Research article

ASSESSMENT OF SHORT-DISTANCE BREASTSTROKE SWIMMING PERFORMANCE WITH CRITICAL VELOCITY

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ABSTRACT

For high-velocity running or swimming, the relationship between velocity (v) and its sustainable duration (t) can be described by a hyperbolic relationship: $(v - V_{crit}) \cdot t = D'$, where V_{crit} is termed critical velocity, and D' is defined as a curvature constant of the hyperbolic curve. The purposes of this study were to examine whether the V_{crit} could be applied to evaluate short-distance breaststroke swimming performance and to evaluate the relative contribution of D' in short-distance swimming performance. Eleven male swimmers performed a series of time trials corresponding to 75, 100, and 150-m in an indoor 50-m swimming pool. The observed records were calculated into average velocities of each event to determine V_{crit} and D'. After the determination of V_{crit} and D', all subjects performed 50-m time trial on another day. A maximal anaerobic power test using cycle ergometer was also performed in the laboratory. The average velocity of the 50-m time trial significantly correlated with the obtained V_{crit}, but not with D'. D' was significantly correlated with the residual error, calculated from the regression analysis for the relationship between V_{crit} and the average velocities of 50-m time trial. A cluster analysis showed that most of the subjects were classified as V_{crit} dependency when performing 50-m time trial. Those results indicated that V_{crit} could be applied to evaluate short-distance swimming performance, and it determined around 80% of the short-distance breaststroke swimming performance.

KEY WORDS: Critical swimming velocity, D', hyperbolic curve, cluster analysis.

INTRODUCTION

Monod and Scherrer (1965) have found a linear relationship between total work done (kJ) at several work intensities and time to exhaustion during high-intensity cycle ergometer exercise. It means that a hyperbolic relationship exists between power output

(watt) and time to exhaustion (sec) during high-intensity cycle ergometer exercise. Such a hyperbolic relationship possesses a curvature constant with an asymptote, which is termed "critical power". Critical power has been utilized as a "fatigue threshold" in consideration of its practical application for high-intensity endurance sports, such

as running (Florence and Weir, 1997; Hughson et al., 1984; Kolbe et al., 1995), swimming (Wakayoshi et al., 1992a; 1992b; 1992c; 1993), and cycling (Housh et al., 1989; Smith et al., 1997). However, the hyperbolic relationship between power output and time to exhaustion has been applied to endurance sports event, completed from, at least, several minutes to 1 hour (e.g., Hughson et al., 1984).

Compared to treadmill running or cycling in the laboratory, it is inconvenient to measure blood lactate concentrations or gas exchange parameters in the swimming pool, so that the application of critical power or "critical velocity (V_{crit})" will give valuable information for swimmers to estimate swimming potential as a non-invasive and inexpensive method. To date, previous studies regarding critical velocity and swimming performance were quite limited (Dekerle et al., 2002; Martin and Whyte, 2000; Wakayoshi et al., 1992a; 1992b; 1992c; 1993). Almost all of the previous studies focused on middle- and/or long-distance free-style swimming. In other words, it has not been revealed whether the critical velocity can be applied to shorter swimming events with other swimming styles.

Fukuba et al. (1996) suggested that previously defined indices for evaluating physical fitness (e.g. maximal oxygen uptake) always have a physiological background, on the other hand, critical velocity is obtained from the actual performance done by the subject. The first purpose of this study was to examine whether the critical velocity could be applied to estimate short-distance swimming performance in a breaststroke style. It was hypothesized that critical velocity could be a useful predictor even in short-distance swimming events.

The curvature constant of the hyperbolic curve between power output and time to exhaustion during high-intensity cycle ergometer exercise has attracted a great deal of research attention (Fukuba et al., 2003; Miura et al., 1999, 2000, 2002). Indeed, the curvature constant of the hyperbolic curve can be expressed by the product of velocity and time above V_{crit}, thus, it was suggested that the curvature constant related to a possible distance being performed by anaerobic working capacity. However, as far as we know, nothing has been discussed regarding curvature constant in swimming yet. If the curvature constant is solely reflecting anaerobic working capacity, then it will significantly contribute to the short-distance swimming performance. The second purpose of this study was to evaluate the relative contribution of the curvature constant of the hyperbolic curve in swimming. It was also hypothesized that the curvature constant of the hyperbolic curve could be explained by the anaerobic working capacity, and it would significantly relate to the short-distance swimming performance.

