Abstract

Purpose: To monitor physiological, technical, and performance responses to individualised high-intensity interval training (HIIT) prescribed using the critical speed (CS) and critical stroke rate (CSR) concepts in swimmers completing a reduced training volume programme (≤ 30 km.week⁻¹) for 15 weeks. Methods: Over the 15-week period, twelve highly-trained swimmers (age: 16±1 y; height: 179±8 cm; weight: 66±8 kg) completed four 3-min all-out tests (3MT) to determine CS and the finite capacity to work above CS (D′), and four 200 m tests at CS to establish a CSR estimate. Combining CS and D′, two HIIT sessions designed as 5x3 min intervals depleting 60% of D′ and 3x3.5 min intervals depleting 80% of D′ were prescribed once per week, respectively. An additional HIIT session was prescribed using CS and CSR as 10x150 m or 200 m at CS with 2 cycles.min⁻¹ lower SR than the CSR estimate. Additional monitored variables included peak speed, average speed for 150s (speed₁₅₀s) and 180s (speed₁₈₀s) in 3MT, competition performance and stroke length (SL), count (SC) and index (SI) adopted at CS. Results: At the end of the intervention, swimmers demonstrated faster CS (mean change ± 90% confidence limits: +5.4±1.6%), speed₁₅₀s (+2.5±0.9%), speed₁₈₀s (+3.0±0.9%), and higher SR (+6.4±3.0%) and SI (+4.2±3.6%). D′ was reduced (-25.2±7.5%) whilst peak speed, SL and SC changed only trivially. The change in the swimmers’ personal best times in the 1st and 2nd main event was -1.2±1.3% and -1.6±0.9%, respectively. Conclusion: HIIT prescribed based on the CS and CSR concepts was associated with improvements in several physiological, technical, and performance parameters in highly-trained swimmers whilst utilising time- and resource-efficient approach. This was achieved despite a ≥25% reduction in training volume.

Key words: 3-min all-out test, individualisation, monitoring, swimming, testing
Introduction

The main aim of swimming training is to enable swimmers to swim a given event in the shortest possible time. This is primarily determined by swimmers’ physiological and technical abilities\(^1\). Despite the majority of competitive events lasting less than 5 min, coaches are known to place a great importance on training volume to optimise these abilities (40-70 km.week\(^{-1}\))\(^2\). However, a growing body of research suggests that high-volume, low-intensity focused training strategies provide limited performance advantage over higher-intensity, lower-volume strategies, and have been linked to multiple negative effects (e.g., overuse injuries, early specialisation, burn- or drop-out) \(^3\). Recent findings from the Nugent et al.\(^3\) review suggest that lower-volume, higher-intensity strategies have led to performance improvements in competitive swimmers, however the authors also emphasised the limitations of these studies, which were related to the short duration (<6.5 weeks), lack of swimming-specific methodology and focus on obtaining a combination of physiological, technical and performance measures. Therefore there is a need for studies that explore these training alternatives for a longer period, using more sport-specific but affordable methods, which can be used by coaches beyond research interventions, given the technological and environmental constraints that apply to swimming.

Recently, the critical speed (CS) concept has become a promising tool utilised for testing and prescription of high-intensity interval training (HIIT) in multiple sports\(^4\-\(^6\). Currently, swimming coaches typically prescribe HIIT based on affordable methods (e.g., beats below HR\(_{\text{MAX}}\), race-pace, personal best times, holding best average), which do not take into account the between-subjects differences in anaerobic and/or aerobic capacities. The CS concept may provide a solution to this problem, as it identifies CS as the boundary separating sustainable from non-sustainable exercise intensities, and “D’” as a finite capacity available to work above CS \(^4\). The advantage of utilising CS and D’ in HIIT prescription is that target time intervals for a given distance are based on a partial depletion of D’, relative to an athlete’s CS, meaning that HIIT is personalised to indices related to the individual’s physiological capacity to exercise above CS. The time required to establish CS and D’ has also been recently reduced by the validation of the swimming 3-min all-out test (3MT)\(^7\), allowing easier application of the CS concept in swimming, where several constraints (e.g., multidisciplinary nature, lack of resources, time, expertise) limit regular testing and prescription of individualised training.

