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Original Research

Monitoring Interval-training Responses for Swimming using the 3-min All-out Exercise Test

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ABSTRACT

International Journal of Exercise Science 9(5): 545-553, 2016. The purpose of this study was to determine whether the 3-min all-out exercise test (3MT) could be applied to create an off-season high intensity, interval training (HIIT) program to improve performance, specifically critical velocity (*CV*), in the sport of swimming. We tested a group of competitive female swimmers (age = 19 ± 1 yrs, height = 169 ± 7 cm, body mass = 69 ± 9 kg) to determine their swimming *CV* and finite energy capacity >*CV* (*D′*), and created a four week (2 $d \cdot wk^{-1}$) personalized interval training program. Participants were divided in to two groups, a 150yd interval group (n =11) and a 250yd interval group (n =6). Each group completed a series of intervals designed to deplete a given percentage of *D′* at velocities exceeding *CV*. A 3MT following the training period was administered to assess for any changes in *CV*, *D′*, average velocity during the first 150s of the test (V_{150s}) and total distance traveled (*D*). Both groups improved their *CV* (+0.04 $m \cdot s^{-1}$), V_{150s} (+0.03 $m \cdot s^{-1}$) and *D* (+8.64 m) ($p < 0.05$), however, significant interactions for *D′* between groups was not observed ($p > 0.05$). We conclude that HIIT prescriptions based on a 3MT can improve swim performance over a four-week period. Future research on the fidelity of measuring *CV* and *D′* using a swimming 3MT is needed to help aid practitioners in interpreting true training adaptations.

KEY WORDS: Anaerobic capacity, critical velocity, high intensity interval training

INTRODUCTION

The critical velocity (*CV*) concept explains the limits of high intensity athletic performance by identifying two key components; *CV* and the finite capacity exceeding *CV* (*D′*) (12). The metric of *CV* is purported to represent the limit of aerobic energy, or the maximal oxygen uptake (VO_2) steady state (4). Exercise bouts exceeding *CV* will evoke a VO_2 slow component that can cause the attainment of maximal VO_2 (VO_{2max}) (3).

The capacity for exercise above *CV* threshold is finite (*D′*) and reflective of a combination of aerobic and anaerobic energy systems, the depletion of which can be plotted as a hyperbolic relationship between work above *CV* and time (11). Several models exist to test and predict athletic performance in rhythmic aerobic exercise using *CV* (i.e., running, cycling and swimming) (8, 9, 10, 12). Historically, testing protocols for determining *CV* and *D′* have consisted of ≥ 3 exercise bouts to determine time to exhaustion (t_{lim}) at varying work rates (10). An asymptotic curve is constructed plotting workload and t_{lim}, which is used to predict performance.

The *CV* concept was first applied to the sport of competitive swimming in 1992 (17). These researchers plotted swimming distances (*y*-axis) relative to the swimming times for each distance (*x*-axis), whereby linear regression was used subsequently to determine *CV* (slope) and *D′* (*y*-intercept). Recently a 3-min all-out exercise test (3MT) was conceived which enables the determination of *CV* and *D′* from a single exercise bout. The 3MT was introduced for cycle ergometry and later for running (14,16). The 3MT protocol requires a subject to exercise in an all-out effort for 180s (6). The all-out effort is sufficient to fully deplete a subject's *D′* within 150s resulting in an average velocity for the final 30s that corresponds to *CV* (11).

Although the *CV* model has been applied in the sport of competitive swimming the 3MT protocol has not. Wakayoshi et al. (17) noted a decrease in swimming velocity and distance traveled per stroke throughout the course of subjects' bouts, which we believe to be characteristic of the decrease in velocity over time seen in the 3MT running protocol. Specifically faster velocities are observed for short distances and lower velocities for longer distances with the relationship of velocities relative to distances being hyperbolic; however, the relationship between total distance and time is linear. Using a 3MT, the curvature constant relative for velocities exceeding *CV* can be estimated to model competitive times for a wide range of distances (14). Based on this observation we believe a swimming 3MT protocol could be utilized in a similar manner as running or cycling 3MT (4, 6).