METHODS

Subjects

Eleven male swimmers belonging to the varsity swimming team participated in this study. The

Table 1 Physical characteristics of the subjects and other observed variables.

Subject	Age (yrs)	Height (m)	Mass (kg)	V_{crit} (m·s⁻¹)	D' (m)	MAnP (W·kg⁻¹)	V_{50} (m·s⁻¹)	50m Best (m·s⁻¹)	%WR (%)	Sp
1	20	1.75	81.9	0.989	9.38	11.2	1.217	1.316	65.8	Br
2	21	1.54	60.7	0.771	6.14	12.7	0.878	1.020	51.0	Bt
3	20	1.70	67.1	0.670	18.88	9.1	0.946	1.010	50.5	Fr
4	20	1.72	60.7	0.800	9.70	10.1	0.992	1.042	52.1	Fr
5	19	1.69	64.6	0.978	4.96	10.1	1.087	1.136	56.8	Br
6	20	1.72	71.0	0.869	10.40	9.7	1.094	1.149	57.4	Br
7	19	1.78	83.0	0.943	12.56	10.3	1.232	1.250	62.5	Br
8	19	1.80	61.5	0.947	9.56	12.2	1.176	1.205	60.2	Br
9	19	1.73	63.5	0.858	12.98	9.2	1.151	1.235	61.7	Br
10	21	1.55	49.2	0.717	9.28	11.2	0.904	0.904	45.2	Fr
11	19	1.76	58.0	0.861	8.23	10.5	1.032	1.111	55.5	Br
Mean	19.7	1.70	65.6	.855	10.19	10.6	1.064	1.125	56.2	—
SD	0.9	0.09	10.0	0.106	3.73	1.2	0.124	0.123	6.2	—

V_{crit}, critical velocity; D' curvature constant of the hyperbolic relationship between swimming velocity and its time to exhaustion; MAnP, maximal anaerobic power; V_{50}, average velocity of 50-m time trial. 50m Best, average swimming speed calculated from the best record of 50m breaststroke swimming of each subject; %WR, percentage of the current world record; Sp, most favorite swimming style of each subject; Br, breaststroke; Bt, butterfly; Fr, free-style, respectively.

physical characteristics and other observed variables of each subject were summarized in Table 1. The best record of 50-m breaststroke swimming of each subject was expressed in percentage of the current world record. Most of the subjects were ranked at a regional competition level. After being informed of the purpose and possible risks of this study, the subjects gave their written consent. An approval of the local Ethical Review Committee was obtained for all procedures.

Protocols for V_{crit} and D' determination

A series of time trials for the determination of V_{crit} and curvature constant (D') of the hyperbolic relationship between swimming velocity and time to exhaustion took place in a 50-m indoor swimming pool. On all measurement days, water temperature was set at 28~29 degrees celsius. All data samplings were performed from late April to early May, just before the first competition of each individual's annual race schedule.

Based on a previous study done by Wakayoshi et al. (1992a), each subject performed 75, 100, and 150-m time trials in breaststroke style to determine V_{crit} and D'. The subjects sufficiently stretched and warmed up before the trials. The subjects were instructed to perform each predetermined distance as quickly as they could. Each time trial was performed with a sufficient resting period (~ 2hr). The order of each trial was randomized. At each time trial the same three timekeepers checked the performance time with a stopwatch. Each time measured by three timekeepers was averaged, and the averaged time was regarded as the time of the event. The obtained performance time of each event was further converted into average velocities of each event to calculate V_{crit} and D'. Three days later, each subject performed 50-m time trial in breaststroke style in the same swimming pool, and then the observed time was converted into the average velocity of its event (V_{50}).