To extend the utility of the CS concept, Dekerle\(^8\) postulated critical stroke rate (CSR) as a biomechanical surrogate of the CS, which represents the highest SR that can be maintained for an extended period of time and swimmers spontaneously adopt when swimming at CS \(^8\-\(^9\), this could therefore be utilised for technical training \(^9\-\(^10\)). Indeed, Dekerle\(^8\) suggested constructing training sessions at CS with the SR<CSR, consequently requiring swimmers to adopt and maintain longer stroke length (SL) whilst being under substantial metabolic stress. Swimming coaches have previously suggested that lower-volume, higher-intensity training strategies could be detrimental to technical development, as technique is optimally practiced at low-intensities\(^2\). Whilst acknowledging the need for learning and practicing technical skills at low-intensity, questions have been raised as to how completing high volumes at low-intensity optimises technique adopted in races, which differs as speed increases and fatigue develops\(^1\-\(^2\).

The combination of CS and CSR concepts therefore seem theoretically appealing to provide both physiological and technical race-specific stimuli, however the impact of this strategy on actual development in competitive swimmers has not been investigated to date. Therefore, the aim of the present study was to utilise the CS and CSR concepts to prescribe individualised HIIT to a squad of highly-trained swimmers for 3 days.week\(^{-1}\) over a 15 week period. The purpose of this study was to monitor physiological, technical, and performance changes when
these concepts were applied over a season, and with a reduced training volume (≤30 km.week$^{-1}$).

**Methods**

**Subjects**

A squad of 12 highly-trained swimmers was utilised for analysis in the present study (Table 1), which had received ethical approval from the University of Bath and was undertaken in accordance with the Declaration of Helsinki. All participants were competitive swimmers and previously completed a training volume of ~40-45 km.week$^{-1}$. Prior to testing all participants and parents provided their written informed consent.

*Insert Table 1 here*

**Design**

The present study took place in a short-course season (September-December), and started 2 weeks after the swimmers had returned to training from a 1-2 week break. In total, the testing protocol consisted of eight testing visits, and three HIIT intervention blocks. The duration of the intervention was 4 weeks for the 1st and 2nd block, and 2 weeks for the final block. One week prior to the first intervention block and in the following week after 1st, 2nd and 3rd intervention blocks, the swimmers completed a 3MT and 200 m test at CS on separate days. These tests were performed to (re)prescribe HIIT blocks for each swimmer. During this week, training intensity and volume were reduced in order to optimise results from the tests. The subjects previously performed 3MT, and so were not asked to complete a familiarisation, however, all swimmers completed a familiarisation with the 200 m test at CS. Both tests were preceded by a 5-min low-intensity warm-up and 5-min rest. All trials were completed in a 50 m pool using a push-off start, conventional turns, and occurred at the same time of the day (± 1 h). The subjects completed the tests and intervention in their main stroke (individual medley swimmer in freestyle). In addition to the prescribed HIIT, the swimmers engaged in their land training (2-3 sessions.week$^{-1}$), low-intensity (3-4 sessions.week$^{-1}$), and speed development (repetitions ≤ 100 m) (1 session.week$^{-1}$) swimming sessions, which were not modified.

**Methodology**

**Three-min all-out test**

The test was conducted as previously described by Piatrikova et al.$^{7}$ However, in the situation when a turn was not completed in the last 30 s of the test, CS was calculated as the average speed in the last 50 m of the test to account for the impact of a turn on speed. A visual inspection of each swimmer’s 3MT profile was conducted to identify any occurrence of pacing, and the subjects that paced were asked to repeat the 3MT again on a different day. A peak speed (the first 25 m) and average speed for the first 150 s (speed$_{150s}$) and 180 s (speed$_{180s}$) were also calculated.

