PERFORMANCE AND PHYSIOLOGICAL MONITORING OF HIGHLY TRAINED SWIMMERS

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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 ± 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

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*Australian Sports Medicine Conference, Canberra 2003.*


DEDICATION

To my parents, Alan and Dorothy Anderson

and my grandmother, Edith Haydon.
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REVIEW OF LITERATURE

PERFORMANCE AND PHYSIOLOGICAL MONITORING OF HIGHLY TRAINED SWIMMERS

1.0. Introduction

Swimming performance is determined by a series of interrelated physiological, biomechanical and psychological factors. The ability to train and optimize these characteristics enhances the likelihood of competitive success. In order for successful performance, the athlete needs well-developed physical and physiological characteristics specific to the requirements of swimming and the particular events in which they compete. The mental ability to cope with the rigors of competition and training is another key consideration. Coaches need to apply the scientific principles of training to long-term planning and short-term prescription of the physical preparation and recovery of their swimmers. Current practice in high level swimming involves the regular measurement of a swimmer’s underlying physiological and biomechanical components in order to optimize their performance. Continual improvement of a swimmer’s performance at the elite level is dependent upon a detailed understanding of a swimmer’s performance requirements and adaptation to training.

Swimming differs from many sports in a number of ways. First, it is one of the few sports where athletes compete in events that differ in both distance and technique (206). Swimming includes events involving four different strokes (freestyle, breaststroke, butterfly and backstroke) and an individual medley, where the one swimmer undertakes all in a
predetermined order. Competitive pool swimming events are contested over distances ranging from 50- to 1500-m. These events are typically divided into sprint (50- and 100-m), middle distance (200- and 400-m) and distance (800- and 1500-m) categories. These classifications differ from the physiologically-based definitions used in other sports. For example in running, sprint events are typically classified as 100- to 400-m distances; middle distance as 800- to 5,000-m; and distance as 10,000-m up to a marathon.

Second, competitive swimming is reliant on high rates of energy turnover, with the percentage contribution of the anaerobic systems decreasing as the event distance increases. In the shortest sprint events in swimming (50-m freestyle and form stroke), which last only 22 to 30 seconds, the predominant energy systems are the high-energy phosphate and anaerobic glycolysis. In contrast, aerobic glycolysis is the predominant energy system used in the longest distance pool swimming event of 1500-m lasting 14-16 minutes. Success in competitive swimming is simply defined as the shortest time required to propel the swimmer’s body over a given distance in the water (149). A combination of technique and exceptional physiological attributes are required for successful swimming.

Swimmers traditionally start training at a young age because it takes several years to develop the technical skills of swimming. An unusual feature of elite level swimming is the occasional emergence of outstanding athletes who achieve world-class performances at ages as young as fourteen or fifteen years old. This is particularly true of female swimmers. On the other end of the scale until recently elite swimming careers finished as athletes reached their early twenties. However, in recent times, improved funding and rewards for swimming performance (including commercial contracts) have encouraged modern swimmers to extend their careers for another decade. In fact, at the most recent Olympic Games in Athens, Greece
in 2004, eight swimming finalists were aged in their thirties and a number of others in their late twenties.

The training preparation in elite swimming is usually structured around major national and international competitions each year. A training preparation for specific competition can range in length, but is typically 16 to 20 weeks. The traditional approach to training in swimming is one of high volume, long distance training, although some contemporary coaches have employed lower volume and sprint-oriented training philosophies. The type of training completed will be dependant upon a range of factors including: age of the swimmer, short and long-term background of training, current level of fitness, and the specific event for which the swimmer is preparing for. The sprint athletes have a program that is more speed-orientated, while the middle distance/distance swimmers focus more on developing speed-endurance qualities to a greater extent. The volume of training varies from one individual to another, particularly at the elite level. It also varies according to the swimmer’s current phase of training. While there are marked differences in training between different types of swimmers, there are several common elements. In a usual week, elite swimmers typically train for 8-10 sessions in the pool, and undertake several dry land and weight training sessions, and occasionally add cross-training activities such as running or cycling.

Swimming performance is influenced by biomechanical, physiological and psychological factors. The biomechanical factors include swimming speed, stroke mechanics, starts and turning ability. The physiological factors include aerobic capacity, anaerobic power and capacity, muscle power and flexibility. Psychological factors of motivation and stress management are also critical at the elite level of competition (159, 200). The aim of the coach is to train, adapt and improve the swimmer’s ability in order to maximize the swimmer’s level
of competitive performance. The initial focus is to train the swimmer to withstand the physiological and psychological stresses of training required to prepare for the major competitions. Sport scientists monitor and evaluate the swimmer’s performance during competition and training to quantify changes in fitness and performance. This quantification and evaluation provides short- and long-term feedback to the coach and the swimmer. In competition, performance is typically assessed by analysing the race final and split times, technical components and strategy. In the training environment the scientist measures performance times, stroke mechanics and physiological markers. A major goal for the scientist is to provide objective information complementary to the subjective observations of the coach. Meaningful inferences about the data that is collected require detailed treatment of the reliability of measurements, precision of estimated changes and differences in performance and fitness, as well as reference values for interpreting these changes with respect to performance outcomes (18).

The general physiology of swimming has been previously reviewed (90, 122, 180, 223) although the direct relationships of performance and performance monitoring remain active areas of research. The high performance programs conducted by most of the leading swimming nations for elite swimming rely heavily on sports science, although surprisingly little research has been published on the monitoring of elite swimmers. Only one review by Smith et al. (200) has addressed the issues directly related to performance evaluation in training and competition in swimming. Many pertinent topics central to interpreting tests in cross-sectional and longitudinal settings, as well as new developments in technology as they relate to swimming, remain to be addressed. The purpose of this literature review is to outline the characteristics of elite swimmers, provide a critical commentary on the physiological and performance monitoring tools used to evaluate swimmers in competition and training,
examine important issues in data analysis and interpretation of results, and highlight some of the emerging technologies for monitoring of highly trained swimmers.

1.1. Performance of Elite Swimmers

The fastest swimmer is the athlete who can sustain the greatest power output to overcome the resistance or water drag in an efficient and skilful manner for the duration or distance of the competition (149). Inspection of the chronology of world records in swimming reveal that in most events new records are established on a regular basis, and apart from a small number of exceptions, few records survive more than 5 years. Figure 1-1 illustrates the progression of the 100-m freestyle world records for men and women over the past 20 years. A number of factors have contributed to the rapid progression of swimming world records in the past 20-30 years. While various developments such as the invention of the fast skin suits (21, 23), increased competition pool depth to reduce waves (23), and improved recovery and nutrition (35) have all contributed to improved performance, the characteristics of the swimmers and the training of the swimmers have played and are likely to continue to playing a substantial role in the evolution of world records.
Figure 1-1: Progression of the men’s and women’s 100-m freestyle world records over the past 20 years (1986 to 2006).

Elite swimmers are generally tall and lean with long limbs, wide shoulders, and relatively large muscle masses, especially in their middle and upper bodies (223). Swimmers also have a relatively long upper-body (24). A long upper body is advantageous when starting, turning, and finishing. Long body segments assist in stroking technique by covering a greater distance during a stroke (122, 218). To cover or travel the same distance, a taller swimmer requires
less power than a smaller individual (169, 234). The tallest swimmers are generally seen in the freestyle events from 50- to 200-m and backstroke. On the other hand, competitors in freestyle distances, breaststroke and butterfly competitors are considerably shorter in stature (187, 203). Cross-sectional and longitudinal anthropometric monitoring of swimming is undertaken for tracking changes during growth and maturation in younger swimmers, identifying swimmers who may be suited to particular events, and for monitoring the effectiveness of training and dietary interventions.

Swimmers generally have a well-developed aerobic capacity, but not as large as other endurance sports such as cycling or running. Maximal oxygen consumption (VO$_{\text{max}}$) has traditionally been used as the benchmark of the cardiorespiratory system’s capacity and the gold standard indicator of aerobic fitness. The maximum oxygen consumption of swimmers has been obtained in several different experimental approaches. Much of the early research used running, cycling, and arm cranking to measure capacities of swimmers due to the difficulty of collecting expired gas samples while swimming. Maximum oxygen uptake reported for swimmers during cycling were ~4.3 L.min$^{-1}$ and for running ~4.7 L.min$^{-1}$ (14). However, the evaluation of aerobic capacity should be conducted as close as possible to the real exercise conditions in order to obtain a valid assessment (122). Generally values are about 7% higher on the treadmill than on the cycle ergometer but only highly trained/skilled swimmers attain the same VO$_{\text{max}}$ during swimming as reached in cycling. Less well-skilled swimmers may show reductions (while swimming) of between 15% and 25% in VO$_{\text{max}}$ compared to cycling and running respectively (132). Skilled swimmers may be able to achieve maximum oxygen uptake in either running or tethered swimming.
The specificity of the test is also important as different musculature is involved in different types of exercise. In swimming, a large portion of the muscle mass involved is the arms and upper torso which is smaller than the muscle mass of the legs generally used in other types of exercise or tests. Therefore the use of tests which do not require a large commitment from the upper body may not adequately replicate the demands placed on the swimmer during maximal swimming. Some authors have reported modest correlations between VO2peak for the arms and swimming performance (88) but generally arm cycling or arm-cranking tasks lack the neuromuscular specificity needed for functional testing of the aerobic power of swimmers (122). More specific testing of VO2max of swimmers have utilised dry-land swim simulators, free swimming in the pool, tethered swimming, and swimming flumes.

Swimming engages practically all muscle groups of the body. It is therefore not surprising that very high oxygen uptakes have been obtained on swimmers (13, 88). A maximal oxygen uptake of 3.8 L.min⁻¹ was attained by the female silver medallist in the 400-m freestyle in the Olympic Games in Rome 1960 and another world calibre male swimmer had a maximum of approximately 6.0 L.min⁻¹ (12). In the 1970’s Holmér and co-workers studied 12 elite male swimmers and reported that VO2max averaged 5.1 L.min⁻¹ (range 4.0-5.9 L.min⁻¹) (91). In the same study, eleven elite female swimmers achieved an average VO2max of 3.4 L.min⁻¹ (range 2.9-3.7 L.min⁻¹) (91). Unfortunately, the majority of the studies which have reported oxygen consumption in swimmers were published more than 20 years old and there has been minimal reporting of these measures since.

Muscle fibre type is another area of physiological investigation of trained swimmers. Studies examining muscle fibre types in swimmers using the muscle biopsy technique have reported inconsistent results, with percentages of Type I fibres in competitive swimmers ranging from
40% to 75% (51, 163, 220). The muscle predominately used for fibre type analysis in swimmers has been the *deltoid* given its level of activity during freestyle swimming (103). However the *vastus lateralis*, *triceps*, and *latissimus dorsi* muscles have also been examined (103, 123). Gollnick et al. (79) reported that the *deltoid* of competitive swimmers had a composition of 75% Type I or slow twitch fibres and 25% Type II or fast twitch fibres. Similarly, Costill et al. (52) reported 68% Type I fibres in the *deltoid* muscle of elite collegiate swimmers, while Houston et al. (104) reported 62% were Type I fibres. More recently, Trappe et al. (220) reported a distribution of 65% Type I and 36% Type IIa muscle fibres with no Type IIb fibres identified in collegiate swimmers. Gerard et al (78) reported that there appeared to be no differences in Type I or Type II fibre areas among the different distance groups for the male and female swimmers. The invasive nature of the research in muscle fibre recruitment, and its research orientation, generally preclude use of biopsies in elite swimmers preparing for competition. While the calculation of muscle fibre types may be interesting for profiling purposes, it is probably not particularly useful in practical monitoring of swimmers.

