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Muscular fatigue when swimming intermittently above and below critical speed

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ABSTRACT

Purpose: To examine muscular fatigue of the shoulder's internal rotators alongside swimming biomechanics during long-duration sub-maximal swimming sets performed within two different speed domains. **Methods**: Eight trained swimmers (mean ± SD 20.5 ± 0.9 years, 173 ± 10 cm, 71.3 ± 10.0 kg) raced over three distances (200, 400, 800-m races) for determination of Critical Speed (CS; slope of the *d-t* relationship). Following a familiarisation to muscular isokinetic testing, they subsequently randomly performed two constant-speed efforts (6 x 5-min blocks; 2.5-min recovery) 5% above (T_{105}) and 5% below CS (T_{95}) with Maximal Voluntary Contractions recorded in-between swimming blocks. **Results**: Capillary blood lactate concentration ([La]), RPE, peak torque, stroke length and stroke rate were maintained throughout T_{95} ($P<0.05$). [La], RPE and stroke rate increased alongside concomitant decreases in maximal torque and stroke length during T_{105} ($P<0.05$) with incapacity for the swimmers to maintain the pace for longer than ~20 minutes. For T_{105}, changes in maximal torque (35.0 ± 14.9 to 25.8 ± 12.1 N.m) and in stroke length (2.66 ± 0.36 to 2.23 ± 0.24 m.cycle^{-1}) were significantly correlated (r=0.47, P<0.05).**Conclusion**: While both muscular fatigue (shoulder's internal rotators) and task failure occur when swimming at a pace greater than CS, the 2.5-min recovery period during the sub-CS set possibly alleviated the development of muscular fatigue, for the pace to be sustainable for 6 x 5 min at 95% of CS. A causal relationship between reduction in stroke length and loss of muscular strength should be considered very cautiously in swimming.

KEY WORDS

Endurance, distance-time relationship, injury, critical power

INTRODUCTION

Both internal and external rotators of the shoulders provide stabilisation and mobility of the glenohumeral joint,[1] critical in swimming. A high percentage of training is completed in front crawl [53% in elite swimmers][2] where the shoulder avoids a true impingement position of forward flexion with internal rotation and horizontal adduction.[3] With muscular fatigue affecting the stroke technique,[4] and since poor stroke mechanics is recognised as a key etiological factor associated with the symptoms of the swimmer's shoulder,[3] the process of designing training programmes would benefit from a deeper understanding of the development of muscular fatigue during swimming sets of long duration, changes in swimming technique, focusing on the shoulder's internal rotators in particular.

Muscular fatigue is defined as an exercise-induced reversible decrease in maximal force production [5] so that its direct measurement requires for peak torque during maximal voluntary contraction (MVC) to be measured prior and following exercise. Some investigations of muscular fatigue in swimming reports the use of isokinetic dynamometers to ensure validity and reliability in torque measurement.[4,6,7] Non angle-dependent decreases in peak torque have been evidenced during isometric MVCs performed post a 4 x 50-m [shoulder's flexion][8,9] and a 200-m all-out front crawl effort [shoulder's internal rotators;[10] elbow extensors and flexors at 30° of flexion][4], evidencing the development of muscular fatigue during short-duration, high-speed swims. Studies measuring electromyographic responses during 200-m all-out front crawl swims have also reported increases in the electromyographic activities of upper-limb muscles including the shoulders' internal rotators such as the pectoralis major as fatigue develops.[11] This was suggested to reflect the recruitment of additional motor units in an attempt to maintain the swimming speed as fatigue developed within the already-recruited muscle fibers.[9,12]

According to Taylor and Gandevia,[13] muscular fatigue can be attributed to mechanisms of peripheral (at or distal to the neuromuscular junction) or central origin (proximal to the neuromuscular junction) with a much higher rate of overall and peripheral fatigue developing when exercising above a critical threshold.[14] Indeed, the extent to which peripheral, central and overall fatigue develops is intensity-dependent during single muscle group work (knee extensors).[14] This critical threshold has been identified as critical torque, the asymptote of the hyperbolic relationship relating torque and time to failure for a single muscle action. The authors[14] demonstrated that repeated muscular contractions above critical torque cannot be sustained and lead to the development peripheral, central and overall fatigue, the latter illustrated by a loss of peak torque measured post-exercise when compared to pre-exercise MVC.[14] Conversely, repeated muscular contractions below critical torque can be sustained (60 minutes) despite a mild development of peripheral and central fatigue.[14]

