PERFORMANCE AND PHYSIOLOGICAL MONITORING OF HIGHLY TRAINED SWIMMERS

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ABSTRACT

This thesis examined the benefits of physiological and performance testing of elite swimmers. The study considered the following research questions: the degree to which physiological and performance measures in training contribute to swimming performance; sources and magnitude of variability in testing, training and competition performance; the magnitudes of changes in test measures during routine training; and the reliability, validity and utility of miniaturised and automated smart sensor technology to monitor the stroke and performance times of swimmers in training. The experimental approach involved the retrospective analysis of five years of physiological and performance testing of elite level swimmers, the development of a new accelerometry-based smart sensor device to monitor swimmers in the pool, a cross-sectional study comparing the physiological and performance responses of swimmers of different levels, and the effects of an intensive 14-day training program on submaximal physiological and performance measures. Collectively, the outcomes of these studies provide a strong justification for the physiological and performance testing of elite swimmers, a quantitative framework for interpreting the magnitude of changes and differences in test scores and sources of variation, and highlight the potential utility of new smart sensor technology to automate the monitoring of a swimmer's training performance.

The first study (Chapter 2) characterises the changes and variability in test performance, physiological and anthropometric measures, and stroke mechanics of swimmers within and between seasons over their elite competitive career. Forty elite swimmers (24 male, 16 female) performed a 7 x 200-m incremental swimming step test several times each 6-month season (10 ± 5 tests, spanning 0.5 to 6.0 y). Mixed linear modeling provided estimates of change in the mean and individual responses for measures based on submaximal performance (fixed 4-mM lactate), maximal performance (the seventh step), and lean mass (from skinfolds and body mass). Submaximal and maximal swim speed increased within each season from the pre to taper phase by ~2.2% for females and ~1.5% for males (95% confidence limits ±1.0%), with variable contributions from stroke rate and stroke length. Most of the gains in speed were lost in the off-season, leaving a net average annual improvement of ~1.0% for females and ~0.6% for males (±1.0%). For submaximal and maximal speed, individual variation between phases was ±2.2% and the typical measurement error was ±0.8%. In conclusion, step test and anthropometric measures can be used to confidently monitor progressions in swimmers in an elite training program within and between seasons.

The second study (Chapter 3) quantified the relationship between changes in test measures and changes in competition performance for individual elite swimmers. The primary question addressed was whether test measures could predict a swimmers performance at the major end-of-season competition. The same sample group as in Study 1 was examined. A 7 x 200-m incremental swimming step-test and anthropometry were conducted in up to four training phases each season. Correlations of changes in step-test and anthropometric measures between training phases between and within seasons, with changes in competition performance between seasons, were derived by repeated-measures mixed modeling and linear regression. Changes in competition performance were best tracked by changes in test measures between taper phases. The best single predictor of competition performance was skinfolds for females ($r = -0.53$). The best predictor from the step-test was stroke rate at 4-mM lactate (females, $r = 0.46$; males, $r = 0.41$); inclusion of the second-best step-test predictor in a multiple linear regression improved the correlations marginally (females, $r = 0.52$ with speed in the seventh step included; males, $r = 0.58$ with peak lactate concentration included). Changes in test measures involving phases other than the taper provided weak and

inconclusive correlations with changes in performance, possibly because the coaches and swimmers took corrective action when tests produced poor results. In conclusion, a combination of fitness and techniques factors are important for competitive performance. The step test is apparently a useful adjunct in a swimmer's training preparation for tracking large changes in performance.

