A New Model for Estimating Peak VO2 Based on Post-Exercise Measurements in Swimming

ARTICLE in INTERNATIONAL JOURNAL OF SPORTS PHYSIOLOGY AND PERFORMANCE · SEPTEMBER 2015
Impact Factor: 2.68 · DOI: 10.1123/ijspp.2015-0227

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<tr>
<th>Journal:</th>
<th><em>International Journal of Sports Physiology and Performance</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID:</td>
<td>IJSPP.2015-0227.R2</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Original Investigation</td>
</tr>
<tr>
<td>Keywords:</td>
<td>exercise physiology, sport physiology, kinetics, aerobic</td>
</tr>
</tbody>
</table>
A New Model for Estimating Peak VO₂ Based on Post-Exercise Measurements in Swimming

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ABSTRACT

Purpose: Assessing cardiopulmonary function during swimming is a complex and cumbersome procedure. Backward extrapolation is often used for predicting peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) during unimpeded swimming, but error can derive from a delay at the onset of $\dot{V}O_2$ recovery. We assessed the validity of a mathematical model based on heart rate (HR) and post-exercise kinetics for the estimation of $\dot{V}O_{2\text{peak}}$ during exercise. Methods: 34 elite swimmers performed a maximal front crawl 200-m swim. $\dot{V}O_2$ was measured breath-by-breath and HR from beat-to-beat intervals. Data were time aligned and 1-s interpolated. Exercise $\dot{V}O_{2\text{peak}}$ was the average of the last 20 s of exercise. Post-exercise $\dot{V}O_2$ was the first 20-s average during the immediate recovery. Predicted $\dot{V}O_2$ values ($p\dot{V}O_2$) were computed using the equation:

$$p\dot{V}O_2(t) = \dot{V}O_2(t) \cdot HR_{\text{end-exercise}} / HR(t).$$

Average values were calculated for different time intervals and compared to measured exercise $\dot{V}O_{2\text{peak}}$. Results: Post-exercise $\dot{V}O_2$ (0-20 s) underestimated $\dot{V}O_{2\text{peak}}$ by 3.3% (95% CI = -9.8 under- to 3.2% overestimation; mean difference = -116 ml·min$^{-1}$; $SE_E = 4.2%$; $p = 0.001$). The best $\dot{V}O_{2\text{peak}}$ estimates were offered by $p\dot{V}O_{2\text{peak}}$ from 0-20 s ($r^2 = .96$; mean diff. = 17 ml·min$^{-1}$; $SE_E = 3.8%$). Conclusions: The high correlation ($r^2 = .86$–.96) and agreement between exercise and predicted $\dot{V}O_2$ support the validity of the model, which provides accurate $\dot{V}O_{2\text{peak}}$ estimations after a single maximal swim whilst avoiding the error of backward extrapolation and allowing the subject to swim completely unimpeded.

Key words: maximal oxygen uptake; oxygen kinetics; backward extrapolation; modelling; heart rate