The relationship between swimming velocity (v) and its time to exhaustion (t) is well characterized by the following equation:

$$(v - V_{crit}) \cdot t = D' \qquad (eq.\ 1)$$

where V_{crit} is the critical velocity, t is time represented in seconds, and D' is the curvature constant which represents the total amount of distance which can be performed above V_{crit} (Figure 1a). If the relationship between v and t is hyperbolic, then the rearranged $eq.$ 1 behaves linearly as shown in Figure 1b:

$$v = D' \cdot (1/t) + V_{crit} \qquad (eq.\ 2)$$
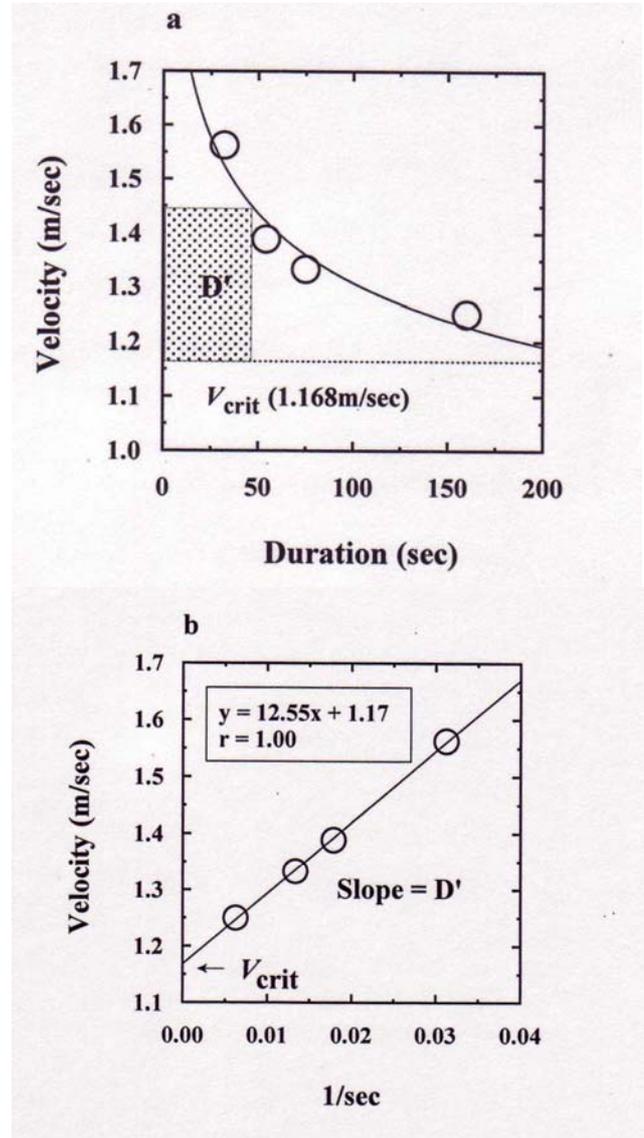
Figure. 1 (a) An example of the calculation of critical velocity (V_{crit}) and curvature constant (D'). The swimming velocity (m·sec^{-1}) and time to exhaustion (sec). **(b)** The linear relationship between inverse of time (1/t) and swimming velocity.

Number of trials

Hill (1993) proposed that four trials be recommended when obtaining critical power and curvature constant during high-intensity cycle ergometer exercise. Wakayoshi et al. (1993) obtained two data sets to determine V_{crit} in highly trained competitive swimmers. The present study employed subjects who were well accustomed to swimming regardless of performance level, and the possible risks of repeatable maximal efforts were also considered for the subjects. For a confirmation of number of trials, an additional subject performed four repeatable measurements at maximal effort (Figure 1), even though this additional subject was not included in the group of subjects because the level of performance was much greater than that of

other subjects. The result clearly showed that three time trials seemed to be sufficient to obtain V_{crit} and D', so the other remaining subjects performed three time trials.

Laboratory test
On the hypothesis that D' represents anaerobic working capacity and it will mainly explain the short-distance swimming performance, each subject performed a maximal anaerobic power (MAnP) test using a cycle ergometer (PowerMax-VII, Combi, Tokyo) based on a standardized procedure (Bulburian et al., 1996; Nakamura et al., 1984). It was recognized that this MAnP test was not performed in the water, thus, the direct comparison between the results obtained from the laboratory test and those in the water might require some caution. However, it is known that this MAnP test has a reliable reproducibility (McCartney et al., 1983), so that it was assumed that the following procedure would have a validity to estimate MAnP in swimmers.

