Relationships between stroke parameters and critical swimming speed in a sprint interval training set

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Abstract
The aim of this study was to determine whether a relationship exists between stroke parameters and critical swimming speed (which is defined as the speed that can theoretically be maintained without exhaustion). Stroke parameters (stroke rate and length) and velocity were recorded for each 25-m length during a controlled sprint interval training set in which participants swam one of the four competitive strokes at a range of intensities below, at, and above critical speed. Eleven participants (8 females, 3 males; age 17.9 ± 0.9 years) completed a progressive (descending) set of 8 × 100 m repetitions in a 25-m pool according to target times that ranged in intensity from 65% to 100% of the swimmer’s best time (the intensity for each repetition increased by 5% throughout the set). The data showed that participants reached critical speed on the fourth repetition and that substantial and unpredictable changes in stroke parameters occurred once critical speed had been reached. Specifically, post-critical speed stroke rate and stroke length were significantly (P < 0.01) greater and less, respectively, than the pre-critical speed values, and these changes occurred in an abrupt and non-linear manner. Overall, the findings suggest that critical speed represents a transition point between two different sets of stroke parameter relationships – one for low-intensity aerobic swimming and one for high-intensity anaerobic swimming.

Keywords: Critical speed, stroke rate, stroke length, interval training set

Introduction
Elite performance in competitive swimming requires superior aerobic and anaerobic conditioning as well as great technical expertise that takes years to develop. Understanding the relationships between stroke rate and stroke length (i.e. the stroke parameters) and velocity can provide important information about the technical development of elite competitive swimmers. Stroke parameter relationships have been investigated during major competitions (Arellano, Brown, Cappaert, & Nelson, 1994; Kennedy, Brown, Chengalur, & Nelson, 1990) as well as in controlled training environments (Barden & Rorke, 1999; Craig, Skehon, Pawelczyk, & Boomer, 1985; Dekkerle et al., 2005; Keskinen & Komi, 1993; Toussaint, Carol, Kranenborg, & Truijens, 2006; Vorontsov & Binevsky, 2003), and have shown that longer stroke lengths are largely responsible for the higher velocities of male and elite swimmers (Arellano et al., 1994; Pelayo, Sidney, Kherif, Chollet, & Tourny, 1996; Toussaint & Beek, 1992). Stroke length has also been shown to decrease at intensities above the anaerobic threshold (Dekkerle et al., 2005; Keskinen & Komi, 1993), while other studies have found that stroke rate is highly correlated with both oxygen consumption and velocity (Wakayoshi, D’Acquisto, Cappaert, & Troup, 1995). As such, stroke parameter analysis can provide a basis from which to understand the interrelationships between the physiological demands of competitive swimming and the associated biomechanical output in terms of stroke mechanics.

In recent years, an important physiologically based parameter that has received considerable attention is critical speed. Critical speed is based on the related concept of critical power, which refers to the intensity of exercise that can, in theory, be maintained indefinitely without exhaustion (Monod & Scherrer, 1965). In the early 1990s, this concept was applied to swimming by Wakayoshi et al. (1992a, 1992b), who demonstrated that the slope of the regression line between swimming distance and time could be used to determine the critical swimming
speed. Because of its practicality, the critical speed test has become a widely adopted and important performance-based field test that provides an index of swimming-specific aerobic performance. Several studies have investigated the specific distances that provide the most accurate critical speed results (Dekerle, Sidney, Hespel, & Pelayo, 2002; Toubekis, Tsami, & Tokmakidis, 2006; Wright & Smith, 1994), but it is generally accepted that the critical speed test is a valid, non-invasive, and practical test that can be used to evaluate the endurance capacity of age-group (Toubekis et al., 2006) and high-performance (Dekerle et al., 2002) swimmers.