INTRODUCTION

The assessment of cardiopulmonary gas exchange and oxygen uptake ($\dot{V}O_2$) in swimming is a complex and cumbersome procedure and still faces limitations imposed by the water environment and the equipment (see Sousa et al. 1 for a review). Specifically, in-water measurements require breathing through a snorkel connected with a system of tubes and built-in valves that allows collecting the expired gases whilst keeping dry the inspiratory and expiratory tubes, as well as the analysers. From a technical standpoint, two main indirect calorimetric approaches have been used to collect and analyse expiratory gases in swimming: (1) measurements during exercise using snorkels with built-in valves connected to Douglas bags, open-circuit metabolic charts, or breath-by-breath portable gas analysers; and (2) post-exercise measurements with gas collection via facemask or mouthpiece connected to Douglas bags or open-circuit metabolic charts. To enable continuous measurements in the field, portable gas analysers are now preferred by many investigators because of their more advantageous sampling capability, practicality, and acceptable level of accuracy. However, the inability for swimmers to execute diving starts and underwater gliding after starts and turns, which play a major role in the overall swimming performance, also impairs the ecological validity of $\dot{V}O_2$ measurements. Even if these constraints do not prevent the investigation of many aspects of the physiological response during swimming,
measurement of the respiratory function during exercise does restrict the full expression of performance capacity in pool conditions, particularly during maximal swimming. For instance, all-out 100-m front crawl and breaststroke swims were ~5-6% slower when using a snorkel compared to unimpeded swimming. An alternative procedure to ‘during-swimming’ measures is the backward extrapolation (BE) of the $O_2$ recovery curve, first described by di Prampero et al. and validated by Léger et al. Montpetit et al. compared $\dot{V}O_{2\text{peak}}$ values obtained using the Douglas bag technique in a multistage free-swimming test with those predicted using the BE method (i.e., recovery from the same swimming test), as well as with those measured during an uphill treadmill running test. Despite finding good method agreement, they concluded that, to ensure the validity of the method, short duration exercises (<5 min) and supramaximal intensities should be avoided as a delay in the onset of $O_2$ recovery may appear. Another approach was used by Costill et al., who showed a good agreement between $\dot{V}O_{2\text{peak}}$ during maximal and submaximal swimming and a single 20-s expired gas collection taken immediately after a 4-7 min swim. However, breath-by-breath post-exercise measurements confirmed the occurrence of a delay at the onset of the $\dot{V}O_2$ recovery curve and identified a plateau in many —but not all— swimmers, suggesting this to be the main source of error in these two estimation procedures.

To overcome these limitations and to improve the estimation of $\dot{V}O_{2\text{peak}}$ from post-exercise measurements, our group recently proposed a mathematical model based on HR and off-transient $\dot{V}O_2$ kinetics. In short, based on the Fick’s principle, the model calculates a predicted $\dot{V}O_2$ at a given time of recovery using the HR as a proxy for changes in cardiac output, and the oxygen pulse as a proxy for the arteriovenous $O_2$ difference.

The aim of the present study was to assess the validity of this model by comparing direct $\dot{V}O_{2\text{peak}}$ measurements during the final period of the swimming exercise (reference method) with the one predicted by the model, as well as the one indirectly estimated from a single 20-s measurement during recovery. Furthermore, different recovery intervals were investigated in an attempt to enhance the accuracy of $\dot{V}O_{2\text{peak}}$ estimation using the model.

**METHODS**

**Subjects**

Thirty-four elite swimmers, all members of national and Olympic teams, including 18 females (mean ± SD: age 20.8 ± 3.5 years, height 173.2 ± 5.8 cm, body mass 64.5 ± 5.6 kg) and 16 males (age 22.7 ± 3.6 years, height 186.8 ± 6.0 cm, body mass 80.8 ± 7.7 kg), voluntarily participated in this study. Informed consent was obtained from all individual participants included in the study and their legal guardians when appropriate. The study had received approval from the Ethics Committee for Clinical Sport Research of Catalonia in accordance of the 1964 Helsinki declaration and its later amendments.

**Design**

All tests were conducted in a 50-m indoor pool (temperature: water 26–27°C, air 27–28°C). After a ~30 min swimming-based warm-up followed by 10 min of passive recovery on pool side, participants completed an all-out 200-m front crawl swim to determine exercise $\dot{V}O_{2\text{peak}}$. After exercise, the swimmers remained still in an upright
position immersed up to the sternum. In-water starts and touched open turns with no underwater gliding were performed.

Methodology

\( \dot{V}O_2 \) was measured using a telemetric portable gas analyser (K4 b², Cosmed, Italy) held over the head of the swimmer by an assistant following the swimmers along the pool. The equipment was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system, previously validated both in vivo¹⁸ and using a gas exchange simulator.¹⁹ The gas analysers were calibrated before each test with gases of known concentration (16% O₂, 5% CO₂) and the turbine volume transducer was calibrated by using a 3-l syringe according to the manufacturer’s instructions. Pulmonary gas exchanges were measured breath-by-breath 1 min before, during, and 3 min post-exercise. HR was continuously measured using waterproof beat-to-beat monitors (CardioSwim, Freelap, Switzerland).

