and separated by at least 48 hours between testing sessions. On the day prior to each testing session, subjects were instructed to avoid any vigorous physical activities, to refrain from alcohol and caffeine consumption, and to follow their usual diets. All tests took place in a thermoneutral laboratory where the mean ambient temperature and relative humidity were maintained between 22-24 ºC and 48-50%, respectively.

Familiarization Session: Subjects attended a familiarization session prior to the start of the study. During this session, instructions regarding the testing protocols, instrumentation, and measurement were provided. Subjects' body mass, height, and percent body fat were also determined. Height and body mass were measured to the nearest 0.1 cm and 0.1 kg using a wall-mounted stadiometer and an electronic weight scale, respectively. Percent body fat was measured by the same researcher who had experience in using the Lange caliper and the sex specific 3-site skinfold techniques as described by Jackson et al (17, 18). Participants were given the opportunity to practice incline running on a treadmill up to ~75% of their age-predicted maximal HR (HR_{max}). In this session, subjects also received instructions regarding physical activity and dietary guidelines that they would need to follow prior to the subsequent tests.

VO_{2max} Tests: VO_{2max} was assessed using a progressive, multi-stage protocol on a treadmill in conjunction with a metabolic system. The protocol consisted of a general warm-up of walking at 3.5 mph followed by running at a constant speed (i.e., between 5 and 6 miles·hr^{-1}) with percent grade increased by 2.5% every 2 minutes (4). All subjects were verbally encouraged to continue exercise until volitional exhaustion. The test was considered valid when the subjects met at least two of the following three criteria: an increase in VO_2 of less than 150 ml·min^{-1} despite an increase in work load, a RER value greater than 1.15, and a HR reaching within 10% of age-predicted maximal HR (15). Throughout the test, VO_2 was obtained breath-by-breath, while HR was recorded every second. Both VO_2 and HR were then averaged over 30 second intervals, and VO_{2max} and HR_{max} were identified as the highest 30-second average from each respective measurement. Upon completion of the test, a best-fit linear regression analysis in which treadmill stage was plotted as a function of VO_2 was calculated. This analysis provided the estimated treadmill speeds and inclines that were used to produce intensities corresponding to 40%, 60%, and 80% of VO_{2max} during the experimental trials.

Experimental Trials: The experimental session consisted of a 15-min resting period and three 10-min treadmill exercise bouts performed at 40%, 60% and 80% of VO_2max. Upon arrival, subjects sat quietly for 10 minutes before resting measurements. Resting VO_2 and HR were measured in a quiet room with dim lights when participants were in a semi-recumbent position. Participants then proceeded with running/walking on a motor-driven treadmill at intensities that elicited 40%, 60%, and 80 % of VO_{2max} in an ascending order. These target intensities were achieved via an initial adjustment made to both speed and incline during the first 2 min of each 10-min exercise period. All subjects began level walking at 4 miles·hr^{-1} followed by a gradual increase in speed and/or incline until a desired level of VO_2 was achieved. Thereafter, VO_2 responses were strictly monitored, and a further adjustment was made to speed and/or incline if necessary in order to maintain the target VO_2. Each level of intensity lasted 10 min, so the entire exercise session was 30 min in duration. The three levels of intensities were given successively without a rest period in between intensities. This protocol was chosen in order to simply produce various levels of exertion so that multiple pairs of VO_2 and HR across a wide range of the intensity spectrum could be recorded and used for prediction by the HRI equation.

Dependent variables including VO_2 and HR were measured continuously during the 15-min rest period and throughout the three stages of exercise. VO_2 was obtained breath-by-breath, while HR was recorded every second. Both VO_2 and HR were then averaged over 30-second intervals. Resting VO_2 and HR were identified as an average of the two lowest 30-second measures collected during the last 5 min of the rest period. Exercising VO_2 and HR were determined for 40%, 60%, and 80 % of VO_{2max} separately by averaging the last 5-min of each 10-min measurement period.

Measurement and Instrumentation: VO_2 was measured in real time breath-by-breath during both the VO_2max tests and the experimental trials using the MedGraphics ULTIMA metabolic system (MedGraphics Corporation, St. Paul, MN). Prior to each testing session, ambient temperature and pressure was checked and gas and volume calibration were performed. The subject wore a face-fitting respiratory mask that was fastened and carefully checked for proper sealing. Gas analyzers were calibrated before each test using gases provided by MedGraphics Corporation: 1) calibration gas: 5% CO_2, 12% O_2, balance N_2; and 2) reference gas: 21% O_2, balance N_2.
HR was recorded every second throughout the testing session with a wireless Polar® HR monitor (Model A300, Polar Electro Inc., Finland) that determined HR based on R-R intervals. Before each test, the subject was fitted snugly with a HR strap around their chest. Upon completing a test, HR data were downloaded and aligned with VO_2 data temporally.

Calculations: HRI was calculated as an intensity-specific HR or HR_{max} divided by HR_{rest} for exercise performed at 40%, 60%, 80% of VO_{2max} and at VO_{2max} separately. VO_2 in MET was then predicted from HRI using the equation proposed by Wicks et al. (28), i.e., MET = 6 × HRI - 5. The validity of using HRI to predict energy expenditure and cardiorespiratory fitness was carried out by comparing VO_2 predicted (VO_2-Pred) with that measured by indirect calorimetry (VO_2-Meas) at each level of submaximal intensity and at VO_{2max}.

Statistical Analysis
Data were first analyzed for its normality using the Shapiro-Wilk test. The prediction accuracy was examined by carrying out paired t-tests of the measured and predicted VO_2 values and the regression analysis that provided correlation coefficients and standard error of the estimate (SEE). In addition, Bland-Altman plots (6) were constructed to provide information regarding the systematic bias and upper and lower limits of agreement between VO_2-Pred and VO_2-Meas for both the submaximal and maximal exercises. For all statistical tests, a probability level of 0.05 was established to denote statistical significance. Statistical analyses were carried out using the Statistical Package for the Social Sciences (Version 25.0, SPSS, Inc. Chicago, IL).

RESULTS

No differences between VO_2-Pred and VO_2-Meas were observed at 40% of VO_{2max} (Table 2). However, VO_2-Pred was higher ($p < 0.05$) than VO_2-Meas at 60 and 80% of VO_{2max}. There was a significant ($p < 0.05$) correlation coefficient between VO_2-Pred and VO_2-Meas at 40% ($r = 0.58$), 60% ($r = 0.53$), and 80% of VO_{2max} ($r = 0.56$). Prediction error as measured by SEE were 0.81, 1.20, to 1.54 METs, representing 14.6, 14.3, and 14.3% of the estimated VO_2 at 40%, 60%, and 80% of VO_{2max}, respectively. Bland and Altman analysis revealed that the mean of the differences between VO_2-Pred and VO_2-Meas and the upper/lower limits of agreement were +0.25 and 2.25 /-1.75 METs, +0.46 and 3.52 /-2.61 METs, and +0.50 and 4.18 /-3.19 METs at 40%, 60%, and 80% of VO_{2max}, respectively (Figure 1).

Table 2. Comparisons of VO_2 predicted (VO_2-Pred) and VO_2 measured (VO_2-Meas) during submaximal and maximal exercise.

Exercise Intensity	VO_2-Pred (MET) (CV)	VO_2-Meas (MET) (CV)	T-test (*p* value)	Mean Bias (MET)(95% CI)	CC (*r*)	SEE (MET)
40% VO_{2max}	5.53 ± 1.21 (21.88%)	5.28 ± 0.98 (18.56%)	0.064	+0.25 (-1.75, 2.25)	0.583#	0.81
60% VO_{2max}	8.42 ± 1.77 (21.02%)	7.96 ± 1.39* (17.46%)	0.029	+0.46 (-2.61, 3.52)	0.533#	1.20
80% VO_{2max}	10.79 ± 2.13 (19.74%)	10.29 ± 1.81* (17.59%)	0.044	+0.50 (-3.19, 4.18)	0.555#	1.54
VO_{2max}	12.32 ± 2.30 (18.67%)	13.38 ± 2.24* (16.74%)	0.001	-1.06 (-5.51, 3.38)	0.501#	1.97

Data are means ± SD; MET: Metabolic equivalent of task; CV: coefficient of variation expressed as percentage; Bias: VO_2-Pred – VO_2-Meas; CI: Confidence Interval; CC: correlation coefficient; SEE: standard error of the estimates. *Significant difference between VO_2-Pred and VO_2-Meas, $p < 0.05$. #Significant correlation coefficient between VO_2-Pred and VO_2-Meas, $p < 0.05$.

As for the maximal exercise, VO_2-Pred was significantly ($p < 0.05$) lower than VO_2-Meas at VO_{2max} (Table 2). There was a weaker but still significant correlation ($r = 0.50$, $p < 0.05$) between VO_2-Pred and VO_2-Meas at VO_{2max}. Prediction errors as measured by SEE was 1.97 METs and this value represented 16% of the estimated VO_{2max}. The mean of the differences between VO_2-Pred and VO_2-Meas was -1.06 METs with the upper and lower limits of agreement being 3.38 and -5.51 METs, respectively (Figure 2).

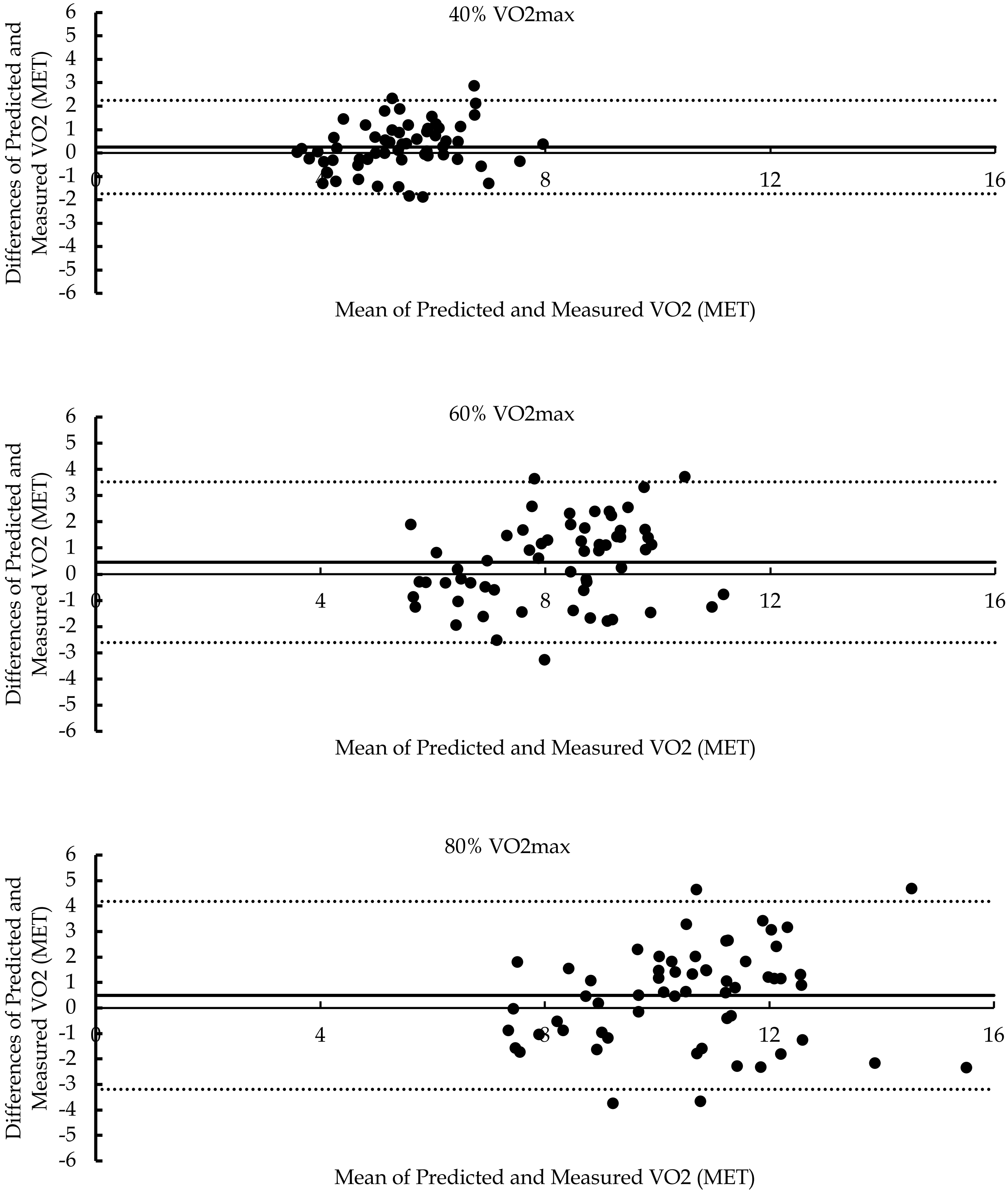

Figure 1. Bland-Altman plots of the differences between VO_2 predicted and VO_2 measured (*y axis*) against their means (*x axis*) at 40%, 60%, and 80% of VO_2max. The bias (solid line: mean difference) and limits of agreement (dash lines: mean difference ± 1.96 SD) are displayed.

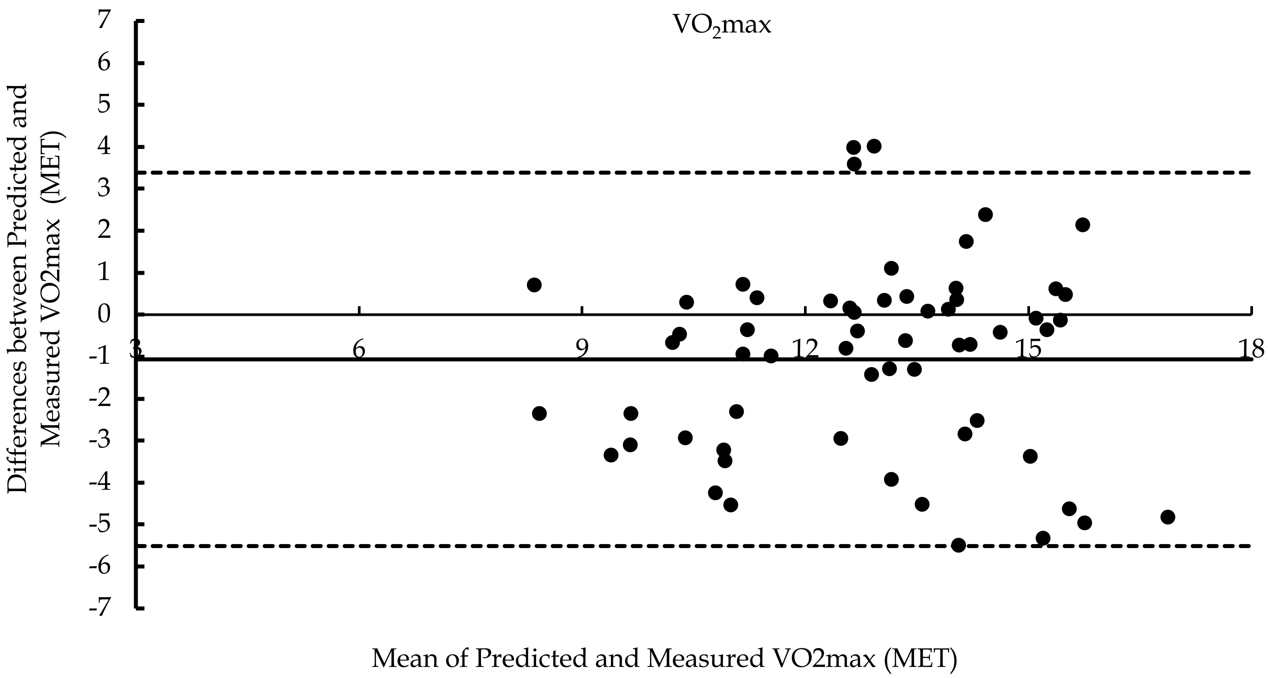

Figure 2. Bland-Altman plot of the differences between VO_2 predicted and VO_2 measured (*y axis*) against their means (*x axis*) at VO_2max. The bias (solid line: mean difference) and limits of agreement (dash lines: mean difference±1.96 SD) are displayed.

DISCUSSION

It appears that a positive relationship exists between VO_2 calculated by the HRI equation and VO_2 measured during both submaximal and maximal exercise in healthy young adults. This can be evidenced by a statistically significant correlation coefficient found at each submaximal intensity as well as at VO_{2max}. The equation, however, yields mixed results on prediction outcome. Although there were no significant differences between VO_2-Pred and VO_2-Meas at 40% of VO_{2max}, VO_2-Pred was significantly higher ($p < 0.05$) than VO_2-Meas at 60% and 80% of VO_{2max}. The prediction agreement shown at 40% of VO_{2max} is encouraging as this intensity (~5 METs) represents a level of exertion often experienced in leisure physical activities (2). However, there was a significant overestimation by ~0.5 METs when exercise was performed at 60 and 80% of VO_{2max}. One possible explanation for this prediction bias could be the difference in testing protocols used between the two studies. Data used for developing the equation was mainly based on incremental protocols in which each stage is usually short lasting 2-3 min, whereas the protocol used in our investigation involved three stages of 10-min steady-state exercise. As shown in Figure 3, there was a continued incline in VO_2 and HR until 5 - 6 min into each stage with VO_2 showing a more noticeable steady-state pattern. In this context, it is likely that the HR-VO_2 relation depicted by the equation may not reflect how VO_2 and HR have responded at higher intensities in the present study. Exercise at higher intensities (i.e., > lactate threshold) of sufficient duration (i.e., >3 min) has been associated with a disproportional rise in VO_2 and HR due to increased muscular fatigue (11). Recently, it has been shown that the upward drift of HR (or HR slow component) would occur at lower intensity and in a greater magnitude as compared to VO_2 slow component (32).

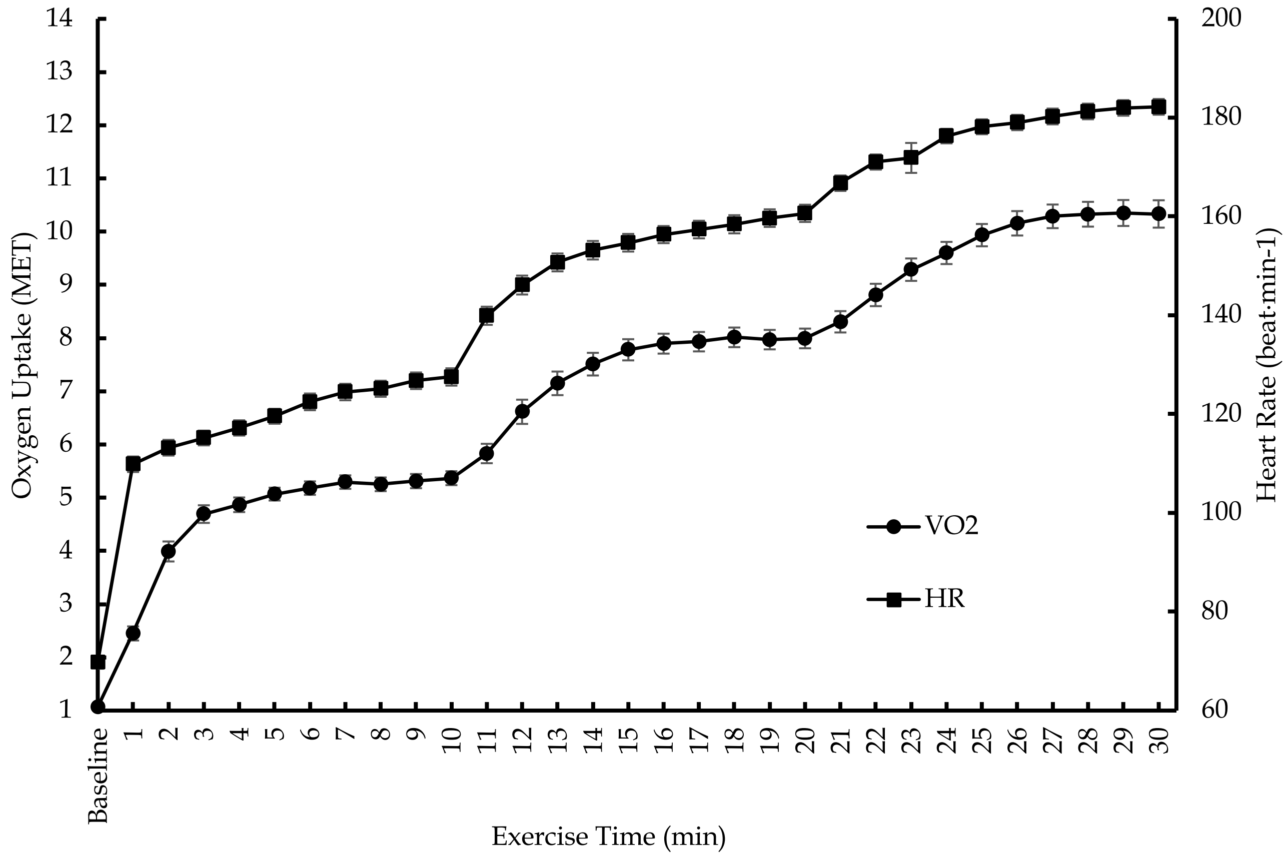

Figure 3. Responses of oxygen uptake and heart rate during the experimental trial. Data are means ± SE.

In the present study, the three levels of intensity were given in an ascending order without a rest period in between intensities. This protocol was chosen simply because we wanted to create various levels of exertion during a 30-min period so that multiple pairs of VO_2 and HR across a wide range of the intensity spectrum could be recorded and used for prediction by the equation. Although high-intensity exercises should be preceded by low-intensity warm-ups, it is possible that the current protocol being incremental yet continuous and longer per stage (i.e., 10 min) could have added effects of fatigue during later stages of the protocol when intensity increases. One such effect is the cardiovascular drift in which HR can increase without a concomitant increase in VO_2 (31). As shown in Figure 3, at each level of intensity HR appeared to still drift up despite the fact that VO_2 was stabilized. This limitation can be overcome by performing exercise bouts of various intensity on separate days so that one could expect less accumulated fatigue during high-intensity trials, although cardiovascular drift may not be preventable if a high intensity exercise is to last for more than 3 min (32).

The HRI equation underpredicted VO_{2max} by ~1 MET in our investigation. This finding is somewhat surprising because based on VO_2 being overpredicted at submaximal intensities, one would assume that the same bias should also occur at the maximal level. An underestimation of VO_{2max} by an average of 5.1 ml·kg^{-1}·min^{-1} (~1.4 METs) was also reported by Haller et al. (13) who evaluated the same HRI model among young and fit men. In this latter study, the authors compared VO_{2max} predicted from the equation with VO_{2max} measured by five incremental protocols and found that VO_{2max} was consistently underestimated, with the Bruce protocol demonstrating the greatest error (i.e. -8.3 ml·kg^{-1}·min^{-1}). In the present study, VO_{2max} was measured with the Åstrand and Rodahl protocol (4) that requires a progressive increase in treadmill incline by 2.5% every 2 min. It is likely that the high incline achieved during both the Bruce and Åstrand protocols may have resulted in disproportional responses between VO_2 and HR later in the test. While a linearity of HR-VO_2 relation on which the HRI equation is based generally holds, there is evidence suggesting that at the near-maximal workloads, VO_2 can increase to a greater extent relative to an increase in HR (5, 9), and this nonlinear response is more prevalent among fitter individuals (5). In fact, a loss of linearity between HR and VO_2 at high intensities has been considered a major limitation for using submaximal HR to predict VO_{2max} (15).

The underprediction of VO_{2max} by the HRI equation may also be explained by the fact that our participants are generally younger and fitter than those used to establish the equation. Indeed, the average VO_{2max} in the present study was ~13.4 METs, whereas the highest VO_{2max} of the entire sample cohort of 11257 participants was ~14 METs (28). In fact, among the 60 studies chosen to develop the equation, 38 of them used individuals with chronic conditions such as coronary heart disease, congestive heart failure, diabetes, and pulmonary disorders (28). It is quite likely that most of the VO_{2max} values we obtained were beyond the highest VO_2 used for establishing the equation, and this could result in error in predictions. The HRI equation has been claimed to be able to predict VO_2 independent of age, sex, body mass, and fitness (28). However, this may not be the case when the equation is used to predict VO_{2max} of highly fit individuals.

