Prediction of Peak Oxygen Uptake From a Maximal Treadmill Test in 12- to 18-Year-Old Active Male Adolescents

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The aims were to develop and validate a VO2peak prediction equation from a treadmill running test in active male adolescents. Eighty-eight athletes (12–18 yrs.) performed a maximal exercise test on a treadmill to assess the actual VO2peak and a 20m Shuttle-Run-Test (20mST). A step-wise linear regression analysis was used and the following equation for estimation of VO2peak (mL∙kg⁻¹∙min⁻¹) = 35.477 + 1.832 × duration in min - 0.010 × duration × body mass in kg was developed. The cross-validation statistics were: R = .54, CE = 0.1 mL∙kg⁻¹∙min⁻¹, SEE = 2.5 mL∙kg⁻¹∙min⁻¹ (4.6%), and TE = 2.6 mL∙kg⁻¹∙min⁻¹ (4.9%). The cross-validation values (CE, SEE, and TE) were lower compared with those of previously published equations in adolescents that estimated VO2peak using anthropometric data, performance in 20mST, and energy cost at submaximal speeds.

Maximal oxygen uptake (VO2max), an important predictor of aerobic performance, has been used for evaluating the efficacy of training, for prescribing aerobic exercise, and in clinical settings for assessing the health-risk status (1,2). Open-circuit spirometry is the most accurate method for measuring VO2max. However, the expensive laboratory equipment, skill, and time requirements associated with this direct method often limit its cost to benefit utility. Thus, a large number of studies have been conducted for the development of VO2max prediction models. It has been

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widely accepted that a regression equation is valid for individuals representative of the population used to develop the equation. Therefore, many youth-specific VO$_2$$_{peak}$ prediction models were developed, a few based on anthropometrical data (11,19) and others based on submaximal (9,11,12,14,19,41,48,58) or maximal exercise data.

The tests that estimated VO$_2$$_{peak}$ in youth using maximal effort included timed distance field runs (14,20,35,36,39), cycle ergometer tests (3,4,27) and the 20m shuttle run test (20mST; 5,12,17,32,40). Timed distance field runs for VO$_2$$_{max}$ prediction have been criticized because they may be influenced by anaerobic capacity, the motivation, and the ability of the subject to adopt a proper running pace (31). Cycling exercise is a good choice for testing inactive and obese children. However, it may underestimate VO$_2$$_{max}$ (10,53), it does not resemble the form of activity (running) usually performed by active children, it may cause greater local fatigue, and some youth may have difficulty pedaling at constant rates.

To date, Leger’s et al. (32) equation is one of the best alternatives for prediction of VO$_2$$_{peak}$ in Caucasians throughout the wide range of development (12–18 years). Although the test is generally valid and accurate (15,33,54,57), the validity coefficient in children and adolescents ranged from 0.51 to 0.92 with SEE of 3.1–5.9 mL·kg$^{-1}$·min$^{-1}$ (57) or about 8–12% (5,32,42). It has been suggested that its validity and accuracy may be limited by the nature of the test (shuttle running with accelerations and decelerations) compared with that of the gold standard treadmill test (forward running) (23,43), the contribution of anaerobic capacity (22,42,52), greater peripheral fatigue due to effort to overcome body inertia at each shuttle, and the use of participants with a wide range of aerobic fitness (22,45,49). Furthermore, less motivated subjects may have more difficulty to sustain the pace generated by the audio device. The maximal speed attained in the 20mST is lower compared with the speed attained during a continuous incremental test on a treadmill or in a field (8,30,57). Thus, it is difficult to use %VO$_2$$_{peak}$ or VO$_2$$_{peak}$ values in terms of speed to set up training intensities (8).

While, in children and adolescents a treadmill ergometer has been repeatedly used for developing equations to predict the energy cost of walking or running at submaximal speeds (34,44,48,56), there is no equation for prediction of VO$_2$$_{peak}$. This is surprising since a maximal incremental treadmill test is generally considered as the gold standard measurement of VO$_2$$_{max}$ in laboratory, it involves a form of activity (running) that is performed by most children and it utilizes an equipment found in any fitness facility. The use of a treadmill protocol to develop an equation for VO$_2$$_{max}$ is in line with the view that alternative tests to estimate VO$_2$$_{max}$ should mimic the energy utilization of the reference standard test for increasing the prediction power (23). Furthermore, a running test on the treadmill can provide information on the maximal aerobic speed, another parameter for evaluating the individual’s aerobic capacity, that can be used for designing and monitoring aerobic training programs.

