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Physiological Responses and Swimming Technique During Upper Limb Critical Stroke Rate Training in Competitive Swimmers

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The aim of this study was to examine how arm stroke swimming with critical stroke rate (CSR) control would influence physiological responses and stroke variables in an effort to identify a new swimming training method. Seven well-trained male competitive swimmers (19.9 ± 1.4 years of age) performed maximal 200 and 400 m front crawl swims to determine the CSR and critical swimming velocity (CV), respectively. Thereafter, they were instructed to perform tests with 4 × 400 m swimming bouts at the CSR and CV. The swimming time (CSR test: 278.96 ± 2.70 to 280.87 ± 2.57 s, CV test: 276.17 ± 3.36 to 277.06 ± 3.64 s), heart rate, and rated perceived exertion did not differ significantly between tests for all bouts. Blood lactate concentration after the fourth bout was significantly lower in the CSR test than in the CV test (3.16 ± 1.43 vs. 3.77 ± 1.52 mmol/l, $p < 0.05$). The stroke rate and stroke length remained stable across bouts in the CSR test, whereas the stroke rate increased with decreased stroke length across bouts in the CV test ($p < 0.05$). There were significant differences in the stroke rate (39.27 ± 1.22 vs. 41.47 ± 1.22 cycles/min, $p < 0.05$) and stroke length (2.20 ± 0.07 vs. 2.10 ± 0.04 m/stroke, $p < 0.05$) between the CSR and CV tests in the fourth bout. These results indicate that the CSR could provide the optimal intensity for improving aerobic capacity during arm stroke swimming, and it may also help stabilize stroke technique.

Key words: *arm stroke swimming; stroke rate; stroke length; aerobic performance; swimming training.*

Introduction

Performance in competitive swimming is dependent on the generation of propulsive forces by upper and lower limbs. For front crawl swimming, previous studies have reported that most of the propulsive force depends on the upper limbs (Silveira et al., 2017), whereas the lower limbs mainly aid in maintaining underwater posture (Yanai, 2001). Therefore, it has long been emphasized that increased propulsive force by upper limbs is critical for improving performance during the front crawl.

Arm stroke swimming involving only the upper limbs is frequently used to train competitive swimmers as it improves metabolic capacity and stroke technique (Ogita et al., 1996). Indeed, improving the metabolic capacity and arm stroke technique may enhance performance in whole-body swimming (Ogasawara et al., 2009). However, the physiological load during arm stroke swimming is approximately 20% lower than the load during whole-body swimming at the same relative intensity (Ogita et al., 1996; Ribeiro et al., 2015). Therefore, it is possible that arm stroke swimming does not achieve the intended effect of improving metabolic capacity. Despite this potential shortcoming, few studies have examined methods for enhancing the efficacy of arm stroke training.

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For endurance training, swimmers are generally instructed to swim within a set time based on variables such as the anaerobic threshold (AT) (Fernandes et al., 2011; Keskinen and Komi, 1993), onset of blood lactate accumulation (OBLA) (Stager et al., 2015; Wakayoshi et al., 1992), critical swimming velocity (CV) (Takahashi et al., 2009; Wakayoshi et al., 1992, 1993), and 30-min swimming tests (T-30) (Dekerle et al., 2002; Greco et al., 2007). However, there is usually no attempt to control or measure the stroke rate and stroke length.

Costill et al. (1985) demonstrated that to enhance aerobic performance during swimming, it is important to improve stroke technique as well as metabolic capacity. Dekerle et al. (2002) found a strong linear relationship ($r > 0.999$) between maximum effort swimming time and the number of whole-body crawl stroke cycles and referred to the slope of the regression line as the critical stroke rate (CSR). They found that using the CSR as a training variable enabled control of training intensity and stroke technique in endurance training, suggesting that CSR-based training may also benefit swim strokes that are highly dependent on arm strokes, such as the front crawl. Furthermore, Barden and Kell (2009) demonstrated that monitoring stroke rate might serve as an easy and effective tool for determining submaximal speed above which stroke length would begin to drop in whole-body swimming, and the CSR was useful for identifying that point. Accordingly, to identify a new swimming training method, this study examined how arm stroke swimming with CSR control would influence physiological responses and stroke variables.