\( \dot{V}O_2 \) and HR data were time-aligned to the start of the measurements, 1-s interpolated, and plotted against time. Two \( \dot{V}O_{2\text{peak}} \) values were identified (figure 1): 1) end-exercise \( \dot{V}O_{2\text{peak}} \) was the average value over the last 20 s of exercise²⁰ and was taken as the reference value (criterion) for all comparisons; and 2) post-exercise \( \dot{V}O_2 \) was the average value over the first 20 s of the recovery period (\( \dot{V}O_2(0-20) \)). The 20-s duration of the end- and post-exercise measurements was chosen for the following reasons: 1) to ensure that only last swimming lap data were used, as \( V_2 \) usually decreases during the turns; 2) to minimize the influence of inter-breath fluctuations (i.e., improvement of signal-to-noise ratio); 3) to prevent too high \( VO_{2\text{max}} \) values frequently obtained when using shorter time intervals;²¹ 4) to maintain end- and post-exercise temporal equality as previous results during 200-m maximal swimming showed an on/off symmetry in the \( VO_2 \) kinetic response;²² and 5) previous work showed that 20-s average values produced the same \( VO_{2\text{peak}} \) as the total amplitude of the monoexponential equation fitting the \( VO_2 \) on-kinetics during 200-m maximal swims.²⁰

The rationale of the proposed new model relies on the Fick’s principle relating cardiac output (\( \dot{Q} \)) with \( \dot{V}O_2 \) and arterious-venous \( O_2 \) difference (\( C(a-\bar{v})O_2 \)) according to the equation:

\[
\dot{V}O_2 = \dot{Q} \cdot C(a-\bar{v})O_2
\]  
(1)

On the other hand, \( \dot{Q} \) equals the cardiac stroke volume (SV) times the HR:

\[
\dot{Q} = SV \cdot HR
\]  
(2)

Under the assumption that SV does not significantly change over the first seconds of recovery,²¹ changes in HR can be considered as a proxy for changes in \( \dot{Q} \), and likewise, the \( \dot{V}O_2/HR \) ratio can be used a proxy of the arterio-venous \( O_2 \) difference:

\[
\frac{\dot{V}O_2}{HR} \approx C(a-\bar{v})O_2 \cdot \text{constant}
\]  
(3)

Based on these two assumptions, the mathematical model computes “predicted” \( \dot{V}O_2 \) values (\( p\dot{V}O_2 \)) based on synchronized post-exercise \( \dot{V}O_2 \) and HR measurements (equation 3), and HR at the end of exercise. Thus, at a given time \( t \) during the recovery period, \( p\dot{V}O_2 \) can be calculated according to the equation:
\[ p\dot{V}_O_2(t) = \frac{\dot{V}_O_2(t)}{HR(t)} HR_{\text{end-exercise}} \]  

where, \( p\dot{V}_O_2(t) \) is the predicted (modelled) post-exercise \( \dot{V}_O_2 \) at time \( t \); \( \dot{V}_O_2(t) \) is the post-exercise 1-s interpolated \( \dot{V}_O_2 \) at time \( t \); HR(\( t \)) is the post-exercise 1-s interpolated HR value at time \( t \); and HR\(_{\text{end-exercise}} \) is the highest value of the last 10-s average HR at the end of exercise (excluding single peaks higher than 5 bpm than the rest, corresponding to \( \sim 1 \) SD from mean HR during the last 10 s of exercise).

In an attempt to enhance the accuracy of the estimation, \( \dot{V}_O_{2\text{peak}} \) was compared with \( p\dot{V}_O_2 \) at different time intervals (\( t = 0-20, 5-20, 10-20, 15-20, 5-15, \) and \( 10-15 \) s), which were expressed as \( p\dot{V}_O_2 \)\((0-20)\), \( p\dot{V}_O_2 \)\((5-20)\), \( p\dot{V}_O_2 \)\((10-20)\), \( p\dot{V}_O_2 \)\((15-20)\), \( p\dot{V}_O_2 \)\((5-15)\), and \( p\dot{V}_O_2 \)\((10-15)\).