The nature of swimming and the aquatic environment impose unique stressors on the pulmonary system of swimmers. During swimming, breathing is restricted to, and synchronised with, the arm action and head movement associated with the different swimming strokes. The duration of the inspiratory phase is reduced compared to land-based exercise (except in backstroke) and expiration in all strokes apart from backstroke takes place under the water surface. These water-imposed restrictions elicit a greater resistance than in air (90). Unlike other athletes, swimmers appear to have an enhanced pulmonary structure and function (50), with larger static lung volumes than age- and sex-matched non-swimmers or predicted values (29, 131, 151, 236). While a genetic contribution is likely to underpin the
variation in these traits, it appears that swim training causes a larger expansion of the lungs compared with land-based exercise (6, 17, 46, 235). Elite male and female USA swimmers have significantly larger lung capacities, flow rates and diffusing capacity that predicted values of similar matched athletic groups (29). The larger lung capacities and associated pulmonary characteristics of swimmers highlight the importance of breath timing in swimming, and the limitations imposed by the environment on three of the four strokes (i.e. face underwater restricts the freedom to breath). However in terms of monitoring training adaptations of the individual or a homogenous group of elite swimmers respiratory measures are probably not overly useful characteristics to examine. Typically, lung capacities are only measured when a swimmer is suspected of having exercise-induced asthma or some other medical condition.

1.2. Limitations to Swimming Performance

Fatigue is a daily issue faced by highly trained swimmers preparing for competition. Coaches and swimmers need advice on the strategies required to limit the deleterious effects of fatigue in order to enhance technical, physiological and performance. Physiological and biochemical adaptations that occur in response to physical training and the mechanisms that limit exercise have been extensively studied (11, 70, 81, 159, 160). Impairment of performance is a complex multi-factorial process, in which the underlying physiological mechanisms responsible vary depending on the duration and intensity of the exercise (70). Fatigue has been defined as the failure to maintain the required or expected (muscular) force (66). In swimming, fatigue is generally observed as a reduction in speed. The mechanisms responsible for fatigue is dependent on the fibre type composition of the contracting muscle(s), the intensity, type and duration of the activity and the individual’s degree of fitness (71). Noakes (159) categorised mechanisms of fatigue and exercise performance into five
models. These models are: the cardiovascular/anaerobic model; the energy supply/energy depletion model; the muscle power/muscle recruitment model; the biomechanical model; and the psychological/motivational model. This contemporary approach overcomes some of the limitations of the rather simplistic three-energy systems model that has dominated exercise prescription over the last 30 years.

The cardiovascular/anaerobic model proposes that performance during high intensity swimming is limited when the heart is no longer able to supply sufficient oxygen and remove waste products to and from the working muscles. Based on this model, measures of submaximal and maximal oxygen consumption are routinely measured in athletes to determine their capacity for oxygen delivery and utilisation. However, due to difficulties in measurement of oxygen consumption in the aquatic environment this is not measured routinely in swimmers. Metabolites such as hydrogen ions and lactate accumulate within the working muscle and may possibly inhibit the contractile processes (70). High levels of blood lactate (12-20 mM) are often observed at the end of races, particularly 100-400 m events. However, more recent research has suggested that the production of lactic acid does not impair skeletal muscle function or efficiency, and in fact may have beneficial effect on muscular contraction (32, 37). In this light a high blood lactate level may be a good sign of an accelerated anaerobic metabolism needed to swim at high velocities. Nevertheless the blood lactate concentration is one of the most commonly used measures in sport science to monitor an athlete’s exercise intensity, training adaptation and recovery.

The second Noakes model of exercise performance is based on the concept of a failure to supply sufficient ATP via the various metabolic pathways and that fatigue is the outcome of a depletion of endogenous substrates. In short high-intensity exercise such as competitive pool
swimming the supply of ATP at sufficiently high rates is likely to be more of an issue than the depletion of muscle glycogen. Whereas training in swimming involves a combination of high-intensity efforts and prolonged high volume. Swimming training usually involves at least 2 hours per session and up to 3 sessions per day in some training phases. Consequently the energy/substrate depletion may impact on a swimmer’s ability to consistently train at the level required.

The model of neuromuscular fatigue or muscle power/muscle recruitment proposes that there is a reduction in the force or power production of a muscle, despite increases in perception of effort. The processes in this model include skeletal muscle recruitment, excitation, and contraction. The central nervous system plays a key role in muscle contraction and reduced concentrations of the brain neurotransmitters serotonin and dopamine decrease the flow of neural impulses to the muscle resulting in fatigue (61, 147). Coaches and swimmers are well acquainted with the feeling of fatigue and lethargy which is possibly related to this element of neuromuscular fatigue.

The biomechanical model proposes that fatigue is determined by the efficiency of movement patterns during swimming. Technique and efficiency of movement are important in enhanced swimming performance. Given the drag forces evident in swimming, inefficient movement will come at a substantially greater physiological cost. Improved swimming efficiency will lead to a reduction in the oxygen consumption required to handle a given workload, as well as a delayed accumulation of metabolites and a reduced depletion of energy stores. Another aspect of this model is that the more elastic muscle fibres are more fatigue resistance and may aid in injury prevention. Notions of muscle elasticity have not been considered in the traditional energy systems model of swimming performance.
Finally, the athlete needs the motivation and cognitive ability to withstand the discomfort associated with maximal exercise and sustained high intensity exercise. The central neural drive is reduced with lower motivation and a conscious effort is required to sustain exercise performance. The level of motivation of the athlete certainly will affect their ability to train and perform. In day-to-day training the level of motivation may play a role in tolerating intensive and high volume training. At the elite level of competition, athletes are usually highly motivated to perform and anecdotal accounts of athletes pushing their bodies beyond the extreme are not uncommon.

All five models proposed by Noakes have application to performance in competitive swimming in both competition and training, and the physiological testing used to monitor elite swimmers. It is highly improbable that the factors explaining human exercise performance under all conditions are restricted to a single physiological system or model (159). More recently a complex systems model of fatigue has proposed that fatigue is not dictated by any one of these models alone. Rather exercise performance is continuously manipulated in response to the interactions of numerous physiological systems monitored via constant feed-forward and feedback loops controlled by a central governor (116, 160). The type of fatigue that limits exercise performance is task dependent and involves various mechanisms. A clearer identification of the factors determining fatigue and swimming performance may help coaches and scientists determine which training adaptations are more important for swimming performance, and how training should be structured to maximise those adaptations. Many of the current methods employed by sport scientists to evaluate competition and training performance and adaptations are based on aspects of the Noakes models of fatigue/exercise performance.
1.3. Performance Evaluation of Swimmers

The evaluation of competitive performance provides a framework or reference model for the preparation of swimmers in training. The annual training plan, the detail of the macro- and micro-cycles, and the prescription of individual training sessions and sets, is all based on the competitive race model. At the elite level of swimming, the Olympic Games is the premier competition and forms the basis of the four year planning cycle. The benchmark evaluation measures are competitive performance times across swimming events, distances, strokes and competitions.

Study of the progression and variability in performance time provides a framework for preparing a competitive model that forms the basis of training. A key study that used this approach analysed performance leading to and including the Sydney 2000 Olympic Games (178). This study reported the magnitude of progression within and between competitions for Olympic level competitors. The typical improvement was ~1% in competition time in the 12 months leading to the Olympics. The progression (improvement) from heat to the semi-final and final during a competition was also ~1%. An overall improvement of ~1-1.4% in performance time for elite swimmers was indicated to account for both progression and variability in the pre-Olympic year. These reference values provide valuable information for coaches and swimmers in their long term or annual planning, and also in qualification strategies within a competition.

A major focus of high level swimming programs is the preparation between the national championships (selection trials) and the major international competition for the year. Contrary to popular belief, many swimmers do not swim any faster at the Olympics than in
meets earlier in the year. A marginal decline in mean performance time from the world-rankings time to the Olympics of 0.3% (95% confidence limits; 0.2-0.4%) has been observed (222). It is apparent swimmers need to be ranked in the top 10 of the world ranking to have a realistic chance of an Olympic or World Championships medal. In terms of consistency, modelled as the coefficient of variation in performance time, medallists (~0.7%) are slightly more consistent than non-medallists (~0.8%) (222). Gold medallists showed a larger mean progression (1.0%) than all medallists combined. A majority (60%) of Olympic medallists were ranked top-3 in the world leading up to the Olympics and the majority were ranked top-10 (87%). Half of the swimmers ranked number one went on to win a gold medal in that particular event. Clearly swimmers must be highly ranked in their competitive event to have a realistic chance of success.

A major issue for coaches and swimmers is the absolute world ranking of performances in the lead-up or preparation to major competition. Official world ranking lists are easily accessible on the internet and widely used by coaches and swimming programs to ascertain the positioning of swimmers relative to their competition, and the likelihood of success at forthcoming competitions. Top-50 world ranked swimmers typically did not improve on their previous best time that year at the Olympic event (222). These findings contradict the widely held view that leading swimmers will swim faster at the Olympics than in meets earlier in the year. Medallists demonstrated a substantial improvement in performance of 0.6% (0.4-0.9%) at the Olympics while non-medallists were 0.6% slower (0.5-0.7%) at the Olympics compared with their world-ranking (206).

A critical time point for performance evaluation of the elite swimmer is the taper before competition. The taper is a progressive reduction in training load for a variable period of time
before competition to allow for physiological and psychological recovery from accumulated training stress in order to maximise performance at competition (155). The evaluation in the taper is normally a combination of competitive performance and routine pool-based training. Increasing race speed is the main priority for swimmers and coaches. Mujika et al. (154), reported a 2.2% mean improvement in swimmers performance time during their final 3 weeks of their preparation. Another study reported performance improvements in swimmers of a similar magnitude (~3%) for tapers of 3 and 4 weeks in duration (152). These findings and similar reports indicate that many of the adaptations in performance come late in the preparation in the overall context of a long season. These observations provide some justification for monitoring time trial performances in training during the taper period. Clearly coaches and swimmers should consider the benefits of undertaking minor competitions before the major competition of the season to assess progress and where necessary, make final adjustments to pacing strategies, technical issues or physical preparation.

1.3.1. Analysis of Race Performance

Successful performance in competitive swimming is ultimately determined by a swimmer’s final time and which of the eight swimmers is the first to touch the wall. The overall race time can be divided into four distinct parts: starting, turning, free swimming time, and finish time (170). In the free swimming component of a race (the section excluding starts, turns and finishing) the velocity and stroke characteristics are calculated, where the \( \text{velocity} = \text{stroke rate (SR) x stroke length (DPS)} \) (170). Simplistically, and not accounting for contribution from the leg action, swimming velocity is the product of stroke length and the stroke frequency (59). The analysis of these various components of race performance plays an important part in the identification of weaknesses in techniques or tactics (143). Even at elite
levels and particularly over the middle distance and distance events, it is common for the swimmer with the fastest actual swimming time not win the race due to time lost starting or during turns (142, 143). Competition analysis provides essential information for the athlete, coach and sport scientist, and can be used to alter a swimmer’s strategies in subsequent races. The race analysis data can be used to develop a model for each individual swimmer in the training environment.

Several methods of obtaining competition analysis data both in real time and after the event are currently employed by leading nations at international swimming competitions. An example of a current race analysis report is shown in Figure 1-2. This report combines numerical data with 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. In order for race analysis to be performed, video footage of either individual swimmers, or a series of video cameras covering all eight lanes, is captured. The video footage is usually collected from an elevated view in the grandstand. The electronic starting signal is used and the split and final times from the electronic timing system are synchronized and incorporated into the analysis. The starting time was initially measured as the time from the starting block to 10-m and the turns were determined as 7.5-m in and out (142, 200). However, in 1991, the international governing body of swimming, Federation de Natation Amateur (FINA), modified the rules to allow swimmers to remain completely submerged following the start or a turn for not more than 15-m. Subsequently swimmers, particularly those swimming backstroke stayed underwater longer, which meant that the calculation of free swimming included some of this underwater swimming following the turn. The current international
format for race analysis utilises a 15-m start and a turn distance of 5-m in and 10-m out for all events. Finish distance is set at 5-m from the wall but is taken from when the swimmers head passes the 5-m to the hand touching the wall. The estimated time is actually divided by 4.5-m to account for an estimated arm reach to the wall of 0.5-m.