Clark et al. assigned subjects to two groups (2 and 5-min intervals). Each group completed 7 HIIT sessions over a 4-wk period (2 $d \cdot wk^{-1}$) resulting in improvements in *CV*. In addition, researchers observed heart rate (HR) data that demonstrated progressively increased end-exercise HR after each successive interval. After four weeks both groups demonstrated increases in *CV* and decreases in *D′* (7). Based on the results observed by Clark et al. (7), our hypothesis was that a similar training method should improve *CV* and swimming performance in collegiate swimmers. Therefore the purposes of this study were to determine whether a 3MT protocol can be applied to swimming and determine the effectiveness of prescribe training intervals to increase *CV* in collegiate swimmers.

METHODS

Participants

A sample of 17 participants from a National Collegiate Athletic Association (NCAA) Division II Women's Swim and Diving program (age = 19 ± 1 yrs, height = 169 ± 7 cm, mass = 69 ± 9 kg) were tested. Participants were divided into short or long distance interval groups based on event specialization. In addition to HIIT all participants engaged in a team strength and conditioning program three days per week as well as regular team practice involving swimming skills in the pool. Prior to the first session, all participants read and signed an informed consent document. Our Institutional Review Board for research previously approved the procedures of this study.

Protocol

A group of competitive female swimmers completed a 3MT training program based on the parameters of a similar study involving female collegiate soccer players in which running 3MTs were completed using video digitization to track the subject's self-paced velocity over time on an indoor running surface (7). Distance at 150s and 180s were recorded (D_{150s} and D_{180s}) and used to calculate *CV* and *D′* using the following formulas (14):

$CV(\text{m}\cdot\text{s}^{-1}) = (D_{180}\text{-}D_{150})/\ 30\text{s},$ and [a]

$D'(\text{m}) = [150\text{s} \times (D_{150}/150\text{s})\text{-CV})].$ [b]

Researchers successfully used data from the 3MT tests to prescribe high intensity, individualized training intervals designed to deplete a given percentage of an athlete's *D′* over a specific distance or time (7). Individual interval velocity and total time to deplete a certain percentage of *D′* were determined using the formula (7):

$Int_t = [D\text{-}(D' \text{xInt}\%)]/CV,$ [c]

where Int_t is the interval time in seconds, D is distance in meters, Int% is the percentage of *D′* depleted during the given interval and *CV* is velocity in meters per second. We created a 4 week HIIT program using *CV* and *D′* parameters determined from a swimming 3MT. All participants completed this program.

To estimate how the model compared to actual performance the model time for a competitive distance was determined using the following formula (14):

$\text{Time} = (D\text{-}D')/CV,$ [d]

where the *CV* and *D′* were estimated from the pre test 3MT. Personal best from official times of the preceding season were used as the criterion measure.

Participants completed a pre and post-test 3MT in a 25-yard pool. 3MT bouts were recorded using digital video recording devices (Flip Video San Francisco, CA, USA, Go Pro Hero 3, San Mateo, CA, USA). Start and end times were monitored poolside with a stopwatch (Accusplit, Pleasanton, CA, USA). Fluorescent cones were placed parallel to the swimmer's lane at 5, 10, 15, 20 and 23m along the pool deck as waypoints to enable calculating split times from the digital video recording. As the swimmer's head was visualized passing the cone a split time was recorded from the digital video. Telemetry heart rate monitor values also were recorded with either Polar T31-CODED or EKHO chest strap HR monitors (Polar Electro Inc., Lake Success, NY, USA). Subjects participated in their own one-piece swimsuits, swim caps and goggles. Subjects were instructed to swim at an “all-out” intensity throughout the entire test (i.e. as fast as they could possibly swim at any given moment). These instructions are important to undermine the typical pacing strategy employed by many endurance athletes, which would confound results of this particular test. Subjects were filmed from an elevated vantage point from the opposite end of the pool house via a tripod-mounted camera. Immediately following each bout researchers recorded HR. Commercial video editing software (Windows Live Movie Maker, Redmond, WA, USA) was used to determine displacement (m) and velocity ($m \cdot s^{-1}$) at each cone along the pool deck (5, 10, 15, 20 and 23m). Average displacement (m) was interpolated at 150s and 180s. *CV* and *D′* were determined using Eqn. a. and Eqn. b.