**200 m test at CS**

The swimmers were asked to swim at CS for 200 m which was controlled with a tempo trainer (Finis Inc., California, USA) preprogramed to the CS pace. Swimmers were instructed to perform two underwater dolphin kicks off each wall (the breaststroker completed a single pull-out). The stroke parameters and speed were measured in the last three laps. Based on previous findings$^{8-9}$, the SR associated with the closest 50 m time to CS was used as a CSR (SR@CS) and stroke count (SC@CS) estimates. In most swimmers this corresponded to the 3rd or 4th lap,
where swimmers swam within the acceptable margin of the required CS time (0.90 ± 0.77%; 0.36 ± 0.30 s)\(^9\). The SR was measured from three consecutive stroke cycles in the middle section of each lap. The speed derived from the 50 m time closest to CS was also utilised for calculation of SL@CS and SI@CS estimates\(^{11}\):

\[
\text{SL@CS} = \text{speed/SR@CS}.
\]

\[
\text{SI@CS} = \text{speed x SL@CS}.
\]

**Training intervention**

The HIIT based on fractional D’ depletion was prescribed 2 sessions.week\(^{-1}\) and a “HIIT efficiency session” utilising a combination of CS and CSR concepts was prescribed 1 session.week\(^{-1}\). The 5 x 60% and 3 x 80% D’ depletion interval schemes (% D’) were used to determine the target interval time for specific distances and individual swimmers using the following formula\(^{6,12}\):

\[
\text{Interval time} = \frac{\text{[distance-(D’ x % D’)]}}{\text{CS}}
\]

Each interval time was calculated to accumulate a duration of ~3 min (200-250 m) in 60% D’ and ~3.5 min (250-300 m) in 80% D’\(^{12}\). This HIIT was prescribed with a work-to-rest ratio of 1:1 for 60% D’ and 1:1.5 for 80% D’\(^{12}\). In the HIIT efficiency sessions, the swimmers were instructed to complete 10 repetitions of ~2.5 min (150 m or 200 m) at CS with ~30 s rest, whilst swimming with 2 cycles.min\(^{-1}\) (~5-6%) lower SR than SR@CS\(^{13}\). This SR was imposed by a metronome (Tempo Trainer, Finis, California, USA).

To facilitate performance in the main HIIT sets, prior to each main HIIT set, swimmers completed a ~20 min warm-up which included a short HIIT set designed to accumulate ~6 min in the severe domain depleting ~60% of D’, and was followed by ~15-20 min of recovery\(^{14,15}\). Throughout the intervention, the coach was given a pre-programmed prescription sheet that was designed to personalise HIIT sets and warm-ups for individual swimmers and we also worked with the coach to keep total swimming volume ≤ 30 km.week\(^{-1}\) at all times. Throughout the study, volume of training in kilometres (km), number of swimming sessions, and distribution of the volume performed at low-intensity (<CS) and at high-intensity (≥CS) were monitored. Progression in personal best (PB) times for the swimmers’\(^1\)\(^{14,15}\) and 2\(^{nd}\) main events was also monitored. To capture performance changes corresponding to the individual testing time points, performance for 200 m was predicted utilising the following equation\(^{12}\):

\[
\text{Predicted 200 m time} = \frac{\text{distance-D’}}{\text{CS}}
\]

**Statistical analysis**

The investigated variables were log-transformed and effects were adjusted for sex by including a binary covariate in the model. Magnitude-based inferences were used to provide an interpretation of the real-world relevance of the outcomes\(^{16}\). The smallest worthwhile change (SWC) in performance-related variables was 0.3 × coefficient of variation (CV)\(^{17}\). The CV values were obtained from a previous reliability study in the same population\(^7\), or from literature in similar populations\(^{18,19}\). For technique-related parameters, the SWC was defined as a small standardised effect based on Cohen’s effect size principle (0.2 × between-athlete SD). The size of the percentage change was also interpreted by using thresholds for moderate (0.9 x CV), large (1.6 x CV), very large (2.5 x CV) and extremely large effects (4 x CV)\(^{17}\). Threshold values for effect size statistics were >0.2 (small), >0.6 (moderate), >1.2 (large), >2.0 (very large), and >4.0 (extremely large). An effect was deemed ‘unclear’ if the chance that the true value was beneficial was >25%, with odds of benefit relative to odds of harm <66.
Otherwise, the effect was deemed clear, and was qualified with a probabilistic term using the following scale: <0.5%, most unlikely; 0.5-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99.5%, very likely; >99.5%, most likely. For succinctness in the figures, symbols were utilised to illustrate beneficial (√), harmful (×) and trivial (↔) effects. The number of symbols indicate the likelihood for the differences to be substantial, with one symbol referring to possible, two to likely, three to very likely and four to most likely substantial effects. The changes are displayed as means ± 90% confidence limits (CL).