**Statistical analysis**

Descriptive data are presented as mean, standard deviation (\( \pm \) SD), and mean difference. Normality of distributions and homogeneity of variances were verified using the Shapiro-Wilk’s and Levene’s tests, respectively. A one-way analysis of variance with repeated measures (RM-ANOVA) and post-hoc Tukey’s test if appropriate were used for multiple comparisons between \( \dot{V}_O_{2\text{peak}} \) (criterion value) and each of the post-exercise measured and predicted values. The Pearson's coefficient of determination (\( r^2 \)) was used to assess correlation between variables. Mean difference plots were used to assess agreement between measured and predicted values. The level of significance was set at \( p < 0.05 \). Statistical analyses were conducted using SPSS 15.0 (SPSS Inc., Chicago, USA).

**RESULTS**

Figure 1 shows an example of HR and \( \dot{V}_O_2 \) over the last 30 s of the exercise and the immediate recovery, as well as the predicted \( p\dot{V}_O_2 \) values for different post-exercise intervals in one participant. In accordance with previous results,\(^22,25\) no evidence of a slow component was observed in any swimmer as exercise duration constrained the appearance of phase III of the \( \dot{V}_O_2 \) kinetics.\(^26\)

***Figure 1***

Table 1 summarizes the comparisons between \( \dot{V}_O_{2\text{peak}} \) measured during exercise and post-exercise measured and predicted values at different time intervals. End-exercise \( \dot{V}_O_{2\text{peak}} \) (criterion value) was 3.3% higher than post-exercise \( \dot{V}_O_2 \)\((0-20)\). All predicted \( p\dot{V}_O_2 \) were highly correlated with (\( r^2 = 0.86-0.96 \)) and were not different from the criterion value (\( p > 0.001 \)). The best estimate (i.e. lowest bias) of exercise \( \dot{V}_O_{2\text{peak}} \) was offered by \( p\dot{V}_O_2 \)\((0-20)\) (\( r^2 = 0.96 \); mean diff. = 17 ml\( \cdot \)min\(^{-1}\); \( SE_E = 3.8\% \)) and \( p\dot{V}_O_2 \)\((5-20)\) (\( r^2 = 0.94 \); mean diff. = 13 ml\( \cdot \)min\(^{-1}\); \( SE_E = 4.7\% \)).

***Table 1***
Figure 2 provides the Bland-Altman difference plots showing good agreement between exercise \(\dot{V}O_{2\text{peak}}\) and predicted recovery \(p\dot{V}O_{2}(0-20)\) and \(p\dot{V}O_{2}(5-20)\) data.

***Figure 2***

**DISCUSSION**

Our main finding was that the proposed mathematical model based on HR kinetics and post-exercise \(\dot{V}O_2\) measurements in a maximal 200-m swim is a valid procedure of estimating \(\dot{V}O_{2\text{peak}}\) in competitive swimmers, with optimal predictive capacity if based on measurements obtained during 20 s after the cessation of exercise. We also found that assessing \(\dot{V}O_{2\text{peak}}\) by using a single 20-s measurement during recovery as proposed by Costill and coauthors\(^{14}\) is likely to underestimate true exercise \(\dot{V}O_{2\text{peak}}\) by 3.3% on average (95% CI \(9.8\) under- to 3.2% overestimation).

As previously explained, the model relies on the Fick’s principle (eq. 1 and 2), and its basic assumption is that SV remains nearly constant during the first seconds of recovery (eq. 3). The validity of this assumption needs further discussion. Following light to moderate exercise, it has been shown that SV does not fall as rapidly as HR does after exercise and remains above exercise levels\(^{23}\) for as long as 3 to 5 min,\(^{23,27,28}\) especially in the upright position.\(^{28}\) Sustained high \(\dot{Q}\) during the recovery phase was also demonstrated, explaining the on-/off-transient \(\dot{V}O_2\) kinetics asymmetry (i.e. slower off-transient time constant, also confirmed in 200-m maximal swimming\(^{22}\)), appearing to be a result of both SV and HR being maintained to ensure a sufficiently high \(O_2\) flow to the muscle during recovery at a time when the muscle \(\dot{V}O_2\) remains high.\(^{29}\) Therefore, the decrease in \(\dot{Q}\) (and consequently \(\dot{V}O_2\)) would occur mainly by decreased post-exercise HR. On the other hand, Sheldahl et al.\(^{30}\) suggested that the central redistribution of blood volume with head-out water immersion cycling exercise at 40, 60 and 80% of \(\dot{V}O_{2\text{max}}\), leading to an increase in SV without a proportional decrease in HR, evidences that \(\dot{Q}\) is regulated at a higher level during upright exercise in water compared with that on land. Although there is no available evidence that this response pattern takes place during maximal exercise, in line with these reports, some of our subjects showed a little rise in \(\dot{V}O_2\) while HR remained constant immediately after the cessation of exercise, which can be loosely interpreted as a rise in SV. This rise could also be explained by the change in body position from horizontal to vertical; the lower part of the body is now deep immersed and under a hydrostatic pressure gradient, which would translocate blood from the lower limbs and abdomen into the thoracic region, thus increasing venous return and SV compared to the horizontal position.\(^{31}\) We suggest that this increase in SV is possibly the reason for the small overestimation of exercise \(\dot{V}O_{2\text{peak}}\) when shorter time intervals were used, such as in calculating \(p\dot{V}O_{2}(5-15)\) and \(p\dot{V}O_{2}(10-15)\) (table 1).