These initial studies identified stroke mechanics as a major determinant of a swimmer's performance. Chapter 4 details the development of a small tri-axial accelerometry-based smart sensor device (the *Traqua*) that enables continual monitoring of various performance/stroke characteristics in swimming. The initial focus was to develop a device that automated the detection of a swimmer's movements, specifically lap times, stroke rate and stroke count. The *Traqua* consists of a tri-axial accelerometer packaged with a microprocessor, which attaches to the swimmer at the pelvis to monitor their whole body movements while swimming. This study established the failure/error rate in the first generation algorithms developed to detect the swimming-specific movements of stroke identification, laps (start, turn and finish), and strokes (stroke count and stroke rate) in a cohort of 21 elite and sub-elite swimmers. Movements were analysed across a range of swimming speeds for both freestyle and breaststroke. These initial algorithms were reasonably successful in correctly identifying the markers representing specific segments of a swimming lap in a range of swimmers across a spectrum of swimming speeds. The first iteration of the freestyle algorithm produced error-rates of 13% in detection of lap times, 5% for stroke rate, and 11% for stroke count. Subsequent improvements of the software reduced the error rate in lap and stroke detection. This improved software was used in the following two studies.

The next study (Chapter 5) evaluated the reliability and validity of the *Traqua* against contemporary methods used for timing, stroke rate and stroke count determination. The subjects were 14 elite and 10 sub-elite club-level swimmers. Each swimmer was required to swim seven evenly paced 200-m efforts on a 5-min cycle, graded from easy to maximal. Swimmers completed the test using their main competitive stroke (21 freestyle, 3 breaststroke). Timing was compared for each 50-m lap and total 200-m time by electronic touch pads, video coding, a hand-held manual stopwatch, and the *Traqua*. Stroke count was compared for video coding, self-reported counting, and the *Traqua*, while the stroke rate was compared via video coding, hand-held stopwatch, and the *Traqua*. Retest trials were conducted under the same conditions 7 d following the first test. All data from the *Traqua* presented in this and the subsequent studies were visually inspected for errors in the automated algorithms, where the algorithms had either failed to correctly identify the start, turn, finish or individual strokes and corrected prior to analysis. The standard error of the estimate for each of the timing methods for total 200 m was compared with the criterion electronic timing. These standard errors were as follows: *Traqua* (0.64 s; 90% confidence limits 0.60 – 0.69 s), Video (0.52 s; 0.49 – 0.55 s); Manual (0.63 s; 0.59 – 0.67 s). Broken down by 50-m laps, the standard error of the estimate for the *Traqua* compared with the electronic timing for freestyle only was: 1st 50-m 0.35 s; 2nd and 3rd 50-m 0.13 s; 4th 50-m 0.65 s. When compared with the criterion video-coding determination, the error for the stroke count was substantially lower for the *Traqua* (0.6 strokes.50 m^{-1}; 0.5 – 0.6 strokes.50 m^{-1}) compared to the self-reported measure (2.3 strokes.50 m^{-1}; 2.5 – 2.9 strokes.50 m^{-1}). However, the error for stroke rate was similar between the *Traqua* (1.5 strokes·min^{-1}; 1.4 – 1.6 strokes·min^{-1}) and the manual stopwatch (1.8 strokes·min^{-1}; 1.7 – 1.9 strokes·min^{-1}). The typical error of measurement of the *Traqua* was 1.99 s for 200-m time, 1.1 strokes·min^{-1} for stroke rate, and 1.1 strokes·50 m^{-1} for stroke count. In conclusion, the *Traqua* is comparable in accuracy to current methods for determining time and stroke rate, and better than current methods for stroke count. A substantial source of error in the *Traqua* timing was additional noise in the detection of the start and finish. The *Traqua* is probably useful for monitoring of routine training but electronic timing and video are preferred for racing and time trials.