Results

The average total volume and intensity distribution for individual weeks in the investigated season is displayed in the Figure 1. Average total volume swam per week was 20.80 ± 6.52 km, with 15.69 ± 5.39 km (75.31 ± 9.25 % of total volume) undertaken below CS and 5.11 ± 2.24 km (24.69 ± 9.25% of total volume) undertaken at or above CS. On average, swimmers completed 7 ± 1 swimming sessions.week⁻¹. Compliancy to the planned HIIT was 80 ± 12% (24 ± 4 completed of 30 planned sessions).

Insert Figure 1 here

Mean speed-time 3MT profiles for baseline and tests 1-3 are illustrated in the Figure 2. Mean ± SD values, mean ± 90% CL changes with effect size thresholds, and individual changes for the investigated physiological, performance and technical parameters are illustrated in the Figures 3, 4 and 5.

Insert figure 2 here
Insert figure 3 here
Insert figure 4 here
Insert figure 5 here

Discussion

The principal finding of the present study is that HIIT prescribed based on the CS and CSR concepts was associated with beneficial changes in several aspects of swimming performance, despite a reduced training volume during one season. Specifically, the training format was associated with beneficial increases in CS, speed150s, speed180s, SR@CS and SI@CS. Despite a D’ decrease, the changes in modelled 200 m performance and actual competitive performance (PB times) represented beneficial effects in relation to SWC. Changes in SL@CS and SC@CS were trivial, suggesting that the swimmers were able to hold similar SL and SC despite swimming at higher CS. To our knowledge, this is the first study to: 1) implement the CS concept and 3MT for personalised HIIT for an extended period (>4 weeks); 2) implement a combination of CS and CSR concepts for training prescription; 3) explore the parameters related to swimmers’ technical ability at CS (i.e., SR, SL, SI and SC) in response to HIIT.

Overall, a 5.4% (+0.07 m.s⁻¹) seasonal improvement in CS was observed. The greatest proportion of this improvement was observed after the first training block (4.3%; +0.05 m.s⁻¹), after which changes in CS stabilised (test 1-2), before increasing again by 1.1% (+0.02 m.s⁻¹) (tests 2-3). The CS improvement achieved in the first HIIT block is higher compared to Courtright et al.⁹ who utilised 60-80% D’ schemes for 4 weeks (2 days.week⁻¹) and observed an increase of 3.3% (+0.04 m.s⁻¹) in CS of competitive swimmers. The observed CS improvement is also greater compared to the studies of Faude et al.²⁰ and Nugent et al.²¹, who observed 0.7% increase in individual anaerobic threshold and a 1.5% decrease in speed at a fixed blood lactate of 4 mmol.L⁻¹ (speed4MMOL) after 4 and 7 weeks of low-volume, high-
intensity focused programmes in competitive swimmers, respectively. The potential
equation for the greater CS increase in the present study could be related to the HIIT design.
In contrast to the aforementioned studies, we adjusted distance interval to allow each swimmer
to work for greater durations (~3-3.5 min) which were previously recommended for CS and
VO₂MAX improvement and to account for the time required to achieve and accumulate time at
VO₂MAX (T@VO₂MAX) \(^{12,22}\). In addition to this, the swimmers in the present study completed a
HIIT warm-up set prior to the main HIIT set. We had no access to VO₂ measurements to
demonstrate T@VO₂MAX, key for evoking adaptations, however, considering that shorter
intervals might not allow as great T@VO₂MAX as longer intervals \(^{22,23}\) and effect of HIIT warm-
up on T@VO₂MAX \(^{14,22}\), the intervention designed in the present study potentially allowed the
recruited swimmers to accumulate more T@VO₂MAX, which could have allowed for greater CS
improvement. In relation to the seasonal improvement, the observed CS improvement is greater
compared to studies that have explored changes in CS (2.8-4.3\%) \(^{24-25}\) and speed\(_{4\text{MMOL}}\) (1.5-
2.2\%) \(^{26}\) over an extended period (12-26 weeks) in competitive swimmers, who however
completed substantially greater training volumes compared to the present study (40-60
km.week\(^{-1}\)).

