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ORIGINAL RESEARCH

Use of the HR index to predict maximal oxygen uptake during different exercise protocols

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Abstract

This study examined the ability of the HR_{index} model to accurately predict maximal oxygen uptake ($\dot{V}O_{2max}$) across a variety of incremental exercise protocols. Ten men completed five incremental protocols to volitional exhaustion. Protocols included three treadmill (Bruce, UCLA running, Wellness Fitness Initiative [WFI]), one cycle, and one field (shuttle) test. The HR_{index} prediction equation ($METs = 6 \times HR_{index} - 5$, where $HR_{index} = HR_{max}/HR_{rest}$) was used to generate estimates of energy expenditure, which were converted to body mass-specific estimates of $\dot{V}O_{2max}$. Estimated $\dot{V}O_{2max}$ was compared with measured $\dot{V}O_{2max}$. Across all protocols, the HR_{index} model significantly underestimated $\dot{V}O_{2max}$ by 5.1 $mL \cdot kg^{-1} \cdot min^{-1}$ (95% CI: −7.4, −2.7) and the standard error of the estimate (SEE) was 6.7 $mL \cdot kg^{-1} \cdot min^{-1}$. Accuracy of the model was protocol-dependent, with $\dot{V}O_{2max}$ significantly underestimated for the Bruce and WFI protocols but not the UCLA, Cycle, or Shuttle protocols. Although no significant differences in $\dot{V}O_{2max}$ estimates were identified for these three protocols, predictive accuracy among them was not high, with root mean squared errors and SEEs ranging from 7.6 to 10.3 $mL \cdot kg^{-1} \cdot min^{-1}$ and from 4.5 to 8.0 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively. Correlations between measured and predicted $\dot{V}O_{2max}$ were between 0.27 and 0.53. Individual prediction errors indicated that prediction accuracy varied considerably within protocols and among participants. In conclusion, across various protocols the HR_{index} model significantly underestimated $\dot{V}O_{2max}$ in a group of aerobically fit young men. Estimates generated using the model did not differ from measured $\dot{V}O_{2max}$ for three of the five protocols studied; nevertheless, some individual prediction errors were large. The lack of precision among estimates may limit the utility of the HR_{index} model; however, further investigation to establish the model's predictive accuracy is warranted.

Introduction

High cardiorespiratory fitness (CRF) is associated with health benefits, a lower risk of all-cause mortality, (Blair et al. 1989; Kodama et al. 2009; Lee et al. 2011) and a high physical work capacity (Astrand 1956; Balke and Ware 1959). CRF is assessed for diagnostic and prognostic objectives, the evaluation of fitness, the development of exercise prescriptions, and the appraisal of training programs; hence the assessment of CRF is of interest to researchers and clinicians alike. Maximal oxygen uptake ($\dot{V}O_{2max}$) is considered the criterion measure of CRF (American College of Sports Medicine [ACSM] 2006). Direct measurement of $\dot{V}O_{2max}$, however, requires expensive laboratory equipment, trained personnel, and does not lend itself to testing large numbers of individuals; therefore, $\dot{V}O_{2max}$ is often estimated indirectly rather than measured.

Estimates of $\dot{V}O_{2max}$ obtained using maximal exercise protocols are typically based on a performance measure such as time or distance covered (Balke and Ware 1959; Cooper 1968; Bruce et al. 1973; Cureton et al. 1995) or in cycle ergometry, peak work rate (Storer et al. 1990). Alternatively, prediction models employing submaximal exercise tests, generally base predictions on the heart rate (HR) response and its well-established linear relationship with oxygen uptake ($\dot{V}O_2$) over a wide range of exercise intensities (Astrand and Ryhming 1954; Asmussen and Hemmingsen 1958; Margaria et al. 1965). However, it is equally well known that the use of a submaximal HR response to estimate $\dot{V}O_2$ involves assumptions that do not always hold true, such as a uniform age-related maximal heart rate (HR_{max}) and the linearity of the HR and $\dot{V}O_2$ relationship (Davies et al. 1984; Shephard 1984).

Recently, Wicks et al. (2011) conducted a retrospective analysis of data extracted from 60 published studies and investigated the relationship between various HR measures and oxygen uptake. The authors concluded that the prediction model employing the ratio of HR during exercise ($HR_{absolute}$) to resting HR (HR_{rest}), which was termed the HR_{index}, was the preferred model and could be used to predict submaximal and maximal $\dot{V}O_2$. Furthermore, the researchers indicated that the HR_{index} method was independent of testing mode (e.g., treadmill, cycle, free-range-activity) and accounted for factors known to contribute to variability in $\dot{V}O_{2max}$, including age, sex, fitness, and body mass.