Subjects completed 8 sessions of HIIT over a 4 week period at a frequency of 2 $d \cdot wk^{-1}$ separated by 1 day of rest. Subjects were placed in either a short interval (137.16 m) (n=11) or long interval (228.6 m) (n=6) group based on typical event participation. Subjects in the short group consisted of swimmers who competed in freestyle events ≤ 200yds while the long group competed in events ≥ 500 yds. Individual intervals were created for each subject to deplete a specific percentage of their *D′* per interval using Eqn. c where *D* is equal to either 137.16m or 228.6m depending on group placement. In order to prescribe intervals in a 25-yard pool all distances were converted to m.

Interval training sessions consisted of 5 x 60%, 4 x 70% or 3 x 80% intervals (7) (Table 1). For example, a swimmer’s fastest time for 150 yd (137.16 m) might be 97.63 s. Using equation d, we resolve the *CV* and *D′* as 1.2 $m \cdot s^{-1}$ and 20 m, respectively (i.e., 97.63 s = (137.16 m – 20 m)/1.2 $m \cdot s^{-1}$). Their 60% *D′* interval using equation d would entail swimming 150 yd intervals with a time of 104.3 s (i.e., 137.16 m – 12 m)/1.2 $m \cdot s^{-1}$). A period of 5 minutes was provided for relief intervals; therefore, the work to rest ratio was higher for the short group. Subjects’ HR were recorded immediately following each interval.

Table 1. HIIT schedule.

	Week 1		Week 2		Week 3		Week 4	
	Tuesday	Thursday	Tuesday	Thursday	Tuesday	Thursday	Tuesday	Thursday
D′ Depletion	60%	60%	70%	70%	70%	80%	80%	80%
Short Group	5 x 150yd	5 x 150yd	4 x 150yd	4 x 150yd	4 x 150yd	3 x 150yd	3 x 150yd	3 x 150yd
Long Group	5 x 250yd	5 x 250yd	4 x 250yd	4 x 250yd	4 x 250yd	3 x 250yd	3 x 250yd	3 x 250yd

D′ depletion expressed as percentage of total *D′*.

We compared predicted performance using *CV* and *D′* from post-test swimming 3MTs to top times from freestyle events from the previous competitive season. Data was available for 10 races that fell within the limits of this model (500 and 1650 yds·race^{-1}) from 6 participants. Differences between actual and predicted times are reported as a percentage error, where $3MT_t$ is predicted performance for a given distance calculated using Eqn. d and Act_t is the actual top time for said distance.

Statistical Analysis

Pre and post-testing comparisons for *CV*, *D′*, V_{150s} and total *D* were evaluated with a series of paired t-tests. Rank-ordering at pre and post-testing was evaluated using Pearson-product moment correlation coefficients. Descriptive statistics are reported as mean ± SD along with effect size (ES) differences from pre to post-testing calculated using Cohen's d (mean difference divided by pooled SD). Statistical significance was accepted at $p < 0.05$.

RESULTS

The 4-wk training regimen evoked an improvement in *CV* (t = 2.26, p = 0.038, ES = 0.53). There was a small decline in *D′*; however, that result did not achieve statistical significance (t = 0.97, p = 0.346, ES = -0.32). Further, both V_{150s} (t = 4.09, p = 0.001, ES = 0.36) and total *D* (t = 6.68, p < 0.001, ES = 0.71) improved. A summary of these 3MT results appears in Table 2. The V_{150s} and total *D* metrics maintained rank ordering whereas rank ordering was moderate for *CV* and poor for *D′* (Table 3). Graphic representations of the pre and posttests were similar to those from running and cycling 3MT studies, with the exception of increases in velocity associated with each flip turn. Figure 1 illustrates the shift in performance from pre to post testing for a representative subject.