Therefore, the primary aim of this study was to develop and cross-validate a new equation that predicts VO$_2$$_{peak}$ in active (regularly involved in training) children and adolescents 12–18 years old using a conventional maximal incremental treadmill test. The secondary aim was to compare the validity of the new equation with previously published equations that predict VO$_2$$_{peak}$ in youths based on anthropometrical data and performance on 20MST, and with equations developed to estimate energy cost (VO$_2$) at submaximal speeds.
Methods

Eighty-eight trained male adolescents (12–18 years old) volunteered to participate in this study. The participants were randomly assigned either into a derivation group \( (n=70) \) or a cross-validation group \( (n=18) \). All participants were healthy and were enrolled in regular soccer training (1–2 hr session\(^{-1}\), 3–5 sessions·week\(^{-1}\)) from the age of 8–10 years. Before the start of the study, the institutional review board committee approved the experimental protocol and the adolescents’ parents signed the written informed consent form and completed a medical questionnaire, to ensure that participants were not taking any drugs and/or medications and were free of cardiac, respiratory, renal, or metabolic diseases. All volunteers followed their normal diet for three days before the study, abstained from exercise activity for 48 hr before the study, and had sufficient rest the night before the study.

Study Design

The present study used a stepwise linear regression analysis for the development of a prediction equation for \( \text{VO}_2\text{peak} \). A cross-validation design was used for the determination of the validity and accuracy of our prediction equation and comparisons of our equation with previously published ones. Each participant reported to the Orthopedic Sports Medicine Center on two separate occasions. On one visit the subject underwent assessment of physical characteristics and performed a maximal exercise test on a treadmill for the measurement of the actual \( \text{VO}_2\text{peak} \) and on the other visit he performed a 20mST (1-min stage) field test. The two visits were scheduled 1 week apart and were performed in counterbalanced order to avoid carry-over effects.

Testing Procedures and Instrumentation

Upon arrival to the Laboratory, height and body mass (Philips, USA) were measured by the same investigator. Next, each participant underwent a maximal incremental test on the treadmill (Technogym, Runrace 1200, Italy). Respiratory gas exchange was measured using a breath by breath gas analysis sytem (CPX Ultima Series, Medical Graphics, USA). Before each test the \( \text{O}_2 \) and \( \text{CO}_2 \) analyzers were calibrated using ambient air and gases of known composition provided by MedGraphics Corporation. Next the subject wore a facemask and rested at seated position for 5 min. Following the 5-min rest, the incremental exercise protocol started at 8 km·h\(^{-1}\) (zero grade) and the speed was increased by 1 km·h\(^{-1}\) every 2 min until volitional exhaustion. This protocol was selected because the velocity at final stage can provide information on the maximal aerobic velocity which is often used for prescribing the training velocity in adolescent athletes (7). During the test, inspired and expired gases were measured every breath and heart rate (HR, \( \text{b} \cdot \text{min}^{-1} \)) was monitored continuously by the metabolic cart using a chest belt telemetry (Polar Electro, Kempele, Finland). Criteria for the achievement of \( \text{VO}_2\text{peak} \) were RER >1.00, signs of maximal effort, and volitional fatigue (46). All participants satisfied these criteria. The \( \text{VO}_2 \) values were averaged over 30 s periods. \( \text{VO}_2\text{peak} \) was defined as the highest 30 s \( \text{VO}_2 \) value of the maximal incremental treadmill exercise test. The duration of the incremental protocol was measured in min and seconds. The
speed at the last stage that was maintained for at least 1 min was defined as the final speed on the maximal incremental test.