Having established the reliability and validity of the *Traqua*, Chapter 6 addressed the ability to discriminate the pattern of pacing between different levels of swimmers in the 7 x 200-m incremental step test. This study also sought to quantify the differences in pacing between senior and junior swimmers. Eleven senior elite swimmers (5 female, 6 male) and 10 competitive junior swimmers (3 female, 7 male) participated in this study. Each swimmer was required to swim seven evenly paced 200-m freestyle efforts on a 5-min cycle, graded from easy to maximal. The *Traqua* was used to measure time, stroke rate and stroke count. The senior swimmers were better able to descend in each of the 200-m efforts. Overall the senior swimmers were ~2-3 s per 50 m faster than the junior swimmers. Both groups were fastest in the first 50-m lap with the push start. The senior swimmers then descended the 50-m time for each of the subsequent laps, getting ~0.5 s faster per lap, with the final lap the fastest. In contrast, the junior swimmers swam a similar time for each of the subsequent laps. The junior swimmers were marginally more variable in their times (coefficient of variation: ~2%) compared with the senior swimmers (~1.8%). In comparison to junior swimmers, the senior swimmers in this study were faster, adopted a more uniform negative split strategy to pacing within a 200-m effort, and were more consistent in reproducing submaximal and maximal swimming speeds.

The final study (Chapter 7) analysed the effect of 14-d of intensive training on the reproducibility of submaximal swimming performance in elite swimmers. Submaximal physiological and performance testing is widely used in swimming and other individual sports but the variability in test measures, and the effects of fatigue, during intensive training have surprisingly not been quantified systematically. Seven elite swimmers (3 male and 4 female) participated in an intensive 14-d training camp one month prior to the National championships. The aim of the study was to characterise the intra-session, daily and training block variability of submaximal swimming time, physiological and stroke characteristics in elite swimmers. The swimmers performed a specified submaximal 200-m effort in most sessions, after the warm-up and at the end of the session for both morning and afternoon sessions. During the efforts, swimming time and stroke mechanics were measured and physiological measures were recorded immediately on completion. The *Traqua* was worn by all swimmers in every training session. Mixed linear modeling was used to provide estimates of changes in the mean and individual responses (within-athlete variation as a coefficient of variation) for all measures. The swimmers were moderately slower (1.4%; ±1.4%) over the 14-d training camp. The mean submaximal 200-m effort was very likely to be faster (0.7%; confidence limits ±0.7%) in the afternoon compared with the morning session. The females were more variable in their submaximal performance times (CV=2.6%) than the male swimmers (1.7%). Blood lactate concentration was almost certainly lower (-23%; ±10%) following higher volume in the previous session; however a higher intensity workout the previous session almost certainly leads to higher lactate (21%; ±15%) in the current session. Considered together, these results indicate that the 200-m submaximal test is useful in monitoring submaximal physiological and performance measures and the negative effects of cumulative fatigue.

In conclusion, changes in the physiological and performance measures derived from the pool-based progressive incremental step test are moderately correlated with changes in end-of-season competition performance. The magnitudes of changes and differences in test measures between phases within a season, from season to season, and between males and females, established in this study can be applied to similar elite level swimmers preparing for major competition. The quantification of typical error of the same measures demonstrates that coaches and scientists can distinguish real and worthwhile improvements using the 7 x 200-m step test. Continual pool-based monitoring with the automated smart sensor *Traqua* device may provide more accurate and detailed information about a swimmer's training adaptation than current fitness tests and monitoring methods. Finally, submaximal testing in trained swimmers is useful in monitoring progress in physiological and performance measures, and the impact of cumulative fatigue during an intensive period of training. Collectively, the outcomes of these studies indicate that routine physiological and performance testing can provide measurable benefits for elite swimmers and their coaches.

CERTIFICATE OF AUTHORSHIP OF THESIS

Except where indicated in footnotes, quotations and the bibliography, I certify that I am the sole author of the thesis submitted today entitled:

Performance and Physiological Monitoring of Highly Trained Swimmers

in terms of the Statement of Requirements for a Thesis issued by the University Higher Degrees Committee

Signature of Candidate: ……………..……………..

Megan Anderson

Date: ……..………………….. **18th May 2007**

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Publications and Presentations by the Candidate Relevant to the Thesis

Publications:

Anderson, M.E., W.G. Hopkins, A.D. Roberts, D.B. Pyne. Ability of performance-test measures to predict competitive performance in elite swimmers. *Journal of Sports Sciences.* 2007 *(in press).*

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DEDICATION

To my parents, Alan and Dorothy Anderson

and my grandmother, Edith Haydon.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES