Application of the Critical Power Concept to Young Swimmers

David W. Hill, Robert P. Steward Jr., and Cindy J. Lane

The purpose of this study was to evaluate use of the critical power concept with swimmers ages 8 to 18 years. Critical velocity (CV) and anaerobic swimming capacity (ASC) were determined from the results of three short time trials (n = 86) or competition swims (n = 60). Data fit the critical power model well, as evidenced by high \( R^2 \) and low SEE of CV and ASC estimates. CV was correlated with velocity in an endurance swim (\( r \geq 0.86 \)) and ASC was correlated with peak lactate (\( r \geq 0.69 \)). Thus, even in very young swimmers, CV and ASC provide mode-specific indices of endurance and anaerobic capacity, respectively.

The critical power concept, which was first proposed by Monod and Scherrer (17) for synergistic muscle groups, was extended to whole-body cycle ergometer exercise by Moritani et al. (18). The concept is based on a hyperbolic relationship between power output and time to exhaustion. It provides an estimate of anaerobic work capacity (AWC) and an index of endurance ability, namely critical power (CP). The nonlinear hyperbolic power–time relationship is described by the equation time = AWC/(power – CP). This power–time relationship can be manipulated into two linear relationships: (a) a power–l/time model, where power = (AWC/time) + CP, and (b) a work–time model, where work = (CP • time) + AWC.

Critical power is the power asymptote in the power–time relationship, the y-intercept with the power–l/time model, and the slope with the work–time model. It is an index of aerobic (endurance) performance which has been shown to be different from, but related to, the ventilatory threshold (18, 21), the lactate threshold (9, 16), and the fatigue threshold estimated via electromyographic data (2, 3). The CP parameter has been shown to be high in endurance trained athletes (13) and to increase after endurance training (14). Jenkins and Quigley (12) noted that the CP parameter provides a simple and inexpensive means for evaluating endurance without the need for expensive equipment and without the methodological difficulties associated with estimating anaerobic or fatigue thresholds or \( \dot{V}O_2 \)max.

Anaerobic work capacity is the degree of curvature in the power–time relationship, the slope with the power–l/time model, and the y-intercept with the work–time model. It is a measure of anaerobic capacity that is related to

The authors are with the Department of Kinesiology, PO Box 13857, University of North Texas, Denton, TX 76203.
work performed in a 30-s Wingate test (19, 23) and to work performed during five all-out 1-min bouts of exercise (13). It is related to, and does not differ from, the maximal oxygen deficit (6). AWC has been shown to increase following high intensity training (15).

The critical power concept has been extended from a power–time relationship in cycle ergometry to a velocity–time relationship in running (11) and swimming (1, 24, 25, 26). Biggerstaff et al. (1) found a good fit of time trial data from 9 intercollegiate swimmers to the velocity–time model and reported that the anaerobic parameter (ASC, for anaerobic swimming capacity) was related to peak blood lactate levels; in addition, there was a strong correlation between actual time for a 914-m swim and time predicted from the results of three shorter swims. Wakayoshi et al. (24) found a good fit of data from flume swimming to the distance–time model and reported a high correlation between the aerobic parameter (CV, for critical velocity) and velocity associated with a blood lactate accumulation of 4 mM and between CV and velocity in an all-out 400-m swim. Wakayoshi et al. (25, 26) used time trial data and found a high correlation between critical velocity and velocity associated with a blood lactate accumulation of 4 mM. They concluded that CV, calculated from four (25) or only two (26) all-out swims, may correspond to highest exercise intensity that could be sustained with a steady-state lactate response.

All four studies investigating application of the critical power concept to swimming were limited to sample sizes of 8 or 9 subjects and to swimmers of college age. No study has applied the critical power concept to data from swimmers of other ages or to larger groups of swimmers.

The purpose of this study was to determine the usefulness of the critical power concept with young age-group swimmers. The usefulness of the concept was determined first in terms of the fit of data to the hyperbolic velocity–time relationship. Then the validity of critical velocity as an index of endurance was determined by comparison of CV with velocity in an endurance swim. The validity of anaerobic swimming capacity as a measure of anaerobic capacity was determined by comparing ASC with peak blood lactate concentration.