On a separate occasion, participants performed a 20mST in a fitness facility (indoor facility, tartan tracks). The participants underwent testing in groups of three to five persons. They ran to volitional exhaustion between two parallel lines spaced 20m apart, while a CD player emitted sound signals for the determination of running pace. The starting speed was 8.5 km·h⁻¹, and then the speed increased by 0.5 km·h⁻¹ every minute. HR was monitored throughout the test (Polar Heart Rate Monitor RS100, USA). VO₂peak was predicted using the last fully completed 1-min stage, according to Leger et al. (32).

**Statistical Analysis**

All data are presented as means ± SD. Differences in physical characteristics between the derivation and the cross validation groups were examined using t-tests. A stepwise multiple linear regression analysis technique with collinearity diagnostics was employed to identify the significant explanatory variables for our dependent variables, absolute VO₂peak (mL·min⁻¹) and relative VO₂peak (mL·kg⁻¹·min⁻¹). Using this procedure, we tested performance variables (duration and velocity) combined with traditional anthropometrical variables such as body mass, height, age, and their interaction terms based on previously published studies and logic. The stepwise analysis first computes the correlations of independent variables with the dependent and then identifies the best subset of predictors. The stepwise criteria were: probability of F to enter ≤ 0.050, probability of F to remove ≥ 0.100. The following assumptions of multiple linear regression were examined: normality of the dependent and independent variables (skewness and kurtosis between -1 and 1), independence of errors (Dubin-Watson value of 1.5–2.5), no multicollinearity (tolerance value > 0.20), no outliers / influential cases (standardized residual scores < 3.0), normal distribution of residuals.

The predictions equations obtained from the derivation group were then validated in the cross-validation group (these subjects were not included in the derivation group), using the following criteria: (i) the Pearson product-moment correlation coefficient (R) between actual and predicted values, (ii) the constant error (CE = mean difference for actual VO₂peak-predicted VO₂peak), (iii) the standard error of estimate (SEE = SD[\sqrt{1-r^2}]), (iv) the total error (TE = \sqrt{S(actual VO₂peak-predicted VO₂peak)^2/n}), (v) the proximity of SEE and TE, (vi) no relationship between CE and actual VO₂peak (37), and (vii) the predicted residuals sum of squares (PRESS) adjusted R² (R_p² = 1-PRESSSS_total) that determines the generalizability of the new equation (26,29,38). Low values of R_p² indicate a model that predicts poorly. A Bland-Altman graph was used to present the agreement between the actual and the predicted VO₂peak values.

Next, we predicted VO₂peak and calculated the cross-validation statistics for previously published equations that (i) estimate VO₂peak using anthropometrical data (11) and performance on the 20mST (5,17,32,40) and (ii) estimate energy cost (VO₂) at submaximal speeds (34,56). Finally, we compared the predicted VO₂peak and cross-validation statistics of our equation vs. those obtained from previous studies. All data were analyzed using the statistical package SPSS (version 13, SPSS Inc., Chicago, Illinois, USA) and the significance level was set at a = .05.
Results

The physical characteristics of the participants are presented in Table 1. No differences were detected between the derivation and the cross-validation groups in the anthropometric and physiological variables from maximal treadmill exercise.

Stepwise multiple linear regression analyses were employed to identify the best subset of predictors for absolute VO\textsubscript{2peak} (mL∙min\textsuperscript{-1}) and relative VO\textsubscript{2peak} (mL∙kg\textsuperscript{-1}∙min\textsuperscript{-1}) values. The prediction models satisfied all the assumptions of stepwise multiple linear regression, as described in the methods section. Based on evaluation of the cross-validation statistics the most valid and accurate equations to predict absolute and relative VO\textsubscript{2peak} were:

\[
\text{VO2peak (mL min}^{-1}) = -597.877 + 45.676 \times \text{body mass in kg} + 73.480 \times \text{duration in min} (R = 0.93, \text{SEE} = 226 \text{ mL min}^{-1}) \text{ (eq. 1)}
\]

\[
\text{VO2peak (mL kg}^{-1}\text{ min}^{-1}) = 35.477 + 1.832 \times \text{duration in min} - 0.010 \times \text{duration} \times \text{body mass in kg} (R = 0.67, \text{SEE} = 3.8 \text{ mL kg}^{-1}\text{ min}^{-1}) \text{ (eq. 2)}
\]