After warming-up at 50 W for 10 minutes, subjects were instructed to perform a pre-maximal trial at 1kp. When subjects were accustomed to cycle ergometer exercise, the first maximal trial started. The initial workload for determining maximal anaerobic power was determined based on the subjects' body mass (less than 60 kg, 3 kp, n = 2; 61 to 80 kg, 4 kp, n = 7; above 81 kg, 5 kp, n = 2). The second work load was determined based on the rotations at the initial stage (less than 149 rpm, + 1 kp, n = 1; 150 to 179 rpm, + 2 kp, n = 8; above 180 rpm, + 3 kp, n = 2). The final workload was determined with the same criteria as the second stage. These maximal efforts were performed within 10 seconds at each stage with 120 seconds resting. Maximal anaerobic power (MAnP) was calculated based on the observed maximal rotations at each stage with Nakamura et al. (1984)'s calculation.

Statistical analyses
The observed values were presented as mean and standard deviation (SD). The relationships between V_{50} and V_{crit} and/or D' as well as between V_{crit} and MAnP were evaluated using a simple linear regression analysis. The residual error of V_{50} was obtained from the relationship between V_{50} and V_{crit}. The relationship between D' and its residual error was also evaluated by a simple linear regression analysis. Statistical significance was established at the 0.05 probability level. A cluster analysis, particularly in Ward method with a squared Euclidean distance, was further applied for the observed values of V_{crit} and D' to classify the

characteristics of subjects' physical fitness either V_{crit} or D' dependency. The result of the cluster analysis was described as a dendrogram.

RESULTS

A high correlation was found in the relationship between $1/t$ and v in each subject when obtaining D' and V_{crit} using *eq*. 2. The correlation coefficient values between $1/t$ and v of each subject ranged from 0.97 to 1.00.
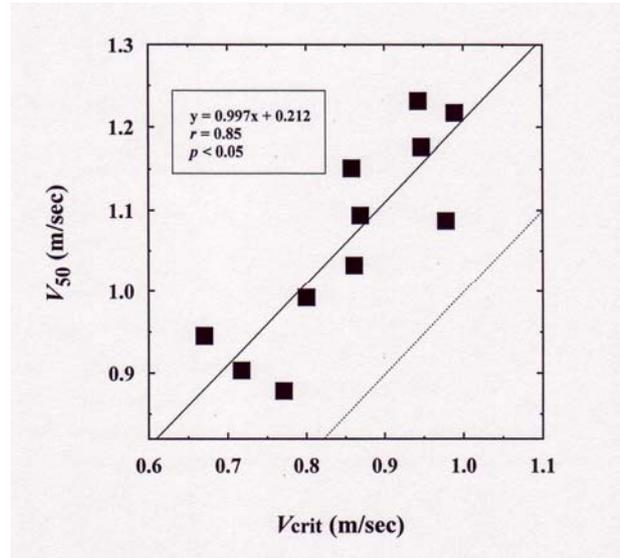
Figure 2. Relationship between critical velocity (V_{crit}) and 50-m breaststroke swimming performance (V_{50}). Dotted line represents identity line.

Table 1 shows the physical characteristics of the subjects and data obtained from the tests in the present study. The average V_{crit} was 0.855 ± 0.106 m/sec, ranging from 0.670 to 0.989 m/sec. The average velocity of 50-m breaststroke swimming was 1.064 ± 0.124 m/sec, ranging from 0.878 to 1.232 m/sec. Linear regression analysis indicated that there was a strong relationship between V_{crit} and V_{50} (r = 0.85, p < 0.05; Figure 2). V_{crit} was not significantly correlated with MAnP. D' widely ranged from 4.96 to 18.88 m, with an average value of 10.19 ± 3.73 m. D' was significantly correlated with neither V_{50} nor MAnP. D' was significantly correlated with the residual error, calculated from the regression analysis for the relationship between V_{crit} and V_{50} (r = 0.84, p < 0.05; Figure 3).