Methods

Critical velocity and anaerobic swimming capacity were determined in a large group of age-class swimmers based on the results of all-out swims over three distances. Three studies were conducted: Study 1 involved data collected from all-out time trials of 86 swimmers; Study 2 involved data from best performances of 60 swimmers in competition; and Study 3 involved data from time trials of 18 swimmers from Study 1 who consented to provide blood samples after each trial for determination of blood lactate concentration.

Subjects

Young swimmers ranging in age from 8 to 18 years volunteered to participate. In accordance with the guidelines of the institutional review board at the university, each swimmer provided written informed consent to participate; because of the subjects’ ages, written informed consent was also obtained from a parent or guardian of each subject.
Study 1

A total of 86 swimmers participated: 21 in the 8- to 10-year age category (mean age 9.0 ± 0.8 yrs), 25 in the 11- to 13-year age category (11.9 ± 0.7 yrs), and 40 in the 14- to 18-year age category (15.3 ± 1.1 yrs). The subjects performed three all-out time trials over distances their coaches selected for them individually based on their age and swimming experience. The shortest distance was 23 m, for the youngest swimmers, and the longest was 457 m. Only one all-out swim was undertaken on a given day; each swim was performed at the beginning of a regularly scheduled practice session after a warm-up and before any other hard training was begun.

The swimmers also took part in a long time trial as a criterion measure of endurance performance. Distances for this trial were individually selected by the coaches and ranged from 183 m for the youngest swimmers to 2,286 m. Critical velocity and anaerobic swimming capacity were determined from the data obtained in the three short all-out swims using an SPSS program that generated parameter estimates based on the velocity–time model, the velocity–1/time model, and the distance–time model. Means were determined for subjects grouped according to age.

The fit of data to the critical power model was evaluated in terms of (a) the $R^2$ describing the overall fit of data to each of the three regression models, (b) the magnitude of the standard errors of the estimates (SEE) associated with the CV and ASC estimates, and (c) the similarity among parameter estimates generated by the different regression models (4). The latter comparison was made using a two-factor (Age Group × Regression Model) ANOVA. Follow-up one-way ANOVAs and Tukey post hoc tests were employed as appropriate. Age group was included as a factor because the effects of age (i.e., maturation) on endurance and anaerobic capacity have been documented (22, 27).

The validity of the CV parameter as an index of endurance ability was evaluated. This was done by examining the correlations between CV estimates and velocity in the long time trial and evaluating differences using paired-means $t$ tests. It should be noted that the criterion measure for endurance, velocity in the longest swim, was not used in determining CV.

Study 2

Sixty young swimmers competed in sanctioned races over various distances during the course of a competitive season. The swimmers were divided into two groups based on the distances their coaches selected for them. The 34 younger swimmers had a mean age of 11.9 ± 0.9 yrs and competed over 46, 91, 183, and 457 m. The 26 older swimmers had a mean age of 15.1 ± 1.5 yrs and competed over 91, 183, 457, and 1,509 m. Critical velocity and anaerobic swimming capacity were derived from the season’s personal bests in the three shorter races using all three regression models, as above. The fit of data to the critical power model was evaluated as in Study 1. The validity of the CV parameter as an index of endurance ability was evaluated by comparison with velocity over the longest competition distance using correlations and paired-means $t$ tests.
Critical velocity and anaerobic swimming capacity were determined from time trial data in a subset of 18 of the 86 young swimmers in Study 1. Their mean age was 14.5 ± 1.8 yrs. These 18 swimmers also consented to provide fingerprick blood samples.

Each swimmer performed all-out trials over 91, 183, and 457 m. Exactly 5 min after each swim, a 40-microliter fingerprick blood sample was obtained in an EDTA-treated microcapillary tube and immediately diluted in a preservative cocktail containing sodium fluoride and Triton X-100 (5). For each individual, blood lactate concentration was determined using a YSI 2300 Stat analyzer and the highest value was taken as the peak blood lactate concentration. Individual variability in ASC estimates derived using the three regression models was determined as the coefficient of variation of that individual’s ASC. Subjects were then grouped according to the magnitude of this coefficient of variation, since it has been suggested that the validity of the anaerobic parameter is dependent upon a low variability among the estimates generated by the three models (6). We wanted to determine whether ASC was a more valid estimate of anaerobic capacity, as reflected by postexercise blood lactate concentration, in the individuals with the lower coefficients of variation. Therefore correlations between ASC and lactate concentration for the two groups were calculated separately.