An increase in CS was accompanied by a seasonal D’ reduction of 25\% (-4.7 m). The greatest
proportion of this decrease occurred after the first intervention block (-3.9 m; -26\%), after
which D’ remained below baseline values. This is consistent with the findings of Courtright et
al.\(^{6}\) and Clark et al.\(^{4}\) who observed 16\% (-3.5 m) and 11\% (-24 m) D’ reduction in swimmers
and soccer players completing similar HIIT, respectively. The greater D’ decrease in the present
study could be related to the design of longer HIIT intervals, which may have increased CS at
the expense of D’ \(^{12}\). Clark et al.\(^{4}\) suggested that to increase D’, intervals of less than 2 min
performed at intensity exceeding 130\% VO₂MAX should be applied. Indeed, supramaximal
interval training has been previously shown to increase D’/W’ \(^{25,27}\). Similarly to D’, peak speed
was below baseline values in test 1 (-0.9\%; -0.01 m.s\(^{-1}\)) and test 2 (-0.7\%; -0.01 m.s\(^{-1}\)) before it
returned to the baseline values at the end of the intervention. Therefore, our results suggest that
whilst the present intervention benefited CS this was at the expense of D’ and temporarily peak
speed.

The present intervention allowed for a beneficial increase in SR@CS (6\%) and SI@CS (4\%)
whilst changes in SL@CS and SC@CS exhibited only trivial changes. To our knowledge, no
previous studies have assessed the impact of HIIT on technical parameters at CS. Anderson et
al.\(^{26}\) observed a 2-4\% increase in SR\(_{4\text{MMOL}}\), which was accompanied by a corresponding
decrease in SL\(_{4\text{MMOL}}\) in national and international swimmers, who however engaged in high-
volume training. Accumulating evidence suggests that intensity rather than volume may play a
key role in eliciting performance changes in highly-trained swimmers including those related
to technique \(^{28}\). Termin and Pendergast \(^{29}\) observed a shift in the SR-speed relationship so the
swimmers engaging in a HIIT focused programme were able to swim with greater SL, SR and
with lower energy cost at a range of velocities, whilst the recent study of Nugent et al.\(^{21}\)
reported compromised SL and SI in 50 m freestyle time trial of swimmers who engaged in
high-volume, low-intensity focused programme for 7 weeks, with no clear change being found
in the same parameters of the swimmers who completed lower-volume, higher-intensity
programme for the same period. Therefore, perhaps the present HIIT format in which
swimmers spent time adopting and optimising stroke mechanics at intensities close to race-
pace, could have allowed the swimmers to develop a capacity to maintain similar SL/SC despite
swimming at greater CS in subsequent tests, as demonstrated through ~4\% increase in SI@CS.

The recruited squad of swimmers improved their predicted 200 m time by 2.7\% and their PB
times for 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) main events improved by 1.2\% and 1.6\%, respectively. The PB
improvement for the 2nd event represented greater and clearer magnitude of improvement compared to the 1st event, which is perhaps due to greater room for improvement in this event. This magnitude of improvement is in contrast with studies that employed lower-volume, higher-intensity focused strategies in similar populations and found smaller and non-significant performance improvements \(^{3,20,21}\), with exception of Termin and Pendergast\(^{39}\) who observed ~2.3% yearly performance improvements in national swimmers engaging in this training format for 4 years. The magnitude of improvement is also similar to typical yearly performance improvements in similar population of swimmers specialising in similar distances (i.e., ~1.8% in 100 and 400 m; ~1.3% in 200 m)\(^{30}\). In addition to this, compared to the performance improvements observed in the same swimmers and events in the season prior to the intervention (i.e. long-course season) (1st event: -1.0±0.9 %; 2nd event: -0.7±0.8 %), the PB improvement achieved in this study is similar to that achieved in the 1st event and ~2-fold greater in the 2nd main event. Consequently, despite being implemented for shorter time (3.5 months) and with lower volume, the present intervention was associated with: 1) similar PB improvements compared to those typically achieved by similarly-aged and trained swimmers in a year; and 2) improvements similar (1st event) and greater (2nd event) compared to those observed in the season prior to the beginning of the intervention in the same swimmers.