At major international competitions, such as the 2000 Olympic Games a competition analysis system was used to analyse all eight lanes of a race (141). This approach involved a large-scale operation of technicians to collect and analyse the races including video recording, clip acquisition and data analysis. However, in recent times a single operator for single-swimmer systems has become increasingly employed due to its portability, cost-effectiveness and ease of use. However a comparison of the accuracy and reliability of the different systems has not been reported in the published literature. Both the single-swimmer/operator and the large scale methods of competition analysis have advantages and limitations which influence the accuracy and reliability of the information provided.
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 that of the women’s 200-m breaststroke world record (as at June 2006). Segments are: Vel = velocity; SR = stroke rate; DPS = distance per stroke or stroke length; In/Out (BO) = the time from 5 m into the wall and 10 m out of the wall on a turn; Turn = the total time of the In/Out; Split = 25 m times; Lap = 50 m lap times; 100 m = 100 m split times (report provided from the Queensland Academy of Sport).

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<th>Segment</th>
<th>Vel (m/s)</th>
<th>SR (str/min)</th>
<th>DPS (m)</th>
<th>Count</th>
<th>In/Out (BO) (s)</th>
<th>Turn (s)</th>
<th>Split (m:ss.00)</th>
<th>Lap (m:ss.00)</th>
<th>100m (m:ss.00)</th>
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<td>40.4</td>
<td>2.17</td>
<td>10</td>
<td>3.20~4.50</td>
<td>9.76</td>
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<td>39.9</td>
<td>2.24</td>
<td>18</td>
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<td>125-150m</td>
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Summary Data

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</table>

| FINA Pointscore: | 1072 |

![Diagram](image-url)
Studies analyzing the stroking techniques and comparisons of elite swimmers in competition have been published since the late 1970s and early 1980s (59, 60, 170). In a number of studies, the relationships between velocity, stroke rate and distance per stroke or stroke length has been examined in detail. A number of researchers have examined the typical stroke characteristics in high level competitions, including the Olympic Games (43, 45, 60, 109, 124, 170). These studies have outlined the changes in stroke rates and stroke lengths lap by lap for the various swimming events and strokes. To improve performance, swimmers can make changes to their either the stroke length or their stroke rate. The relationship between velocity and stroke rate has been previously illustrated as a stroke rate-velocity curve (60). In a comparison between the 1976 and 1984 Olympic finalists across all events, Craig et al. (60) found that improvements in velocity between the two competitions was attributable to an increased stroke length, combined with a decreased stroke rate in 9 out of the 11 events. A study of Seoul 1988 Olympic competitors identified that for male and female competitors in the 100- and 200-m single stroke events (i.e. not individual medley) stroke length was the single most important factor affecting final time. A strong relationship was also shown between height and final time (43, 109).

1.3.2. Biomechanical Monitoring of Training

Swimming is a highly technique orientated sport. The best swimmers are characterised by better efficiency in propulsion over a set distance conducted in a fluid environment (186). Biomechanical factors are a key aspect of swimming performance. The tools that can be used to assess the technique and biomechanics of a swimmer range from highly sophisticated, such as computational fluid dynamics, to simple measures like stroke rates which can be easily used by coaches. Observational monitoring of technique with the use of video cameras is also frequently used.
In swimming, biomechanical skill is arguably of far greater importance for metabolic economy than in running and cycling. Elite swimmers adopt combinations of stroke parameters which are very different from those used by their less proficient counterparts. The regular monitoring of stroke rates and stroke counts is important, given that the economy of a swimmer’s stroke technique impacts substantially on the energy cost of swimming and subsequently performance (39). Wakayoshi and co-workers reported a significant correlation between oxygen uptake and stroke rate and between stroke rate and swimming velocity cubed, for all subjects tested (230). These authors suggested that the slope of the regression line between oxygen uptake and stroke rate was an effective index for evaluating swimming. Swimmers need to be advised by coaches about the different combinations of stroke rate and stroke length to develop fitness and speed. Experienced coaches use stroke rate monitoring in the practical setting, but the benefits are difficult to obtain when faced with large squads of swimmers.

1.3.3. Anaerobic Power and Strength Evaluation

The assessment of anaerobic performance is another important aspect of the holistic assessment of the requirements of an elite swimmer in competition and therefore training. Several studies have reported that improvements in swimming performance are associated with increased power output (53, 194, 219). Moreover there are strong relationships between arm muscle power, determined on a biokinetic swim bench, and sprint freestyle swimming performance (157, 194). Studies have shown that swimmers with a higher optimal speed during the biokinetic testing had a faster maximal swimming speed (194). Reilly and co-workers found no relationship between swimming performance and isokinetic strength, power, or endurance of the shoulder, elbow, wrist, hip, knee, or ankle (179). Another study of
elite freestyle swimmers also failed to establish a substantial relationship between biokinetic power measured biokinetically and swimming performance (193). Biokinetic swim benches are unable to duplicate the specific three-dimensional arm and hand action used in the water. Given these limitations, the swim bench only enjoys moderate popularity among higher level swimming programs.

Other disadvantages of swim benches are the absence of leg work and limited shoulder rotation. In free swimming the disruption of steady-state work by turns and the manoeuvrability of the accessories attached to the swimmer may pose problems. In tethered swimming the swimmer stays virtually stationary and pulls a weight in a line-pulley system while employing the swimming action. A disadvantage of tethered swimming is the alignment of the swimmer’s body and the water flow around the swimmer differs from that in true swimming (122). A swimming flume allows for the swimmer to swim in a tank against water flow that has a controlled velocity, however similar to the disadvantages of tethered swimming, the water flow around the swimmer may not exactly replicate that experienced in the swimming pool. Access and the expense of some of this equipment such as a swimming flume also limit their use. Other researchers have developed further in-water methods of measuring strength, such as the MAD system developed by Toussaint and colleagues (218). This system is comprised of pads mounted underwater that measure the force produced by the swimmer as they use the pads to propel themselves forward while swimming (218, 219). New insights and technologies that do not interfere with the swimmer and that can be used routinely in training are needed to advance the monitoring and assessment of highly trained swimmers.
1.3.4. Critical Speed

The concept of critical speed has received attention by swimming researchers since the 1980’s. Critical swim speed is based on the linear relationship between swimming distance and exhaustion time. However this relationship cannot simply be described by a single linear expression and is actually the complex interaction of several linear relationships. Critical speed has been proposed as a means of assessing changes in physical performance, primarily aerobic fitness without the need for blood sampling (232). Critical swimming speed is typically estimated from a series of maximal effort swimming speeds over common race distances. From the linear regression equation swimming speeds (for distances of 200- to 1500-m) which can theoretically be maintained without fatigue are calculated (231). Wakayoshi and co-workers reported that critical swimming speed determined both from free and flume swimming was correlated with speed at the onset of blood lactate accumulation, maximal lactate steady state, and 400-m swimming speed (231, 232). These researchers suggested that this method was a viable means of assessing performance without the need for blood sampling (232). Dekerle and others (63), in a study of high level French swimmers reported that critical swimming speed could be used as relevant criteria for a physiological and technical evaluation of the aerobic status. In contrast, a more recent study from the same group of researchers found that critical swimming speed does not represent the maximal speed that can be maintained without a continuous rise of blood lactate concentration (62). Despite the interest of researchers in the concept, critical speed has not been widely employed in the field by high level coaches and swimmers. The reluctance to incorporate this form of evaluation is partly related to the need for mathematical modelling or processing of data, and the logistical difficulties in getting swimmers to routinely undertake maximal effort time trials in testing.
1.3.5. **Body Composition**

A high lean body mass and a low relative fat mass are morphological traits common to outstanding male and female athletes, particularly in sports where speed, power and strength are important (84). Swimmers, however, appear to have moderately higher levels of body fat than other elite athletic groups (217). A certain level of body fat may be useful for the swimmer, by enhancing buoyancy and body position in the water, or by providing rounded body surfaces which are more favorable for streamlining with less drag characteristics (23, 205). Male swimmers are primarily of an ectomesomorphic somatotype while females are principally endomesomorphic (1, 8, 197). Sprint swimmers typically have a higher mesomorphic component of the somatotype than distance swimmers (69). Despite some anecdotal claims of a relationship between fatness and performance in swimming, a number of studies report that body fatness per se is relatively unimportant (205, 229). Stager et al. (205) reported that the faster swimmers in a group of female 12-17 year old competitive swimmers had a greater fat free mass but did not differ in body fatness (as measured by hydrodensitometry) from the slower swimmers. Nevertheless, coaches at the elite level of swimming place an emphasis on the achievement of low levels of body fat and consequently routine the monitoring of subcutaneous body fat is undertaken.

The measurement of skinfold thickness over seven sites is commonly used as a measure of body fat. Although there are acknowledge flaws in the skinfold measurement techniques used to estimate body fat, the measurement of skinfolds is relatively straightforward and readily implemented in practice. The subcutaneous region is a primary site of body fat and changes in the sum of skinfolds are widely used to infer changes in body fat storage. Other common methods used to evaluate body composition include hydrodensitometry, bioelectrical impedance, and dual X-ray absorptiometry (DXA) (129). Recently, a novel method of
monitoring changes in lean mass based on skinfold and mass changes has been evaluated (199). The lean mass index (LMI) is an empirical measure that tracks within-subject proportional changes in body mass adjusted for changes in skinfolds (173, 199). The LMI method has been validated against the four compartment method (body density, total body water, isotopic deuterium dilution, and DXA) and has similar accuracy as other skinfold-based measures of lean mass (199). Consequently the LMI can provide a convenient alternative to other more time consuming methods for the routine monitoring of lean mass.

Only a small number of studies have examined changes in the body composition of highly-trained swimmers during a season or across several seasons. A study of 21 collegiate swimmers reported declines in fat mass during the season for female swimmers but not male swimmers (161). In a study of 15 collegiate female swimmers, a substantial decrease in body fat as measured by hydrodensitometry and skinfolds measures (3 sites) was observed following nine weeks of competitive training (229). Another study of 15 elite female swimmers monitored at three points during a competitive season, also reported substantial changes in body composition (148). However, these changes were only evident during the early part of the season when training was intense (10 sessions per week versus six sessions later in the season) and the reduction in body fat paralleled gains in lean body mass (148). Alméras and co-workers (3) reported a stable body composition in elite female swimmers over a 13-month period of training, but a body weight gain of ~3 kg predominately from fat gain during a 2 month period of detraining. The body fat gain during the period of no training was purportedly due to a failure to reduce the energy and fat intake to the level required for the lower energy expenditure. A case study of two male swimmers showed variable individual responses, with one swimmer increasing his lean mass and reducing body fat, while the other losing both lean body mass and body fat (84).
More recently, a comprehensive longitudinal analysis of the body composition (body mass and sum of 7 skinfolds) of 77 elite male and female swimmers over a 14 year period has been conducted (173). In this study, there were seasonal reductions in body mass of ~1%, together with a ~10% reduction in skinfolds. However, between seasons, there was a 0.9% increase in mass for the males and a 0.4% increase for the females, with minimal changes in skinfolds. Changes in lean mass using the novel LMI method have also been reported (173). LMI increases for the male swimmers during a season were approximately twice as great as those observed in the female swimmers (1.1% versus 0.6%). Similarly there were substantial increases in LMI each year. Over a season, there were marked reductions in body fat accompanied by modest changes in total body mass and lean mass. The majority of the studies report either stable levels or a decline in body fat in swimmers over a training season, whereas in the long-term there were likely to be minimal changes. The impact of these body composition changes during and between training seasons on performance has not been assessed in any of these studies. The question of whether body fat changes have a substantial influence on an individual swimmer’s ability to perform warrants further investigation.