The cross-validation statistics for the absolute VO\textsubscript{2peak} were: \( R = .94, \text{ CE} = -6 \text{ mL} \cdot \text{ min}^{-1}, \text{ SEE} = 157 \text{ mL} \cdot \text{ min}^{-1}, \%\text{SEE} = 4.8, \text{ TE} = 163 \text{ mL} \cdot \text{min}^{-1}, \%\text{TE} = 5.0, \) no significant correlation between CE and the actual VO\textsubscript{2peak} (mL∙min\textsuperscript{-1}), and \( R_{p}^2 = 0.98. \) The cross-validation statistics for the relative VO\textsubscript{2peak} were: \( R = .54, \text{ CE} = 0.1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}, \text{ SEE} = 2.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}, \%\text{SEE} = 4.6, \text{ TE} = 2.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}, \%\text{TE} = 4.9, \) no significant correlation between CE and the actual VO\textsubscript{2peak} (mL∙kg\textsuperscript{-1}∙min\textsuperscript{-1}), and \( R_{p}^2 = 0.93. \) The linear correlations between the actual and predicted absolute and relative values VO\textsubscript{2peak} values and the Bland-Altman graphs, which express the agreement between two methods for measuring the same thing, are presented in Figure 1.

| Table 1 Physical Characteristics and Maximal Incremental Exercise Data of the Participants in Derivation and Cross-Validation Groups (Mean ± SD) |
|-----------------|-----------------|-----------------|
| Variable        | Derivation Group | Cross-Validation Group |
|                 | \((n = 70)\)    | \((n = 18)\)    |
| Age             | 14.9 ± 1.4      | 14.8 ± 1.7      |
| Height (cm)     | 170.6 ± 8.7     | 172.2 ± 10.2    |
| Body mass (kg)  | 59.6 ± 10.8     | 60.1 ± 9.1      |
| BMI (kg∙m\textsuperscript{-2}) | 20.3 ± 2.4 | 20 ± 1.8 |
| Incremental treadmill test |           |                |
| HRpeak (b∙min\textsuperscript{-1}) | 200 ± 7       | 200 ± 8        |
| VO\textsubscript{2peak} (mL∙min\textsuperscript{-1}) | 3186 ± 600  | 3241 ± 498    |
| VO\textsubscript{2peak} (mL∙kg\textsuperscript{-1}∙min\textsuperscript{-1}) | 53.58 ± 5.07 | 53.55 ± 2.59 |
| RERpeak         | 1.11 ± 0.05     | 1.11 ± 0.06     |
| Final Velocity (km∙h\textsuperscript{-1}) | 14.3 ± 1.4  | 14.5 ± 1.2     |
| Duration of exercise (min) | 14.4 ± 2.6 | 14.7 ± 2.3    |
Figure 1 — Linear correlations between the actual and predicted VO₂peak values and the Bland-Altman graphs for the cross-validation group.
Cross-Validation of Previously Published Equations

The final stage of the analysis involved the cross-validation of selected previously published models in youths that derived VO2peak from anthropometrical data (11), from performance on the 20mST (5,17,32,40) and from equations that estimate energy cost (VO2) at submaximal speeds (34,56). The measured VO2peak in the cross-validation group was 53.6 ± 2.6 (mL·kg⁻¹·min⁻¹), while the predicted VO2peak was 53.5 ± 2.9 mL·kg⁻¹·min⁻¹ using our equation and 48.7 ± 3.1 mL·kg⁻¹·min⁻¹ using Bonnen’s et al. The predicted VO2peak from various equations based on the 20mST performance were: (i) 51.1 ± 3.6 mL·kg⁻¹·min⁻¹ using Leger’s et al. (32) equation, (ii) 54.3 ± 2.3 mL·kg⁻¹·min⁻¹ using Barnett’s et al. equation, (iii) 50.0 ± 4.2 mL·kg⁻¹·min⁻¹ using Chia’s et al. equation, and (iv) 54.0 ± 3.9 and 53.1 ± 3.7 mL·kg⁻¹·min⁻¹ using Matsuzaka’s et al. equations for speed and total shuttles, respectively. From the equations developed to predict energy cost for submaximal speeds (that is, VO2 not VO2peak) the predicted values for VO2peak were 52.2 ± 3.6 and 54.9 ± 4.4 mL·kg⁻¹·min⁻¹ using MacDougall’s et al. and Walker’s et al., respectively. Sheffe’s post hoc comparisons revealed significant differences between actual VO2peak and those estimated by Bonen’s et al. and Chia’s et al. equations.

