

**PERFORMANCE AND PHYSIOLOGICAL  
MONITORING OF HIGHLY TRAINED  
SWIMMERS**

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# ABSTRACT

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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 ( $10 \pm 5$  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  $\sim 2.2\%$  for females and  $\sim 1.5\%$  for males (95% confidence limits  $\pm 1.0\%$ ), 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  $\sim 1.0\%$  for females and  $\sim 0.6\%$  for males ( $\pm 1.0\%$ ). For submaximal and maximal speed, individual variation between phases was  $\pm 2.2\%$  and the typical measurement error was  $\pm 0.8\%$ . 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 *Traqa*) 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 *Traqa* 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 *Traqa* 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 *Traqa*. Stroke count was compared for video coding, self-reported counting, and the *Traqa*, while the stroke rate was compared via video coding, hand-held stopwatch, and the *Traqa*. Retest trials were conducted under the same conditions 7 d following the first test. All data from the *Traqa* 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: *Traqa* (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 *Traqa* compared with the electronic timing for freestyle only was: 1<sup>st</sup> 50-m 0.35 s; 2<sup>nd</sup> and 3<sup>rd</sup> 50-m 0.13 s; 4<sup>th</sup> 50-m 0.65 s. When compared with the criterion video-coding determination, the error for the stroke count was substantially lower for the *Traqa* (0.6 strokes.50 m<sup>-1</sup>; 0.5 – 0.6 strokes.50 m<sup>-1</sup>) compared to the self-reported measure (2.3 strokes.50 m<sup>-1</sup>; 2.5 – 2.9 strokes.50 m<sup>-1</sup>). However, the error for stroke rate was similar between the *Traqa* (1.5 strokes min<sup>-1</sup>; 1.4 – 1.6 strokes min<sup>-1</sup>) and the manual stopwatch (1.8 strokes min<sup>-1</sup>; 1.7 – 1.9 strokes min<sup>-1</sup>). The typical error of measurement of the *Traqa* was 1.99 s for 200-m time, 1.1 strokes min<sup>-1</sup> for stroke rate, and 1.1 strokes.50 m<sup>-1</sup> for stroke count. In conclusion, the *Traqa* 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 *Traqa* timing was additional noise in the detection of the start and finish. The *Traqa* 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 *Traqa*, 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 *Traqa* 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 *Traqqa* 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%;  $\pm 1.4\%$ ) over the 14-d training camp. The mean submaximal 200-m effort was very likely to be faster (0.7%; confidence limits  $\pm 0.7\%$ ) 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%;  $\pm 10\%$ ) following higher volume in the previous session; however a higher intensity workout the previous session almost certainly leads to higher lactate (21%;  $\pm 15\%$ ) 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 *Traqva* 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

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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: **18<sup>th</sup> May 2007** .....

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# PUBLICATIONS AND PRESENTATIONS BY THE CANDIDATE

## RELEVANT TO THE THESIS

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### **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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M.E. Anderson, W.G. Hopkins, A.D. Roberts, and D.B. Pyne. Monitoring long-term changes in test and competitive performance in elite swimmers. *Medicine & Science in Sports & Exercise*. 35(5) Supplement 1:S36, May 2003.

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## DEDICATION

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To my parents, Alan and Dorothy Anderson  
and my grandmother, Edith Haydon.

# TABLE OF CONTENTS

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<b>LIST OF FIGURES .....</b>	<b>xix</b>
<b>LIST OF TABLES .....</b>	<b>xxii</b>
<b>LIST OF APPENDICES.....</b>	<b>xxiii</b>
<b>CHAPTER ONE: Review of Literature.....</b>	<b>1</b>
<b>1.0. Introduction .....</b>	<b>1</b>
<b>1.1. Performance of Elite Swimmers .....</b>	<b>5</b>
<b>1.2. Limitations to Swimming Performance .....</b>	<b>10</b>
<b>1.3. Performance Evaluation of Swimmers.....</b>	<b>14</b>
1.3.1. Analysis of Race Performance .....	16
1.3.2. Biomechanical Monitoring of Training.....	20
1.3.3. Anaerobic Power and Strength Evaluation .....	21
1.3.4. Critical Speed .....	23
1.3.5. Body Composition.....	24
1.3.6. Physiological Monitoring of Training.....	26
1.3.6.1. Blood Lactate .....	28
1.3.6.2. Heart Rate .....	30
1.3.6.3. Oxygen Uptake and Swimming Economy Testing.....	31
<b>1.4. Interpreting Test and Performance Results .....</b>	<b>32</b>
1.4.1. Variability in Swimming Performance .....	34
<b>1.5. New Technologies for Monitoring Sports Performance .....</b>	<b>36</b>
1.5.1. Principles of Accelerometers .....	38
1.5.2. Use of Accelerometers in Swimming.....	40
<b>1.6. Summary.....</b>	<b>43</b>
<b>1.7. Aims of the Thesis .....</b>	<b>43</b>
<b>CHAPTER TWO: Monitoring Seasonal and Long-Term Changes in Test Performance in Elite Swimmers .....</b>	<b>45</b>
<b>2.0. Introduction .....</b>	<b>45</b>
<b>2.1. Method .....</b>	<b>47</b>
2.1.1. Subjects .....	47
2.1.2. Study Design and Procedures.....	48