1.3.6. Physiological Monitoring of Training

The monitoring of physiological variables in training is routinely conducted within many high level swimming programs. In the case of swimming, there is typically only one major competition at the end of the season, and therefore time trials, fitness tests and monitoring of training are employed to monitor the progression of a swimmer’s performance. Physiological monitoring can be conducted in the laboratory or pool. Methods of physiological monitoring are either those that produce an integrated or average measure of training over a period of time such as a fitness test, or those that monitor a training session while it is in progress (97).
Monitoring can include includes the measurement of blood lactate, heart rate, or oxygen consumption at maximum effort and/or at a submaximal pace such as at the anaerobic (lactate) threshold.

The value in performance tests lies in well-designed routine monitoring of individuals within and between seasons rather than ad hoc or one-off testing. Furthermore, parallel monitoring of maximal and submaximal physiological and performance measures has not been systematically undertaken in previous longitudinal studies of collegiate (137, 181, 195) or elite (27, 171, 176) swimmers within a training phase or over several phases. Some investigators have attempted to develop mathematical models of training and performance in elite swimmers (16, 86) but these have not been widely used in practice.

Progressive incremental tests are commonly used to assess the physiological adaptations of swimmers, and measure blood lactate and heart rate over a range of intensities culminating in a maximal effort (85, 176). Incremental swimming tests can also provide feedback on pacing and stroke/movement characteristics at increasing speeds. The evaluation of physiological and sport-specific performance measures provides fundamental information to the coach, athlete and sport scientist on the athlete’s response to the training program (200). Given that performance in swimming is closely related to the physiological adaptations induced by the athlete’s training program (65), the assessment of various components of performance provides important information on training progress and competition potential. The most practical tests for elite athletes are generally those that are easily administered in the training environment. Ease of testing in the field is especially important in swimming where the demands cannot be easily replicated in a laboratory setting (56).
1.3.6.1. Blood Lactate

Measurements of lactate and swimming velocity have been widely used to monitor the training state of swimmers by identifying an intensity (velocity) at a fixed blood lactate or lactate threshold (85, 137). The main premise for this type of testing is that the lactate threshold is a useful measure of submaximal endurance fitness and assumed to reflect training-induced adaptations occurring in the skeletal muscle (176). Figure 1-3 shows the rightward shift expected in a blood lactate-velocity curve associated with improvements in an incremental swimming test. The changes in the lactate threshold through a training season have been previously documented in swimmers (176), but there is limited information available on international level swimmers, or on any swimmers taken consistently within and between seasons.

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.
Several studies have used the relationship between blood lactate concentration and swimming velocity to predict performance or determine the appropriate exercise intensities during competition (41, 176, 189, 231) or training (130, 137, 176), and to gauge swimmers’ adaptation to training programmes (111, 188). Theoretically, the velocity eliciting a blood lactate concentration of 4-mM (or similar reference level) provides information that can be used to establish training zones for prescription of training speeds. Blood lactate tests must be reproducible and able to detect meaningful changes to confidently monitor changes in training status.

In a study of female collegiate swimmers of a high standard (i.e. 8 of 25 were Olympians), Ryan and co-workers used a three stage incremental (aerobic, threshold and maximum) 500 yard swim to assess the adaptations of the swimmers periodically throughout a training season (188). This study observed an increase in swimming velocity at a 4-mM blood lactate concentration when training volume increased early in the season; however the swimming velocity at a 4-mM blood lactate then remained stable throughout remainder of year, despite further increases in the volume. Heart rate and blood lactate profiles have been shown to track concurrent (within 2 days) performance changes in competitive swimmers over a season (195). Mean velocity predicted from lactate profiles had a large correlation ($r = 0.61$) with actual competition velocity (195). However, other researchers have found only trivial relationships between changes in competition performance and a change in physiological variables when there are two or more months between testing and competition (176).

The measurement of blood lactate in training is commonly used in high-performance programs, despite the associated costs and time. In some cases blood lactate testing can be
Blood lactate is a highly variable measure, with levels influenced by several factors including diet and muscle glycogen availability. Data should also be interpreted in conjunction with swimming times. Nevertheless blood lactate is a viable and easy to use measure of intensity and adaptations to training loads and therefore applications of lactate testing in swimming warrant further investigation.

1.3.6.2. Heart Rate

Heart rate testing is one of the most common forms of physiological monitoring, given the availability of several different heart rate monitors that can be used in the pool. Heart rates are often taken during submaximal and maximal effort swimming to evaluate the response to different training sets. During swimming, peak heart rates are typically lower than those obtained on land (14, 90, 133), approximately 12 to 15 beats min\(^{-1}\) when comparing maximal swimming to maximal running (90). Several reasons for the blunted heart rate response in the pool have been proposed, including the utilization of a smaller muscle mass (89, 133), or altered hemodynamics associated with a horizontal body position or reduced effects of gravity (134).

Studies of heart rates obtained from highly trained college swimmers using tethered and free-swimming ranged from 181-186 beats min\(^{-1}\) (132). Magel and co-workers (134) reported that swim events of longer duration tend to elicit higher peak heart rates (~173 beats min\(^{-1}\) for 50-100 m versus ~181 beats min\(^{-1}\) for 200-m events). With the exception of breaststroke which tended to have a lower heart rate, there were no differences observed in heart rate between the other three swimming strokes (134). It appears that establishing heart rate profiles for each individual swimmer in the various strokes employed in training is useful. Heart rate is a
measure that coaches and scientists can routinely use in training as means of determining training intensity and evaluate changes in physical condition (136).

1.3.6.3. Oxygen Uptake and Swimming Economy Testing

Measurement of expired ventilation for swimmers has involved several different techniques including the swimming flume, tethered and free swimming. In free swimming, two methods have primarily been used to measure oxygen uptake. The first method uses a mask or snorkel device to gather expired gases in Douglas bags (26), or more recently as breath by breath gas analysis (112). Critics of this technique feel that swimming with a mask and tubes increases the workload so that swimmers consume more oxygen at a given speed than they would when swimming without any equipment (136). They also argue that the equipment may inhibit performance and prevent the athlete from reaching true maximum levels of oxygen consumption (136). The second procedure, known as backward extrapolation was developed to estimate an athlete’s oxygen consumption during the preceding swim. This method requires the swimmer to hold their breath for the last stroke and upon finishing swimming put a mask on and provide a 20-30 second sample of expired ventilation (150). The value for oxygen consumption is extrapolated backward to the last minute of the swim and is presumed to be equivalent to the athlete’s rate of oxygen consumption per minute during the swim. Critics of the backward extrapolation method believe that the potential for error is too great when measurements are taken from such small samples of air immediately after a swim effort (136).
1.4. Interpreting Test and Performance Results

At the elite level of competition, athletes are managed on an individual basis. In research settings, on the other hand, experimental variables are manipulated and reported in terms of the mean effects on the sample. This may mean that the results of experimental studies do not readily translate to the real-world for all athletes. Another challenge in the elite sporting setting is the difficulty of incorporating a control group into the experimental design. Factors that are difficult to control can impact on an individual’s performance and their long-term variability, such as the residual fatigue from heavy training, psychological factors, or even weather conditions if testing, training, or competing outdoors.

Standard statistical significance testing provides only a limited interpretation of the meaningfulness of changes and differences in performance for the elite level athlete (15, 208). Interpretation of test results to a coach and/or athlete should account for the magnitude of the effect, the smallest worthwhile change in performance for that sport or event, and the precision of the estimate (95). More contemporary methods involving precision of estimation and magnitude-based inferences provide a means to interpret whether an intervention has a practical benefit or harm rather than ruling out results based on a predetermined significance level of $p < 0.05$ (18, 99, 100, 208).

The magnitude of error or noise in a test is usually obtained from establishing the test retest reliability. The other aspect of the contemporary analytical approach is the need to use confidence limits which specify the range that the true value is likely to fall. Accounting for the typical error of an instrument or procedure allows for better judgements about whether a result is real and not simply an artefact of inaccuracies or variation in equipment (80).
The within-subject variation also affects the precision of estimates of change in a dependent performance, physiological or biomechanical measure. The smaller the within-athlete variation, the more likely a change in performance will be able to be measured. The within-athlete variation is expressed as a coefficient of variation (CV) or the percent of random error. For example, the variability of performance as a CV, is the standard deviation of performance time expressed as a percentage of mean performance time (96). This statistic is important when investigating strategies or factors that might affect performance (206). Consideration of the relative magnitudes of the signal (magnitude of observed change or difference) and the noise (magnitude of typical error in the measurement) is a clearly a critical issue for sports performance researchers.

Another important aspect in sports performance research is establishing the magnitude of the smallest meaningful performance change. Hopkins et al. (100) has championed the concept of the smallest worthwhile change or enhancement, which is the amount of improvement required to substantially increase a top athlete’s chance of winning a medal. The smallest worthwhile change is calculated as an amount equivalent to approximately 0.5 of the coefficient of variation (100) based on computer simulations of real world performances. The magnitude of the smallest worthwhile change has been established in several sports, primarily track and field events, cycling and swimming (94, 101, 178, 206, 222). In Olympic-level swimmers, the smallest worthwhile improvement has been estimated as 0.4% (178, 222). When interpreting an effect in research or practical settings in the field, it is informative to describe the probability that the effect was beneficial (substantial improvement), trivial or harmful (substantial impairment) in performance terms (99). Using the probabilities of practical significance takes into account the precision of estimation and the smallest
worthwhile change. Furthermore, assessing the responses of individual athletes should also provide more useful information to the coach and scientist (175).

1.4.1. Variability in Swimming Performance

The variability of individual responses in physiological measures and performance, rather than purely reporting the mean trends, has not normally been addressed in studies. Hopkins and co-workers used simulations of competitive running events to demonstrate that the reliability of performance in the same event between competitions is the key factor in determining the extent to which a performance-enhancing strategy affects the chances of an athlete winning a medal (100). In swimming, the variability of performance in competition has been established in elite and sub-elite swimmers (178, 206, 222).

Stewart and Hopkins reported that elite junior swimmers were more consistent in using a single stroke across several distances than in swimming different strokes over different distances (206). At the Olympic-level, a slightly greater variation was observed for both male and female swimmers across different distances than between strokes, with a typical coefficient of variation of ~0.8% between strokes and ~0.9% between distances (222). In that study, greater consistency was observed both across different strokes, and across different distances for the male swimmers when compared with the female swimmers (222). Pyne and co-workers observed that among USA and Australian swimmers, freestyle and backstroke swimmers were the most consistent within a competition and between competitions, while butterfly swimmers were the least consistent of the four swimming strokes (178). However, the freestyle events did not include the distance events (800- and 1500-m) as this would have over-inflated the within-competition variability. These data are important for swimmers and
coaches in practice, and for researchers interpreting the magnitudes of training interventions on swimming performance.

Regardless of distance or stroke, the magnitude of variability in competition performance observed in the Olympic-level swimmers was substantially smaller than that observed in the elite junior swimmers. Trewin et al. (222) reported a variation of 0.8% in performance for Olympic swimmers in major competitions from one year to the next, in comparison to the coefficient of variation of 1.4% reported for elite junior swimmers (206). Furthermore in the study by Stewart and Hopkins, the faster swimmers displayed greater consistency than the slower swimmers (206). Faster swimmers may prepare more consistently for competitions, pace their races more effectively, and are more likely to maintain effort right to the end of the race because they are in the running for a medal. This observation also appears to be replicated at the Olympic level between medallists and non-medallists (206). Medallists demonstrated a greater consistency in performance (~0.6%) at the Olympics than non-medallists swimmers who were still top-50 world ranked (~0.9%) (206).

While the variability of swimming performance within a competition across different strokes, genders, and distances, and the progression over several competitions has been established, the variability of performance in swimming training is yet to be established. This information would be useful when interpreting changes in test performance in training and tracking long-term changes of individuals. Establishing the variability in training performance in different phases of training, as well as in the long-term, would enable a better understanding of consistency and adaptations of elite swimmers.
Two key considerations in physiological monitoring with routine pool tests are progression in performance and the expected magnitude of variation. Pyne et al., (176) reported that the typical variations in performance times were ~2-4% in international Australian swimmers over a 4 month period. These results indicate that highly trained swimmers exhibit a two to three-fold greater variability in training performance during the season than during end-of-season competition performance. The greater variability in training performance probably reflects the influence of cumulative training fatigue during high volume/high intensity phases of training. A key consideration with heart rate and blood lactate testing is that the magnitude and variability in physiological responses should be interpreted in the context of performance times.

1.5. New Technologies for Monitoring Sports Performance

Over recent years, high level sport has shifted from laboratory testing to the measurement of performance, the physiological responses, and biomechanical characteristics, in a sport-specific setting in the field. This has been facilitated by the emergence of smart sensor technology for tracking sporting movements and offers a number of potential solutions for improved monitoring of athletes in competition and training. The development of high precision, lightweight sensors such as global positioning systems (GPS), power monitoring strain gauges, gyroscopes, magnetometers, and accelerometers has wide-ranging sporting applications. The use of these devices in isolation, or collectively, can provide powerful information which was previously unattainable or very labour-intensive to collect. Across many sports, the emerging capability for obtaining data during exercise in field situations will facilitate new insights into training stress and competition demands.
One such example of the shift away from the laboratory is in the sport of road, track, and mountain-bike cycling. In cycling, the development of portable power monitoring devices, such as the SRM and the Power-tap, have enabled scientists to compare power output data from elite cyclists in the laboratory, with that in training and competition (77). Recent research using this technology has been able to characterise the pedalling rate and power output relationship and the association of these measures with fatigue (139). The use of these devices in cycling has allowed researchers to improve their understanding of the physiological demands of competition and training (138, 221). The use of power monitoring devices in cycling is now widespread at the recreational, development and elite levels of the sport. These developments have stimulated interest in similar kinematic and kinetic investigations in other sports including swimming.

GPS has enormous potential for the assessment of performance and monitoring of training in elite athletes and the possibility to overcome some of the previous limitations which have impeded the monitoring of athletes in sport-specific settings (117-120, 210, 233). GPS is a satellite-based navigation system which uses a series of satellites and low power radio signals that travel by the line of sight (210). The GPS receiver uses a process of triangulation to calculate precise location information by comparing the time the signal was transmitted by a satellite to the time it was received. The time difference between the receiver and the satellite is used to estimate the distance between the two objects. With information from a number of satellites, the receiver can calculate precise position. This information can then be used to derive speed, distance travelled, and altitude/inclination with a high degree of accuracy. Researchers have used GPS to quantify speed, stride length, and stride frequency in walking and running (191, 211). GPS-derived kinematic analysis has been successfully used in conjunction with other equipment such as portable metabolic gas analysers to assess the
demands and performance in orienteering (118, 120) and cross country skiing (119). While technologies such as GPS will not be a substitute for high precision video-analysis of human movements, the increased miniaturisation and improved accuracy of these devices offer promise in sports such as distance running, triathlon, team sports, cycling, and cross-country skiing (209). Unfortunately, the application of GPS in swimming is currently restricted to outdoor pools because there must be a line of sight between the swimmer and the satellites. Future developments of more local positioning systems may be more appropriate for swimming applications.

1.5.1. Principles of Accelerometers

Unlike GPS systems, accelerometers are sensors which may have potential applications for sport that can be used indoors and in water. The use of accelerometry sensors in sporting applications is also becoming increasingly common, particularly in monitoring activity and movement patterns. An accelerometer is a device that measures body movements in terms of acceleration, which is the change in speed with respect to time. The use of accelerometry sensors in sporting applications is also becoming increasingly common, particularly in monitoring activity and movement patterns. Much of the initial interest in accelerometry has focussed on estimating the daily energy expenditure during lifestyle activities (30, 31, 158, 224). The body-mounted sensors are accurate, inexpensive, and portable, which allows for long-term recordings in clinical, sport, and ergonomics settings (144). Most accelerometers in current use are piezoelectric sensors that detect accelerations in one to three orthogonal planes (42). Triaxial accelerometers essentially have three single axis accelerometers integrated into a single package. Accelerometers can be modelled as a mass-spring-(damper) system fixed to a base, which is subject to the acceleration measured (107, 114) (as shown in Figure 1-4). The movement of the seismic mass (or silicon structure) relative to the
movement of the base, or the force of the mass exerted on the spring is a measure of the exerted translational acceleration on the system. The acceleration is usually measured in gravitational acceleration units (g: 1 g = 9.8 m.s\(^{-1}\)). Accelerometers are calibrated by carefully aligning their axis of sensitivity with and against the direction of gravity.

**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 (107).

There are two components of acceleration that occur in the context of human swimming motion: static and dynamic acceleration (185). Static acceleration is a prolonged acceleration relative to the earth’s gravitational field. In contrast, dynamic acceleration is generated by the movement of the swimmer and typically much smaller in magnitude than the static acceleration. When the device is located on a moving swimmer, the primary acceleration observed is related to the static acceleration. Since the earth’s gravitational acceleration is always in a constant direction towards the centre of the earth, movement of the swimmer in
relation to gravity will exert a static acceleration. This static acceleration will overwhelm any
dynamic acceleration caused by the swimmer’s arm stroke propulsion. The movement of the
swimmer in relation to gravity provides a consistent pattern for most of the features of interest
required to track a swimmer’s movement.

1.5.2. Use of Accelerometers in Swimming

The application of sophisticated technology to swimming has the potential to permit
automated and eventually real-time feedback to the coach and swimmer. Preliminary research
has been conducted in swimming using accelerometer technology to provide information on
technique (105, 106, 165, 166, 168), lap times (185), stroke rate and stroke count (106, 164,
185), fatigue (164), and energy expenditure (108). To date, the research on the application of
these technologies in swimming has primarily been limited to conference proceedings with
reports being supported by only minimal numerical data and/or sophisticated data analysis.
Nonetheless, the research reported provides an important starting point in the development of
this technology for use in swimming.

A group of Japanese researchers first reported how triaxial accelerometers could be used to
analyse the technique of freestyle swimmers (105, 166). In a series of studies, Ohgi and co-
workers argued that accelerometers could provide a more automated and accurate method for
analysing technique in freestyle and breaststroke (105, 106, 164-166, 168). Previous
analytical methods had utilised underwater video and then digitised the swimmer’s
movements (38, 127). However these methods are time-consuming in the digitising and
analysis, and the arm and leg movements are obscured by the turbulence and bubbles around
the body making it difficult to digitise the movement (105, 166, 168). Using a triaxial
accelerometer combined with a microprocessor in a watch face, the three-dimensional
wrist/arm movements of the swimmer could be recorded. Preliminary data with freestyle (105, 166) could discriminate each stroke and the down-sweep, in-sweep, up-sweep, out-sweep and recovery labelled by Maglishco (135). Swimming at different velocities changed some components of the stroke pattern and the time-span of each stroke, and these could be observed in the wrist accelerometer trace (105). While further work by this group using triaxial accelerometers showed it was possible to calculate a stroke rate from the data obtained (106), the reliability and validity of these estimates were not reported.

Accelerometry has also been used to investigate changes in technique as a consequence of fatigue in a training set (106, 164). However, the changes reported were observed in one of the five subjects tested and so these findings must be treated as pilot data. The prototype used in these studies was quite bulky and cumbersome. Weighing 50 g and strapped to the forearm, this substantial mass may have influenced the observed changes in the accelerometer traces over the 24 x 50-m in the study. Nevertheless, the use of the accelerometer technology has the potential for continuous measurement of strokes and stroke rate in swimming training. The information may be a potentially useful coaching tool in automating the collection of performance and stroke information with a reasonable level of confidence in the reliability and validity (165). Further studies confirming the reliability and validity of accelerometer device in swimming, its utility in discriminating different swimmers and for monitoring changes in a given individual over time, are clearly warranted.

Other investigators have proposed a similar device to measure whole-body repetitive movements applicable to monitoring swimming movements (33, 185). Buchner and Markus (33) attached an accelerometer-based device the size of a cassette Walkman to the swimmer’s lower back. The device contained a 2-dimensional accelerometer and a gyroscope. The
investigators provided preliminary information on the horizontal acceleration-time curve for butterfly and breaststroke and were able to identify the different phases of the stroke. Similarly, Roncallez and others proposed a triaxial accelerometer device also located on the lower back of the swimmer to monitor swimming strokes, starts and turns (185). However, to obtain an individual’s “stroke signature” or their stroke pattern with their individual idiosyncrasies, the device required an initial calibration for use with each individual swimmer. Although these investigators speculated that breathing and the kick could be detected from this device, they failed to provide any data to support their claim. This preliminary work shows potential in detecting the different strokes of swimming (freestyle, butterfly, backstroke, and breaststroke), lap times, stroke rates, and stroke counts, and the important technical elements of the start, turn, and kicks. Nevertheless, comprehensive systematic study in elite swimmers is required.

Swimming researchers have also recognised that stroke mechanics play a critical role in the fatigued/training state of the swimmer (230). Adaptation to training and the tolerance of fatigue is a highly individual phenomenon (16, 86, 153), and swimmers of similar standard in similar events can respond quite differently to the same high training loads (86). A more complete picture of an swimmer’s status in training involving parallel measurement of performance time, heart rate, blood lactate, stroke mechanics and self-reported perceived exertion is generally considered a better approach than any single measure (156, 202). The use of accelerometer technology may provide another tool to enhance the assessment of the adaptation to training of swimmers.
1.6. Summary

The training regime of a highly trained competitive swimmer is carefully planned and monitored. The aim is to enhance competitive performance by optimising the physical, technical and tactical preparation for enhancing the competitive performance. Sports scientists monitor swimmers in order to make informed judgements on their progress in fitness and performance. Testing also provides an historical record, which is useful for future planning for the individual swimmer, or as a reference point for other swimmers. Training and competition performance is best evaluated by the physiological and technical components and not just by the final performance time. The specific research questions addressed in this thesis centre on 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 capacity of miniaturised and automated smart sensor technology for monitoring the stroke and performance times of swimmers in training.

1.7. Aims of the Thesis

The aims of the studies in this thesis are:

1. To establish the effectiveness and utility of submaximal (4 mM) and maximal (200-m time) testing to monitor the performance changes in swimmers within and between seasons.
2. To establish the utility of submaximal and maximal testing to effectively monitor the changes in heart rate and blood lactate measures, and derived indexes, in swimmers within and between seasons.
3. To establish the utility of submaximal and maximal testing to effectively monitor the technical stroke changes in swimmers within and between seasons.
4. To quantify the magnitude of the relationship between changes in measures obtained from the 7 x 200-m step test in training and changes in competition performance over the course of a season.

5. To establish the validity and reliability of smart sensor accelerometry technology for the purpose of non-invasive, valid and reliable measurement of swimmers’ stroke mechanics and times.

6. To determine whether smart sensor accelerometry can discriminate the difference in performance and stroke characteristics of senior and junior swimmers.

7. To determine the magnitude of changes and typical individual variation of junior and senior swimmers and in elite swimmers both in the short term (within a session, over a day, over a training block) and also over the longer term (a season and several seasons).
CHAPTER TWO

MONITORING SEASONAL AND LONG-TERM CHANGES IN TEST PERFORMANCE IN ELITE SWIMMERS

2.0. Introduction

The evaluation of physiological and sport-specific performance measures provides fundamental information to the coach, athlete and sport scientist on the athlete’s response to the training program (200). Given that performance in swimming is closely related to the physiological adaptations induced by the athlete’s training program (65), the assessment of various components of performance can provide important information on training progress and likely competition potential. The demands of swimming cannot easily be replicated in a laboratory setting (56), therefore the most practical tests for elite athletes are generally those that can be readily administered in the training environment.