A prediction model that accurately predicts $\dot{V}O_{2max}$ independent of protocol from readily obtained variables would be an attractive tool for field, laboratory, and clinical settings. Wicks et al. (2011) recently reported that their HR_{index} prediction equation could accurately predict $\dot{V}O_{2max}$. Therefore, the purpose of this exploratory study was to examine the validity of the HR_{index} prediction equation proposed by Wicks et al. (2011) in predicting $\dot{V}O_{2max}$ in healthy, active subjects performing a variety of maximal incremental protocols.

Methods

Experimental design

This retrospective study utilized data from a parent study that examined the effects of exercise protocol and mode on cardiovascular and metabolic responses to graded exercise testing. These data were further analyzed to investigate the accuracy of the HR_{index} model for predicting $\dot{V}O_{2max}$. The parent study employed a within-subjects repeated measures design in which participants completed five different incremental exercise tests to volitional exhaustion. Incremental tests were presented in a randomized order and completed on different days. Experimental trials were completed at the same time of day and separated by at least 48 h; all trials were completed within a 14-day period. Participants were instructed to stay well hydrated and to maintain their current diet and exercise patterns throughout the data collection period.

Participants

Ten healthy, physically active, college-aged men were recruited from the campus community. Individuals were given a detailed account of the study and all participants provided written informed consent prior to the initiation of study procedures. All participants completed a medical history and received a medical evaluation from a health care provider prior to participation in the study. Exclusion criteria included diagnosed cardiorespiratory diseases, use of medication known to alter HR or metabolic rate, or orthopedic problems that interfered with performance of the tests. The study was approved by the college's Institutional Review Board.

Experimental trial

Participants fasted and abstained from caffeine and nicotine in the 4 h preceding the test and abstained from strenuous exercise and alcohol within 24 h of testing. Hydration status was assessed via urine specific gravity (Schueco Clinical Refractometer 5711-2020; Erma Inc, Tokyo, Japan) to ensure that participants were tested in a euhydrated state ($USG \leq 1.020$) (Sawka et al. 2007). Height was measured prior to the first experimental trial using a stadiometer (Seca, Hanover, MD; accuracy $\pm$ 0.01 m). Body mass was measured prior to each experimental trial (Befour Inc., Saukville, WI; accuracy $\pm$ 0.1 kg). All participants had previous experience completing graded exercise tests to volitional exhaustion; details for each protocol were provided prior to each incremental test. Resting measurements were obtained in a thermoneutral laboratory (21.6 $\pm$ 1.2°C; 48.1 $\pm$ 6.8% relative humidity) before the incremental test. Participants were outfitted with a portable metabolic measurement system and HR monitor and were instructed to sit quietly for a 10-min period while resting HR and $\dot{V}O_2$ data were collected.

Participants then completed one of five incremental protocols: Bruce, UCLA running, Wellness Fitness Initiative (WFI), Shuttle, and Cycle. Protocols were chosen to represent common modes used in clinical and performance exercise tests (running and cycling), different stage durations and workload increments within a mode, an occupationally relevant test (WFI), and a field test (Shuttle). The Bruce, UCLA, and WFI protocols were completed on a motorized treadmill (PPS Med; Woodway USA Inc., Waukesha, WI). The Shuttle run was administered in an indoor gymnasium and the Cycle protocol was performed on an electronically braked cycle ergometer (Velotron; RacerMate Inc., Seattle, WA). During all protocols, verbal encouragement was provided to promote maximal effort. Tests were terminated upon volitional exhaustion of the participant or the participant's inability to maintain the target cadence or speed.

The Bruce protocol (Bruce et al. 1973) included 3-min stages, with the first stage beginning at a gradient of 10% and a speed of 2.7 $km \cdot h^{-1}$. At the end of each stage the gradient increased by 2%; the speed increased to 4.0, 5.5, 6.8, 8.0, and 8.8 $km \cdot h^{-1}$ for the subsequent stages.