2.1.3.	7 x 200-m Testing Procedure .....	48
2.1.4.	Reliability Testing .....	50
2.1.5.	Statistical Analyses .....	50
<b>2.2.</b>	<b>Results .....</b>	<b>52</b>
2.2.1.	Within-Season Changes .....	52
2.2.2.	Progressive Yearly Changes.....	55
<b>2.3.</b>	<b>Discussion.....</b>	<b>60</b>
<b>2.4.</b>	<b>Conclusions .....</b>	<b>65</b>
<b>CHAPTER THREE:</b>	<b>Ability of Test Measures to Predict Competitive Performance</b>	
<b>in Elite Swimmers.....</b>	<b>.....</b>	<b>66</b>
<b>3.0.</b>	<b>Introduction .....</b>	<b>66</b>
<b>3.1.</b>	<b>Method .....</b>	<b>67</b>
3.1.1.	Subjects .....	67
3.1.2.	Study Design and Procedures.....	68
3.1.3.	Statistical Analyses .....	70
<b>3.2.</b>	<b>Results .....</b>	<b>73</b>
3.2.1.	Change in Competition Performance .....	73
3.2.2.	Changes in 4-mM Lactate (Submaximal Speed).....	75
3.2.3.	Correlations Between Test Measures and Competition Performance.....	75
3.2.4.	Off-Season and Within-Season Correlations .....	78
<b>3.3.</b>	<b>Discussion.....</b>	<b>78</b>
<b>3.4.</b>	<b>Conclusion.....</b>	<b>84</b>
<b>CHAPTER FOUR:</b>	<b>Development of a Swimming Monitoring Device – Traqua</b>	
<b>.....</b>	<b>.....</b>	<b>86</b>
<b>4.0.</b>	<b>Introduction .....</b>	<b>86</b>
<b>4.1.</b>	<b>Swimming Monitoring Device - Prototype Considerations and Development..</b>	<b>88</b>
4.1.1.	Proof of Concept .....	88
4.1.2.	Location Considerations on Body .....	91
4.1.3.	Orientation.....	93
4.1.4.	Packaging .....	94
4.1.5.	Swimming Monitoring Device Evolution .....	95
4.1.5.1.	Prototype 1 .....	96
4.1.5.2.	Prototype 2 .....	97
4.1.5.3.	Prototype 3 .....	99
4.1.5.4.	Prototype 4 - <i>Traqua4</i> .....	100
4.1.5.4.1.	Technical Specifications of the <i>Traqua4</i> .....	100

<b>4.2. Swimming Monitoring Device - Software and Algorithm Development.....</b>	<b>102</b>
4.2.1. Calibration.....	102
4.2.2. Swimming-Specific Algorithms.....	102
4.2.2.1. Start Identification .....	102
4.2.2.2. Turn Identification .....	105
4.2.2.3. Stroke Identification.....	107
4.2.2.4. Lap Finish .....	112
4.2.3. Validation of Swimming-Specific Algorithms with Video Synchronisation and a Global Positioning Device (GPS) .....	114
<b>4.3. Error Frequency in the Algorithms Developed for Swimming .....</b>	<b>114</b>
4.3.1. Criteria for Manual Correction of Algorithms .....	116
4.3.2. Results – Frequency of Errors.....	117
<b>4.4. Conclusion.....</b>	<b>118</b>
<b>CHAPTER FIVE: Reliability and Validity of a New Accelerometer-Based Sensor to Measure Lap Times and Stroke Mechanics in Highly Trained Swimmers .....</b>	<b>120</b>
<b>5.0. Introduction.....</b>	<b>120</b>
<b>5.1. Method .....</b>	<b>122</b>
5.1.1. Subjects .....	122
5.1.2. Experimental Design and Procedures .....	123
5.1.3. Timing and Stroke Information Instruments.....	124
5.1.4. Statistical Analysis .....	126
<b>5.2. Results .....</b>	<b>128</b>
5.2.1. Uniformity of Residual Errors.....	128
5.2.2. Validity and Reliability .....	129
5.2.3. Stroke Counts and Stroke Rates.....	130
5.2.4. Standard Error of Estimate and Mean Bias in Estimation of 50-m Split Times.....	132
5.2.5. Within-Athlete Error .....	133
<b>5.3. Discussion.....</b>	<b>133</b>
<b>5.4. Conclusion.....</b>	<b>138</b>
<b>CHAPTER SIX: Variability in Swimming Performance Measures in Junior and Senior Swimmers .....</b>	<b>139</b>
<b>6.0. Introduction.....</b>	<b>139</b>
<b>6.1. Method .....</b>	<b>140</b>
6.1.1. Subjects .....	140