Since the physiological value of the critical speed concept is based on its ability to represent the limits of sustained aerobic metabolism, it is reasonable to infer that the point at which critical speed is reached is associated with the development of increasing anaerobic energy production, which has been suggested by the results of at least one previous study (Wakayoshi et al., 1993). As such, it provides a practical basis to address important questions about the way in which the intensity of exercise affects the stroke mechanics of elite competitive swimmers. Given that critical speed provides an index of maximum sustainable swimming intensity and that stroke length has been shown to decrease beyond the anaerobic threshold, it is reasonable to propose that the stroke parameter relationships associated with swimming velocities greater than critical speed will be substantially different from those associated with lower speeds. The purpose of this study, therefore, was to determine whether critical speed is related to, and therefore indicative of, the point at which stroke parameters begin to change substantially. This was accomplished by determining the velocity, stroke rate, and stroke length during a controlled, progressive sprint interval training set in which participants swam at a range of intensities below, at, and above critical speed. It was hypothesized that substantial changes in the stroke parameter relationships would correspond to the point at which critical speed was reached; that is, that the changes in stroke rate and stroke length that occurred before critical speed would be substantially different from those that occurred after critical speed.

Methods

Participants

Eight female (mean ± s: age 17.3 ± 1.5 years, height 1.71 ± 0.04 m, body mass 65.1 ± 6.1 kg) and three male (age 18.4 ± 0.2 years, height 1.80 ± 0.04 m, body mass 84.2 ± 3.1 kg) elite national-level swimmers (all Canadian National qualifiers, one Olympic team member) participated in the study. The participants provided informed consent in compliance with ethical policies and procedures outlined by the Ethics Review Board of the University of Regina, which approved all aspects of the study.

Critical speed protocol

Each participant completed a critical speed test that included three timed maximal-effort swims at distances of 200, 400, and 1000 m. The three timed swims were completed on successive days (one distance for each day) during the course of regular training and 2 days before the test set described below. Participants completed the critical speed test using their best stroke. As such, all four competitive swimming strokes were represented in this study: two participants swam butterfly, three backstroke, one breaststroke, and five freestyle (front crawl). The decision to perform the test using multiple strokes was made for several reasons. First, given that critical speed is a physiologically based parameter, it was assumed that the metabolic effects of critical speed on the normalized (relative to minimum values) stroke parameter relationships would be the same for all strokes. Second, conducting the study using each participant’s best stroke would provide data that are indicative of the highest level of performance possible from this particular sample of elite swimmers. And third, the study would result in findings that are generalizable (potentially) to all strokes rather than just front crawl.

The distances used for the critical speed test were selected so that the results would be consistent with the protocol developed by the Canadian National Sport Centre, which has used these specific distances to determine the critical speed of Canadian National team members (Smith, Norris, & Hogg, 2002; Wright & Smith, 1994). In line with other critical speed studies, the three timed performance swims were used to calculate each swimmer’s critical speed based on the slope of the regression line for distance versus time (Dekerle et al., 2002; Toubekis et al., 2006; Wakayoshi et al., 1992b).

Training set protocol

A sprint interval training set was designed based on the results of the critical speed test. The results showed that the critical speed of each swimmer corresponded to approximately 80% of their best 100-m time. Consequently, the participants completed a progressive interval training set (known as a descending set) at a range of intensities above and below critical speed, so that the relationships between stroke rate, stroke length, and critical speed
could be investigated. The set consisted of 8 × 100 m repetitions, in which each repetition was completed according to target times that corresponded to a percentage of each swimmer’s best 100-m time for their selected stroke. The participants were instructed to complete each 100-m repetition of the set according to the following target times: repetition 1 (65% of best time), repetition 2 (70%), repetition 3 (75%), repetition 4 (80%: the target time that corresponded to critical speed), repetition 5 (85%), repetition 6 (90%), repetition 7 (95%), and repetition 8 (100%: this target time was equivalent to the swimmer’s best time). Rest intervals between repetitions were individualized according to a 1:1 work-to-rest ratio. This work-to-rest ratio was selected so that stroke rate and stroke length could be observed under fatigued conditions, as well as at lower submaximal intensities before the onset of fatigue. The set was specifically designed to be challenging, so that the swimmers would fail towards the end of the set. The participants completed the entire set using the stroke selected for the critical speed test. No specific instructions were provided to the participants pertaining to swimming performance or technique (i.e. they were not told to monitor stroke count or to maximize distance per stroke), other than to swim at the appropriate pace so that each repetition corresponded to the specified target time.