**Practical applications**

The present study extended the 3MT’s utility such that the derived parameters can be used to regularly monitor progress as well as to prescribe HIIT specific to swimmer’s physiological and technical capacities in the given stroke. Compared to the methods typically utilised by coaches, the investigated methods consider both the individual’s aerobic capacity (CS), and capacity to work above CS (D’) in HIIT design, allowing swimmers to complete similar work and recovery, regardless of stroke specialty or performance level. The approaches utilised in the present study require feasible resources, time and expertise and the prescribed HIIT times and SR can be imposed by affordable tempo trainers, allowing the coaches to observe technique and give more frequent feedback to swimmers. The feasible methodology utilised in the present study can also allow coaches to test multiple strokes in swimmers specialising in individual medley, in order to optimise progression in this event.

This study also demonstrates that lower volumes prescribed did not limit positive changes in the several performance aspects of highly-trained swimmers. Therefore, this strategy may also reduce the risk of overuse injuries, early specialisation, and burnout or drop-out, which were previously associated with the high-volume demands that traditional swimming training can pose on swimmers \(^3\). The present study might also provide a strategy for coaches striving to deliver effective sessions despite limited pool time. Further research examining the application and the effects of the investigated approaches (i.e., CS and CSR concepts) on performance, physiological and technical parameters for consecutive seasons and in different levels of swimmers would be useful to confirm the utility of this training strategy across a wider spectrum of swimmers (elite vs. youth) and coaches. Finally, the omission of a control group represents a limitation to this study and therefore, future research studies should investigate the discussed approaches alongside other approaches traditionally utilised by swimming coaches.

**Conclusion**

In conclusion, the present study demonstrated that HIIT prescribed based on CS and CSR concepts for 3 days.week\(^{-1}\) for one season was associated with meaningful beneficial changes in several physiological, technical, and performance parameters in highly-trained swimmers who completed a reduced training volume. The feasible approach associated with testing and application of these concepts in training represents a promising start for the improved
prescription and monitoring of swimming training, whilst also potentially reducing the risk of overuse injuries, burnout or early specialisation in swimmers.

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References


**Figure captions**

**Figure 1.** Average total volume and intensity distribution during a 15-week intervention period. The error bars represent standard deviations.

**Figure 2.** Mean speed-time profiles for the 3-min all-out tests for baseline and tests 1-3.

**Figure 3.** Changes in critical speed (A), D' (B), speed_{150s} (C) and speed_{180s} (D) from baseline to tests 1-3. Data are presented as means ± 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects. The symbols illustrate beneficial (✓), harmful (✗) and trivial (↔) effects. The number of symbols indicate the likelihood for the differences to be substantial, with one symbol referring to possible, two to likely, three to very likely and four to most likely substantial effects.

**Figure 4.** Changes in peak speed (A) and predicted 200 m time (B) from baseline to tests 1-3, and in PBs for 1st (C) and 2nd main event (D). Data are presented as means ± 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects. The symbols illustrate beneficial (✓), harmful (✗) and trivial (↔) effects. The number of symbols indicate the likelihood for the differences to be substantial, with one symbol referring to possible, two to likely, three to very likely and four to most likely substantial effects.

**Figure 5.** Changes in stroke length (A), stroke index (B), stroke rate (C) and stroke count (D) adopted at critical speed from baseline to tests 1-3. Data are presented as means ± 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects. The symbols illustrate beneficial (✓), harmful (✗) and trivial (↔) effects. The number of symbols indicate the likelihood for the differences to be substantial, with one symbol referring to possible, two to likely, three to very likely and four to most likely substantial effects.

**Table captions**

**Table 1.** General and performance characteristics of the recruited competitive swimmers.