6.1.2.	Experimental Design and Procedures .....	141
6.1.3.	Statistical Analyses .....	142
<b>6.2.</b>	<b>Results .....</b>	<b>143</b>
<b>6.3.</b>	<b>Discussion.....</b>	<b>147</b>
<b>6.4.</b>	<b>Conclusion.....</b>	<b>153</b>
<b>CHAPTER SEVEN: The Effect of an Intensive Training Phase on the</b>		
<b>Reproducibility of Submaximal Swimming Performance in Elite Swimmers .....</b>		
<b>7.0.</b>	<b>Introduction .....</b>	<b>154</b>
<b>7.1.</b>	<b>Method .....</b>	<b>156</b>
7.1.1.	Subjects .....	156
7.1.2.	Training Structure .....	156
7.1.3.	Experimental Design and Procedure .....	157
7.1.4.	Statistical Analyses .....	160
<b>7.2.</b>	<b>Results .....</b>	<b>161</b>
7.2.1.	200-m Time .....	161
7.2.2.	Blood Lactate, Heart Rate RPE.....	164
7.2.3.	Stroke Characteristics.....	165
<b>7.3.</b>	<b>Discussion.....</b>	<b>166</b>
<b>7.4.</b>	<b>Conclusion.....</b>	<b>171</b>
<b>CHAPTER EIGHT: Summary and Conclusions.....</b>		
<b>172</b>		
<b>REFERENCES .....</b>		
<b>178</b>		

---

## LIST OF FIGURES

---

---

- Figure 1-1:** Progression of the men's and women's 100-m freestyle world records over the past 20 years (1986 to 2006)..... 6
- Figure 1-2:** Example of a race analysis report used by the Australian Swimming Team compiled from competition video footage. The race analysis report is of the women's 200-m breaststroke world record. This report has a combination of numerical data and a graphical summary. The competition analysis provides details of time, velocity, stroke rate, and stroke length (DPS) for each 25 m of free swimming, as well information on time into turn (5 m), break out (10 m) and turn times. Information can be used in comparison with personal best or comparison with world or national records (report provided from the Queensland Academy of Sport)..... 19
- Figure 1-3:** Comparison of a blood lactate-velocity curve from an elite swimmer taken early in the season to a late season test result..... 28
- Figure 1-4:** Model of a mass-spring accelerometer system where  $X_0$  is at rest and  $X$  is the displacement, shown a) with no acceleration and b) with acceleration. The force of the mass exerted on the spring is a measure of the exerted translational acceleration on the system (71). ..... 39
- Figure 2-1:** Mean within-subject percent changes relative to the pre-season level in submaximal (fixed 4-mM lactate) speed, stroke rate and stroke length for 24 male and 16 female swimmers during the early, mid, and taper phases of the training season. Values are means; error bars are 95% confidence limits..... 54
- Figure 2-2:** Typical within-swimmer mean progressions in maximal speed, stroke rate and stroke length each year for 24 male and 16 female swimmers over 5 y. Values are means; error bars are 95% confidence limits..... 57
- Figure 2-3:** Typical within-swimmer mean progressions in peak lactate and heart rate each year for 24 male and 16 female swimmers over 5 y. Values are means; error bars are 95% confidence limits..... 58
- Figure 2-4:** Mean within-subject yearly progressions in body mass, sum of 7 skinfolds and lean mass index for 24 male and 16 female swimmers. Values are means; error bars are 95% confidence limits..... 59
- Figure 3-1:** Modelled typical within-swimmer mean yearly percent progression in competition time and stroke rate at 4-mM lactate speed over a 5 y period. Values are mean  $\pm$  95% confidence limits. (Females,  $n = 16$ ; Males,  $n = 24$ ). ..... 74
- Figure 3-2:** A negative relationship between stroke rate at the 4-mM lactate in the taper phase and competition time from one season to the next, with swimmers increasing their stroke rate at the reference lactate concentration in the taper phase showing a faster time in competition (males:  $r = 0.41$ ; females:  $r = 0.46$ ). Also shown are the regression lines for the estimated predicted slope; a 1% change in stroke rate at 4-mM lactate would result in a  $-0.09\%$  change for males and a  $-0.14\%$  change for females in competition performance. ○ - - ○