Methods

Participants

Seven well-trained, national-level, male middle- and long-distance swimmers (mean ± SD; age: 19.9 ± 1.4 years, body height: 1.69 ± 0.06 m, and body mass: 65.2 ± 4.7 kg) participated in this study. Their best performance over 400 m was 89.7 ± 2.2% of the mean speed of the world record and 729.3 ± 63.0 points on the *Fédération Internationale de Natation* (FINA) scale for a 50 m pool. All swimmers trained 10 times per week for approximately two hours per session, covering a distance of 6000–8000 m per session. Before participating in this study, swimmers were briefed on the benefits and risks of the tests, and they all provided written informed consent to participate. The protocol was approved by the Kumamoto Gakuen University ethics review committee. All procedures were conducted according to the Declaration of Helsinki guidelines for research on human participants.

Testing procedure

All tests were performed in a 50 m indoor swimming pool (29.0 ± 0.6°C water temperature) and involved front crawl arm stroke swimming initiated with a push-off start. During arm stroke swimming, the lower limbs were supported by a training pull buoy, of which buoyancy was approximately 15.0 N. Using the pull buoy, the participants were asked to perform only upper limb strokes and to maintain a horizontal streamlined position such that no kicks were executed. All tests were conducted within a 14-day period.

Determination of CSR and CV

Swimmers performed 200 and 400 m maximal swimming bouts in a random order for CSR and CV determination. The interval between maximal swimming bouts was at least 2 h, and the second test was not started until the heart rate (HR) decreased to resting values. The CSR was calculated as the slope of the regression line between the time and the number of stroke cycles expressed as cycles per minute (cycles × min^{-1}) according to Dekerle et al. (2002). The swimming times were recorded by an experienced training assistant using a digital stopwatch (SVAS003, SEIKO, Japan). Immediately after the 200 and 400 m maximal swimming bouts, the HR was measured using a wireless HR monitor (RS400, Polar, Finland). The 200 and 400 m maximal swimming bouts were recorded using a video camera (HX-WA20-W operating at 60 Hz, Panasonic, Japan) positioned on a perpendicular plane 10 m from the swimmers at the center of the pool above the water. The mean stroke time between 15 and 35 m was recorded every 50 m. One stroke cycle was defined as the unit from the entry of one hand to the following entry of the same hand. The number of stroke cycles was calculated by dividing the swimming time by the mean stroke time at each 50 m. Following Wakayoshi et al. (1992), CV was determined as the slope of the linear regression between the swim distance and time.

CSR and CV test protocol

One week after the maximal effort swimming sessions for the determination of the CSR and CV, participants performed 4 × 400 m bouts based on the CSR and again at CV (CSR test and CV test, respectively) in random order. Each bout was separated by 40 s of passive rest (Tsalis et al., 2012; Wakayoshi et al., 1993). For the CSR and CV tests, the swimming times were recorded by an experienced training assistant. During the four bouts of the CSR test, no set swimming time was imposed, but the stroke rate was controlled by a metronome (Tempo Trainer Pro, Finis, USA) placed in the swimmer's cap. The metronome had a width of 4.8 cm, a thickness of 1.4 cm, and a weight of 19.5 g. No set stroke rate was imposed during the CV test; rather, swimmers were prompted to maintain CV by following an experimenter walking along the side of the swimming pool (Tsalis et al., 2012). During the CSR and CV tests, swimmers assessed their HR and rated perceived exertion (RPE) using the Japanese version of the Borg scale immediately after each bout (Onodera and Miyashita, 1976), and blood lactate concentration (BLa) was measured in capillary blood samples taken from the finger-tip (5 μl) using a portable lactate analyzer (Lactate Pro, ARKRAY, Japan). Blood samples were collected one, three and five minutes after the fourth bout and the highest values were recorded. For verification of stroke variables, the CSR and CV tests were recorded using a video camera from the same position as in the recording of the 200 and 400 m maximal swimming bouts. The mean stroke time was recorded using the same method as the 200 and 400 m maximal swimming bouts. The stroke rate (SR) was calculated by dividing 60 by the mean stroke time, and the stroke length (SL) was calculated based on the relationship denoted by velocity = (SR / 60) × SL. In each bout, SR and SL were calculated as the mean value of the data obtained at each 50 m. They performed both tests on the same day in random order. The interval between the tests was at least 2 h, and the second test was not started until the HR decreased to resting values.

Statistical analysis

All performance, physiological, and stroke variables were expressed in terms of mean ± standard deviation. Normality of distribution was assessed with the Shapiro-Wilk's test. Two-way analysis of variance for repeated measures with factors (CSR or CV) and the bout (first to fourth) was used for statistical analysis of the swimming time, HR, RPE, SR, and SL, with the use of a Bonferroni post hoc test when appropriate. Measures of BLa were compared between the tests using the paired-samples Student's t-test, and the level of significance was set at 5% ($p < 0.05$). Effect size (ES) was calculated. In accordance with Cohen (1988), ES was considered small if the absolute value was between 0.2 and 0.5, medium if it was between 0.5 and 0.8 and large if it was greater than 0.8.