The cross-validation results for the prediction of VO2peak from the equation developed in this study and previously reported equations in youths are presented in Table 2. The R, CE (mL·kg⁻¹·min⁻¹), %SEE, and %TE in our equation were 0.54, -0.1, 4.6%, and 4.9%, respectively. The respective values for previously published equations the values ranged from 0.10 to 0.49 for R, from -0.4 to 4.8 for CE, from 3.8 to 7.3% for SEE, and from 4.9 to 11.4% for TE. The examination of the last cross-validation criterion revealed a significant \((p < .01)\) correlation between CE and the actual VO2peak only in Bonen’s et al. \((r = .603)\) and Barnett’s et al. \((r = .613)\) equations.

Discussion

This study developed and cross-validated an equation for VO2peak using treadmill running in active male adolescents and compared this equation with previously published equations from anthropometrical data, performance data on the 20mST, and equations to predict energy cost using submaximal speeds. The sources of variation in VO2peak that we have tested included performance variables (duration and velocity) combined with traditional variables such as body weight, height, age, and their interaction terms. From these variables, body mass and duration of exercise contributed significantly to the absolute VO2peak prediction, while the addition of height, age, and their interaction terms did not further improve the prediction accuracy of the equation. For the prediction of relative VO2peak, the duration of exercise and duration × body mass interaction was the best subset of predictors.

In activities requiring large muscle groups and especially in ball games such as soccer, aerobic endurance performance is determined by VO2max, anaerobic (lactate) threshold, and running economy (25). Although VO2max is considered to be an important parameter for evaluating the aerobic capacity of the athlete, coaches are often interested at the final speed achieved during a field incremental running test for designing training programs (7). Thus, a running test that provides estimates of VO2peak and information on the final speed during an incremental maximal treadmill
Table 2  Comparison of Cross-Validation Statistics of $\text{VO}_{2\text{peak}}$ Prediction Equations vs. Maximal Treadmill Incremental Test in the Cross-Validation Group

<table>
<thead>
<tr>
<th>Equation</th>
<th>R</th>
<th>$\text{VO}_{2\text{peak}}$ mL·kg$^{-1}$·min$^{-1}$</th>
<th>CE mL·kg$^{-1}$·min$^{-1}$</th>
<th>SEE mL·kg$^{-1}$·min$^{-1}$</th>
<th>SEE%</th>
<th>TE mL·kg$^{-1}$·min$^{-1}$</th>
<th>TE%</th>
<th>R of CE and $\text{VO}_{2\text{peak}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>0.54</td>
<td>53.5 ± 2.9</td>
<td>0.1</td>
<td>2.5</td>
<td>4.6</td>
<td>2.6</td>
<td>4.9</td>
<td>NS</td>
</tr>
<tr>
<td>Anthropometric Bonen et al. 20m shuttle test</td>
<td>0.10</td>
<td>48.7 ± 3.1</td>
<td>4.8</td>
<td>3.0</td>
<td>5.7</td>
<td>6.1</td>
<td>11.4</td>
<td>S</td>
</tr>
<tr>
<td>Leger, et al. (32)</td>
<td>0.44</td>
<td>51.1 ± 3.6</td>
<td>2.5</td>
<td>3.2</td>
<td>6.0</td>
<td>4.1</td>
<td>7.7</td>
<td>NS</td>
</tr>
<tr>
<td>Barnett et al.</td>
<td>0.46</td>
<td>54.3 ± 2.3</td>
<td>-0.8</td>
<td>2.0</td>
<td>3.8</td>
<td>2.6</td>
<td>4.8</td>
<td>S</td>
</tr>
<tr>
<td>Matsazuka et al. for speed</td>
<td>0.43</td>
<td>54.0 ± 3.9</td>
<td>-0.4</td>
<td>3.5</td>
<td>6.6</td>
<td>3.6</td>
<td>6.7</td>
<td>NS</td>
</tr>
<tr>
<td>Matsazuka et al. for total shuttles</td>
<td>0.49</td>
<td>53.1 ± 3.7</td>
<td>0.4</td>
<td>3.3</td>
<td>6.1</td>
<td>3.3</td>
<td>6.1</td>
<td>NS</td>
</tr>
<tr>
<td>Chia et al.</td>
<td>0.43</td>
<td>50.0 ± 4.2</td>
<td>3.5</td>
<td>3.8</td>
<td>7.1</td>
<td>5.1</td>
<td>9.6</td>
<td>NS</td>
</tr>
<tr>
<td>Energy cost on treadmill</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MacDougall et al.</td>
<td>0.43</td>
<td>52.2 ± 3.6</td>
<td>1.4</td>
<td>3.2</td>
<td>6.0</td>
<td>3.6</td>
<td>6.7</td>
<td>NS</td>
</tr>
<tr>
<td>Walker et al.</td>
<td>0.45</td>
<td>54.9 ± 4.4</td>
<td>-1.3</td>
<td>3.9</td>
<td>7.3</td>
<td>4.1</td>
<td>7.6</td>
<td>NS</td>
</tr>
</tbody>
</table>