**Equipment**

All tests for this study were conducted in a 25-m pool. Participants swam in an individual lane with lane ropes that were marked at 5-m intervals. A digital video camera (Panasonic PV-GS29) and Vicon Motus 9.2 motion analysis software (Englewood, CO, USA) were used to record and calculate, respectively, the stroke parameters for each 25-m length of each repetition throughout the interval training set.

**Video analysis and calculation of stroke parameters**

A 5-m zone in the middle of the 25-m pool (10 m on either side) was used to measure velocity (i.e. clean swimming speed) and stroke rate once every 25-m length. Stroke rate was determined by measuring the time taken to complete four stroke cycles (for example, from left or right hand entry until the fourth ipsilateral hand entry). This method was used because it was found that four stroke cycles corresponded closely to the 5-m recording zone for all four competitive strokes (Kennedy et al., 1990). Stroke length was calculated based on the relationship: velocity=stroke rate × stroke length. The digital video camera was positioned approximately 5 m from the edge of the pool with the optical axis of the camera perpendicular to the pool’s length. A 1 × 1 m four-point calibration grid and lane rope markings were used to control for any perspective differences and to ensure consistency of the 5-m zone across all lanes.

**Data analysis**

To account for absolute differences between the four strokes, the stroke parameter data for all participants were normalized. This allowed relative changes in stroke rate and stroke length to be compared across participants who swam different strokes. Velocity was normalized based on its relationship with critical speed (i.e. it was expressed as a percentage of each participant’s critical speed value), whereas stroke rate and stroke length were normalized according to each participant’s minimum value for the set. Linear regression and dependent t-test statistical analyses were conducted to compare relative changes in mean group stroke rate and stroke length before and after critical speed. Given that critical speed was attained on the fourth repetition of the set, the data for repetitions 1–4 were compared with the data for repetitions 5–8. In all cases, probability (P) values less than 0.01 were considered to be statistically significant.

**Results**

Changes in the normalized mean velocity, stroke rate, and stroke length for all participants for each 100-m repetition of the interval training set are shown in Figure 1. The data show that the average velocity (averaged across participants and lengths) reached critical speed on the fourth repetition of the set and that the fastest speed occurred on the sixth repetition. Beyond this point, swimming velocity did not increase but was essentially maintained throughout the remainder of the set (i.e. for repetitions 7 and 8). Figure 1 shows that the data were consistent with *a priori* expectations that critical speed would be attained midway through the set, and that the target times and work-to-rest ratio would be sufficiently challenging so that the swimmers would begin to fail towards the end of the set. Figure 1 also shows the general trend in the stroke parameter relationships as swimming speed, and therefore intensity, increased throughout the set; namely, that stroke rate increased progressively for the entire set, whereas stroke length was more consistent and decreased until no further increases in speed were possible. With respect to the data in Figure 1, it should be noted that the lowest values for mean stroke rate and stroke length were both greater than 100% because they were normalized to the minimum 25-m value for each
parameter. Consequently, when the data were averaged across the four 25-m lengths of each repetition and across participants, the mean values were greater than the single 25-m minimum value which represented 100%. It can also be seen in Figure 1 that a substantial increase in stroke rate occurred after the fourth repetition, and that this increase coincided with a reduction in stroke length which was greater than that which had occurred earlier in the set.

The specific relationship between stroke rate and critical speed is presented in Figure 2, which shows the mean normalized stroke rate in relation to the change in velocity (relative to critical speed) that occurred throughout the set. From this perspective, it can be seen that there was a strong linear relationship between stroke rate and velocity throughout the first half (repetitions 1–4) of the set, up to and including the point at which critical speed was reached. For the second half of the set (repetitions 5–8), after critical speed, an abrupt change in stroke rate occurred such that stroke rate continued to increase, but at a higher level than would have been predicted by the previous (i.e. pre-critical speed) relationship. To characterize changes in the stroke parameter data that occurred before and after critical speed, the data were separated into two equal portions (repetitions 1–4 and repetitions 5–8), so that lines of best fit using linear regression analysis could be applied to each portion. This analysis shows that before critical speed is reached, the normalized change in stroke rate can be predicted by knowing the speed of the swimmer expressed as a percentage of the critical speed. It also shows that 90% of the increase in velocity can be explained by the increase in stroke rate ($R^2 = 0.90$). Therefore, the stroke rate–critical speed relationship for the first half of the set was given by:

$$y = 1.369x - 14.3,$$  \(1\)

where $y = (SR_n/SR_b) \times 100$ and $x = (V_n/V_{cs}) \times 100$, such that $SR_n$ is the $n$th stroke rate, $SR_b$ is the baseline or minimum stroke rate, $V_n$ is the $n$th velocity, and $V_{cs}$ is the critical speed. When $V_n = V_{cs}$ such that $x = 100$ (i.e. when $x = 100\%$ of critical speed), equation (1) becomes

$$\frac{SR_n}{SR_b} \times 100 = 1.369 \times 100 - 14.3,$$  \(2\)

which can be reduced to

$$SR_n = SR_b \times 1.23.$$  \(3\)

Consequently, if the minimum or baseline stroke rate ($SR_b$) is known, equation (3) can be used to predict the stroke rate ($SR_n$) at which critical speed occurs.
The stroke rate data for the second half of the set (i.e. the post-critical speed repetitions 5–8) also showed a linear pattern, but one that was different and less strong than that for the first half of the set ($R^2 = 0.57$ and $R^2 = 0.90$ for the second and first halves, respectively). To determine whether the post-critical speed changes in stroke rate were significantly different from those that occurred during the first half of the set (i.e. before critical speed), the actual stroke rate values for repetitions 5–8 were compared with the predicted stroke rate values as determined by the regression equation for repetitions 1–4. The actual values along with the predicted values are shown in Figure 2. The difference in means for the actual versus predicted stroke rate (142% vs. 133%) was statistically significant ($P < 0.01$). Therefore, the results show that the increase in stroke rate that occurred after critical speed exceeded that which was expected based on the pre-critical speed relationship.

Similarly, Figure 3 shows that the changes in mean normalized stroke length before and after critical speed were consistent with those observed for stroke rate. Specifically, it can be seen that stroke length was essentially maintained throughout the first half of the set up to the critical speed point. This is consistent with the pre-critical speed linear relationship for stroke rate, which indicated that 90% of the increase in swimming velocity can be explained by the increase in stroke rate. Following the point at which critical speed was reached, the data show that stroke length dropped substantially to a level that was different from the first half of the set, and that this new level was generally maintained throughout the last four repetitions. A comparison of the mean stroke length for repetitions 5–8 versus repetitions 1–4 revealed that the post-critical speed stroke length was significantly less than the pre-critical speed stroke length ($P < 0.01$). Consequently, the data in Figure 3 show that the attainment of critical speed was associated with a pronounced and immediate drop in stroke length (about 6.5%) and that despite this change, the average stroke length was generally maintained throughout the second half of the set.

**Discussion**

The purpose of the current study was to determine whether a relationship exists between critical speed and the point at which substantial changes in the stroke parameter relationships occur. The hypothesis that the changes in stroke rate and stroke length before critical speed would be substantially different...
from those that occurred after critical speed was supported. Specifically, the results of this study show that the intensity represented by critical speed is associated with, and therefore can be used to predict, the point at which substantial changes in stroke rate and stroke length will occur. The results also demonstrate that the basic strategy employed by elite swimmers to increase velocity throughout a progressive interval training set was to increase stroke rate while attempting to maintain stroke length. While this basic strategy prevailed throughout the set, participants were not able to maintain stroke length beyond the critical speed point, and as such the preliminary stroke parameter relationship changed. Given that the average velocity of the participants did not increase after the sixth repetition, the results suggest that the set was sufficiently demanding such that the participants were unable to reach the designated target times for repetitions 7 and 8. This presumably occurred because the consistent inter-repetition recovery interval (1:1 work-to-rest ratio) became increasingly insufficient relative to the intensity of exercise at the end of the set.