**Results**

**Study 1**

Mean (±SD) values for the descriptors of the velocity–time relationship are presented in Table 1. Results of the two-factor (Age Group × Regression Model) ANOVA indicated a significant effect of regression model on the estimate of CV ($F_{2,170} = 21.48, p < .01$); that is, the value for CV was dependent upon the model used to derive it. Results of Tukey post hoc tests revealed the following specific effects of model on CV: velocity–time > distance–time = velocity–time. There was also an effect of regression model on the estimate of ASC ($F_{2,170} = 13.19, p < .01$), with velocity–time < distance–time = velocity–time.

Results of the two-factor ANOVA also revealed significant effects of age group on the estimates of CV ($F_{2,83} = 14.35, p < .01$) and ASC ($F_{2,83} = 20.32, p < .01$). Results of Tukey post hoc tests indicated that 14- to 18-year-olds had higher CV and ASC than 11- to 13-year-olds, who in turn had higher CV and ASC than the 8- to 10-year-olds. CV was about 26% higher in the 14- to 18-year-olds than in the 8- to 10-year-olds, while ASC was over 100% higher in the 14- to 18-year-olds than in the 8- to 10-year-olds.

The correlations between critical velocity and the velocity for the longest swim ranged from 0.86 to 0.99 ($p < .01$ in all cases). Results of paired-means $t$ tests revealed that, regardless of the age group or regression model used to derive the CV, values for CV were slightly but consistently higher ($p < .01$ in all cases) than the mean velocity during the endurance swim. Mean values are provided in Table 1.
Table 1  Descriptors of Hyperbolic Velocity–Time Relationship Based on Time Trial Data for 86 Young Swimmers

<table>
<thead>
<tr>
<th>Age group</th>
<th>CV (m·s⁻¹)</th>
<th>SEE&lt;sub&gt;CV&lt;/sub&gt;</th>
<th>ASC (m)</th>
<th>SEE&lt;sub&gt;ASC&lt;/sub&gt;</th>
<th>R²</th>
<th>V long (m·s⁻¹)</th>
<th>Correlation (CV vs. V long)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td></td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td></td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>8-10</td>
<td>0.959</td>
<td>0.177</td>
<td>0.017</td>
<td>0.014</td>
<td>9.3</td>
<td>3.0</td>
<td>0.998</td>
</tr>
<tr>
<td>11-13</td>
<td>1.113</td>
<td>0.155</td>
<td>0.013</td>
<td>0.013</td>
<td>14.0</td>
<td>7.7</td>
<td>0.992</td>
</tr>
<tr>
<td>14-18</td>
<td>1.212</td>
<td>0.202</td>
<td>0.020</td>
<td>0.042</td>
<td>20.9</td>
<td>11.0</td>
<td>0.992</td>
</tr>
<tr>
<td></td>
<td>8-10</td>
<td>0.985</td>
<td>0.151</td>
<td>0.040</td>
<td>7.7</td>
<td>2.1</td>
<td>0.957</td>
</tr>
<tr>
<td></td>
<td>11-13</td>
<td>1.136</td>
<td>0.140</td>
<td>0.029</td>
<td>11.9</td>
<td>5.9</td>
<td>0.968</td>
</tr>
<tr>
<td></td>
<td>14-18</td>
<td>1.230</td>
<td>0.181</td>
<td>0.037</td>
<td>18.9</td>
<td>6.8</td>
<td>0.968</td>
</tr>
<tr>
<td>8-10</td>
<td>0.965</td>
<td>0.167</td>
<td>0.027</td>
<td>0.021</td>
<td>8.6</td>
<td>2.4</td>
<td>0.998</td>
</tr>
<tr>
<td>11-13</td>
<td>1.118</td>
<td>0.149</td>
<td>0.025</td>
<td>0.025</td>
<td>13.2</td>
<td>6.7</td>
<td>0.999</td>
</tr>
<tr>
<td>14-18</td>
<td>1.215</td>
<td>0.194</td>
<td>0.021</td>
<td>0.018</td>
<td>20.4</td>
<td>8.7</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Note. CV = critical velocity, ASC = anaerobic swimming capacity, V long = velocity in each subject’s longest swim (used as a measure of endurance but not used in the derivation of CV and ASC).