Figure 4 showed that only one subject was classified as D' dependency, while the remaining ten subjects were classified as V_{crit} dependency if the subjects were classified into two groups. Moreover, if the subjects were classified into three groups, two subjects were classified as "intermediate between V_{crit} and D'".
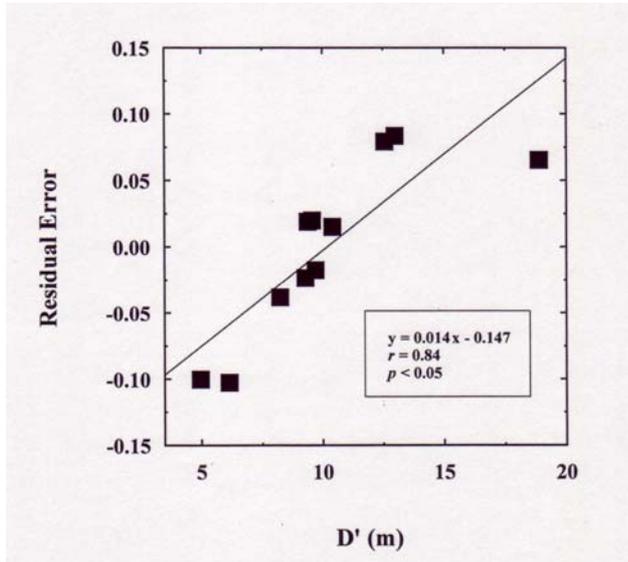
Figure 3. Relationship between D' and residual error of V_{50}, calculated from the regression analysis for the relationship between V_{crit} and V_{50}.

DISCUSSION

In support of our first hypothesis, the strictly new finding of the present study was that V_{crit} was significantly correlated with the average V_{50} even though the average V_{50} was 24.4% faster than the observed V_{crit} (Figure 2). This result simply proposed that V_{crit} be of potential to estimate short-distance swimming event done in breaststroke style.

Many previous studies have employed various physical fitness relating indices to evaluate endurance sports performance. However, it has been pointed out that those previously defined indices cannot always explain the variation of endurance

sports performance (Abe et al., 1998;1999). It is assumed that those previously employed indices for evaluating physical fitness are solely defined under consideration of its physiological mechanism (Fukuba et al., 1996). In contrast, observed hyperbolic relationship between swimming velocity and its time to exhaustion in this study directly measured performance itself done by the athletes.

In relation to V_{crit}, it was possible to estimate a predictable V_{crit} from the time required to swim 50-m at the time trial (t_{50}) and observed D' with an average value of 10.19 ± 3.73 m. The equation for predictable V_{crit} was calculated as follows:

$$\text{predictable } V_{crit} = (50 - D')/t_{50} = (50 - 10.19)/46.99$$
$$= 0.847 \text{ m/sec}$$