Progressive incremental tests are commonly used to assess the physiological adaptations of swimmers, measuring blood lactate and heart rate over a range of intensities culminating in a maximal effort (85, 176). Incremental swimming tests can also provide feedback on performance measures such as pacing and stroke/movement characteristics at increasing speeds. Relationships between lactate and velocity have been widely used as a means to monitor the training state of swimmers by identifying an intensity (velocity) at a fixed blood lactate or lactate threshold (85, 137). The main premise for this type of testing is that the lactate threshold is a useful measure of submaximal endurance fitness and presumably reflects training-induced adaptations occurring in the skeletal muscle (176). The changes in the
lactate threshold through a training season have been previously documented in swimmers (176), but there is limited information available on international level swimmers or on any swimmers monitored serially within and between seasons. Furthermore, parallel monitoring of maximal and submaximal physiological and performance measures has not been systematically addressed in previous longitudinal studies of collegiate (137, 181, 195) or elite (27, 171, 176) swimmers within a training phase or over several phases, although some investigators have attempted to develop models of training and performance in elite swimmers (16, 86).

The implementation of systematic training and performance diagnostic testing, facilitates the analysis of changes in fitness and performance elicited through training (200). Analysis of these trends allows for reference values of changes in performance and physiological measures to be developed to assist coaches and swimmers in the preparation of annual plans and the prescription of training programs. Assessing the responses of individual swimmers should also provide more useful information to the coach and scientist. The progression and variability of individual responses in these physiological measures and performance, rather than purely reporting the mean trends, has not been previously addressed in other studies. Therefore the purpose of this study was to model the within-swimmer changes in the progression in test performance of swimmers and characterize the changes and variability within and between seasons over their elite competitive career.
2.1. Method

2.1.1. Subjects

The subjects were forty national and international representative middle distance swimmers, all scholarship holders at the Australian Institute of Sport. The study sample consisted of 24 male (age at commencement 19 ± 2 y; mean age 22 ± 2 y, mass 80 ± 6 kg and height 1.85 ± 0.05 m for time in program, mean ± SD) and 16 female (age at commencement 18 ± 3 y; mean age 20 ± 3 y, mass 64 ± 6 kg and height 1.74 ± 0.07 m) swimmers. During the study period three swimmers were ranked number one in the world in their specialist event and 11 others were ranked Top 10 in the world at some stage during the 6 y period. Fifteen of these swimmers (38%) had won an individual or relay medal at a major international competition. All procedures undertaken in this study were routinely conducted within the training environment and had approval from the Ethics Committee of the Australian Institute of Sport. All athletes provided written informed consent for sports science and sports medicine testing at the commencement of their scholarship.

The swimmers generally trained 44-48 weeks each year with pool and dry land training typically reaching a total of 20 hours per week. Typical weekly average training distance was ~50-60 km. Dry land training typically involved short 20-30 min circuits of calisthenics, body weight exercises, stretching before training and three 1-1.5 h gymnasium sessions per week consisting of traditional resistance training and swimming-specific exercises. Male and female swimmers were in mixed training groups and essentially completed the same training programs.
2.1.2. Study Design and Procedures

During the study period, the swimmers performed a 7 x 200-m incremental step test several times each season (n = 396 tests, 10 ± 5 per swimmer; spanning 1 season to 6 y). Each season was arbitrarily divided into four phases according to the training plan: pre-season (tests conducted >16 wk to competition), early-season (10-16 wk to competition), mid-season (4-10 wk to competition), and taper (<4 wk to competition), with swimmers usually undertaking at least one test in each phase.

Body composition measurements were taken regularly throughout a season (~once per month). The same anthropometrist recorded the body mass and sum of seven skinfold thicknesses on each occasion over the 6 y period. Measurements of body mass and skinfolds were generally made between 0800 and 0900 h with the athletes presenting after training in a fasted state. Body mass was measured to the nearest 0.1 kg with digital standing scales (Model DS-410, Teraoka Seiko, Tokyo, Japan). Skinfold thickness was measured using calibrated Harpenden skinfold calipers (Model HSK-BI, Baty International, West Sussex, UK) in accordance with recommended methods of the International Society for the Advancement of Kinanthropometry (162). The seven sites used were: triceps, subscapular, biceps, supraspinale, abdomen, thigh, and calf. The anthropometrist’s typical error of measurement for the sum of seven skinfold thicknesses was 1.3 mm or 2.8%. A derived lean mass index described by Hopkins et al. (173, 199) was used to track changes in lean mass controlled for changes in skinfolds.

2.1.3. 7 x 200-m Testing Procedure

The 7 x 200-m test consisted of seven even-paced swims on a 5-min cycle, graded from easy to maximal (176). Swimmers usually completed the test using the stroke of their main
competitive event and employed the same stroke for all tests during the study period. Individualized target times based on each swimmer’s personal best time were calculated prior to testing. Swimmers were typically within 2 s of target times for the first 6 efforts, with the final effort maximal. All testing was conducted in a 50-m pool and swims utilised a push start. Speeds for the swims ranged ~30 s from slowest to fastest for each 200-m effort (e.g. 2:30 to 2:00 min), with the seventh and final swim a maximal effort.

Each 100-m split and the total 200-m time were timed manually. Stroke rate was measured on the third lap by manually timing three complete stroke cycles with a stopwatch (Seiko, Model S120-4020, Japan). The number of strokes taken per 50-m lap (stroke count) was determined on the fourth lap of each 200-m effort. Given that speed is the product of stroke length and stroke rate, stroke length was determined as the quotient of speed and stroke rate (59). On completion of each effort, heart rate (HR) was measured using a heart rate monitor (Polar Electro Oy, Kempele, Finland). The swimmer then exited the pool and a 5-µl blood sample taken from the earlobe or fingertip, with the location standardised for each subject, and analysed for lactate concentration using a portable hand-held blood lactate analyser (Lactate Pro, Arkray, Japan). Blood samples were taken within 1 min of completion of the swim for the first 6 efforts and 3 min after for the final maximal effort.

Derived values at a fixed 4-mM blood lactate were determined using a modification of the log-log model originally described by Beaver et al. (20). A straight line was fitted to the log-log transformed plots of the last five steps for blood lactate and swimming speed. To establish the criteria for the linear regression analysis 20 representative data sets were plotted. Only the last five steps of log-transformed values for speed and blood lactate were used to improve the linear fit of the lactate-speed curve (correlation of $r = 0.92$ for the representative
data sets) and on the basis that the first two steps were generally less than 2 mM. The speed at a fixed blood lactate concentration of 4-mM was determined using the 4-mM y-intercept on the blood lactate-time curve. This procedure was then repeated for the other measures, with the log of time plotted against the log of heart rate, stroke rate, stroke count and stroke length. However, on the basis of initial inspection of the 20 representative data sets, the first two steps of these measures were included, the 7th step excluded for heart rate, stroke rate and stroke length, and the last two steps excluded for stroke count. A straight line was fitted to the log-log plots (r >0.80 from the representative 20 plots) and the submaximal values at a fixed 4-mM lactate determined for heart rate, stroke rate, stroke count and stroke length by linear regression.

2.1.4. Reliability Testing

Test-retest reliability of the 7 x 200-m incremental step test was assessed prior to analysis of the longitudinal data. Twenty-two competitive swimmers (12 male, 10 female) completed the incremental 7 x 200-m test twice ~72 h apart under similar conditions. All subjects were familiar with the testing protocol and undertook a standardized warm-up. Typical error of measurement (96) was determined on maximal and 4-mM lactate measures of time, lactate, heart rate, stroke rate, stroke count, and stroke length.

2.1.5. Statistical Analyses

Log transformation and repeated measures mixed linear modeling (Proc Mixed) using Statistical Analysis System (SAS) software (Version 8.1, SAS Institute, Cary, NC) provided estimates of percent change in the mean (fixed effects) and within-swimmer coefficient of variation (CV) (random effects) for maximal and derived 4-mM lactate step test measures and body composition between phases and years for each sex. The fixed effects in the SAS model
were Phase, ProgTime, ProgTime*ProgTime, AgeRel, ProgTime*AgeRel, AgeRel*AgeRel. Phase was a within-subject effect with values for pre, early, mid and taper representing the effect of the training phase at the time of each assessment. ProgTime was a numeric within-subject effect representing the duration the swimmer had been in the program at the time of each assessment. AgeRel was a within-subject effect representing the age of the swimmer relative to the reference age of 19 y. The random effects were Athlete (estimating pure between-athlete variation), Athlete*Season (estimating within-athlete variation additional to the residual arising between tests performed in different seasons), and the residual (estimating within-athlete variation for tests within a season). Expressed as coefficients of variation, within-athlete variation represents typical variation in an athlete's test scores; for typical variation in an athlete's change score between two tests, the typical variation needs to be multiplied by $\sqrt{2}$.

Data are shown as a mean or range ± 95% confidence limits. Magnitudes of the change scores were assessed by calculating the chance that the true value of the effect was practically beneficial, trivial, or harmful (99). To calculate these chances it was assumed that the smallest worthwhile change in measures which could have a direct relationship with performance (speed and stroke characteristics) was $0.5 \times$ within-athlete coefficient of variation (CV) for competitive performance, equating to 0.4% for elite swimmers (222). For all the non-performance measures (heart rate, blood lactate and body composition), the smallest worthwhile change was calculated as Cohen’s smallest effect size of $0.2 \times$ the between-athlete CV (48). Thresholds for assigning qualitative terms to chance of a substantial increase or decrease were as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely or probably not; <50%, possibly not; >50%, possibly; >75%, likely or probable >95%, very likely; >99%, almost certain (99).
2.2. Results

Representative mean data for male and female freestyle swimmers in the group are shown for all the 7 x 200-m step test measures in Table 2-1. The typical error of measurement for each of the maximal and 4-mM lactate measures in the 7 x 200-m step test, derived from the reliability testing are also shown in Table 2-1.

Table 2-1: Descriptive statistics (mean ± 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.

<table>
<thead>
<tr>
<th></th>
<th>Male (n=17)</th>
<th>Female (n=11)</th>
<th>Typical error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal (final 200-m step):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200-m time (s)</td>
<td>120.9 ± 4.5</td>
<td>130.1 ± 2.2</td>
<td>0.8%</td>
</tr>
<tr>
<td>Stroke rate (strokes min⁻¹)</td>
<td>40.5 ± 2.2</td>
<td>40.5 ± 3.5</td>
<td>2.1%</td>
</tr>
<tr>
<td>Stroke length (m)</td>
<td>2.47 ± 0.15</td>
<td>2.29 ± 0.16</td>
<td>2.3%</td>
</tr>
<tr>
<td>Stroke count (stroke 50 m⁻¹)</td>
<td>36.2 ± 2.6</td>
<td>40.7 ± 2.7</td>
<td>2.9%</td>
</tr>
<tr>
<td>Lactate (mM)</td>
<td>10.5 ± 2.1</td>
<td>9.2 ± 1.9</td>
<td>16%</td>
</tr>
<tr>
<td>Heart rate (beats min⁻¹)</td>
<td>182.9 ± 6.9</td>
<td>179.7 ± 8.5</td>
<td>2.3%</td>
</tr>
<tr>
<td>Submaximal (Fixed 4-mM lactate):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time per 100-m (s)</td>
<td>65.2 ± 1.8</td>
<td>68.9 ± 1.6</td>
<td>0.8%</td>
</tr>
<tr>
<td>Stroke rate (strokes min⁻¹)</td>
<td>34.3 ± 2.9</td>
<td>36.1 ± 3.9</td>
<td>3.3%</td>
</tr>
<tr>
<td>Stroke length (m)</td>
<td>2.70 ± 0.21</td>
<td>2.44 ± 0.20</td>
<td>2.9%</td>
</tr>
<tr>
<td>Stroke count (stroke 50 m⁻¹)</td>
<td>32.6 ± 2.5</td>
<td>37.2 ± 3.1</td>
<td>3.5%</td>
</tr>
<tr>
<td>Heart rate (beats min⁻¹)</td>
<td>166.7 ± 7.0</td>
<td>166.0 ± 9.9</td>
<td>3.2%</td>
</tr>
</tbody>
</table>

2.2.1. Within-Season Changes

Improvements of 1.5-2.0% were generally observed in submaximal 4-mM swimming speeds during a training season. The within-season mean changes in 4-mM lactate speed, stroke rate and stroke length are shown in Figure 2-1. Typically mean increases of 2-4% were observed
in stroke rate accompanied by a corresponding decrease in stroke length. The swimmers showed similar mean changes in maximal performance to those seen at 4-mM lactate within a season. At maximal speeds, female swimmers improved from the pre to taper phase by 2.3% (95% confidence limits ±1.2%), with most of the gains in the mid (1.6%; ±1.2%) and taper (1.5%; ±1.0%) phases. Conversely, at maximal speed, male swimmers were very likely to get faster over the season but only in the mid phase (1.4%; ±1.1%). Individual swimmers varied ~±2.6% in their maximal performance and ~±2.2% in their 4-mM lactate speed between tests within a season. Accompanying the changes in maximal speed were indications of 2-5% changes in the stroke characteristics. Individual variations of ±4-6% were observed in maximal and 4-mM lactate stroke characteristics between tests within a season.