Changes in stroke rate

The results show that the stroke rate for each 100-m repetition increased gradually and predictably until the fourth repetition, where critical speed was reached. Beyond the critical speed point, there was clearly a substantial and significant change in stroke rate between the fourth (80% of best time) and fifth (85% of best time) repetitions. The findings show that there is a strong linear relationship between stroke rate and velocity up to and including the point at which critical speed is reached. Previous studies have shown that positive correlations exist between stroke rate and the volume of oxygen (VO₂) consumed (Wakayoshi et al., 1995), as well as the number of stroke cycles and time taken to swim a particular distance (Dekerle et al., 2002). Indirectly, the findings of this study are consistent with those of Wakayoshi et al. (1995), as it is reasonable to expect a positive linear relationship between velocity and oxygen consumption, given that this study has shown that there is a positive linear relationship between velocity and stroke rate. They are also consistent with those of Dekerle et al. (2002), who proposed using the linear relationship between the number of strokes and time to predict the critical stroke rate, which was defined as the stroking frequency that could be theoretically maintained without exhaustion. In the current study, this finding is extended to show that the pre-critical speed linear relationship between stroke rate and velocity can be used to predict the stroke rate at which critical speed will occur (i.e. the
critical stroke rate). The results also suggest that, based on this relationship, the critical speed can be predicted if the minimum (or baseline) stroke rate is known. Most importantly, the results of this study show that beyond the critical speed threshold, a substantial and significant increase in stroke rate occurs which cannot be predicted by the pre-critical speed relationship. Consequently, the results demonstrate that non-linear changes in stroke rate occur when swimming speeds exceed the critical point that separates sustainable from non-sustainable swimming intensity.

Changes in stroke length

The results show that although the general trend for stroke length was to decrease, it was relatively consistent and stable as swimmers increased speed throughout the first four repetitions of the set. Before critical speed, as the linear relationship between stroke rate and velocity shows, any increase in velocity occurred primarily as a result of a change in stroke rate, not stroke length. This suggests that the participants may have selected the most effective or optimal stroke length to satisfy the requirements of the task at sustainable swimming speeds. However, beyond critical speed, at which the intensity became non-sustainable, there was an immediate and significant drop in stroke length, which was presumably offset by an abrupt, non-linear increase in stroke rate. The current results for stroke length are consistent with the findings of two other studies that found that decreases in stroke length occur at intensities above anaerobic threshold (Keskinen & Komi, 1993), and above the speed at which maximal lactate steady-state occurs (Dekerle et al., 2005).

General interpretation

The findings of this study are especially important in the context of their application to competitive swimming, but also in the context of understanding the interrelationships between metabolic and mechanical efficiency as they apply to swimming propulsion. If the accumulation of lactic acid beyond maximal lactate steady state and/or the anaerobic threshold is responsible for the decrease in stroke length, as has been suggested previously (Dekerle et al., 2005; Keskinen & Komi, 1993; Wakayoshi et al., 1993), then the post-critical speed stroke parameter changes observed in this study were likely the result of metabolic changes that occurred when the target times surpassed the critical speed point (i.e. the maximum sustainable swimming intensity). Once critical speed was reached and until the end of the set, there would have been an increased reliance on anaerobic energy production and a subsequent increase in peripheral muscle fatigue. Given these conditions, it would appear that the only strategy available to the central nervous system to compensate for the drop in stroke length, while attempting to continue to increase speed in the face of increasing metabolic acidosis, would be to increase stroke rate to a higher level than that which would typically occur. Consequently, given the theoretical and physiological basis of the critical speed concept, it is likely that the changes in stroke rate and stroke length that occurred immediately after critical speed were related to the increased demand for energy and the associated increased dependence on anaerobic metabolism.