The HR data collected following each interval (Figure 2.) demonstrated an increase in metabolic response per interval as seen in previous studies. This HR response, seen in Figure 2, is indicative of the values associated with aerobic interval training. Finally in Table 4, we report the accuracy of the ability of the 3MT to predict race times using formula [d].

Table 2. Results of the 3-min all-out exercise tests.

	Short Distance Group (n = 11)			Long Distance Group (n = 6)			Total Team (n = 17)		
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES
CV (m·s^{-1})	1.16 ± 0.10	1.22 ± .07	+0.71	1.28 ± 0.71	1.31 ± 0.05	+0.08	1.21 ± 0.11	1.25 ± 0.08	+0.53*
D′ (m)	26.34 ± 14.38	21.07 ± 8.50	-0.46	13.47 ± 7.16	13.19 ± 5.34	-0.04	21.80 ± 13.62	18.29 ± 8.31	-0.32
V_{150s} (m·s^{-1})	1.34 ± 0.08	1.36 ± 0.07	+0.27	1.38 ± 0.03	1.40 ± 0.03	+0.67	1.35 ± 0.07	1.38 ± 0.06	+0.36*
Total Distance	225.73 ± 12.27	234.91 ± 12.69	+0.74	238.50 ± 4.51	246.17 ± 9.70	+1.08	230.24 ± 11.83	238.88 ± 12.68	+0.71*

V_{150s} = average velocity during the first 150s of the 3MT; *CV* = average velocity during the final 30 s of the 3MT; *D′* represents displacement capacity above *CV*. Effect size (ES) values were calculated using Cohen's d. *Significant pre/post differences (p < 0.05).