The UCLA running protocol consisted of 1-min stages. During the first 3 min, the gradient was held at 0% and the speed increased from 4.8 to 5.5 to 6.0 $km \cdot h^{-1}$. Between minutes 3 and 12, the treadmill gradient was set at 2% and speed was increased by 1.1 or 1.3 $km \cdot h^{-1}$ each minute until the maximum speed of 16.7 $km \cdot h^{-1}$ was reached. At the beginning of minute 12, the gradient was increased by 2% each minute while the treadmill speed remained constant at 16.7 $km \cdot h^{-1}$.

For the WFI (National Fire Protection Association [NFPA] 2006), the gradient was held at 0% and the speed at 4.8 $km \cdot h^{-1}$ for the first 3 min. The speed was then increased to 7.2 $km \cdot h^{-1}$ while the gradient remained at 0%. The treadmill gradient and speed were then alternately increased by 2% and 0.8 $km \cdot h^{-1}$, respectively, at the end of each minute.

The Cycle protocol began at a power output of 60 watts for 3 min. Thereafter, the work rate was increased by 40 watts (Heyward 2010) at the end of every 2-min stage. Target cadence was 60 revolutions per min.

For the Shuttle test (Léger et al. 1988), participants were required to run between two lines located 20 m apart at a set pace that was established using recorded signals. The test started at a speed of 8.5 $km \cdot h^{-1}$ and was increased by 0.5 $km \cdot h^{-1}$ every min. If the participant failed to cover the distance between signal emissions, a warning was given. If the participant failed to cover the distance on two consecutive lengths, the test was terminated.

Measurements

Oxygen uptake was measured continuously during the testing session using a portable metabolic system (Oxycon Mobile; Care Fusion, Yorba Linda, CA). Before each testing session, ambient temperature and pressure, delay, gas, and volume calibrations were performed. The Oxycon Mobile was worn on the back in a specially designed harness. Expired air was collected with a face mask connected to the flow sensor unit and sampling line of the Oxycon Mobile. Data were transmitted wirelessly to a personal computer. Breath-by-breath data were averaged over 15-sec intervals.

Heart rate was measured continuously throughout the testing session (Zephyr BioHarness BT2, Annapolis, MD). Following testing, HR data were downloaded to a laptop and stored for subsequent analysis. HR data were temporally aligned with $\dot{V}O_2$ data and the second-by-second data were averaged over 15-sec intervals.

During each trial, the participant indicated his rating of perceived exertion (RPE) using the 6–20 Borg Scale (Borg 1982). Incremental tests were considered maximal if two of the following three criteria were met: (1) a plateau in oxygen uptake despite an increase in work rate, (2) respiratory exchange ratio (R) $\geq$1.1, and (3) a HR within 12 beats of age-predicted maximal HR (HR_{max}) (Plowman and Smith 2014).

Resting HR was identified as the lowest HR among the eight 15-sec intervals between minutes 7 and 9 of the rest period. The highest HR among all 15-sec intervals during the incremental test was considered HR_{max}. The HR_{index} was calculated using the following equation: $HR_{index} = HR_{max}/HR_{rest}$. The HR_{index} was used to predict energy expenditure using the equation proposed by Wicks et al. (2011):

$$METs = 6 \times HR_{index} - 5 \quad (1)$$

Predicted energy expenditure in METs was converted to mass-specific $\dot{V}O_2$ using the conversion factor of 3.5 $mL \cdot O_2 \cdot kg^{-1} \cdot min^{-1}$ per 1 MET. The conversion factor was selected to correspond to the factor used by Wicks et al. (2011) when converting body mass-specific $\dot{V}O_2$ to METs in the development of the HR_{index} prediction model. The highest measured $\dot{V}O_{2max}$ value among all 15-sec intervals during the incremental test was identified as the criterion $\dot{V}O_{2max}$.

Statistical analyses

Data are presented as mean $\pm$ SD unless indicated otherwise. A one-way (protocol) analysis of variance with repeated measures was used to detect differences in HR_{rest}, HR_{max}, HR_{index}, and $\dot{V}O_{2max}$ across the protocols. The accuracy of the $\dot{V}O_{2max}$ predictions was assessed by computing the bias (mean difference between predicted and measured $\dot{V}O_{2max}$) and 95% confidence intervals (CI) for each protocol and overall. If the CI did not include zero, predicted and measured $\dot{V}O_{2max}$ were considered statistically different at an alpha level of 0.05. Precision of the predictions overall and for each protocol were assessed using the root mean squared error (RMSE) and the standard error of the estimate (SEE). The RMSE is the square root of the mean of the squared prediction errors (predicted $\dot{V}O_{2max}$ − measured $\dot{V}O_{2max}$) and expresses the total error of the prediction equation, which includes the variation due to the lack of association between two measurements quantified by the SEE (Lohman 1981). A Bland–Altman plot was constructed to depict the overall bias and display any systematic error in the prediction. Pearson product-moment correlation coefficients (r) were computed to describe the strength of the linear relationship between measured and predicted $\dot{V}O_{2max}$. Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, Inc., Chicago, IL; software version 19). The level of statistical significance was set at $P < 0.05$.