Results

The respective mean swimming time and HR in the 200 and 400 m maximal swimming sessions were 128.27 ± 4.52 s and 264.98 ± 8.94 s, and 172.29 ± 15.77 bpm and 172.29 ± 11.34 bpm, respectively. The mean calculated CSR and CV values were 39.49 ± 3.26 cycles/min and 1.46 ± 0.05 m/s, respectively.

The results of the CSR and CV tests are presented in Table 1. There was no significant interaction effect between factors (test and bout) in all variables ($p > 0.05$). The swimming time was significantly reduced in the third bout compared with the first bout in the CSR test ($p = 0.02$, ES = 0.27), but did not differ between bouts in the CV test. The HR significantly increased after the second bout in both tests. In addition, the RPE significantly increased after the second bout in the CSR test and after the third bout in the CV test. No differences were observed in swimming time, HR, and RPE between the tests for all bouts, yet BLa was significantly lower after the fourth bout in the CSR test (3.16 ± 1.43 mmol/l) compared with that in the CV test (3.77± 1.52 mmol/l) ($p = 0.04$, ES = 0.42).

The SR (Figure 1) did not differ between bouts in the CSR test, but significantly increased during the fourth bout compared with the second bout in the CV test ($p = 0.04$, ES = 0.23). SL (Figure 2) also did not differ among bouts in the CSR test, but significantly decreased during the fourth bout compared with the first and the second bout in the CV test ($p = 0.02$, ES = 0.29 and $p = 0.02$, ES = 0.39, respectively). Moreover, significant differences were observed in the SR and SL in the fourth bout between tests ($p = 0.03$, ES = 0.68 and $p=0.04$, ES = 0.74, respectively).

Table 1

Swimming time, heart rate and RPE during the CSR and CV tests (n = 7).

		First	Second	Third	Fourth
Swimming time (s)	CSR test	280.87 ± 6.80	279.27 ± 7.00	278.96 ± 7.16[a]	279.28 ± 7.57
	CV test	276.82 ± 9.78	276.17 ± 8.89	277.04 ± 9.24	277.06 ± 9.62
Heart rate (bpm)	CSR test	128.71 ± 11.69	138.71 ± 6.87[a]	142.43 ± 7.11[a]	147.00 ± 10.76[a, b]
	CV test	134.43 ± 12.54	143.57 ± 7.25[a]	148.14 ± 9.10[a]	151.43 ± 8.89[a, b]
RPE	CSR test	14.3 ± 2.1	15.3 ± 2.1[a]	16.1 ± 2.0[a]	16.0 ± 2.3[a]
	CV test	15.1 ± 1.7	15.9 ± 1.7	16.6 ± 2.0[a]	16.7 ± 1.9[a]

Data is expressed as the mean ± standard deviation. CSR: critical stroke rate; CV: critical swimming velocity. [a] $p < 0.05$, significantly different from the first bout; [b] $p < 0.05$, significantly different from the second bout.

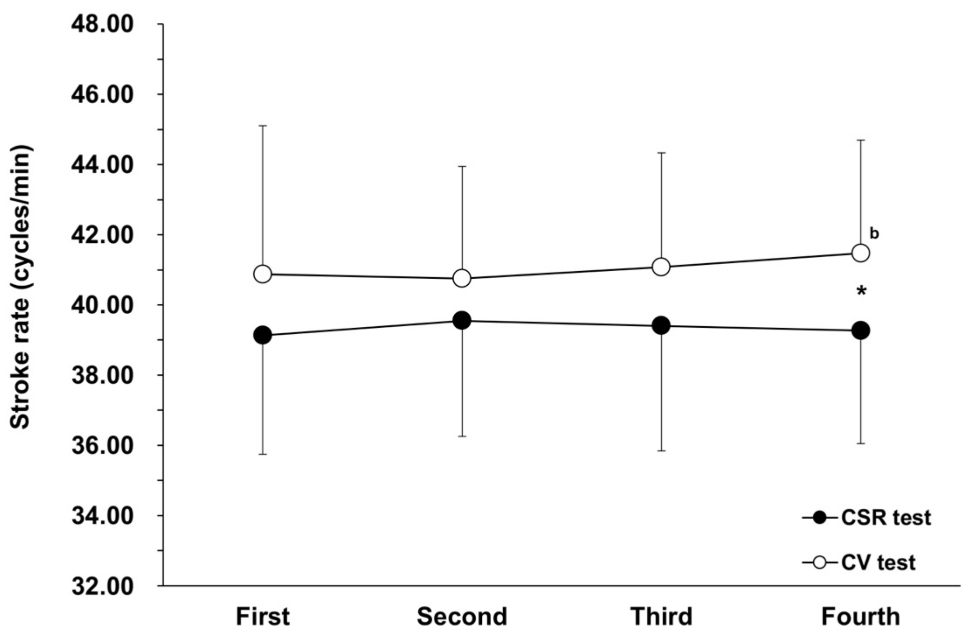

Figure 1

Stroke rate in the CSR and CV tests (n = 7 per group).
*Data is expressed as the mean ± standard deviation. CSR: critical stroke rate; CV: critical swimming velocity. [b] $p < 0.05$, significantly different from the second bout; * $p < 0.05$, significant difference between the CSR and CV tests.*

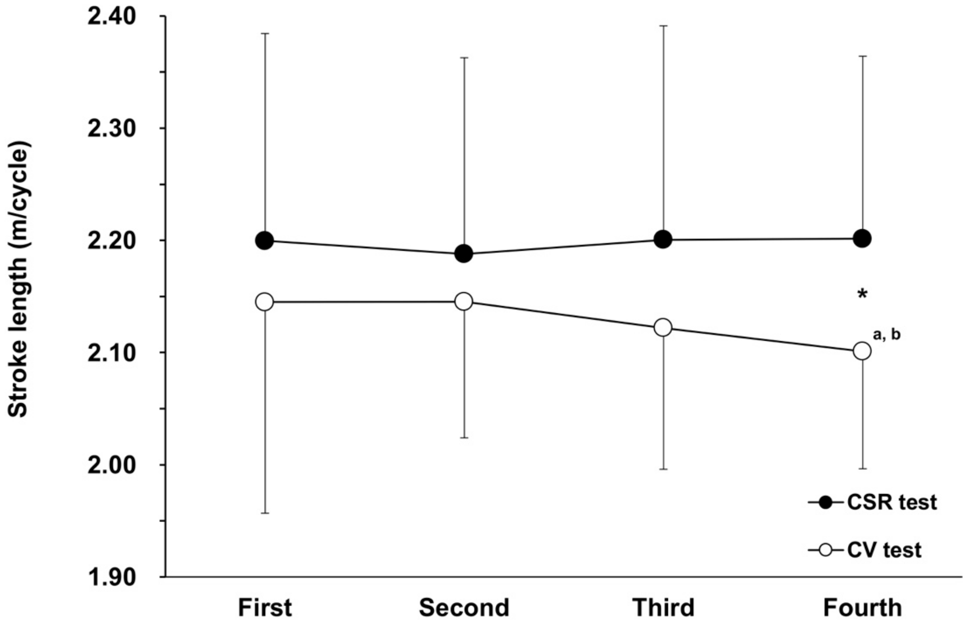

Figure 2

Stroke length in the CSR and CV tests (n = 7 per group).
Data is expressed as the mean ± standard deviation. CSR: critical stroke rate; CV: critical swimming velocity. [a] $p < 0.05$, *significantly different from the first bout;* [b] $p < 0.05$, *significantly different from the second bout;* * $p < 0.05$, *significant difference between the CSR and CV tests.*

Discussion

Despite reports that most of the propulsive force required for the long-distance front crawl event is generated by the upper limbs (Silveira et al., 2017), there are few studies investigating methods for enhancing the training effect of arm stroke swimming. Thus, to identify a new swimming training method, this study examined how arm stroke swimming with CSR control would influence physiological responses and stroke variables. Indeed, front crawl swimming with CSR control was as intense as with CV control. Swimming with CSR control reduced the variability in the SR and SL across bouts, which is indicative of a more consistent stroke technique.

Specifically, no differences were observed in the swimming time, HR, and RPE between the CSR and CV tests for all bouts. However, BLa was significantly lower in the CSR test after the fourth bout. A few studies have examined physiological responses during swimming under CSR control. For example, Maglischo (2003) found that endurance training with BLa in the range of 3–5 mmol/l, which is classified as threshold endurance training, improved oxygen utilization and lactate removal. Thus, although there was a significant difference in BLa following the CSR and CV tests, it appears that both tests were performed at almost the same intensity level. CV, expressed as the slope of a regression line between the swimming distance and sustained time, has been utilized as a training index for endurance interval training to improve aerobic capacity in competitive swimmers (Wakayoshi et al., 1992, 1993). The current results suggest that the CSR could be utilized as an alternative training intensity index for endurance interval training in arm stroke swimming to improve aerobic capacity.