Present study: $35.477 + 1.832 \times \text{duration (min)} - 0.010 \times \text{duration} \times \text{body mass (kg)}$
Bonen et al.: $17.84 + 1.341 \times \text{age (yrs)} + 0.248 \times \text{height (cm)} - 0.522 \times \text{body mass (kg)}$
Leger et al.: $31.025 + 3.238 \times \text{maximal speed (km·h}^{-1}) - 3.248 \times \text{age (yrs)} + 0.1536 \times \text{maximal speed} \times \text{age}$
Barnett et al. for males: $24.2 - 0.8 \times \text{age (yrs)} + 3.4 \times \text{maximal speed (km·h}^{-1})$
Matsazuka et al.: $-4.75 + 4.76 \times \text{maximal speed (km·h}^{-1})$
Matsazuka et al.: $35.4 + 0.22 \times \text{total shuttles}$
Chia et al.: $53.5 - 0.31 \times \text{body mass (kg)} + 0.19 \times \text{shuttles completed}$
MacDougall et al.: $22.859 + 1.913 \times \text{speed (km·h}^{-1}) - 0.8664 \times \text{age (yrs)} + 0.0667 \times \text{speed} \times \text{age}$
Walker et al.: $2.1124 + 0.2184 \times \text{speed (m·min}^{-1})$

NS = non significant; S = significant; R = correlation coefficient; CE (mL·kg$^{-1}$·min$^{-1}$) = mean actual $\text{VO}_{2\text{peak}}$—mean predicted $\text{VO}_{2\text{peak}}$; SEE (standard error of estimate) = $SD_y \sqrt{1-r^2}$; %SEE = $(\text{SEE} \div \text{actual VO}_{2\text{peak}}) \times 100$; TE (total error) = $\sqrt{\text{S(\text{actual VO}_{2\text{max}}—\text{predicted VO}_{2\text{max}})^2/n}}$; %TE = $(\text{TE} \div \text{actual VO}_{2\text{peak}}) \times 100$
test (0% grade) could be a very useful tool for coaches for assessing aerobic capacity, as well as, for prescribing and monitoring aerobic training programs in active adolescents.

The VO\textsubscript{2peak} values in this study (44–65 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}) are relatively similar to those previously reported in young athletes (6) and young soccer players 12–17 years old (5,6,18,55,57). Therefore, the sample that we used for the derivation of prediction equation for VO\textsubscript{2peak} is representative, in terms of cardiorespiratory fitness, of active (moderately-trained) youth that is regularly involved in training and generally present VO\textsubscript{2peak} values within 45–65 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}.