Results

Ten young, fit men (age 22 ± 2 year; height 1.76 ± 0.08 m; body mass 78.0 ± 8.5 kg; body mass index 25.2 ± 2.7 kg·m^{-2}) completed the study. On average, participants engaged in regular aerobic physical activity for ~40–45 min on 3 day·week^{-1}. All incremental tests were considered maximal based on the attainment of at least two of the three established criteria described in the Methods section.

Heart rate and metabolic data are summarized in Table 1. There were no differences in HR_{rest} ($P = 0.091$) or HR_{max} ($P = 0.183$) among trials. The HR_{index} was significantly lower for the Cycle compared with the Shuttle protocol ($P = 0.002$). No significant differences were detected for other HR_{index} contrasts, however, there was a trend for the HR_{index} to be lower for the Cycle than the UCLA protocol ($P = 0.058$). There was no difference in R among protocols ($P = 0.053$). $\dot{V}O_{2max}$ was significantly greater for the Bruce ($P = 0.004$) and WFI ($P = 0.026$) protocols compared with the Cycle protocol.

Figure 1 presents predicted versus measured $\dot{V}O_{2max}$ for all trials. Table 2 provides a comparison of measured versus predicted $\dot{V}O_{2max}$, including prediction bias, RMSE, SEE and correlation between measured and predicted $\dot{V}O_{2max}$. Over all trials, the prediction equation significantly underestimated $\dot{V}O_{2max}$ by 5.1 ± 8.3 mL·kg^{-1}·min^{-1} when compared with measured $\dot{V}O_{2max}$ (95% CI = −7.4, −2.7). The negative bias for all protocols indicated a consistent underestimation of $\dot{V}O_{2max}$ on average by HR_{index} model, whereas a 95% CI that did not span zero for the Bruce and WFI protocols indicated a significant difference between predicted and measured $\dot{V}O_{2max}$. The RMSE was 9.6 mL·kg^{-1}·min^{-1} overall and ranged from 7.6 (Shuttle) to 11.2 mL·kg^{-1}·min^{-1} (Bruce) among the five protocols. The SEE was lowest for the Shuttle and highest for the Cycle protocol. Low to moderate correlations between measured and predicted $\dot{V}O_{2max}$ were identified.

The Bland–Altman plot (Fig. 2) displays the dispersion of the individual prediction errors and the overall bias and limits of agreement. The wide limits of agreement

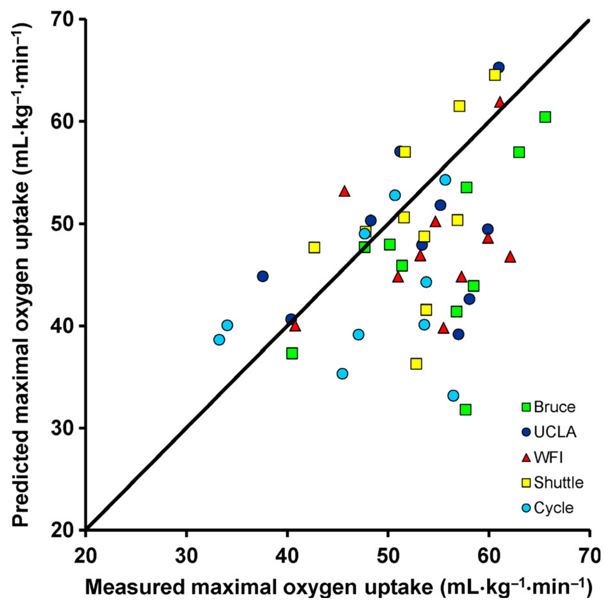

Figure 1. Scatter plot of predicted versus measured $\dot{V}O_{2max}$ with points identified by protocol. The line of identity denotes perfect agreement.

Table 1. Heart rate, metabolic, and perceptual effort among protocols (N = 10).