Although this would seem to be the most likely interpretation, there are several other possibilities that should be considered given the number of metabolic and/or mechanically related factors that have the potential to affect stroke rate and length. These include the potential differential effects of anaerobic metabolism on the relative contribution of propulsion from the arms and legs, the effects of increased active drag (the resistive forces to which swimmers are exposed while stroking) on stroke mechanics and metabolic efficiency, as well as the stability of the stroke-specific coordination patterns between the arms and legs before and after the critical speed point. Thus, it is unlikely that the observed changes in stroke parameters were the result of a single key variable (for example, an increase in blood lactate), but rather occurred as a consequence of the interaction of several variables. For example, given that active drag increases exponentially with increasing velocity, it may have been that the combined effect of an increase in active drag and a decreased contribution to propulsion from the swimmer’s pull and/or kick (due to the accumulation of lactic acid in the large muscles of the arms and legs), was responsible for producing the non-linear changes in stroke rate and stroke length that occurred after critical speed. Given the abrupt nature of the stroke parameter changes observed in this study, the results are also interesting from a dynamical systems perspective, whereby non-linear changes in complex systems have been shown to occur when control parameters such as velocity push the dynamics of the system to a critical point from which new stable patterns of behaviour emerge (Kelso, 1995). What is particularly intriguing about the current findings is that they are consistent with the dynamics of the walk–run transition that occurs in human locomotion. Specifically, a non-equilibrium phase transition occurs at the point where walking changes to running, and it has been shown that this transition is associated with an increase in stride frequency and a decrease in stride length (Diedrich & Warren, 1995). Consequently,
with respect to the non-linear changes in stroke parameters associated with critical speed, future studies should investigate whether dynamic systems theory can provide any insight or explanation for this particular phenomenon.

**Training applications**

For coaches and swimmers, the most important outcome of this study is that the results suggest that a simple stroke count can be used to predict critical speed. Although this study had several limitations, such as an unequal number of male and female participants and an unequal number that swam each individual stroke (for example, only one swimmer swam breaststroke), the results are important in that they show that it is possible to predict critical speed from the change in stroke rate relative to a minimum value, which in this study occurred at a pace that was equivalent to 65% of the participant’s best 100-m time. While the stroke rate at this particular speed does represent a very low swimming intensity, it is unclear whether it represents the true minimum stroke rate. Nevertheless, the results show that there is a practical and time-saving alternative to the current procedure to test for critical speed, in that coaches can use a chronometer to obtain a swimmer’s stroke rate when swimming at a low intensity (65% of best 100-m time) and can multiply this value by 1.23 to obtain the critical speed (or critical stroke rate; i.e. the stroke rate at which critical speed occurs). Once the critical stroke rate/speed has been determined, stroke counts can be used regularly to monitor the training intensity and to determine whether the intensity is above or below the critical speed threshold. Because the practical application of this method relies on the ability to accurately predict the critical stroke rate, which in turn depends on determining the minimum stroke rate, future studies should investigate whether there is a better and/or more reliable way to determine the minimum stroke rate. Although this is important from the perspective of providing an accurate tool for coaches (i.e. determining and/or refining the specific proportionality between the minimum value and the critical stroke rate value), the results of this study and others (Dekerle et al., 2002) suggest that the basic linear relationship between stroke rate and velocity can be used to predict the critical speed, and that this prediction can easily be obtained by recording a swimmer’s baseline stroke rate. Consequently, the practice of monitoring stroke rate has the potential to provide coaches with an easy and effective tool to determine, on an individual basis, the submaximal speed above which stroke length will begin to drop. The findings also suggest that it would be advantageous for coaches to regularly monitor stroke counts during training and to use the critical stroke rate to identify the threshold between sustainable and non-sustainable swimming intensity. Given the observed effect of intensity on stroke rate and length, coaches should consider the development of specific training protocols to address the different stroke parameter relationships that are associated with low-intensity, sustainable swimming speeds and high-intensity, non-sustainable swimming speeds.

**Conclusions**

We have shown in this study that the concept of critical speed, which is a non-invasive method of quantifying aerobic capacity in swimmers, is associated with the point at which substantial changes in stroke rate and stroke length occur. The results suggest that the linear relationship between stroke rate and velocity can be used to predict the critical speed, and that this prediction can easily be obtained by recording a swimmer’s baseline stroke rate. Consequently, the practice of monitoring stroke rate has the potential to provide coaches with an easy and effective tool to determine, on an individual basis, the submaximal speed above which stroke length will begin to drop. The findings also suggest that it would be advantageous for coaches to regularly monitor stroke counts during training and to use the critical stroke rate to identify the threshold between sustainable and non-sustainable swimming intensity. Given the observed effect of intensity on stroke rate and length, coaches should consider the development of specific training protocols to address the different stroke parameter relationships that are associated with low-intensity, sustainable swimming speeds and high-intensity, non-sustainable swimming speeds.

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**References**