The SR did not differ among bouts in the CSR test, which aligns with a previous report that found that the SR was maintained throughout endurance training in whole-body swimming under the CSR (Dekerle et al., 2002), thus suggesting that the CSR test was properly conducted. SL was not significantly different among bouts under the CSR, and the stroke technique appeared stable throughout the CSR test. On the other hand, in line with previous studies using a similar protocol (Ribeiro et al., 2010; Tsalis et al., 2012), the SR increased to compensate for reduced SL during the CV test. Moreover, Alberty et al. (2008) found that SL did not change with a controlled SR, but that the SR spontaneously increased to compensate for decreased SL. These results imply that training with a spontaneous SR may promote an inconsistent stroke technique. During the maximal swimming test, the duration of the non-propulsive phases (glide + catch, recovery) decreased when the SR was increased (Alberty et al., 2009; Bassan et al., 2016) and the duration of the propulsive phases (pull, push) increased (Bassan et al., 2016). This could lead to a reduced capacity to generate a propulsive impulse per stroke (Alberty et al., 2009). In addition, changes in stroke variables have been linked to blood lactate accumulation (Dekerle et al., 2005; Figueiredo et al., 2013) and arm muscle fatigue (Bassan et al., 2016). Indeed, BLa was significantly higher in the CV test, possibly due to disturbance of the stroke technique. Accordingly, fatigue in swimming training can be induced by increasing the SR to compensate for the reduced propulsive impulse per stroke.

A swimmer who specializes in 1500 m and open water swimming must increase the total distance of endurance training for competition (D'Acquisto et al., 1992; VanHeest et al., 2004). Generally, a 2000–4000 yard (1828.8–3657.6 m) swim is recommended for enhancing the effectiveness of threshold endurance training sets (Maglischo, 2003), as it is assumed that the influence on the stroke technique may be higher during long distance training sets than in short sets. Conventional training does not require any special tools because competitive swimmers are generally required to swim within a set time based on a variables such as CV. It is thought that training based on the CSR variable is more difficult than training based on CV, since the use of a metronome is essential for controlling the SR. However, in this experiment SL was significantly longer during the fourth bout in the CSR test, and the effect size (ES = 0.74) approached the "large" category as defined by Cohen (1988), which suggests higher increases in the effectiveness of endurance training using the CSR after 1200 m compared with the conventional training intensity index. Therefore, the use of the CSR for long-distance training sets may be an effective method to maintain the stroke technique, and swimming at a consistent stroke technique under the CSR could be more advantageous than conventional swimming training.

Training with monitoring the stroke rate is a potentially easy and effective tool for determining submaximal speed above which stroke length will begin to drop in whole-body swimming, and the CSR is useful for identifying that point (Barden and Kell, 2009). However, few studies have examined the effects of arm stroke swimming in competitive swimmers, and the CSR has not previously been applied to arm stroke swimming. In front crawl swimming, most of the propulsive force depends on the upper limbs (Silveira et al., 2017). Arm stroke swimming is considered to be important for long-distance swimmers, who require particularly high propulsive force in the upper limbs (Silveira et al., 2017). Namely, improving the function of upper limbs by arm stroke swimming may be an essential factor in improving performance of whole-body swimming, particularly among long-distance swimmers. Costill et al. (1985) demonstrated the effectiveness of the stroke technique on energy expenditure while swimming and its subsequent influence on aerobic performance. Consequently, it is considered that arm stroke swimming under CSR control may be effective for propulsive efficiency, which is important for enhancing aerobic performance compared with conventional training. Moreover, maintaining stroke variables using the CSR in arm stroke swimming could be an effective new strategy for improving aerobic performance.

This study has some limitations. First, even if swimming training is carried out using CSR variables, variations in the combination of swimming distance, the number of bouts and rest time may result in different impacts on swimming technique. Therefore, it is necessary to verify whether the results of the study are limited to the conditions as applied in this case. Second, although the swimming technique remained constant in the CSR test, the detailed biomechanical stroke variables were not examined, and these should be determined by underwater image analysis and electromyogram. Future studies should investigate the effect on whole-body swimming performance following arm stroke swimming training using the CSR.

In conclusion, for well-trained middle- and long-distance swimmers performing endurance interval training in arm stroke swimming, the CSR could represent the optimal intensity for the improvement of aerobic capacity, and it may also help stabilize the stroke technique.

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