Physiological changes in submaximal (4-mM fixed lactate) and maximal fitness were represented by changes in blood lactate and heart rate in the step test. Mean peak blood lactate after the final and maximal 200-m effort was ~10 mM, although a large degree of within-athlete variation (±28%) was evident between tests. Only trivial changes in mean blood lactate concentration were seen between each phase within a season. The mean peak heart rate was 183 beats min⁻¹ and mean submaximal heart rate at the 4-mM lactate was 169 beats min⁻¹. Male and female swimmers had only trivial changes in heart rate at both maximal and 4-mM lactate speeds.
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.
Male and female swimmers both had trivial changes in body mass between phases in a season. The sum of skinfolds of the female swimmers progressively decreased in each phase during a season, characterised by a 5.3% (95% CL ±4.1%) decrease from early to mid season and a substantial 8.0% (±4.6%) decrease from the mid to the taper phase. From the pre-season there was a substantial 14.6% (±4.4%) decrease in skinfolds throughout a season. In comparison, male swimmers typically lost 8.5% (±4.5%) throughout the season, with the majority of the decrease occurring in the latter phases of the season. Superimposed on the changes in mean skinfolds were typical variations in an individual’s skinfolds between tests within a season of ±5.8% for females and ±7.0% for males. All changes in lean mass within a season were trivial.

2.2.2. Progressive Yearly Changes

The progression in maximal test performance, stroke rate and stroke length from year to year are presented in Figure 2-2. The mean increase in maximal speed was typically 0.6-0.8% each year for male and female swimmers, but plateaued in males after 2 y. At maximal speed, increases in stroke rate and decreases in stroke length of typically 1-2% each year were observed for the male swimmers. Female swimmers typically had a marginal decrease in stroke rate and an increase of ~0.9% each year in stroke length over 5 y. Female swimmers almost certainly improved their 4-mM lactate speed with a mean improvement of 1.2% each year (95% CL ±1.0%), while males had only trivial changes. Sex differences were also evident in the stroke characteristics at the 4-mM lactate speed over extended periods of time. Each year, female swimmers increased stroke rate ~1.0% and decreased stroke count ~2.5% at 4-mM lactate speeds. In contrast, male swimmers had only trivial changes in stroke characteristics at 4-mM lactate speeds over 5 y. The typical individual variation in an
individual’s stroke characteristics between tests in different seasons was: ~±5.0% for stroke rate, ~±4.8% for stroke count and ~±4.7% for stroke length (±1.1%).

The progressive changes from year to year for peak lactate and heart rate are shown in Figure 2-3. Despite little change within a season, male swimmers showed a progressive increase in peak lactate concentration from year to year, while females had only trivial changes over 5 y. Peak heart rate for the males was relatively stable during the first 3 y in the program before decreasing in subsequent years. Females had a ~1.1% decrease in peak heart rate each year. Only trivial changes were observed in submaximal (4-mM lactate) heart rate from year to year for male and female swimmers. However, the heart rate typically varied from these mean trends by ±3.5% for submaximal (4-mM) lactate heart rate, and females by ±2.0% and males by ±3.2% for peak heart rate.

Sex differences were apparent in the long-term changes in body composition over several years. The typical within-athlete changes in body mass, skinfolds and lean mass over 5 y are shown in Figure 2-4. Male swimmers showed progressive increases in body mass and lean mass after the first 2-3 y in the program, with little change in skinfolds. Female swimmers had substantial decreases in body mass and skinfolds but only trivial changes in lean mass over 5 y. Individual female swimmers tended to vary more in the mean trends between tests in different seasons for body mass (±2.2%) and skinfolds (±11.0%) than between tests within a season. The skinfolds of male swimmers varied more from year to year (±9.2%) than from test to test within a season.
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.
**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.
**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.
2.3. Discussion

In this study the seasonal and long-term changes in a group of elite-level swimmers were examined and performance, anthropometric, physiological and stroke changes were characterised. The present study is the first to systematically analyse such changes in elite swimmers within and between seasons and to estimate the magnitude of individual responses superimposed on these mean changes. Maximal performance tests in training are commonly used to gauge the progress in fitness through a training and competitive season. Swimmers do not always compete on a regular basis, and incremental testing in training has emerged as common practice in many high level programs. The 7 x 200-m step test was used to ascertain the changes in performance and physiological measures in swimmers competing in sprint, middle-distance and distance events and basic anthropometric measures to characterise body composition changes.

The magnitude of the effects was reported using likelihoods and examined the precision of the estimate with 95% confidence limits. Standard statistical significance testing provides only a limited interpretation of the meaningfulness of changes and differences in performance for the elite level athlete (15, 208). No previous study of swimming performance by elite competitors has examined the individual responses to training. The individual variability as well as the mean changes were estimated to give an indication of the typical variations that would be expected when monitoring a randomly selected group of elite swimmers. Several sources may have contributed to the magnitude of individual variations observed in test performance, physiological and stroke parameters. The training groups were of mixed sex and had male and female swimmers undertaking the same or different training depending on their individual squad. Innate differences in the response to training may have contributed to the individual differences in progression. Variability in test measures may also have been
influenced by factors such as levels of hydration, muscle glycogen, illness, recovery from injury and any underlying acute fatigue.

The ability to monitor swimmers' adaptations to the training program within a season is probably the most critical element of testing for the coach and athlete. Quantifying improvements or decrements in performance can be used to determine whether the coach needs to make corrective actions in the training program. Furthermore, speed at a fixed 4-mM blood lactate has been used extensively to determine training speeds for swimmers (137) and correlates highly with 400-m maximum swimming speed (232). The elite swimmers were likely to get 1-2% faster at maximal and 4-mM lactate speeds during the season. Most of the improvement occurred in the mid and taper phases of the season. The improvements in fitness over a training season in the present study confirm earlier investigations (188, 195), and the magnitude of these small but meaningful increases are similar to that of prior observations (176). It should be noted that the information provided from the step test and body composition measurements was considered by the coach and athlete in subsequent preparations, and modifications made to the training program were entirely at the coaches’ discretion.

Although within-season changes in fitness are important for immediate coaching feedback, it is also important to monitor longer term changes. The yearly progression in both maximal test performance and 4-mM lactate speed were considerably less than those observed within a season. It is apparent that improvements are generally cyclical in nature, whereby swimmers lose some or all their fitness gains in the transition from one season to the next. The importance of maintaining a degree of fitness during the off-season has previously been highlighted (153). Mujika et al. (153) found that lost form at the beginning of the season can
be detrimental to performance during the season. In the present study, test rather than competition performance was compared and there was a substantial decrease in test performance from the end of one season to the start of the next season. However, the effect of the lower test performance and therefore fitness at the start of the season on competition performance at the end of >20 wk of full-time training was not elucidated in the present study.

Differences in the direction and magnitude of changes in fitness between the male and female swimmers were apparent. Sex-specific differences in adaptation to similar training programs may explain the discrepancies between the groups in test performance in the long term. In general, the males became stronger and more powerful whereas the females became leaner and more efficient. The male swimmers tended to increase in mass and lean mass, and developed their anaerobic qualities as indicated by the increase in peak lactate concentration after the maximal 200-m effort. Collectively, with an increase in stroke rate and a decrease in stroke length over time, the increase in lean mass and lactate could possibly translate into improved power applied to the water for the male swimmers. In contrast, the female swimmers showed a decrease in mass and a decrease in skinfolds over time in agreement with previous observations (148). However, only trivial changes occurred in lean mass and peak lactate for the females. An increase in maximal stroke length and stroke rate at 4-mM lactate for the females was also observed and indicative of a possible improved swimming efficiency. The substantial loss of mass and skinfolds and the greater improvement in maximal and 4-mM lactate speed could also be due to the female athletes coming into the program initially in a lower state of training and fitness than the males.

Greater consistency in competitive performance is evident in Olympic-level swimmers compared with age group and national standard swimmers. Trewin et al. (222) reported a
variation of 0.8% for Olympic swimmers in major competitions from one year to the next, while Stewart & Hopkins (206) reported for elite junior swimmers a coefficient of variation of 1.4% between competitions. Consequently, the variability in training performance appears to be substantially larger than that of competition performance in elite swimmers. In the present study, the within-subject between-test variability was 2.6% for maximal test performance and 1.9% for 4-mM lactate speed. The greater variation in performance in the training environment could relate to the individual differences in progression between tests during the season. Other possibilities for the greater variation could be related to variations in motivation and fatigue from one test to the next. The notion of greater variability in training is consistent with an earlier report from our laboratory where typical changes in test performance of 2-3% were observed (176).

Stroke technique plays an important role in the variation of energy cost and efficiency of performance during competitive swimming (39). Stroke rate and stroke length are useful parameters to monitor in swimming as indicators of swimming technique (59, 113). Keskinen et al. (113) reported that stroke length was the predominate factor in producing high swimming velocity. However, Chatard et al. (39) found that stroke rate was a better indicator of swimming technique than stroke length since it explained a greater proportion of the variability in swimming. In the absence of biomechanical or video-based analysis in the present retrospective study, manually recorded stroke count and stroke rate and a derived stroke length were reported. A substantial mean increase was observed in stroke rate through the early and mid phases of the season with a slight decline in the taper phase. The magnitude of measurement error is quite large, but this is most likely owing to the manual methods used, which will have contributed additional variation from test to test when monitoring an individual swimmer. The development and implementation of more sophisticated
accelerometry-based systems to measure this characteristic in the future may assist with more confidently tracking changes in the individual.

Blood lactate measurements have provided the basis for estimating changes in aerobic fitness at a fixed blood lactate value as a function of velocity or power output to monitor training-induced changes, or for prescription of training sets (22, 137). Previous reports in elite speed skaters (73) and cyclists (128) have shown that mean heart rate remains stable at reference blood lactate and ventilatory thresholds during the course of a training year despite significant training-induced improvements in fitness and performance. The present study confirms the stability of heart rate at a fixed lactate value in elite swimmers. Changes in heart rate at the 4-mM lactate within a season and over several years were less than the typical error of measurement and the smallest worthwhile change. However the earlier studies did not address the variation of individuals, which can provide more information than the stability of the mean. In the present study, the mean heart rate and 4-mM lactate showed only trivial changes, whereas individual swimmers could actually vary quite substantially (±3.5%).

There are several practical implications arising from this study for coaches and sport scientists wanting to employ similar tests to monitor changes in fitness and performance of highly trained swimmers. First, testing should be conducted periodically throughout the season to establish baseline values (early season), assess progress (mid-season), and finalize the preparation (taper). In a mixed group setting, coaches will need to manage the testing and training of swimmers on a sex-specific basis with individualized training prescription. Secondly, given the evidence that the performance and physiological measures for an international swimmer tend to plateau over a longer competitive career, coaches will need to modify long-term training programs accordingly. Thirdly, scientists should administer a
comprehensive battery of tests involving a combination of performance (total time and split times), stroke (stroke rate and stroke count), physiological (heart rate and blood lactate) and body composition (mass and skinfolds) measures. Finally, both the mean changes and individual responses of the swimmers to training should be considered.