A second assumption of the model is that \(C(a-\bar{V})O_2\) remains nearly constant during the first seconds of recovery. This assumption relies on the fact that a certain venous volume with constant \(O_2\) saturation can be assumed to occur during the immediate recovery while arterial saturation is constant. Because of the distance...
between muscle and mouth, substantial changes in $C(a - \overline{V}_O_2)$ over the first seconds of recovery are not to be expected, as shown by Drescher et al.\textsuperscript{17} As shown in figure 1, $p\dot{V}O_2$ values do not decline over the first 20 s after the cessation of exercise, which is likely the time for the onset of changes in $C(a - \overline{V}_O_2)$ perceivable in the exhaled air. On the other hand, the high correlation and the low mean difference between $\dot{V}O_2$ and SV occurred within this time period. Therefore, it seems justified to use HR on- and off-kinetics as a proxy of $\dot{V}O_2$ dynamic response during the early recovery within the limited scope of practical application of the model.

From another standpoint, the observation that $p\dot{V}O_2(0 - 20)$ and $p\dot{V}O_2(5 - 20)$ provided the smallest estimation bias of $\dot{V}O_2$ during exercise is in agreement with previous findings, showing a time-variable delay in the $\dot{V}O_2$ recovery curve after maximal swimming.\textsuperscript{15} Our results show that this was likely to be the reason for (1) the ~20% overestimation of $\dot{V}O_2$ found by Lavoie et al. after an 400-m swim,\textsuperscript{32} and (2) the similar results reported by Costill et al., who found a decline in $\dot{V}O_2$ during the first 20 s after the cessation of exercise causing a ~6% overestimation of $\dot{V}O_2$ after 4-7 min of tethered swimming.\textsuperscript{14} Differences in methods of assessment and instrumentation among these studies (e.g., Douglas bags vs. modern breath-by-breath oximeters) would certainly explain at least some of these discrepancies. Concerning the variability of the estimated parameters (figure 2, table 1), in which some predicted values deviate up to ~8% from measured values, we need to consider that the $SE_E$ for $p\dot{V}O_2(0 - 20)$, the best predictor variable, was 3.82%, very similar to the $SE_E$ for postexercise measured $\dot{V}O_2$ (4.15%). This suggests that the main reason for these larger deviations is measurement error, not inherent to the modelling procedure. Hyperventilation during the immediate recovery appears to be the most straightforward explanation.

Practical applications

The proposed model allows to minimize the error in predicting $\dot{V}O_2$ from recovery measurements after a maximal swim, with the practical advantage of avoiding the use of respiratory equipment during swimming and, thus, allowing the swimmer to utilise their normal breathing pattern and the full use of high-speed swimming technique and of the specifically trained muscle mass in pool conditions.

From a technical standpoint, three conditions are required to ensure the validity of the results: 1) obtaining quality beat-to-beat HR recordings, 2) obtaining the first breath-by-breath $\dot{V}O_2$ values as fast as possible while avoiding missing breaths and hyperventilation (e.g., as when swimmers are incorrectly advised to hold their breath during the final strokes), and 3) monitoring HR and $\dot{V}O_2$ during a recovery period of at least 20 s to avoid over- or underestimation.