Critical torque is one of many applications of the Critical Power concept.[15] Applied to swimming, the concept offers for two distinct swimming speed domains to be characterised by different physiological and mechanical characteristics.[16] While increases in capillary blood lactate concentration ([La]), oxygen uptake and RPE can be observed when swimming above or at Critical Speed (CS), steady states in these physiological and perceptual variables have been reported below CS.[16] Like critical torque, CS is represented by an asymptote, but the asymptote of the relationship relating swimming speed - and not torque – to time to exhaustion (Figure 1).[17] CS can equally be represented by the slope of the linear distance – time relationship plotted from several maximal performances.[18] The ease in the CS determination made this method of assessment of aerobic capacity[19] particularly attractive in the swimming world.

A better understanding of the potentially intensity-dependent muscular stress caused by long-duration swimming sets, should help coaches optimising training programmes to maximise training adaptations, while avoiding non-functional overreaching, as well as shoulder's overuse or abuse.[3] This could also support medical practitioners when investigating the etiology of shoulder's pain in swimmers. The aims of this study were therefore (1) to ascertain whether swimmers lose muscular strength, and therefore muscular fatigue occurs when swimming above CS; and (2) to explore potential explanations for the reduction in stroke length when swimming within the severe intensity domain. We hypothesised for a decrease in the shoulder's internal rotators when swimming above but not below CS. Concomitant decreases in stroke length and increase in stroke rate were also expected when swimming above CS but not below CS. In the literature, muscular fatigue has often been put forward as the main explanatory mechanism underpinning stroke changes observed during a 200-m all-out swim [4,20,21] so that the development of muscular fatigue should relate to a decrease in stroke length. This has been recently demonstrated for the first time as a loss of strength in the elbow flexors was related to the loss of stroke length observed during a 400-m front crawl all-out swim.[2] Therefore, we were further hypothesising that the loss of strength would be related to changes in stroking parameters during the fatiguing exercise.

METHODS

Subjects

Eight trained swimmers, 4 male and 4 female (mean ± SD 20.5 ± 0.9 years, 173 ± 10 cm, 71.3 ± 10.0 kg) took part in this study. Each participant had a minimum of 8 years of competitive experience and trained and competed with their university team when the study took place (> 6 hours per week; 400-m best time: 71.7 ± 4.7% of WR). All participants were briefed as to the benefits and risks of participation and gave their written informed consent to participate in the study, which was approved by the University Ethics Committee. All were familiarized with the swimming-pool testing procedures. Participants were instructed to arrive at the swimming-pool at the same time of day, in a rested and fully hydrated state, at least 3 h postprandial, and to avoid strenuous exercise in the 48 h preceding a test session. All were free of cardiac, metabolic or respiratory diseases.

Equipment

MVCs were performed on an isokinetic dynamometer (Con-Trex multi-joint module; CMV AG; Switzerland; 256 Hz sampling rate) located 12 meters from the edge of an indoor 25-m pool (Pool temperature: 28.4 ± 0.20°C; air temperature: 27.2 ± 0.2 °C and humidity: 66.5 ± 5.21%). Measurements for capillary blood lactate samples [La] were obtained from the fingertip (10μL) into capillary tubes (CB300, Microvette, Germany) using a disposable lancet and analysed using a desktop lactate analyser (YSI-2300 STAT, yellow springs instruments, OH). The analyser was automatically recalibrated every 40 minutes. During the two experimental trials, the swimming speed was imposed using a waterproof MP3 player (FINIS Neptune, US). Each .mp3 file commenced with a reminder of the pace, a “3,2,1 and GO” command, followed by different cues indicating the 5-m flag line, 12.5-m half-length mark, the second 5-m flag line, and the touch of the wall on the turn or upon arrival at the end of the 5-min swims (< 3% time accuracy). A base 3 stopwatch (FINIS 3x-300m, US) was used to measure stroke rate.[18]

Experimental design

Participants attended 6 sessions of testing (~ 72 hours apart) with all visits taking place at the same time of day (± 2 hours) to avoid the effect of circadian rhythm on the results.[22] The first stage of testing was carried out within 10 days and consisted of 5 randomly assigned sessions: (visit 1) a familiarisation to both the muscular testing procedure on the isokinetic dynamometer and the pool to dynamometer transition so that the time between the end of the swim and the first isometric MVC could be standardised; (visits 2-4) three maximal swimming performances performed to exhaustion to determine critical speed and anaerobic distance capacity[16]. The next testing stage included two experimental trials performed at random (visits 5-6), within 5 days, and consisted of a series of 6 x 5-min front crawl swims performed either at 95% (T_{95}) or 105% of critical speed (T_{105}), with measurement of shoulder's internal rotators MVCs between the 5-min swims. The same warm-up was replicated prior each swimming-based test. The set included some full stroke, arm only and leg only sections, and was performed in front crawl with the swimmers asked to swim at around 60% of their maximum for 500 meters (~10 minutes).

Determination of critical speed

Following the standardised warm-up, each swimmer performed a 200-m, 400-m or 800-m maximal effort, each swim was recorded to the nearest 100th of a second.[13] A method of least squares was used to model the linear relationship between distance and time (Figure 1).[12]

The experimental trials: T_{95} and T_{105}

Baseline measurements were recorded for [La] and MVC before the series of 6 x 5-min sub-maximal swims performed above (+ 5%; T_{105}) or below CS (- 5%; T_{95}). During the 2.5-min break between two 5-min swims, swimmers performed 2 x 5-s MVCs with 20-s recovery in-between. The warm-up prior the pre-swim MVCs consisted in 7 x 5-s voluntary contractions performed at 25% (x 2), 50% (x 2), 75% (x 2) and 100% effort (x 1) with 20-s of recovery in-between. This warm-up was followed by a 60-s resting period. The arm height, position and handgrip placements were set to the specifications of the individual following the user guide recommendations. The position was kept consistent from the initial familiarisation visit. Subjects were positioned adjacent to the dynamometer in a supine position and maximal isometric strength of the right shoulder's internal rotators was measured with the arm at the side in 90° of abduction and elbow supported and positioned in 90° of flexion. All participants were right handed. The shoulder was placed in the anatomical zero position (0°). The upper trunk was firmly strapped to the seat. The weight of the upper limb was recorded and all measurements were corrected for gravity. Average torque was recorded for each MVC with the highest score from the two attempts recorded as peak torque (4.8% typical error). Percent changes in torque were calculated for each block as the difference between the post- minus pre-value divided by the pre-value. Swimming speed ($m.s^{-1}$) was calculated from the measure of the time taken to swim the 5-min block. Stroke rate ($cycles.min^{-1}$) was recorded twice per 25-meter length and averaged for each 5-min block. Stroke length ($m.cycle^{-1}$) was calculated as the speed / stroke rate ratio. For each block percent changes (%) in these biomechanical variables were expressed as the difference from the last to the first 50-m value, expressed relative to the first 50-m value.

Statistical analysis

All statistical procedures were performed using SPSS (version 22.0, Chicago, USA) with the null hypothesis rejected at an alpha level of 0.05. For each set of data, normal distribution was verified (Kolmogorov-Smirnov test). The compound symmetry, or sphericity, was checked using the Mauchly's test for comparisons of more than two data sets. A two-way ANOVA with repeated-measures was performed to identify within- (pre-to post-exercise only) and between-test differences for each variable. A one-way ANOVA with repeated-measures was performed to identify differences over the 5-min blocks of swimming for each experimental trial. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure. Significant differences were followed up using planned pair-wise comparisons employing the Bonferroni corrected post hoc test. Relationships were explored using Pearson's product-moment correlation. Data are reported as mean ± SD unless stated otherwise.

RESULTS

The performances for the 200-m, 400-m and 800-m races lasted 147 ± 19 s, 313 ± 33 s, and 660 ± 65 s. The goodness of fit of the distance-time relationship was evidenced by adjusted r^2 values systematically close to 1 (Range: 0.999-1.000). CS was 1.18 ± 0.11 $m.s^{-1}$ or 91.3 ± 3.7% of the 400-m maximal speed with an associated standard error of 0.01 ± 0.01 $m.s^{-1}$ or 1.1 ± 0.8 % of CS. The intercept of the relationship equalled 31.4 ± 12.7 m (standard error: 4.6 ± 4.2 m). The swimming speeds for T_{95} and T_{105} were therefore 1.12 ± 0.11 $m.s^{-1}$ (86.7 ± 3.5% of the 400-m maximal speed) and 1.23 ± 0.12 $m.s^{-1}$ (95.9 ± 3.9% of the 400-m maximal speed), respectively.

No swimmer could complete the 6 x 5-min blocks at 105% of CS (1, 4, and 2 swimmers completed 5, 4 and 3 repetitions, respectively). The 2-way ANOVA with repeated measures for within- and between-experiment comparisons were therefore based on the baseline and last measurement for each swimmer. Maximal torque significantly decreased from baseline to end-exercise (Table 1; F=43.1, P<0.01) with no test-difference (F=3.52, P=0.10) but a greater decline observed for T_{105} (F=19.9, P<0.01). Torque did not change significantly over the 6 x 5-min blocks of T_{95} (F=0.85, P=0.54). A decrease (~23%) was significant over the 3 x 5-min blocks of T_{105} (F=27.3, P<0.01) with baseline significantly greater than the three other torque measurements, but no subsequent change during the test (P>0.05). Mean ± SD are presented in Table 1.

Figure 2 and 3 illustrates the changes in SR and SL during T_{95} and T_{105}. The 2-way ANOVA with repeated measures revealed a time (SR: F=23.7, P<0.01; SL: F=29.5, P<0.01), test (SR: F=84.4, P<0.01; SL: F=192.7, P<0.01), and time x test interaction effect for both stroking parameters (SR: F=6.3, P<0.05; SL: F=8.84, P<0.05). SR increased significantly during T_{105} (F=10.1, P<0.01) with a significant increase between the first and third 5-min swim (P<0.05). SL decreased significantly during T_{105} (F=15.7, P<0.01) with a significant change between the first and second (P<0.05), and then second and third 5-min repetition (P<0.05). Neither SR (F=0.94, P=0.46) nor SL (F=0.74, P=0.59) changed significantly over the 6 x 5-min blocks of T_{95}.

SL decreased significantly throughout each block of T_{105} (F=28.8, P<0.01). The decreases from the first to the last 50-m sections were of 10 ± 6% (from 2.66 ± 0.36 to 2.40 ± 0.33 $m.cycle^{-1}$; P<0.01), 9 ± 6% (from 2.53 ± 0.39 to 2.30 ± 0.34 $m.cycle^{-1}$; P<0.01), and 8 ± 6% (from 2.44 ± 0.33 to 2.23 ± 0.24 $m.cycle^{-1}$; P<0.01) for the first, second and third block, respectively. SL recovered to initial values (first 50 m of the first block) at the beginning of the second block (P=0.08) but not in the first 50 meters of the third block (P<0.01). The changes in maximal torque were of -21 ± 8%, -4 ± 13% and a further 1 ± 11% following the first, second and third 5-min block. These changes in torque were significantly correlated with the above mentioned changes in SL as illustrated in Figure 4 ($r=0.47$, $P<0.05$). Interestingly when investigating each block separately, the relationship was only significant for the last one ($r=0.80$; $P<0.05$; first block: $r=-0.30$; $P=0.51$; second block: $r=0.43$; $P=0.29$). Table 1 presents the mean [La] and RPE values recorded during the two tests conditions. [La] was significantly higher for T_{105} ($F=37.9$, $P<0.01$) compared to T_{95} with significant changes over time ($F=24.4$, $P<0.01$) and a time x test interaction effect ($F=82.0$, $P<0.01$). A significant increase in [La] was indeed found for T_{105} ($F=5.23$, $P<0.05$) from the 5th to 10th minute ($P<0.01$) with no subsequent increase ($P=0.11$). [La] did not change significantly over the 6 x 5-min blocks of T_{95} ($F=0.92$, $P=0.48$), with individual changes ranging from -0.61 to 0.62 mmol.L^{-1} between the second (10 minutes) and last block of swimming (30 minutes). RPE increased significantly over time ($F=101.7$, $P<0.01$), was significantly higher for T_{105} ($F=169.8$, $P<0.01$) and increased more rapidly during T_{105} ($F=24.5$, $P<0.05$). Despite a general overall time-effect over the 6 blocks of T_{95} ($F=7.6$, $P<0.01$), no post-hoc test significance was identified ($P>0.05$). RPE increased significantly over the 3 blocks of T_{105} ($F=89.1$, $P<0.01$), with significant increase from the 1st to the 2nd ($P<0.05$) and the 2nd to the 3rd repetition ($P<0.05$).

DISCUSSION

The present findings confirm CS demarcates two distinct swimming speed domains of differing physiological ([La], maximal torque) and perceptual (RPE) characteristics. In line with these results, the present study also found that stroking parameters (SR, SL) remain unchanged when swimming slightly below CS, with the pace sustainable over a 30-min period (5-min swims intercepted with 2.5 min of recovery). However, no steady states were evident during the above-CS swim, and the participants could not maintain the pace for more than ~ 20 minutes. A loss of strength in the shoulder's internal rotators was also observed alongside these physiological, perceptual and biomechanical changes with a positive linear relationship between strength's loss stroke length decreases from block to block (Figure 4).

In agreement with previous findings,[16] the slight but non-significant change in the [La] response when exercising below CS characterises a metabolic steady state. Individual changes between the 10th and 30th minute of exercise (or following the 2nd and 4th 5-min bout of exercise) were systematically smaller than 1 mmol.L^{-1} (range: -0.61 to 0.62 mmol.L^{-1}) so that the T_{95} pace was below MLSS as defined by Beneke.[23] All participants completed the 6 x 5-minute bouts of exercise. The perception of effort was also steady over the trial corroborating previous reports.[16] Of interest is the lack of change in the stroke mechanics which suggest for the pace to be MLSS or below.[24] Interestingly, and demonstrated for the first time in swimming, muscular fatigue is not evidenced when maintaining a sub-CS pace. It should be noted that the standard deviations in the torque measurement (Table 1) are rather large and may prevent from depicting significance (Type 2 error). Maximal torque showed a 13 ± 8% decrement after the 3rd repetition to recover to 5 ± 11% below the pre-exercise measure after the 6th repetition. A power analysis ($\beta=0.80$; $\alpha=0.05$) revealed that for the post-exercise scores to be significantly lower than those recorded pre-exercise, a sample of 38 swimmers would have been required.

This slight loss in the internal rotators' strength after 30 minutes of intermittent swimming in our study (-5%) was somehow lesser than strength loss reported previously following 30 minutes of submaximal (80 and 90% of critical torque) intermittent isometric contractions of the knee extensors[14] (a reduction of approx. 15%). In the present study, the pool to dynamometer transition time was standardised to 2.5 minutes with torque measurements done within the first 90 seconds. This delay in the performance of the MVC would allow for a certain level of muscular recovery: Only one minute of recovery from end exercise has been shown to enhance torque production during a knee extension MVCs by 17% (with a further 10% improvement within the following minute) .[25] The difference in the present study and those of Burnley et al. could also be explained, among other mechanisms, by the extreme differences in the sizes of the muscle mass involved in the two protocols: While fatigue was targeting the knee extensors during the intermittent isometric contractions performed below critical torque,[14] the swim in the present study involved a much large muscle mass with the shoulder's internal rotators representing only one of many muscle actions contributing to a stroke cycle. Compensations could take place during the stroke so that the loss of strength in one muscle group is compensated by another muscle group for the swimming speed to be maintained. A change in the 3-dimensional kinetic of the arm stroke could occur despite a lack of change in stroke length and stroke rate. Further studies would be required to investigate this matter further.

A slight change in the pace around CS (+/-5%) clearly induces very different physiological and biomechanical responses (sustainable / non sustainable) that can be attributed to the inherent characteristics of the water field. Because of the water resistances, the distance-time relationship is distorted in swimming [26] with narrow speed domains as a result.[27] For all swimmers, swimming at a pace 5% faster than CS led to an accumulation of [La] and increase in RPE over time before exhaustion occurred, again supporting previous results.[16,28] The times to exhaustion for the present study (~20 minutes) are also close to those previous reported for the same pace (~ 21 minutes)[16] and demonstrates the non-sustainability of a speed greater than CS. The incapacity for the participants to maintain the supra-CS pace was despite a 2.5-min resting period between the 5-min blocks. The increase in [La] and RPE was expected from previous observations [16,28] but in this study, accompanied with a clear increase in stroke rate, and decrease in both stroke length (-16%) and maximal torque (-28%). Muscular fatigue is evident when working slightly above CS, as demonstrated previously in swimming, but within the upper end of the severe intensity domain.[4,8-10] In accordance with the recent findings of Bassan et al.,[4] the present study shows that the decrease in stroke length during the constant-speed exercise performed above CS is related to the loss in the shoulder's internal rotators' strength (Figure 4). However, it must be noted that this only remains a general trend: A within-block analysis (8 data points) revealed a positive correlation between the change in SL and the loss of torque for the third block only. Interestingly, this loss of torque occurred mainly during the first block of swimming (-21% for a -3% subsequent change) while stroke length decreased in similar magnitudes from block to block (around 10% throughout each block). A change in SL when exercising within the severe intensity domain is not solely due, and is only partially explained by a loss of muscular fatigue. Three-dimension kinetic analysis would be required to investigate the change in stroke mechanics, with a drop of the elbow potentially related to a loss of strength in the internal rotators.[29]

PRACTICAL APPLICATIONS

The shoulders' internal rotators lose strength in the first 5 minutes of an intermittent swim (2.5 min of recovery between 5-min blocks) performed at 105% of critical speed (the pace could be maintained for about 20 minutes). No change is observed when swimming below critical speed (95%; repetitions of 5 minutes; 2.5-min in-between). This intensity-dependency of muscular fatigue should be considered when determining training workload and recovery strategies.

A loss of muscular strength (shoulders' internal rotators) is related to a reduction in stroke length in front crawl but this relationship seems too weak for a causal relationship to be certain. A reduction in stroke length is not systematically associated with a development of muscular fatigue.

CONCLUSION

The shoulder's internal rotators fatigue when swimming in front crawl at a sub-maximal intensity (~85% of the 400-m front crawl pace) for a long duration (~30 minutes). But in the present study, with 2.5-min recovery periods between the 5-min swimming blocks, the swimming speed had to be above a critical level – critical speed – for muscular fatigue to develop. Coaches should be cautious with possible adverse effect caused by muscular fatigue during supra-critical speed training. This study also confirms critical speed demarcates two swimming speed domains characterised by different physiological, perceptual and biomechanical responses. Indeed, the decrease in the strength of the shoulder's internal rotators when swimming above critical speed was concomitant to increases in [La], RPE, and stroke rate. The loss of muscular strength was also related to a decrease in stroke length. None of these changes could be observed when swimming below critical speed. Further studies could focus on the peripheral *vs* central origin of muscular fatigue in swimming alongside a better understanding of the mechanisms underpinning stroke length reduction during fatiguing swimming.

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TABLES

Table 1: Torque, [La], and RPE measurements during T_{95} and T_{105}

(*n*=8)	**Maximal torque (N.m)** ^{I}		**RPE** ^{I}		**[La] (mmol.l^{-1})** ^{I}	
	T_{95}	**T_{105}** ^{Time}	**T_{95}**	**T_{105}** $^{Time, Test}$	**T_{95}**	**T_{105}** $^{Time, Test}$
Pre-swim	32.1 ± 14.4	35.0 ± 14.9			1.5 ± 0.7	2.2 ± 0.6
5 minutes	30.1 ± 12.9	28.4 ± 14.0 *	10 ± 1	15 ± 2	2.2 ± 1.2 *	4.6 ± 1.3 *
10 minutes	28.3 ± 13.1	27.3 ± 13.6 *	11 ± 1	16 ± 2 $^{\$}$	2.5 ± 1.2 *	5.6 ± 1.8 *$^{,\$}$
15 minutes	28.6 ± 15.8	27.1 ± 12.7 *	11 ± 1	18 ± 1 $^{\$}$	2.2 ± 0.8 *	5.8 ± 1.8 *
20 minutes	30.2 ± 18.5		11 ± 1		2.4 ± 1.0	
25 minutes	30.8 ± 17.6		11 ± 1		2.5 ± 1.2	
30 minutes	30.7 ± 14.3		11 ± 1		2.5 ± 1.1	
End-swim	30.7 ± 14.3	25.8 ± 12.1	11 ± 1	19 ± 1	2.5 ± 1.1	6.5 ± 2.3

* Significantly different from pre-swim ($P<0.05$); $^{\$}$ Significantly different from previous measure ($P<0.05$); ^{Time} Significant main time-effect ($P<0.05$); ^{I} Significant time x test interaction effect; ^{Test} Significantly different to T_{95} ($P<0.05$)

FIGURE LEGENDS

Figure 1: distance-time relationship plotted for a swimmer. Critical Speed, slope of the relationship was 1.19 m.s^{-1}.

Figure 2: Changes in stroke rate during the swimming set performed at a pace 5% greater than (T_{105}), and 5% lower than Critical speed (T_{95})

Figure 3: Changes in stroke length during the swimming set performed at a pace 5% greater than (T_{105}), and 5% lower than Critical speed (T_{95})

Figure 4: Scatter plot representing the percent change in stroke length against the percent change in maximal torque (r=0.47, P<0.05)