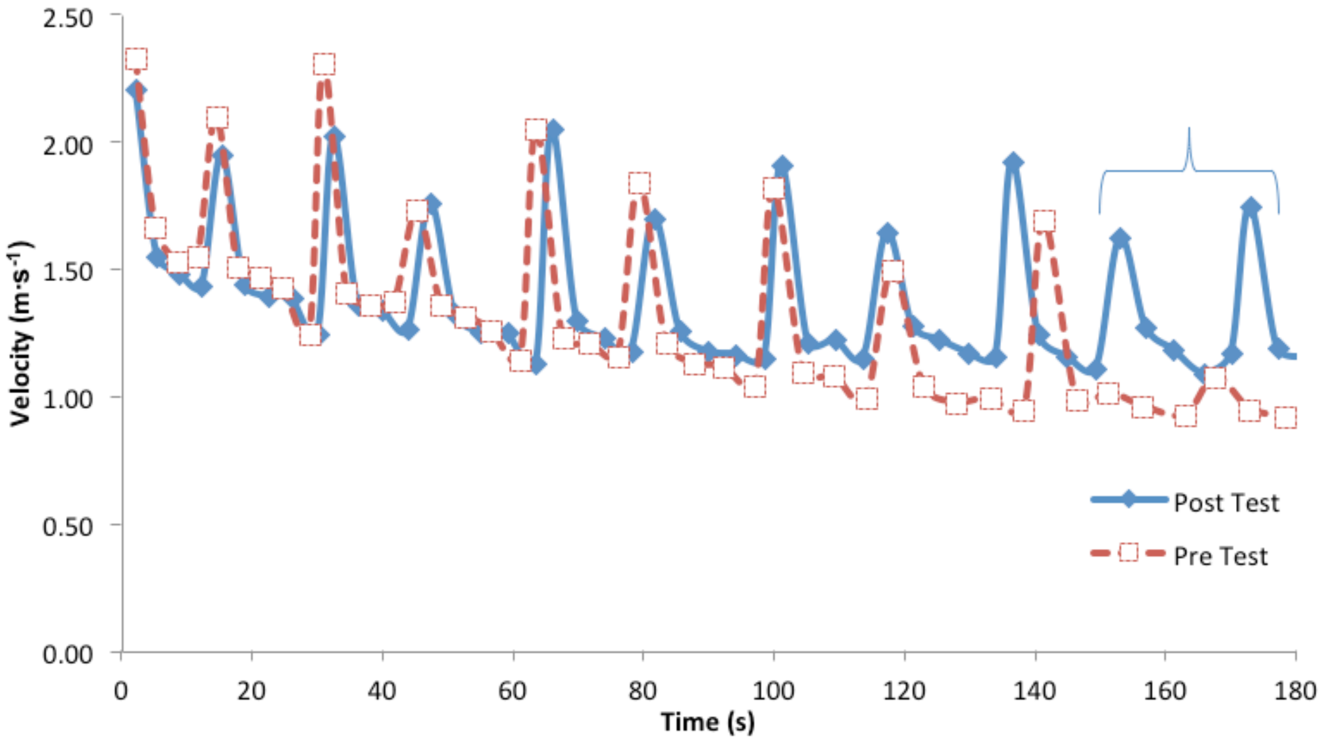

Figure 1. Depletion in velocity over time for a representative subject during a 3MT during pre and post testing. Note the increase in critical velocity during the final 30s of the posttest.

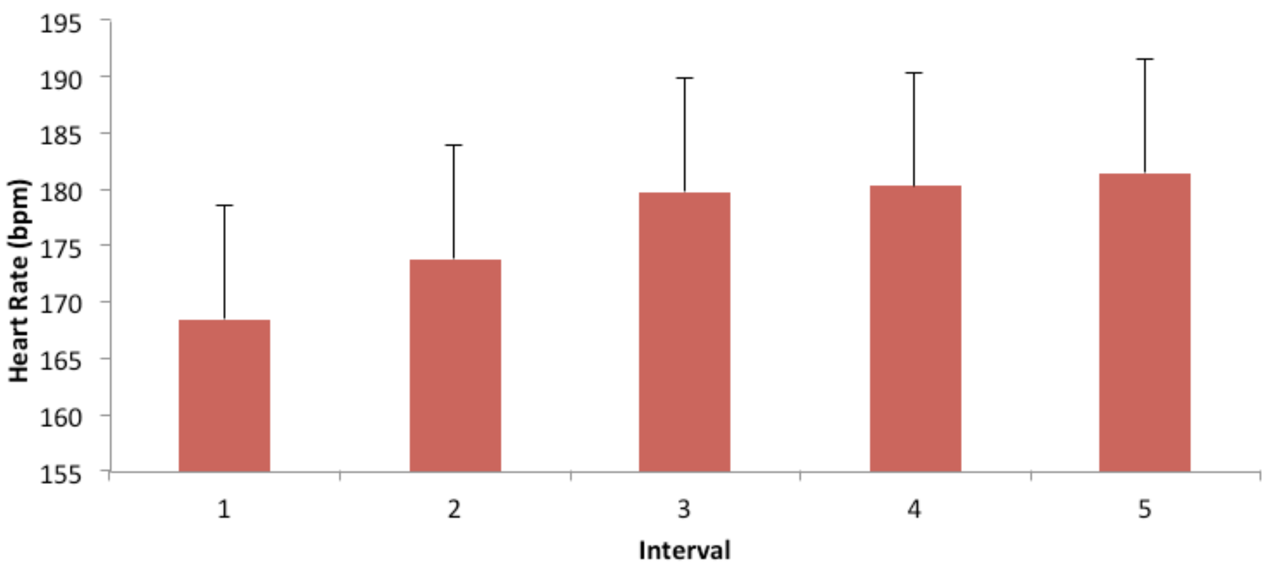

Figure 2. End-exercise HR (mean ± SD) responses between both groups (n = 17) during HIIT to deplete 60% of *D′* per interval.

Table 3. Rank Ordering of Metrics from the 3-min All-out Exercise Test between Pre and Post-Testing

Metric	R-value	p-value
CV	0.57	0.017
D'	0.14	0.585*
$V_{150\,s}$	0.93	< 0.01
Total *D*	0.91	< 0.01

*Not significant

Table 4. Percent Error for Predicted Swim Times Using *CV* and *D′*

Distance (yds)	Actual Time (s)	Predicted Time (s)	Average % Error
500	326 ± 21	351 ± 17	7.6 ± 0.02
1650	1125 ± 71	1172 ± 56	4.3 ± 0.05

DISCUSSION

The results from this study suggest that HIIT prescribed using a 3MT can be effective for improving performance in trained swimmers over a four-week period. The increase in *CV* and decrease in *D′* observed following the training program was consistent with previous research concerning HIIT derived from a 3MT with trained athletes (7). The athletes spent more time in the severe domain of exercise during the HIIT training that would contribute to the increase in *CV* (4,11,13). The magnitude of improvement observed in total *D* represents a significant competitive advantage, with participants traveling roughly five body lengths (8 meters) further in the given time limit during the post-test. This improvement becomes even more significant given the HIIT method's low volume (900-3000 $yds{\cdot}wk^{-1}$) and time efficient nature (40-60 $min{\cdot}wk^{-1}$) relative to typical training methods.

Although this is the first paper to report swimming *CV* and *D′* measured via the 3MT, our mean and SD data are comparable to values derived using the linear distance-time model (17). In our sample, *D′* represented 9% of the total distance covered in 180s. That result compares well with data collected on distance runners of similar competitive status (i.e., NCAA Division II) (14). These distance runners had a *CV* of 4.4 $m{\cdot}s^{-1}$ and a *D′* of 85m. By reversing the math for solving *CV* and *D′* with the 3MT, we determined *D′* contributed 11% to the total distance traveled. The stop-start nature and flip turns may account for the subtle differences in the contribution of *D′* to total performance. There are marked similarities between the present study and research on HIIT with running (7). Firstly, as the athletes completed their respective intervals, HR was observed to climb higher during each subsequent interval (Figure 2). Secondly, in comparing each metric from pre to post testing significance was observed for *CV*, V150s and total D. Conversely, there was considerable shifting in rank order for *D′* (Table 3).
In many respects the sport of swimming is similar to other sports for which a 3MT has been validated. It is rhythmic and repetitive in nature, and allows for the use of aerobic and anaerobic energy pathways for extended periods of time. However, the results from this test are specific to the stroke, and pool length in which it was performed. For instance, an athlete's *CV* and *D′* measured during a 3MT in which they performed the freestyle stroke cannot be used to prescribe intervals for a backstroke.

Examination of the data confirmed that participants accelerated following each flip turn and decelerated throughout each length of the pool during the test, as seen in Figure 1. The corresponding peaks associated with each turn decrease over time producing an augmented, but predictable, *V-t* curve that can be used to prescribe training intervals. Due to the sharp increase in *V* following each flip turn, and its subsequent contribution to measured *CV* and *D′*, we recommend that testing and interval training take place in the same length pool. Completion of a 3MT in a longer pool in which athletes complete fewer flip turns throughout the test would likely result in lower *CV* and *D′* relative to the same athlete completing a 3MT in a shorter pool where more flip turns were performed. Completing a 3MT in a longer pool, or open water will more accurately reflect the critical swimming speed of a specific stroke, but may not be as relevant for athletes who compete in shorter pools.

Given that a wide array of overuse injuries in the shoulder are common in the sport of swimming this lower volume approach to training with increased emphasis on proper stroke mechanics may have some benefit for injury prevention, depending on the specific mechanism of injury (2). The total distance for a given training session during our study was 450-1500 yds while still requiring a great enough metabolic demand to evoke an increase in performance.
It should be noted that this test is only suitable for experienced swimmers due to the significant contribution of stroke mechanics to propulsion in the water. Although improved athleticism can mediate improvements in swim performance, factors such as stroke technique and minimization of drag have a significant impact on swimming speed (15). Inexperienced swimmers would be likely unable to preserve optimal mechanics during an all-out effort to the same degree as those with more experience.

Further research is needed to determine the reliability and validity of the 3MT model for measuring *CV* and *D′* in swimming. The use of an "Endless Pool" could allow for easier collection of swimming specific VO_2 data for a specific velocity however, such a method would not be conducive for the 3MT. To better understand the specific adaptations from this type of training it could be beneficial to regulate strokes per minute during interval training. Researchers have demonstrated how lower RPMs for a given power output in cycling translates to increased mechanical efficiency (5). Measurement of stroke rate during the first 150s and final 30s of the 3MT could provide insight into the nature of an individual athlete's improvement (i.e. did the athlete travel further per stroke or complete more strokes) and its subsequent implications for mechanical efficiency during swimming.

The swimming 3MT appears to be a suitable method of prescribing HIIT and assessing changes to *CV* and *D′*. Using this method, athletes are able to train with low volume yet benefit from improvements in *CV*, which may aid in the prevention of overuse injuries. The reader is cautioned to apply the results of the 3MT to the specific pool dimensions for which the interval training will take place.

REFERENCES

1. Billat LV. Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part II: anaerobic interval training. Sports Med 31(2):75-90, 2001.

2. Brushøj C, Bak K, Johannsen H, Faunø P. Swimmers' painful shoulder arthroscopic findings and return rate to sports. Scand J Med Sci Spor 17(4):373-7, 2007.

3. Burnley M, Doust JH, Vanhatalo A. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. Med Sci Sports Exerc 38(11):1995-2003, 2006.

4. Burnley M, Jones AM. Oxygen uptake kinetics as determinant of sports performance. Eur J Sport Sci 7(2):63-79, 2007.

5. Chavarren J, Calbet J. Cycling efficiency and pedalling frequency in road cyclists. Eur J Appl Physiol Occup Physiol 80(6):555-63, 1999.

6. Clark IE, Murray SR, Pettitt RW. Alternative procedures for the 3-min all-out exercise test. J Strength Cond Res 27:2444-48, 2013.

7. Clark IE, West BM, Reynolds SK, Murray SR, Pettitt RW. Applying the critical velocity model for an off-season interval training program. J Strength Cond Res 27(12):3335-41, 2013.

8. Dekerle J. The use of critical velocity in swimming. A place for critical stroke rate. Port J Sport Sci 6(2):201-5, 2006.

9. Dekerle J, Brickley G, Sidney M, Pelayo P. Application of the critical power concept in swimming. Port J Sport Sci 6(2):121-4, 2006.

10. Johnson TM, Sexton PJ, Placek AM, Murray SR, Pettitt RW. Reliability analysis of the 3-min all-out exercise test for cycle ergometry. Med Sci Sports Exerc 43(12):2375-80, 2011.

11. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: implications for the determination of VO2 max and exercise tolerance. Med Sci Sports Exerc 42:1876-90, 2010.

12. Kolbe T, Dennis SC, Selley E, Noakes TD, Lambert MI. The relationship between critical power and running performance. J Sports Sci 13(3):265-9, 1995.

13. Pettitt RW, Clark IE. High-Intensity Exercise Tolerance: An Update on Bioenergetics and Assessment. Strength Cond J 35(2):11-6, 2013.

14. Pettitt RW, Jamnick N, Clark IE. 3-min all-out exercise test for running. Int J Sports Med 33(6):426-31, 2012.

15. Toussaint H, Truijens M. Biomechanical aspects of peak performance in human swimming. Anim Bio 55(1):17-40, 2005.

16. Vanhatalo A, Doust JH, Burnley M. Determination of critical power using a 3-min all-out cycling test. Med Sci Sports Exerc 39(3):548-55, 2007.

17. Wakayoshi K, Yoshida T, Kasai T, Moritani T, Mutoh Y, Miyashita M. Validity of critical velocity as swimming fatigue threshold in the competitive swimmer. Ann Physiol Anthropol 11(3):301-7, 1992.