The developed equation for prediction of absolute VO\textsubscript{2peak} takes into account body mass and duration, while the equation that predicts VO\textsubscript{2max} in relative terms includes duration and the “duration × body mass” interaction as the best subset of predictors. This is consistent with previous investigations that used anthropometrical data (11,19) or incremental tests with constant stage duration and intensity incrementation and have reported that body mass and/or performance-related variables, such as power, duration of exercise or total shuttles completed accounted significantly in the variation of VO\textsubscript{2peak} in youths and adults (3–5,13,17,21,24,27,40,51).

Height and age failed to account for additional variance in VO\textsubscript{2max}. This may be explained by two facts collectively: (i) the higher correlation of body weight compared with height and age with VO\textsubscript{2max} in this study and (ii) the high collinearity of body weight with these two variables. This is in accordance with previous studies that used incremental exercise and have not considered height and/or age to predict VO\textsubscript{2max} in youth (4,17). However, others have included age as a predictor variable (over height and body mass) (5,32) or both age and anthropometrical data (27,40) in their equations. Leg length, stride length, stride frequency, and skinfold measurements are other variables that have been reported to be influential variables related to VO\textsubscript{2} when running (16,47). However, it would be more difficult for coaches to accurately measure all of the above variables and therefore, the equation would have been less practical to use. Previous studies have reported that the addition of percent body fat or skinfold measurements did not (4,56) or did (5) improve their model in estimating the energy cost of running or VO\textsubscript{2max} in youth. The influence of these variables to VO\textsubscript{2} prediction models requires further research. Since no female participants were tested in our study, our results are limited to active male adolescents 12–18 years old.

For testing the accuracy of our regression equations we performed cross-validation analyses. The mean values of the actual and predicted absolute VO\textsubscript{2peak} (3241 mL·min\textsuperscript{-1} vs. 3247 mL·min\textsuperscript{-1}, respectively) and relative VO\textsubscript{2peak} (53.6 vs. 53.5 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}, respectively) were comparable. TE, which is a measure of variability in prediction errors around the line-of-identity and reflects the true difference between the actual and predicted VO\textsubscript{2peak} from our equation, was 162 mL·min\textsuperscript{-1} and 2.6 mL·kg\textsuperscript{-1}·min\textsuperscript{-1} for absolute and relative VO\textsubscript{2peak}. This fairly small TE (below 5%) for both absolute and relative VO\textsubscript{2peak} values suggests a high overall cross-validation accuracy of our prediction models. The SEE, which is a measure of variability in the prediction errors around the line-of best fit and is not affected by the variability of the samples, was also relatively small (157 mL·min\textsuperscript{-1} and 2.5 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}). In addition, the differences between the SEE and TE for both absolute (157 vs. 162 mL·min\textsuperscript{-1}) and relative (2.5 vs. 2.6 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}) predicted VO\textsubscript{2peak} values were trivial, thus the likelihood of systematic over or underestimation by these
prediction models is small. Finally, there were no relationship between CE and actual VO\textsubscript{2peak}, and R\textsuperscript{p} ranged from 0.93 to 0.98. All the above data suggest a good cross-validation accuracy and generalizability of our prediction models (37,38) for both absolute and relative VO\textsubscript{2peak}.

Next, we compared our equation for relative VO\textsubscript{2peak} prediction to previously published equations derived from anthropometric data, performance on 20mST and equations to predict energy cost using submaximal speeds. Two of the 9 equations (Bonen’s and Chia’s) cross-validated in this study significantly underestimated VO\textsubscript{2peak}. However, both equations were developed using subjects of a different age span (7–15 and 15–17 years for Bonen’s and Chia’s equations, respectively) compared with our cross-validation group (12–18 years old). In addition, there were significant (\( p < .01 \)) positive correlations between the CE and the actual VO\textsubscript{2peak} for Bonen’s (\( r = .603 \)) and Barnett’s (\( r = .613 \)) equations. Thus, the difference between actual and predicted VO\textsubscript{2peak} was greater at high VO\textsubscript{2} values, suggesting that these two equations predict better VO\textsubscript{2peak} in subjects with low aerobic fitness (37).

The validity coefficient of our equation was 0.54. Bonen’s equation showed the lowest validity coefficient, while for all other equations it ranged from 0.43 to 0.49. These values are lower compared with those reported by the original studies. However, as previously suggested the cross-validation analysis may reduce the correlation reported by multiple regression that was used to develop the equation (37). Furthermore, the relatively homogeneous group with narrow range of VO\textsubscript{2peak} that we used may have also contributed to lower validity coefficients (28,49).

The magnitude of SEE and TE, as well as, the proximity of these two error terms provide evidence for the accuracy of the prediction model (37). The SEE in our validation group was 2.5 mL·kg\textsuperscript{-1}·min\textsuperscript{-1} (4.6%) and TE 2.6 mL·kg\textsuperscript{-1}·min\textsuperscript{-1} (4.9%). These values appear to be lower than the respective ones from all other equations tested with the exception of Barnett’s et al. that demonstrated lower SEE. All equations showed SEE and TE below 10% of the actual VO\textsubscript{2peak} with the exception of Bonen’s et al. (11.4% of VO\textsubscript{2peak}). This is despite the fact that the equations were developed with subjects of different age ranges, different ethnicities, and some were developed for estimating VO\textsubscript{2peak} using the 20mST and others for estimating the energy cost at submaximal speeds.

Leger’s et al. (32) and Matsuzaka’s et al. equations produced the best overall cross-validation statistics among tested equations that estimate VO\textsubscript{2peak} from the performance in the 20 mST. The error in the VO\textsubscript{2} prediction of the 20mST with Leger’s formula (32) was larger (SEE 3.2 mL·kg\textsuperscript{-1}·min\textsuperscript{-1} or 6.0% of the actual VO\textsubscript{2peak}) compared with our model, but similar (42,57) or somewhat smaller compared with previous reports (3.6–5.3 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}) that validated the 20mST in young males (12,33,40,54). It is possible that the wider age span (6–18 yrs. old) and aerobic fitness of the subjects that were used in Leger et al. study (32) may have contributed to the greater error terms compared with those recorded this study. Even though Matsuzaka’s et al. equation was developed for Japanese children 8–17 years old, it demonstrated cross-validation statistics in Caucasian children at least as good compared with those of Leger’s et al. equation (32). Despite the fact that Leger’s equation has been criticized because VO\textsubscript{2} was not directly measured during the test, but it was estimated by the retroextrapolation method of VO\textsubscript{2} recovery curve using the first four 20s samples (50), it may be the best choice, along with Matsukaka’s et al., when a 20mST is to be used for prediction of VO\textsubscript{2peak} in youth.
The equations of McDougall et al. and Walker et al. were developed for estimating energy cost at submaximal speeds and not VO$_{2\text{peak}}$. Walker et al. also suggested that their equation was developed for running speeds up to 13 km·h$^{-1}$ and it might not be valid for higher speeds. Yet, the cross-validation of Walker’s et al. and McDougall’s et al. equations revealed TE of a 4.1 mL·kg$^{-1}$·min$^{-1}$ (7.6%), and 3.6 mL·kg$^{-1}$·min$^{-1}$ (6.7% of the actual VO$_{2\text{peak}}$), respectively. These values appear very close to those generated by Leger’s and Matsazuka’s equations from the 20mST.

The equation developed in this study for the prediction of VO$_{2\text{max}}$ in active youth utilizes a test that mimics the form of activity and the energy utilization of the gold standard measurement of VO$_{2\text{max}}$ in a laboratory. Based on the view that the cross-validation analysis is the strongest evidence of an equation’s validity and accuracy, it appears that the equation of this study accurately predicts VO$_{2\text{max}}$ in active (44–65 mL·kg$^{-1}$·min$^{-1}$) male adolescents (12–18 years old) using a maximal incremental treadmill test. The new equation demonstrates lower values of CE, SEE, and TE compared with previously published equations for youth. It should be noted that the use of a more homogenous sample with a narrow range of VO$_{2\text{peak}}$ values in this study compared with previous studies may have contributed to the lower error terms and increased the accuracy of our equation. Along with predicted VO$_{2\text{peak}}$ values the use of a maximal treadmill test allows estimation of maximal aerobic speed that may be used by coaches and athletic practitioners to set up intensities for designing aerobic training programs. Nevertheless, the 20mST still remains a good choice for VO$_{2\text{peak}}$ prediction in adolescents when a field test with a large number of participants is involved.

References