HR_{rest} is another predictor in this equation, but how HR_{rest} was determined in the study that developed the equation was not clearly defined. For example, only 20% of the 60 chosen studies indicated the methods used to obtain HR_{rest}, yet specific procedures varied significantly with resting periods from 2 to 90 min in either seated or supine position (28). For this reason, the authors who developed the equation recommended that HR_{rest} be measured after 20 min of rest in a seated position in a quiet and thermoneutral environment with a 1-min recording of HR being repeated twice and averaged (28). The method for obtaining HR_{rest} in the present study followed this recommendation. HR_{rest} used for analysis was after the participants completed 10 min of quite sitting and 10 min of resting measurement. The mean HR_{rest} of males and females were 64.51 ± 6.37 and 73.4 ± 8.67 beats·min^{-1}, respectively. These values are consistent with subjects' fitness status and similar to the sex-specific means reported in the study that validated the same HRI equation (27). One may argue that HR_{rest} should be best measured in the morning when the person wakes naturally. HR measured in supine position is usually about 5-10 beats lower compared to sitting (16), and this could raise VO_{2max} values and thus reduce the prediction bias. However, it is difficult to determine the role HR_{rest} plays in this prediction model as methods for obtaining HR_{rest} were inconsistent in studies that were selected to develop the equation. One unique aspect of the HRI equation is that it can predict one's VO_{2max} without having to measure gas exchange parameters. However, this would require both HR_{rest} and HR_{max} to be measured accurately and consistently.

It appears that prediction with the HRI equation is also associated with a relatively large variance. In the present study, SEEs were 0.81, 1.20, and 1.54 METs at 40%, 60%, and 80% of VO_{2max}, respectively. The SEEs found presently represented 14-15% of the actual means, yet a relative SEE of < 10% has been considered statistically acceptable in studies that validated HR monitoring against indirect calorimetry (7, 20, 23). This raises an additional question concerning the use of the HRI equation even at a low intensity where a prediction agreement was found. SEEs found at lower intensities (i.e., 40% of VO_{2max}) in this study compared favorably with those of Lee et al. (19) who reported a SEE of 1.1 METs as they cross-validated a HRI equation (i.e., MET = 2.49 HRI – 0.99) designed for paraplegic individuals, although, in this latter study, a much higher accuracy was found when the prediction was made by using individualized equations. With regard to VO_{2max}, the prediction error appears much larger as evidenced by a wider dispersion of prediction errors as shown in the Bland and Altman plots and a higher SEE (i.e., 1.97 METs) associated with VO_{2max}. Relatively large SEEs (i.e., 1.3-2.3 METs) were also reported by Haller et al. (13) who demonstrated a similar bias against VO_{2max}. Most submaximal exercise tests used for predicting VO_{2max} have been associated with SEEs of 2.1 – 4.9 $ml \cdot kg^{-1} \cdot min^{-1}$ or 0.6-1.4 METs (10, 12, 14, 24). While the large variation found in our investigation may be attributable to the methodological issues discussed earlier, it appears that a predictive model that uses HRI may still bear some level of variation associated with HR recording even though HR_{rest} is already figured in.

There are a few limitations in this study. The fact that this study used treadmill exercises at relatively large inclines could limit the generalizability of the study as this type of exercise is not the form of physical activity commonly chosen by the general population. In the present study, we did not assess the test-retest reliability of VO_{2max} tests, and as such we cannot rule out the possibility that our results may be affected by the normal day-to-day variations associated with cardiorespiratory responses. In addition, the female participants were not controlled for their menstrual cycle and the use of contraceptives. It is likely that hormonal changes and their effect on water retention during various phases of menstrual cycle can influence exercise responses especially at high intensities.

In conclusion, the HRI equation yielded mixed results on prediction outcome during submaximal and maximal exercise in healthy young adults. Although the equation provided a reasonable estimate of metabolic demand at lower intensities, its utility at higher intensities remains questionable. Caution should be taken also because this predictive approach is associated with a relatively large variance. Future studies may consider assessing validity and reliability of the equation using a different experimental approach, and this may include using a sample of less active or older individuals and leisure physical activities of varying intensities. In addition, the proper procedure of how HR_{rest} is best measured should also be addressed.

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