*p < .01.
Study 2

Mean values for the descriptors of the velocity–time relationship based on the results of competitive swims undertaken by these 60 young athletes are presented in Table 2. Results of the two-factor (Age Group x Regression Model) ANOVA indicated a significant effect of regression model on the estimate of CV ($F_{2,118} = 70.41, p < .01$); results of Tukey post hoc tests revealed the following effects of model on CV: velocity–time > distance–time > velocity–time. There was also an effect of regression model on the estimate of ASC ($F_{2,118} = 47.28, p < .01$), with velocity–time < distance–time < velocity–time.

Results of the two-factor ANOVA also revealed significant effects of age group on the estimates of CV ($F_{58} = 7.84, p < .01$) and ASC ($F_{58} = 84.11, p < .01$). The older swimmers (mean age 15.1 yrs) had higher values for CV and ASC than the younger swimmers (mean age 11.9 yrs). CV was about 5% greater in the older swimmers; ASC was over 50% higher in the older swimmers.

Correlations between critical velocity and the velocity for the longest race ranged from 0.91 to 0.92 ($p < .01$ in all cases). Results of paired-means $t$ tests revealed that, regardless of the age group or regression model used to derive the CV, values for CV were slightly but consistently higher ($p < .01$ in all cases) than the mean velocity during the endurance swim.

Study 3

Mean data for the 18 swimmers who consented to provide blood samples are presented in Table 3. Their mean age was 14.5 years and these swimmers were representative of the 11- to 18-year-olds in Study 1.

For 9 of the 18 subjects, the different but mathematically equivalent models generated similar estimates (defined as a coefficient of variation less than 15%, with an average of 6%). For the other 9 subjects, variability among the three ASC estimates generated using the three models was high (coefficient of variation greater than 15%, with an average of 24%). Correlations between the anaerobic swimming capacity estimates and peak blood lactate concentration for the two groups are shown in Table 3. When the variability among ASC estimates was low, each model generated an anaerobic parameter that was positively and significantly correlated with peak blood lactate concentration. But for the subjects for whom variability among ASC estimates was high, there was no significant correlation between lactate concentration and any of the ASC estimates.

Discussion

The main finding of this study was that the critical power concept can be applied to data obtained from time trial or competition results obtained from young, even very young, age-class swimmers. The two parameters generated, CV and ASC, provide mode-specific noninvasive indices of endurance and anaerobic capacity, respectively.

Previously the concept had been applied only to small groups of college-age swimmers (1, 24, 25, 26). Values reported in this paper for the descriptors of the velocity–time relationship in young swimmers are consistent with values reported for older swimmers. For example, Wakayoshi et al. have applied the
Table 2 Descriptors of Hyperbolic Velocity–Time Relationship Based on Competition Results From 34 Younger and 26 Older Swimmers

<table>
<thead>
<tr>
<th>Age group</th>
<th>CV (m·s⁻¹)</th>
<th>SEEcv</th>
<th>ASC (m)</th>
<th>SEEASC</th>
<th>R²</th>
<th>V long (m·s⁻¹)</th>
<th>Correlation (CV vs. V long)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>Nonlinear velocity–time model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>Younger</td>
<td>1.487</td>
<td>0.093</td>
<td>0.017</td>
<td>0.008</td>
<td>11.4</td>
<td>2.3</td>
<td>0.990</td>
</tr>
<tr>
<td>Older</td>
<td>1.566</td>
<td>0.102</td>
<td>0.007</td>
<td>0.001</td>
<td>16.4</td>
<td>3.8</td>
<td>0.995</td>
</tr>
<tr>
<td>Linear velocity–time model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>Younger</td>
<td>1.520</td>
<td>0.091</td>
<td>0.033</td>
<td>0.016</td>
<td>8.9</td>
<td>1.4</td>
<td>0.970</td>
</tr>
<tr>
<td>Older</td>
<td>1.580</td>
<td>0.104</td>
<td>0.023</td>
<td>0.013</td>
<td>14.7</td>
<td>2.8</td>
<td>0.977</td>
</tr>
<tr>
<td>Linear distance–time model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>Younger</td>
<td>1.499</td>
<td>0.091</td>
<td>0.026</td>
<td>0.014</td>
<td>10.2</td>
<td>1.6</td>
<td>0.999</td>
</tr>
<tr>
<td>Older</td>
<td>1.570</td>
<td>0.102</td>
<td>0.015</td>
<td>0.013</td>
<td>15.7</td>
<td>2.9</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Note. CV = critical velocity, ASC = anaerobic swimming capacity, V long = velocity in each subject’s longest swim (used as a measure of endurance but not used in the derivation of CV and ASC).

*p < .01.
Table 3  Descriptors of Hyperbolic Velocity–Time Relationship for the 18 Swimmers Who Provided Blood Samples

<table>
<thead>
<tr>
<th>Math model</th>
<th>CV (m·s⁻¹) M ± SD</th>
<th>SEEcv (m) M ± SD</th>
<th>ASC (m) M ± SD</th>
<th>SEEASC (m) M ± SD</th>
<th>R² (mM) M ± SD</th>
<th>Peak [La] (mM) M ± SD</th>
<th>Correlation ([La] vs. ASC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subjects with high variability among AWC estimates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity–time</td>
<td>1.423 ± 0.174</td>
<td>0.020 ± 0.012</td>
<td>16.2 ± 4.7</td>
<td>3.4 ± 1.2</td>
<td>0.991 ± 0.014</td>
<td>6.7 ± 1.1</td>
<td>0.50</td>
</tr>
<tr>
<td>Velocity–1/time</td>
<td>1.417 ± 0.138</td>
<td>0.036 ± 0.012</td>
<td>16.2 ± 4.7</td>
<td>3.4 ± 1.2</td>
<td>0.955 ± 0.021</td>
<td>6.7 ± 1.1</td>
<td>-0.35</td>
</tr>
<tr>
<td>Distance–time</td>
<td>1.417 ± 0.161</td>
<td>0.020 ± 0.006</td>
<td>16.4 ± 7.0</td>
<td>4.4 ± 1.5</td>
<td>0.996 ± 0.007</td>
<td>6.7 ± 1.1</td>
<td>0.49</td>
</tr>
<tr>
<td><strong>Subjects with low variability among AWC estimates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity–time</td>
<td>1.171 ± 0.118</td>
<td>0.007 ± 0.005</td>
<td>23.0 ± 7.9</td>
<td>2.6 ± 2.0</td>
<td>0.997 ± 0.002</td>
<td>7.1 ± 1.7</td>
<td>0.80*</td>
</tr>
<tr>
<td>Velocity–1/time</td>
<td>1.184 ± 0.111</td>
<td>0.024 ± 0.014</td>
<td>20.3 ± 5.0</td>
<td>2.5 ± 1.5</td>
<td>0.986 ± 0.012</td>
<td>7.1 ± 1.7</td>
<td>0.69**</td>
</tr>
<tr>
<td>Distance–time</td>
<td>1.174 ± 0.115</td>
<td>0.017 ± 0.014</td>
<td>21.9 ± 6.4</td>
<td>3.0 ± 1.9</td>
<td>0.999 ± 0.000</td>
<td>7.1 ± 1.7</td>
<td>0.80*</td>
</tr>
</tbody>
</table>

*Note. CV = critical velocity, ASC = anaerobic swimming capacity, [La] = blood lactate concentration.

*p < .01, **p < .05.
distance–time model to data obtained from 8 or 9 college-age subjects and calculated mean values for CV: 1.116 m·s⁻¹ [flume] (24), 1.437 m·s⁻¹ [pool] (25), and 1.543 m·s⁻¹ [flume] and 1.555 m·s⁻¹ [pool] (26); they have also reported a mean value for ASC of 23.3 m [pool] (25).

**Fit of Data to the Model**

There was a very good fit of data to the critical power model, whether the data were in the form of time trial results (Study 1) or seasonal personal bests in competition (Study 2). $R^2$ were high, with an average of 0.987 across all age groups, sources of data, and models. A good fit of swimming data to the critical power model was also found by Wakayoshi et al., who reported $R^2$ of ≥0.998 for the relationship described by the distance model (24, 26). In this study, $SEE$ for critical velocity were very small, ranging from 1 to 4% of the mean value for CV. $SEE$ for anaerobic swimming capacity were somewhat higher, ranging from 12 to 21% of the mean value for ASC. Other researchers have not reported the $SEE$ of estimates.