Further validation of the model would imply comparing direct $\dot{V}O_2$ measurements with model-predicted values on swimming bouts of different duration.
and intensity (e.g., 100- to 400-m submaximal and maximal swims). In addition, more basic studies investigating directly measured $\dot{Q}$ kinetics after maximal swimming exercise would be required to confirm the physiological assumptions of the model.

CONCLUSION

We propose the new model, based on continuous beat-to-beat HR and post-exercise breath-by-breath $\dot{V}O_2$ measurements during 20 s, as a valid and accurate procedure for estimating $\dot{V}O_{2\text{peak}}$ in competitive swimmers. This calculation method avoids the bias of $\dot{V}O_{2\text{peak}}$ estimations incurred by using the backward extrapolation method and overcomes the constraints imposed by the use of respiratory equipment during swimming.

ACKNOWLEDGEMENTS

This work was partially supported by grants awarded by the Ministry of Science and Innovation of Spain (DEP2009-09181), Higher Sports Council of Spain (CSD 35/UPB/10, 005/UPB10/11, 112/UPB10/12, CAR-UGr 2009, CAR-UGr 2011), and INEFC (Research Support Grants 2011, 2012). The contribution of Anna Barrero (INEFC) in data acquisition is acknowledged. We are indebted to the coaches and staff of the participating teams: Fred Vergnoux (C. N. Sabadell and RFEN); Jordi Murio, Juan J. Castillo and Victor Mancha (RFEN); David Lyles, Jenny Lyles and Xu Feng Jie (Shanghai Province Swimming and Chinese Swimming Federation); Miha Potočnik, Gorazd Podržavnik and Roni Pikec (Slovenian Swimming Federation); Rohan Taylor, Jeremy Oliver and Danielle Stefano (Victorian Institute of Sport); and Patrick Pearson (EIFFEL Swimmers PSV-Eindhoven). A very special note of appreciation goes to each and all the swimmers who served as subjects and rendered their valuable time and effort.

REFERENCES


FIGURE LEGENDS

Figure 1. Heart rate (light grey diamonds) and \( \dot{V}_O_2 \) (dark grey squares) kinetics over the last 30 s of exercise and immediate recovery during a 200-m maximal swim in one swimmer. Vertical lines indicate time intervals during exercise (\( t < 0 \)) and recovery (\( t > 0 \)). In black circles, modelled (predicted) values (\( p\dot{V}_O_2 \)) during recovery. Short dashed lines indicate different time intervals used for comparisons.

Figure 2. Bland-Altman difference plots between peak \( \dot{V}_O_2 \) at the end of exercise (criterion) and the two best estimates calculated by the model, \( p\dot{V}_O_2 (0 - 20) \) (panel A), and \( p\dot{V}_O_2 (5 - 20) \) (panel B), respectively. The equality (solid), mean difference (long-dashed), and ± 95% limits of agreement (short-dashed) lines are depicted.
Table 1. Oxygen uptake measurements during exercise (criterion value) and recovery (post-exercise), and $\dot{V}O_2$ values predicted by the model at different time intervals.

<table>
<thead>
<tr>
<th>Time interval</th>
<th>$\dot{V}O_2$ (ml·min$^{-1}$)</th>
<th>95% CI (ml·min$^{-1}$)</th>
<th>Mean diff. (ml·min$^{-1}$)</th>
<th>$r^2$</th>
<th>$SE_E$ (ml·min$^{-1}$)</th>
<th>Significance</th>
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<tr>
<td>Exercise (criterion)</td>
<td>-20–0 3547 ± 692</td>
<td>3305 3788</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Post-exercise</td>
<td>0–20 3431 ± 685</td>
<td>3192 3670</td>
<td>-116</td>
<td>.959</td>
<td>142 4.15</td>
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<td>Predicted</td>
<td>0–20 3564 ± 698</td>
<td>3320 3807</td>
<td>17</td>
<td>.963</td>
<td>136 3.82</td>
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<tr>
<td></td>
<td>5–20 3559 ± 705</td>
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Values are mean ± SD. 95% CI, 95% confidence interval; Mean diff., mean difference with criterion value; $r^2$, Pearson’s coefficient of determination; $SE_E$, standard error of estimate; Significance, compared with criterion value; *Significantly different from criterion value ($p < 0.05$).