Variable	Bruce	UCLA	WFI	Shuttle	Cycle
HR_{rest} (beats·min^{-1})	62 ± 8	61 ± 7	62 ± 5	59 ± 6	65 ± 6
HR_{max} (beats·min^{-1})	187 ± 9	192 ± 12	192 ± 8	189 ± 11	186 ± 11
HR_{index}	3.0 ± 0.4	3.2 ± 0.4	3.1 ± 0.3	3.3 ± 0.4*	2.9 ± 0.3
RPE_{peak}	19.1 ± 0.9	19.7 ± 0.5	19.6 ± 0.5	19.3 ± 1.0	19.3 ± 0.7
R_{peak}	1.29 ± 0.06	1.27 ± 0.05	1.25 ± 0.08	1.23 ± 0.04	1.27 ± 0.05
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	54.9 ± 7.5*	52.2 ± 8.0	54.1 ± 6.8*	52.9 ± 5.0	47.8 ± 8.3

Values are mean ± SD. HR_{rest}, resting heart rate; HR_{max}, maximum heart rate; HR_{index}, HR_{max}/HR_{rest}; RPE, rating of perceived exertion; R, respiratory exchange ratio; $\dot{V}O_{2max}$, maximal oxygen uptake; WFI, Wellness Fitness Initiative.
*$P < 0.05$ compared with the Cycle protocol for the given variable.

Table 2. Comparison of measured and predicted maximal oxygen uptake ($\dot{V}O_{2max}$).

	Bias (95% CI) (mL·kg^{-1}·min^{-1})	RMSE (mL·kg^{-1}·min^{-1})	SEE (mL·kg^{-1}·min^{-1})	*r*
Bruce	−8.3 (−14.0, −2.6)*	11.2	6.4	0.53
UCLA	−3.3 (−9.7, 3.0)	9.1	7.4	0.38
WFI	−6.4 (−11.8, −1.1)*	9.6	6.3	0.36
Shuttle	−2.1 (−7.7, 3.4)	7.6	4.5	0.45
Cycle	−5.2 (−11.9, 1.6)	10.3	8.0	0.27
Overall	−5.1 (−7.4, −2.7)*	9.6	6.7	0.42

N = 50 for Overall and *N* = 10 for all other protocols. WFI, Wellness Fitness Initiative; Bias, predicted $\dot{V}O_{2max}$ − measured $\dot{V}O_{2max}$; CI, confidence interval; RMSE, root mean squared error; SEE, standard error of the estimate; *r*, Pearson product-moment correlation.
*Predicted $\dot{V}O_{2max}$ significantly different than measured $\dot{V}O_{2max}$.

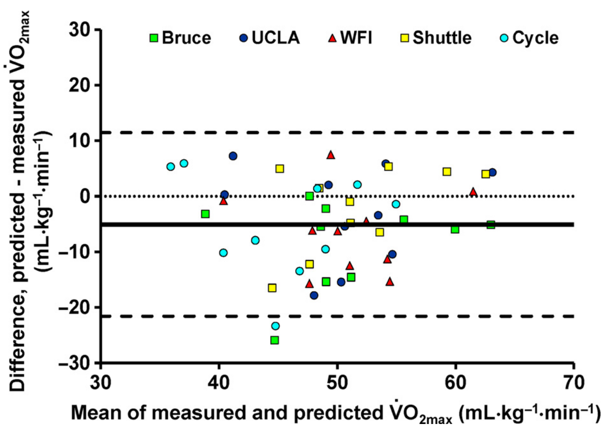

Figure 2. Bland–Altman plot of the prediction errors (predicted $\dot{V}O_{2max}$ − measured $\dot{V}O_{2max}$). The bias (solid line) and the limits of agreement (dashed lines; mean difference ± 1.96 SD) are displayed.

Table 3. Individual prediction errors (predicted $\dot{V}O_{2max}$ − measured $\dot{V}O_{2max}$) across all trials.

	Protocol				
Part #	Bruce	UCLA	WFI	Shuttle	Cycle
01	−25.9	2.0	−6.2	−4.9	−13.5
02	0.0	7.2	7.5	1.4	5.3
03	−6.0	−10.5	−15.3	−1.0	−9.6
04	−2.3	−5.5	−4.5	−12.3	−10.2
05	−5.5	−3.4	−15.7	5.3	−8.0
06	−4.3	5.8	−6.3	4.4	2.1
07	−15.4	−17.9	−12.5	−16.5	−23.4
08	−3.2	0.2	−0.8	4.9	5.9
09	−5.2	4.3	0.8	3.9	−1.5
10	−14.6	−15.5	−11.3	−6.6	1.3

$\dot{V}O_{2max}$, maximal oxygen uptake; Part #, participant number; WFI, Wellness Fitness Initiative; units are mL·kg^{-1}·min^{-1}.