yielding a very close value with the observed V_{crit} (0.855 m, see Table 1). The difference between predictable V_{crit} and observed V_{crit} was less than 1%, meaning that the observed V_{crit} from a series of time trials has a high reliability. It has been considered that the anaerobic contribution for 50-m or 100-m swimming event was 80% or more (Holmer 1983), thus, it was quite surprising to note that D' contributed only 20.4% to the 50-m breaststroke swimming performance in the present study, being consistent with 29.6% in 50-m free-style swimming performance (Dekerle et al. 2002). The swimming velocity associated with V_{crit} was identical with that associated with onset of blood lactate accumulation (Wakayoshi et al. 1992c; 1993). Moreover, in cycle ergometer exercise, the curvature constant of the hyperbolic relationship between power output and its tolerable duration was significantly decreased
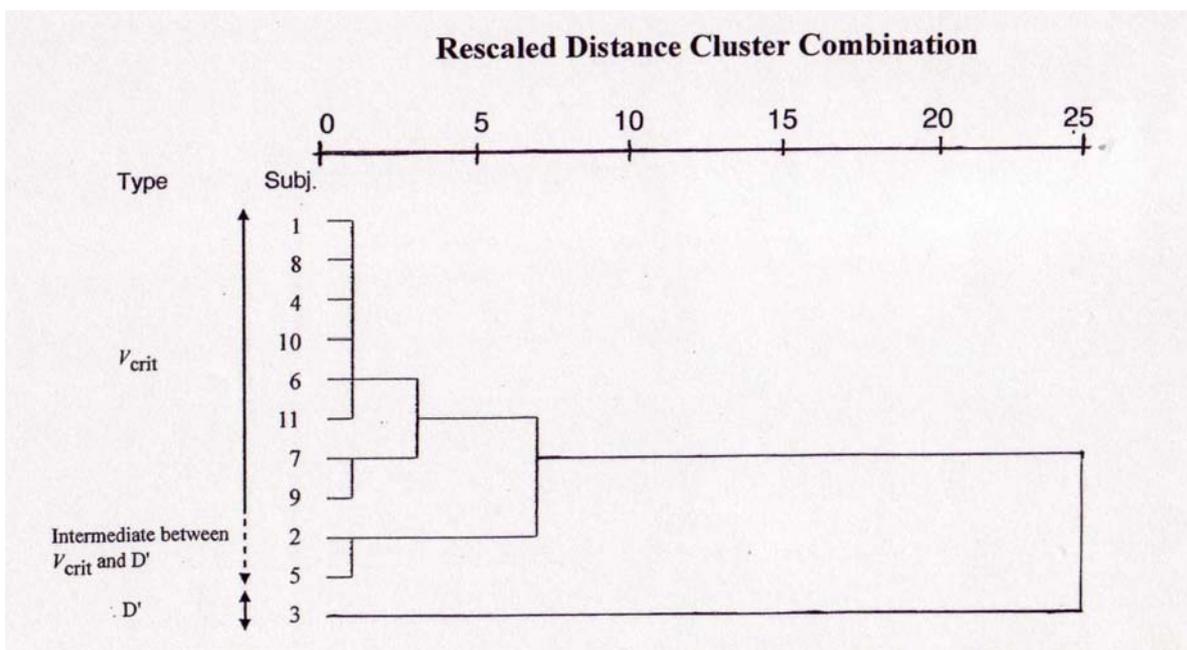
Figure 4. Rescaled distance cluster combination obtained from hierarchical cluster analysis.
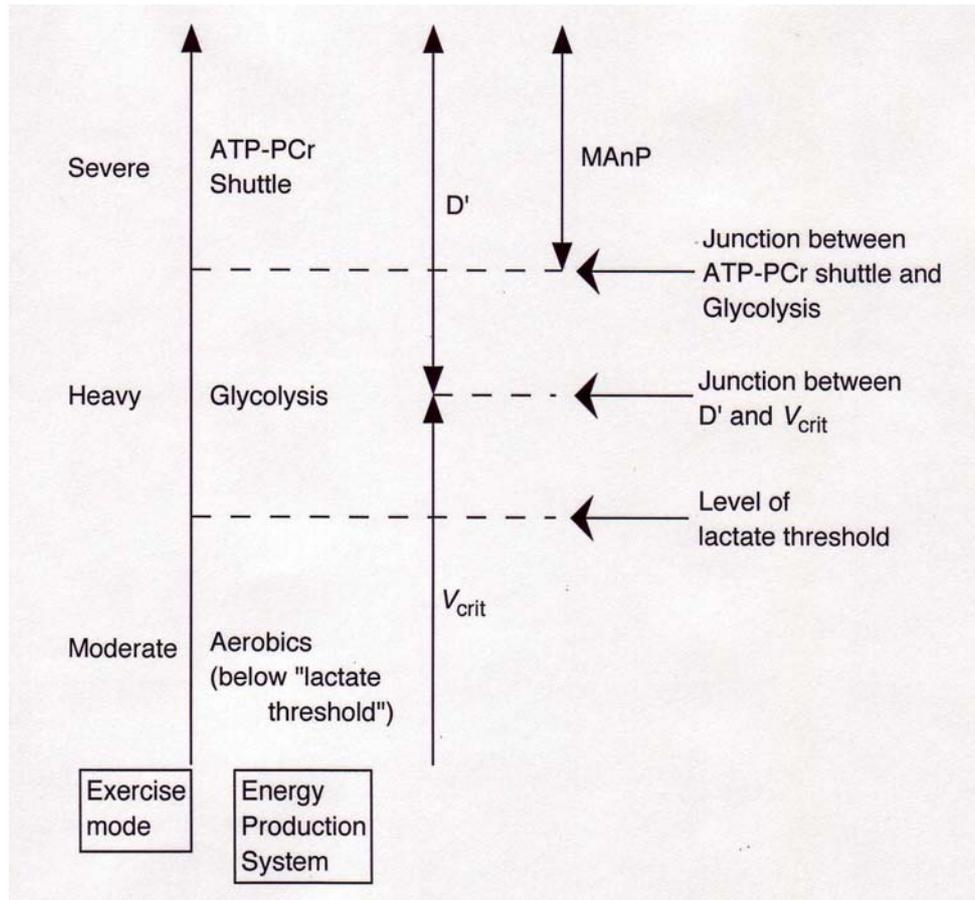
Figure 5. Illustration of the relationship among MAnP, D', V_{crit}, and energy production system as a function of exercise intensity.