	Males; ●—●Females. (Females n = 8, total number of tests = 30; Males n =15, total number of tests = 48).....	77
<b>Figure 4-1:</b>	Accelerometer traces from the proof of concept trial. The yellow lines indicate where a simple algorithm (not developed on swimming data) has identified a stroke occurring. ....	90
<b>Figure 4-2:</b>	Location of the accelerometer device on the lower back .....	92
<b>Figure 4-3:</b>	Accelerometer orientation when placed on the back of a swimmer while swimming and direction of the three axes in relation to location and swimming position. X is the forward/backward movements; Y is the up/down movement and Z is the sideways or left/right movement.....	93
<b>Figure 4-4:</b>	Evolution of a device to monitor swimming movements. The package shown in the far left of the picture is the first prototype, second left is the second prototype, second to the right is the third prototype, and far right is the final prototype or <i>Traqua4</i> .....	96
<b>Figure 4-5:</b>	The various designs that were proposed for Prototype 2.....	98
<b>Figure 4-6:</b>	Final design for Prototype 2 ( <i>Traqua</i> ) sitting on its charging/download cradle. ....	98
<b>Figure 4-7:</b>	Final prototype version of the swimming monitoring device, the <i>Traqua4</i> – on the left, is the top view of the device in the charging/download cradle and on the right, is the underside view of the device, where the five gold bump connectors for data transfer and charging are shown. ....	100
<b>Figure 4-8:</b>	Electronic configuration of the final prototype of the swimming-monitoring device ( <i>Traqua4</i> ). ....	101
<b>Figure 4-9:</b>	Accelerometer trace of a typical push start shown by the green line, highlighted in the red-circled area (top panel: X or forwards/backwards; middle panel: Z or sideways; bottom panel: Y or up/down). ....	104
<b>Figure 4-10:</b>	Accelerometer trace of a typical turn as indicated by the green line, highlighted in the red-circled area (top panel: X or forwards/backwards; middle panel: Z or sideways; bottom panel: Y or up/down). ....	106
<b>Figure 4-11:</b>	Accelerometer trace of freestyle with each yellow line indicating where the algorithm has identified a stroke occurring both left and right strokes (top panel: X or forwards/backwards; middle panel: Z or sideways; bottom panel: Y or up/down).....	108
<b>Figure 4-12:</b>	Accelerometer trace of backstroke with each yellow line indicating where the algorithm has identified a stroke occurring both left and right strokes (top panel: X or forwards/backwards; middle panel: Z or sideways; bottom panel: Y or up/down).....	109
<b>Figure 4-13:</b>	Accelerometer trace of breaststroke with each yellow line indicating where the algorithm has detected a stroke (top panel: X or forwards/backwards; middle panel: Z or sideways; bottom panel: Y or up/down). ....	110
<b>Figure 4-14:</b>	Accelerometer trace of butterfly with each yellow line indicating a stroke (top panel: X or forwards/backwards; middle panel: Z or sideways; bottom panel: Y or up/down).....	111

<b>Figure 4-15:</b>	Accelerometer trace of a typical lap finish, indicated by the red line (top panel: X or forwards/backwards; middle panel: Z or sideways; bottom panel: Y or up/down).....	113
<b>Figure 5-1:</b>	For 200-m time, the <i>Traqa</i> time is plotted against the residuals which are the difference between the criterion measure of electronic timing and the predicted measure of <i>Traqa</i> timing. Zero represents the point at which the electronic times equalled the <i>Traqa</i> times. The error was relatively uniform across all speeds with slightly more error evident in the 140 to 150 seconds (2:20 to 2:30 min:sec) range.....	128
<b>Figure 5-2:</b>	Plot of the raw values from the <i>Traqa</i> timing versus the criterion measure of electronic timing for 200-m swim times for all swimmers (n = 323). The correlation was $r = 0.99$ and the standard error of the estimate was 0.65 s....	129
<b>Figure 6-1:</b>	Difference in the actual 200-m time compared with the target 200-m time (zero) for each of the incremental seven 200-m efforts (1 slowest pace and 7 the maximal effort) for the senior and junior swimmers. Data is presented as mean $\pm$ 90% confidence limits. ....	144
<b>Figure 6-2:</b>	Differences in pacing (50-m lap times) and stroke mechanics (stroke rate and stroke) count over the four consecutive 50-m laps in the 200-m effort for the junior and senior swimmers. Data are represented as mean $\pm$ 90% confidence limits. ....	146
<b>Figure 7-1:</b>	Schematic of the daily training and the timing of the submaximal testing in relation to the morning (AM) and afternoon (PM) training sessions: $\uparrow$ indicates the location of the 200-m submaximal testing in relation to training session.	158
<b>Figure 7-2:</b>	Diagram of the daily training volume (km) represented as the bars and the intensity (rating 1-5, 1: low intensity – 5: high intensity) represented as the line for the 14-day training camp. ....	160
<b>Figure 7-3:</b>	Submaximal 200-m times over the 14 day training camp for the male and female swimmers both pre and post the morning (AM) and afternoon (PM) sessions. Average numbers of tests: total n = $24 \pm 4$ (mean $\pm$ SD); AM Pre n = $11 \pm 2$ ; AM Post n = $7 \pm 1$ ; PM Pre n = $5 \pm 1$ ; PM Post n = $1 \pm 1$ . Overall, the self-paced 200-m time was slower after the 14 days of high volume and high intensity training. The females were substantially more variable in their efforts than the male swimmers. The reference line shows the daily changes in the submaximal effort completed in the morning following the warm-up before the main set (AM Pre). ....	163

## LIST OF TABLES

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---

<b>Table 2-1:</b>	Descriptive statistics (mean $\pm$ SD) of the 7 x 200-m step test measures for male and female freestyle swimmers and the re-test typical error of measurement expressed as a coefficient of variation from the reliability study. ....	52
<b>Table 3-1:</b>	Correlation of individual change scores of taper phase 7 x 200-m step test and anthropometry measures with change scores of competition performance. The slope of the relationship, which is the estimated percent change in competition performance for a 1% change in step test or anthropometric measure, is also shown. ....	76
<b>Table 4-1:</b>	Dimensions of the four fully packaged versions of the swimming monitoring device .....	95
<b>Table 4-2:</b>	Specifications for the final design of the sensor ( <i>Traqua4</i> device).....	101
<b>Table 4-3:</b>	Criterion for manual correction of swimming-specific algorithms.....	116
<b>Table 4-4:</b>	Frequency of errors in swimming-specific algorithms for laps, freestyle stroke count and stroke rate by individual swimmer. ....	118
<b>Table 5-1:</b>	The re-test typical error of measurement expressed as a coefficient of variation (CV) of the video coding method.....	126
<b>Table 5-2:</b>	Comparison of timing, stroke rate, and stroke count detection methods against criterion measure (electronic touch pad for timing; video coding for stroke rate and stroke count). Also shown is the retest reliability for each method. All estimates shown with $\pm 90\%$ confidence limits. ....	131
<b>Table 5-3:</b>	Comparison of the <i>Traqua</i> timing compared with the electronic timing for the 50 m laps combined, and each of the four 50 m laps separately (for freestyle only). The typical error represents the magnitude of noise in the measure and the mean bias represents the mean magnitude the <i>Traqua</i> was different from the electronic timing. All estimates shown with $\pm 90\%$ confidence limits. Total number of samples $n = 989$ ; 1st 50-m $n=254$ ; 2nd 50-m $n=254$ ; 3rd 50-m $n=251$ ; 4th 50-m $n=230$ .....	132
<b>Table 7-1:</b>	The effect of time of day and previous session volume and intensity on the stroke rate and stroke count in the submaximal 200-m effort. All effects are represented as either strokes $\cdot 50\text{ m}^{-1}$ or strokes $\cdot \text{min}^{-1} \pm 90\%$ confidence limits. The qualitative likelihood of the effect being substantial in magnitude is indicated. ....	166

# LIST OF APPENDICES

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<b>Appendix A</b> - Example of the Accelerometer Traces Where the Algorithms Failed to Correctly Detect the Start, Finish, and Stroke Rate .....	203
<b>Appendix B</b> - Published Peer-Reviewed Articles and Abstracts .....	206