(11.5, −21.6 mL·kg^{-1}·min^{-1}) reflect the variability among the prediction errors. Table 3 presents the accuracy of predictions on an individual level, clearly showing that prediction accuracy varies considerably among participants as well as by protocol within participants.

Discussion

Across all test protocols, this study found that the HR_{index} prediction model significantly underestimated $\dot{V}O_{2max}$ in aerobically fit, college-aged men. Furthermore, prediction accuracy was influenced by the incremental test protocol utilized. $\dot{V}O_{2max}$ was significantly underpredicted for the Bruce and WFI protocols; however, no significant differences between estimated and measured $\dot{V}O_{2max}$ were found for the UCLA running, Shuttle, or Cycle protocols. In addition, accuracy of predictions at the individual level was highly variable for all protocols.

CRF is a measure of interest to many clinicians, researchers, and other practitioners who perform graded exercise testing, and the use of prediction equations to estimate CRF is routinely employed, particularly in large-scale studies. In their development of the HR_{index} model, Wicks et al. (2011) identified published studies that reported measured values for HR_{rest}, $HR_{absolute}$, and $\dot{V}O_2$ and extracted 220 data points that were group averages from 60 eligible exercise studies. The large dataset included diverse populations, different modes of exercise, and both submaximal and maximal data. Prediction models were developed to estimate energy expenditure over the range of 1–14 METs ($\dot{V}O_{2max}$ range: 3.5–49.0 mL·kg^{-1}·min^{-1}) using HR as a predictor, with HR expressed as either $HR_{absolute}$, HR_{net} ($HR_{absolute}$ − HR_{rest}) or HR_{index}. The researchers concluded that the best fit model employed the HR_{index}, which explained 99.1% of the variability in the data. Moreover, subgroup analysis, which included testing device (treadmill, cycle ergometer, other), indicated that the prediction equation was robust. Therefore, a single prediction equation, rather than protocol-specific or sex-specific equations, for the prediction of energy expenditure was proposed by Wicks et al. (2011). These researchers used data points based on group means rather than individual data point to develop the HR_{index} model, and it remains unclear how this might impact model performance. Furthermore, the HR_{index} prediction equation was not cross validated; therefore, subsequent performance of the model was uncertain. To our knowledge, no published studies have examined the accuracy of the HR_{index} prediction equation. In this study, the HR_{index} prediction equation was applied using five protocols that included three exercise types. $\dot{V}O_{2max}$ was significantly underestimated overall and a difference in prediction accuracy among protocols was found.

In theory, assuming a uniform HR_{rest}, the direct relationship between HR_{max} and $\dot{V}O_{2max}$ in the HR_{index} model dictates that for estimates of $\dot{V}O_{2max}$ to be the same for two protocols, HR_{max} and $\dot{V}O_{2max}$ must remain the same or change in a similar way between protocols. A review of several studies that compared cycling versus running or different treadmill protocols revealed that the effect of exercise protocol on $\dot{V}O_{2max}$ corresponded to the effect of exercise protocol on HR_{max} in some studies (McArdle and Magel 1970; Miyamura et al. 1978; Pannier et al. 1980; Verstappen et al. 1982; Davies et al. 1984; Fernhall and Kohrt 1990) but not others (Hermansen and Saltin 1969; Faulkner et al. 1971; Froelicher et al. 1974; St Clair Gibson et al. 1999). Thus, a precise estimate of $\dot{V}O_{2max}$ using the HR_{index} model, which includes HR_{max} as a predictor, may be difficult to obtain across different protocols. Results from the present investigation support this point. As shown in Table 1, measured $\dot{V}O_{2max}$ was greater for the Bruce and WFI protocols than the Cycle protocol; however, HR_{max} did not differ among protocols. As the effect of protocol was not the same for HR_{max} and $\dot{V}O_{2max}$, it was not surprising that differences between predicted and measured $\dot{V}O_{2max}$ were observed. Additionally, the combined effect of small nonsignificant differences in HR_{max} and HR_{rest} likely led to the significantly lower HR_{index} for the Cycle than the Shuttle protocol. Accordingly, estimated $\dot{V}O_{2max}$ followed the same pattern as the HR_{index}, which did not match measured $\dot{V}O_{2max}$.

Wicks et al. (2011) developed the HR_{index} model using group averages, with 5–1909 participants contributing to a data point; therefore, the researchers were unable to establish the prediction error for an individual. Examination of the individual prediction errors in this study (Fig. 2 and Table 3) indicated a wide range of errors within all protocols. Moreover, the prediction errors displayed considerable variability in predictive accuracy among individuals across protocols. Uth et al. (2004) used the ratio of HR_{max} to HR_{rest} (i.e., the HR_{index}) to estimate $\dot{V}O_{2max}$, but the researchers derived a prediction equation, which included a proportionality constant and the HR_{index} as factors, based on the Fick equation rather than regressing $\dot{V}O_{2max}$ on HR as Wicks et al. (2011) did. In a group of 46 well-trained men ($\dot{V}O_{2max}$ = 60.9 ± 5.5 mL·kg^{-1}·min^{-1}), Uth et al. (2004) determined the proportionality constant in one subgroup (n = 10) and then predicted $\dot{V}O_{2max}$ in the second subgroup (n = 36). The researchers reported a nonsignificant difference of 0.28 mL·kg^{-1}·min^{-1} between measured and predicted $\dot{V}O_{2max}$ and an SEE of 2.7 mL·kg^{-1}·min^{-1}, indicating good agreement between measured and predicted $\dot{V}O_{2max}$ in the group of well-trained men. Validation studies of maximal performance tests based on time or work rate have reported a wide range of predictive accuracies, nevertheless, the predictive accuracy of commonly used equations (Foster et al. 1984; Storer et al. 1990; American College of Sports Medicine 2006; Heyward 2010) is higher than the accuracy noted for the HR_{index} in this study. Storer et al. (1990) reported an SEE of 2.57 mL·kg^{-1}·min^{-1} for the prediction of $\dot{V}O_{2max}$ from body mass, work rate, and age in cycle ergometry using a sex-specific equation for men. A generalized prediction equation frequently used with the Bruce protocol has an SEE of 3.35 mL·kg^{-1}·min^{-1} (Foster et al. 1984), which is considerably lower than the 6.4 mL·kg^{-1}·min^{-1} identified in this study. In fact, this regression equation for the Bruce protocol, which uses test time to predict $\dot{V}O_{2max}$, produced accurate estimates of $\dot{V}O_{2max}$ when applied to the data collected in this investigation (prediction bias = −2.6 ± 3.2 mL·kg^{-1}·min^{-1}; SEE = 3.3 mL·kg^{-1}·min^{-1}; r = 0.90).

There are several possible explanations for the underestimation of $\dot{V}O_{2max}$ by the HR_{index} model and the high variability in the estimates of $\dot{V}O_{2max}$. One possible reason is that the participants in this study had a higher CRF on average than those in the model development study. For 72% of the incremental tests in this study, the $\dot{V}O_{2max}$ attained was higher than the 49 mL·kg^{-1}·min^{-1} upper limit identified in development of the HR_{index} prediction model. It then follows that HR_{index} values in this study likely exceeded or were near the upper limit of those included as predictors by Wicks et al. (2011). However, Wicks et al. (2011) reported that the HR_{index} model accounted for fitness. Our results indicate that the HR_{index} model did not accurately predict $\dot{V}O_{2max}$ in young, fit men. Furthermore, this study found relatively large prediction errors (>7 mL·kg^{-1}·min^{-1}) in ~30% of the trials where $\dot{V}O_{2max}$ did not exceed 49 mL·kg^{-1}·min^{-1}, indicating that individual prediction errors may be substantial even within the scope of the prediction model.

Both HR_{max} and HR_{rest} are predictors in the HR_{index} model; therefore, a difference in the measurement of these predictors could affect prediction accuracy. Only 20% of the studies included in the development of the HR_{index} model indicated the methods used to obtain HR_{rest}. Moreover, among those studies providing details, procedures were vastly different, with rest periods between 2 and 90 min and inconsistency in the position of the participants (seated or supine). In this study, the method for obtaining HR_{rest} was guided by the technology used and the potential application of the HR_{index} method in a typical cardiopulmonary exercise test setting where prediction of $\dot{V}O_{2max}$ is the objective. Therefore, the measurement was obtained with the participant in a seated rather than supine position. Additionally, the use of the lowest 15-sec sampling interval was easily achieved using a HR monitor, and helped to ensure the obtainment of a HR_{rest} value in a field study. The rest period of 7 min prior to obtaining the measurement was consistent with methods described for obtaining HR_{rest} (American College of Sports Medicine 2008; Heyward 2010). In part, the underestimation of $\dot{V}O_{2max}$ may be a consequence of the seated HR_{rest} measurement, but this is not possible to ascertain because the methods for obtaining HR_{rest} were unknown or inconsistent in the studies used to develop the HR_{index} model. Wicks et al. (2011) justifiably indicate that the measurement of HR_{rest} needs to be standardized for the accurate prediction of the HR_{index} and $\dot{V}O_2$. Notwithstanding standardization of the HR_{rest} measurement, accuracy of individual level predictions using the HR_{index} model may be variable. Lee et al. (2010) used the HR_{index} to predict MET values of various submaximal activities in persons with paraplegia, and the group reported a substantially lower (~23%) absolute error percentage when using prediction equations developed for each individual (individual calibration) compared with a single regression equation developed for all participants (group calibration) despite the use of a standardized procedure to determine HR_{rest}. Previous research (Andrews 1971; Hiilloskorpi et al. 2003) suggests that the incorporation of HR_{rest} in the predictor reduces but does not eliminate the interindividual differences when using HR to predict energy expenditure.

The accuracy of $\dot{V}O_{2max}$ estimates could have been influenced by differences in resting metabolic rate and the use of the standard conversion factor to convert METs to $\dot{V}O_2$. This study used the established conversion factor of 3.5 $mL \cdot O_2 \cdot kg^{-1} \cdot min^{-1}$ per 1 MET, which is the method used in the development of the HR_{index} model. Although this conversion factor is routinely used, research has shown that this value does not always equate to resting $\dot{V}O_2$ (Byrne et al. 2005) and hence this may be a source of error within the HR_{index} model.

This study involved five incremental exercise tests conducted within a 14-day interval. Thus, day to day variability in measurements of HR_{max}, HR_{rest}, and $\dot{V}O_{2max}$ may have contributed to the variability in the predictions between exercise protocols. Day to day variability in HR_{max} is ~2–4 $beats \cdot min^{-1}$ (Achten and Jeukendrup 2003). The standard deviation of HR_{rest} (5–8 $beats \cdot min^{-1}$) in this study suggested considerable variability in this measure. Procedures had been implemented to limit the effect of factors that influence heart rate, but uncontrollable factors, such as stress level or sleep quality, may have contributed to within-participant variability. For repeated measurements of $\dot{V}O_{2max}$, studies have reported a coefficient of variation of 4–5% (Katch et al. 1982; Howley et al. 1995) and a reliability coefficient of 0.95 (Taylor et al. 1955). Thus, trial to trial variability in physiological measures, notably HR_{rest}, could account for some variability in predictions.

The retrospective nature of the study resulted in several inherent limitations, namely the dataset was small and obtained on a homogeneous group, limiting statistical power and generalizability of findings. Protocols employed included different exercise types; however, the use of only protocols with established prediction equations would have permitted comparisons between the HR_{index} and protocol-specific equations. Additional research with larger, more heterogeneous groups is needed to further evaluate the performance of the HR_{index} prediction model.

Conclusions

The use of a simple predictor, such as a HR_{index}, to predict $\dot{V}O_{2max}$ across different exercise protocols is an attractive possibility, and a recently published article (Wicks et al. 2011), which retrospectively analyzed a large number of published studies suggested that this may be possible. However, this study found that the HR_{index} prediction model significantly underestimated $\dot{V}O_{2max}$ in young, fit men across different protocols. Furthermore, the incremental test protocol influenced prediction accuracy, with predicted $\dot{V}O_{2max}$ differing significantly from measured $\dot{V}O_{2max}$ for the Bruce and WFI protocols but not the UCLA running, Shuttle or Cycle protocols. Despite the fact that no significant differences between measured and predicted $\dot{V}O_{2max}$ were found for three of the five protocols studied, examination of the individual data revealed large prediction errors among all protocols. Additionally, prediction accuracy across protocols varied considerably within individuals. Therefore, our results suggest caution is warranted when applying the HR_{index} prediction equation to estimate $\dot{V}O_{2max}$ in young, fit men. The findings from this study are consistent with the view that prediction models often provide valid estimates on a group level, but the accuracy of individual estimates vary considerably.

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Conflicts of Interest

C. B. C. has served as a consultant to CareFusion, the manufacturer of the Oxycon Mobile. The other coauthors have no conflicts of interest to declare.

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