under glycogen-depleted condition (Miura et al.2000). Miura et al. (1999) also reported that the oral creatine supplementation increased the curvature constant by 25%. Those previous results and the current result that D' was not significantly associated with MAnP might give a possible explanation that the curvature constant of such a hyperbolic relationship was consisted of both anaerobic glycolysis and ATP-PCr shuttle. It was also interesting to note that the relative contribution of D' (20.4%) to the swimming performance might explain that the average V_{50} was 24.4% faster than the observed V_{crit}. Figure 3 showed the relationship between D' and the residual error of V_{50} calculated from the regression analysis for the relationship between V_{crit} and V_{50}. Those results indicated that V_{50} could be considerably explained by V_{crit} (Figure 2), however, unexplained residual error could be explained by D' (Figure 3).

As discussed above, little attention has been paid for the physiological implication of D' in sports performance. This study found that D' was not significantly correlated with neither V_{50} nor MAnP, although, as hypothesized above, the curvature constant of the hyperbolic relationship has been recognized as an anaerobic working capacity that

can be performed above the critical power (Fukuba et al. 2003; Miura et al. 2002). Indeed, the result of the present study showed that D' still contributed for the performance by 20%, suggesting that the appropriate training program to improve both critical velocity and D' simultaneously could bring a better performance for breaststroke swimmers. In addition to investigations concerning energetics of swimming, some recent studies have examined the mechanics of the breaststroke swimming to improve the performance (Leblanc et al. 2005; Seifert and Chollet 2005; Takagi et al. 2004). This could be because a greater potential to improve the performance will be available in breaststroke swimming than in free-style swimming due to an existence of a large active drag during swimming. Future investigations considering both mechanics and energetics of swimming will bring a further understanding of swimming, resulting in a development of an efficient training program for swimmers.

The obtained MAnP consisted of three maximal pedalling at different workloads for, at most, 10 seconds each, meaning that the test must be too brief to utilize glycolytic ATP production system completely. This interpretation was in consistent

with Bulburian et al. (1996). It means that MAnP observed in this study would reflect only breakdown of PCr (ATP-PCr shuttle), not anaerobic glycolysis (Figure 5). It was also hypothesized that the observed V_{crit} in swimming was not necessary to reflect pure aerobic working capacity. Indeed, Fukuba et al. (1996) showed that respiratory responses did not reach the steady-state during cycle ergometer exercise at around the critical power, indicating that the exercise intensity associated with critical power exceeds the 'lactate threshold', which, in theory, represents the highest metabolic rate where a steady state response can be achieved during prolonged exercise. The results of the present study and those previous studies suggest that exercise intensity corresponding to V_{crit} be sustained in part by the pure aerobic work capacity and anaerobic glycolysis (Figure 5), supporting an interpretation obtained from the model analysis (Toussaint et al. 1998).

The present study further performed cluster analysis to classify the subjects' physical fitness for either D' or V_{crit} dependency. It was worth noting that ten of eleven subjects showed V_{crit} dependency even in short-distance swimming event (Figure 4). If the cluster was divided into three groups, two subjects were classified as an intermediate situation between V_{crit} and D' dependency, meaning that most of the subjects were still classified as V_{crit} dependency. The result of the present study clearly suggested that V_{crit}, not D', mainly determined athletes' success even in short-distance breaststroke swimming. In other words, the higher the V_{crit}, the better the performance in short-distance breaststroke swimming. Although Dekerle et al. (2002) suggested that D' could not be employed by coaches to control an anaerobic swimming training program, we hereby pointed out that it might be relevant to the maximal swimming velocity, which would be performed at the end and/or start of the race.

CONCLUSION

In conclusion, V_{crit} could be a potential index to evaluate short-distance swimming performance in breaststroke style. V_{crit}, but not D', determined most of 50-m breaststroke swimming performance.

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KEY POINTS

- For high-velocity running or swimming, the relationship between velocity (v) and its sustainable duration (t) can be described by a hyperbolic relationship: $(v - V_{crit}) \cdot t = D'$, where V_{crit} is termed critical velocity, and D' is defined as a curvature constant of the hyperbolic curve. The D' contributed only around 20% of the breaststroke swimming performance even in a short-distance event.
- Critical velocity determined around 80% of 50-m breaststroke swimming performance, and it could be a useful tool for evaluating short-distance swimming performance.
- Most of the swimmers showed characteristics for critical velocity dependent physical fitness even in short-distance swimming event.

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