The disparity among the parameter estimates generated using the three models might seem to suggest a poor fit of data to the critical power model (4). However, the differences were small. Furthermore, in practice, coaches could have athletes repeat a time trial or race distance that contributed to the poor fit to the model. In this study we did not try to improve the appearance of the data by having subjects repeat selected trials or races.

There appeared to be a slightly better fit of competition data than time trial data to the critical power model (i.e., higher $R^2$, lower $SEE$). A better fit might have been expected with competition results because subjects performed only one time trial at each distance but had several opportunities to compete at each distance, with the personal best time used in the calculations. It could also be that the swimmers who were selected to compete had more experience. One possible drawback to using competition times might be that, especially over shorter distances, the velocity–time relationship may be distorted by the use of a competition start from the blocks rather than a pushoff from the wall of the pool.

Variability among estimates derived using the three regression models was greater for anaerobic work capacity than for critical velocity; and the $SEE$ of anaerobic swimming capacity were relatively larger than those of critical velocity. Thus it appears that the CV parameter may be a more precise index of endurance than the ASC parameter is of anaerobic capacity. This was true for both the time trial data in Study 1 and the competition data in Study 2, although the means in Tables 1 and 2 suggest that use of competition data may result in lower $SEE$ and therefore may provide more precision in the estimation of ASC and perhaps also CV. The reason for the lack of precision in the anaerobic estimate, which we have also found in data on running (unpublished observation), is not clear. Studies investigating the cause of the reduced precision of the anaerobic parameter are needed, especially if the critical power test is to be applied to children, whose small anaerobic capacity is more affected by imprecision in estimation.

Possibly the variability in ASC estimates derived using different regression models and the higher $SEE$ associated with this parameter reflect error in the short swims. For 39 of 86 swimmers in Study 1 the shortest swim was 23 m,
for which times ranged from about 14 to 25 sec; and for 34 of 60 swimmers in Study 2 the shortest swim was 46 m. Such short trials may be inappropriate for determining CV and ASC (21), although it must be noted that the shortest swim in the Wakayoshi et al. study (24) was 26.0 ± 4.0 sec. Furthermore, the guidelines for duration of predicting trials that have been developed were based on adult cycle ergometer data (4, 8, 20). Since children have a smaller anaerobic capacity than adults (27), and since propulsive forces in swimming are obtained from the smaller upper body musculature, use of these shorter swims may be appropriate. We included such short swims in order to ensure a range of times in the predicting trials.

CV as an Index of Endurance

In this study there were significant positive correlations between critical velocity and velocity in an endurance swim. These correlations suggested that the CV parameter is an acceptable index of endurance ability. Biggerstaff et al. (1) reported a correlation of .96 between competition velocity over 914 m and CV determined from time trial swims of 91, 183, and 366 m. Wakayoshi et al. (24, 25, 26) reported that CV was correlated \( r = .87, .977, .998 \) to velocity over a 400-m trial in different samples of 8 college swimmers. Their higher correlation may be a function of the choice of subjects, or quite possibly of the fact that in the latter two studies critical velocity was determined from the results of time trials of \( \leq 400 \) m. Since the velocity over 400 m provided up to half of the information used to generate the CV, it is not surprising that the two were very highly correlated. Wakayoshi et al. (24, 25, 26) also reported correlations of .95, .90, and .92 between critical velocity and velocity associated with a blood lactate concentration of 4 mM. In the present study, as in the Biggerstaff study (1), the endurance swims against which CV was compared were relatively longer than the 400-m swim for the college athletes in the Wakayoshi et al. studies (24, 25, 26), and the endurance swim was not used to derive CV.

In our swimmers, although critical velocity was correlated with velocity in an endurance swim, the parameter overpredicted the velocity that could be sustained for the swim. This may be because the relationship between power and velocity in swimming is not strictly linear, or because the long endurance swims were outside the range of exercise durations for which the velocity–time relationship is hyperbolic (and the velocity–1/time and distance–time relationships are linear) in these young subjects. Since the young swimmers would not be able to sustain their individual CV for an extended period of time, there must be an anaerobic contribution at the CV. This is consistent with previous studies using cycle ergometry in which subjects exercised at their critical power and elevations in blood lactate were noted (12, 16). On a practical level, this suggests that while critical velocity is an index of endurance ability that can be used to evaluate and monitor swimmers, the parameter estimate should be interpreted with care if it is to help determine training intensities or predict endurance performance. Although we are confident that critical velocity and anaerobic swimming capacity are fitness measures that separate aerobic and anaerobic components, we have no information that CV can be used in prescribing training intensity.
**ASC as a Measure of Anaerobic Capacity**

The second parameter of the velocity–time relationship theoretically provides a mode-specific measure of anaerobic capacity. There is ample evidence that the anaerobic work capacity parameter of the power–time relationship described for cycle ergometry is a reflection of anaerobic fitness (6, 13, 19, 23). But the same parameter derived from treadmill data has not been shown to be related to indicators of anaerobic capacity (10). Swimming and running are similar in that velocity and power are not related in an absolutely linear fashion.

The validity of anaerobic swimming capacity, the anaerobic parameter of the velocity–time relationship in swimming, has been evaluated in only one study. Biggerstaff et al. (1) reported a correlation of 0.88 between ASC and peak blood lactate concentration in 9 college-age swimmers.

In the present study (Study 3), the correlations between peak lactate and ASC were significant only in subjects for whom the ASC estimates derived using the three regression models were similar. It has been shown that the accuracy of anaerobic work capacity (from cycle ergometry data) as an estimate of anaerobic capacity is ensured when variability among estimates is low (7). The results of Study 3 are in agreement; they suggest that, in swimming, ASC provides a valid mode-specific index of anaerobic capacity when variability among estimates derived using the three regression models is low.

**Effect of Age on Parameter Estimates**

In both Studies 1 and 2, the subjects were grouped by age. The 86 subjects in Study 1 were divided into three groups, with 8- to 10-year-olds comprising the youngest group. There were no subjects under 11 in Study 2, so these subjects were classified based on the competition distances their coaches selected for them. The coaches' decisions were based primarily on swimmers' skills, but resulted in a good division by age (mean ages, 11.9 and 15.1 yrs).

In both studies, critical velocity and anaerobic swimming capacity were a function of age. Higher levels of aerobic power, as reflected by CV, and anaerobic capacity, as reflected by ASC, are consistent with the expected effects of training and maturation (22, 27). We would speculate that maturation was the major factor, as years of training experience were quite similar among the different age groups; that is, many of the older swimmers were relative novices.

In Study 2, CV was approximately 5% higher in the older swimmers than in the younger swimmers; ASC was over 50% higher. In Study 1, CV of the 14- to 18-year-olds was about 25% higher than that of the 8- to 10-year-olds; ASC was more than doubled in the 14- to 18-year-olds. Zauner et al. (27) have discussed the relatively greater effect of maturation on anaerobic capacity than on maximal aerobic power. Our results suggest that the parameters derived using the critical power concept with young swimmers are sensitive to changes in aerobic and anaerobic fitness elicited by training and/or maturation.

There has been discussion on the trainability of children with respect to physiological variables associated with endurance performance such as anaerobic threshold or VO₂max, and also on the ethics of invasive testing in healthy children (22). Critical velocity and anaerobic swimming capacity are noninvasive
variables. Since they are derived from measures of mechanical work, they combine energy production and efficiency into single indices. As such, these indices may be useful in studies of the effects of exercise training on children as well as in the implementation of sport programs.

**Summary**

We have shown that young swimmers’ performances can be described using the critical power model. The source of data can be time trials or competitions. Using personal bests from swim meets allows the collection of data under competitive conditions when the swimmers are highly motivated, and also means that practice sessions need not be adjusted to accommodate the all-out time trials. The results of this series of studies demonstrated the validity of CV and ASC as well as their sensitivity to the effects of training and/or maturation. However, the CV estimate overpredicts the velocity that can be sustained in actual endurance performance, and parameter values determined using competition data may differ from values obtained using time trial data. Although the CV parameter can be precisely identified, the ASC parameter estimates are associated with a relatively larger SEE and are valid indices of anaerobic capacity only when estimates derived using the three mathematically equivalent regression models are similar.

We conclude that application of the critical power concept to swimmers, even very young swimmers, has the potential to provide mode-specific indices of endurance and anaerobic capacity without requiring blood sampling or other invasive techniques, and without the need for expensive equipment.

**References**