2.4. Conclusions

Coaches and sports scientists can be confident in identifying real changes in performance, physical and physiological measure of individual swimmers using pool-based lactate testing and anthropometric testing. The identification of mean trends within a season and the progression over several years provides reference values on the magnitude of typical changes expected for national and international level swimmers. Scientists and coaches should also consider the degree of individual variation around these mean effects when assessing fitness and prescribing training. While routine testing offers insight into the training process, the relationship between testing and competitive performance in international swimmers remains uncertain and needs to be addressed.
CHAPTER THREE

ABILITY OF TEST MEASURES TO PREDICT COMPETITIVE PERFORMANCE IN ELITE SWIMMERS

3.0. Introduction

Seasonal trends and the individual variability in performance need to be considered by sports scientists when using tests to track performance changes resulting from training or other interventions. While short-term estimates of individual variability in performance have been reported (178, 206, 222), only a case study of an elite breaststroke swimmer has reported the typical within-athlete long-term (seasonal) progressions in elite swimmers (213). Furthermore, performance tests are used frequently as part of an elite athlete’s training program to objectively determine adaptations to the training program and to predict the likely outcome of the athlete competitive performance. In the case of swimming, where typically there is only one major long-course competition at the end of a training season with two training preparations per year, one of the main methods coaches and sports scientists use to monitor the progression in a swimmer’s performance is fitness testing systematically implemented within the preparation. Heart rate and blood lactate profiles have been found to track concurrent (within two days) performance changes in competitive swimmers over a season (195). Mean speed predicted from lactate profiles had a large correlation ($r = 0.61$) with actual competition speed (195). Furthermore, a study of elite male breaststroke swimmers reported substantial relationships between submaximal swimming speeds at several fixed blood lactate concentrations and 100- and 200-m competition performance (contested 7-10 days after the testing) (214). In contrast, other researchers have found only trivial
relationships between changes in competition performance and a change in physiological variables after two or more months between testing and competition (176). The purpose of the current study was to evaluate the relationship between changes in fitness test measures and changes in competition performance in elite swimmers over several seasons.

3.1. Method

3.1.1. Subjects

Forty national and international representative middle distance swimmers were the subjects in this investigation. All were scholarship holders at the Australian Institute of Sport. The study sample consisted of 24 male (age at commencement 19 ± 2 y; mean age 22 ± 2 y, mass 80 ± 6 kg and height 1.85 ± 0.05 m for time in program, mean ± SD) and 16 female swimmers (age at commencement 18 ± 3 y; mean age 20 ± 3 y, mass 64 ± 6 kg and height 1.74 ± 0.07 m). During the five year study period fifteen (38%) of these swimmers had won an individual or relay medal at a major international competition, three swimmers were ranked number one in the world in their specialist event, and a further eleven were ranked Top 10 in the world. All procedures undertaken in this study were routinely conducted within the training environment and had approval from the Ethics Committee of the Australian Institute of Sport. All athletes provided written informed consent for sports science and sports medicine testing at the commencement of their scholarship.

The swimmers generally trained 44–48 weeks each year with pool and dry land training typically reaching a total of 20 h per week. Typical weekly average training distances were ~50 km. Dry land training typically involved short 20-30 min circuits of callisthenics, body weight exercises, stretching before training and three 1 h gymnasium sessions per week consisting of traditional resistance training and swimming-specific exercises. Male and
female swimmers were in mixed training groups and essentially completed the same training programs.

3.1.2. Study Design and Procedures

During the study period, the swimmers performed a 7 x 200-m incremental step test (177) several times each season (n = 396 tests, 10 ± 5 tests per athlete; 3.6 ± 2.5 y). Each training preparation concluded with a major competition either the National Championships or an international event (i.e., Olympic Games, World Championships, Pan Pacific Championships or Commonwealth Games) (3.6 ± 2.2 competitions). Competition performance times for each swimmer were taken in the most advanced stage reached (i.e. final, semi-final, or heat) in their best competitive event.

Typically there were two major competitions each year in the current study and thus two training seasons per year. Each season was divided into four phases that reflected the different stages of the training program in the lead-up to a major competition. The phases were pre (tests conducted >16 wks to competition), early (10-16 wks to competition), mid (4-10 wks to competition), and taper (<4 wks to competition). The swimmers usually completed at least one test in each phase.

Within each season, routine measures of performance, physiological and stroke characteristics were taken using the 7 x 200-m incremental swimming step test. Body composition measures (mass, sum of 7 skinfolds, lean mass index) were recorded within 7 d of a 7 x 200-m step test by an accredited anthropometrist in accordance with the recommended methods of the International Society for the Advancement of Kinanthropometry (162). Measurements of body mass and skinfolds were generally made between 0800 and 0900 h with the athletes
presenting after training in a fasted state. Body mass was measured to the nearest 0.1 kg with
digital standing scales (Model DS-410, Teraoka Seiko, Tokyo, Japan). Skinfold thickness
was measured using calibrated Harpenden skinfold calipers (Model HSK-BI, Baty
International, West Sussex, UK). Measurements were taken from seven sites: triceps,
subscapular, biceps, supraspinale, abdomen, thigh, and calf. The anthropometrist’s typical
error of measurement for the sum of seven skinfold thicknesses was 1.3 mm or 2.8%. A
derived lean mass index described by Slater et al. (199) was used to track changes in lean
mass controlled for changes in skinfolds.

The 7 x 200-m test consisted of 7 even-paced swims on a 5-min cycle, graded from easy to
maximal (177). With the exception of butterfly and individual medley swimmers (who swam
freestyle), swimmers usually completed the test using the stroke of their main competitive
events. Individualised target times based on each swimmer’s personal best time were
calculated prior to testing. All testing was conducted in a 50-m pool and swims utilised a
push start. Speeds for the swims ranged ~30 s from slowest to fastest for each 200-m effort
(e.g. 2:30 to 2:00 min), with the seventh and final swim a maximal effort.

Measures of time, heart rate, lactate, and stroke rate were collected on each of the 200-m
efforts. Each 100-m split and the total 200-m time were timed manually. Stroke rate was
measured on the third lap by manually timing three complete stroke cycles with a stopwatch
(Seiko, Model S120-4020, Japan). Given that speed is the product of stroke length and stroke
rate, stroke length was determined as the quotient of speed and stroke rate (59). Immediately
on completion of each effort, heart rate (HR) was measured using a heart rate monitor (Polar
Electro Oy, Kempele, Finland). A 5-μl blood sample was taken from the earlobe or fingertip
and analysed for lactate concentration using a portable hand-held blood lactate analyser.
Samples of blood lactate were collected within one minute of completion of steps 1 to 6, and three minutes after completion of the 7th and final step.

Maximal (from the seventh step) and derived 4-mM lactate values for speed, heart rate, lactate (peak only), stroke rate and stroke length were then calculated. Derived values at a fixed 4-mM blood lactate were determined using a modification of the log-log model originally described by Beaver et al. 20. A straight line was fitted to the log-log transformed plots of the last five steps for blood lactate and swimming speed. To establish the criteria for the linear regression analysis 20 representative data sets were plotted. Only the last five steps of log-transformed values for speed and blood lactate were used to improve the linear fit of the lactate-speed curve (correlation of $r = 0.92$ for the representative data sets). The first two steps were generally less than 2 mM. The speed at a fixed blood lactate concentration of 4-mM was determined using the 4-mM y-intercept on the blood lactate-time curve. This procedure was then repeated for the other measures, with the log of time plotted against the log of heart rate, stroke rate, and stroke length. However, on the basis of initial inspection of the 20 representative data sets the first two steps of these measures were included, while the 7th step excluded for heart rate, stroke rate and stroke length. A straight line was fitted to the log-log plots ($r > 0.80$ from the representative 20 plots) and the submaximal values at a fixed 4-mM lactate determined for heart rate, stroke rate, and stroke length by linear regression.

3.1.3. Statistical Analyses

For the longitudinal progressions, data were log transformed and repeated measures mixed linear modeling in Statistical Analysis System software (Version 8.1, SAS Institute, Cary, NC) used to provide estimates of percent change in the mean (fixed effects) and within-swimmer coefficient of variation (random effects) for competition performance, maximal and
derived 4-mM lactate variability. Thresholds for assigning qualitative terms to chance of a substantial increase or decrease were as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely or probably not; <50%, possibly not; >50%, possibly; >75%, likely or probable >95%, very likely; >99%, almost certain (126).

The ability of step-test or anthropometric measures in the same phase between seasons to predict competition performance between seasons was assessed by investigating the relationship between the change scores. The analysis can be visualised as the relationship between changes in competition performance and changes in the step-test or anthropometric measure, with each subject’s changes calculated relative to his/her mean (see Figure 3-2 for example). The aim of the analysis was to derive a factor to predict a swimmer’s change in competition performance from a change in test measure, between the same phases in different seasons. To this end, mixed modelling was used to fit straight lines to each subject’s competition performance and the given test measure. The straight lines were all constrained to have the same slope (the prediction factor), which is reported as an x% change in competition performance time for a 1% change in test measure (%/1%). The average within-subject correlation, which represents the strength of the relationship between the competition performance and test score, was derived as the square root of the fraction of the within-subject variance explained. The average within-subject variance was the variance of the subject random effect in a simple reliability model with no fixed effects. The variance explained was this subject variance minus the square of the standard error of the estimate from the mixed model used to fit the straight lines. The resultant correlation is effectively adjusted for degrees of freedom and is therefore unbiased. Based on the correlations of individual test measures with competition performance, the best two measures in the taper phase for female and male swimmers were then combined in a multiple linear regression to improve the
An analysis of change scores was also performed to determine the relationship between off-season changes in test measures (taper phase to pre phase) with changes in competition performance. The analysis was performed for swimmers who had competed in two consecutive seasons, with the taper phase preceding the first competition and the pre phase preceding the second competition. Each pair of changes was considered as an independent observation, although some swimmers provided several such observations. Simple linear regression of the change scores was used to derive a Pearson correlation coefficient. Small sample bias in the correlation was removed using the formula for the adjusted $R^2$ from the linear regression theory ($\text{adjusted } R^2 = 1 - [(n-1)(1-r^2)/(n-2)]$, where $r$ is the Pearson correlation; OnLineDoc V8, SAS Institute, Cary, NC). A similar analysis was used to analyse the relationship between changes within a season (first half to latter half of the season) in test measures with change in competition from the preceding season.

Magnitudes of all the correlations were interpreted using the following thresholds: $<0.10$ trivial, 0.10-0.30, small, 0.30-0.50 moderate, and $>0.50$ large (48). Data are shown as mean ($\pm 95\%$ confidence limits). To calculate the smallest worthwhile change in performance $0.5 \times$ within-athlete coefficient of variation (CV) for competitive performance was used, equating to 0.4% for Olympic swimmers (222).
3.2. Results

3.2.1. Change in Competition Performance

As shown in Figure 3-1, the swimmers had substantial mean improvements in competitive performance over the 5 y. The male swimmers initially swam ~0.9% (±0.6%) faster each year, with this improvement reaching a plateau of 2.6% (±1.6%) after 4 y. While the female swimmers also swam faster each year, the magnitude of their improvement was much smaller at ~0.4% (±0.7%) each year. The coefficient of variation in performance from competition to competition for individual swimmers was typically 1.1% (95% confidence limits: ×/±1.6%) for females and 1.0% (×/±1.3%) for males.
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 ± 95% confidence limits. (Females, n = 16; Males, n = 24).
3.2.2. Changes in 4-mM Lactate (Submaximal Speed)

Figure 3-1 shows modelled longitudinal changes in stroke rate at the 4-mM lactate to illustrate how mean changes in step-test measures tracked mean changes in competition performance. There was a (likely) substantial change of 4.0% (±4.5%) mean increase in stroke rate at the 4-mM lactate over the 5 y in the program for the female swimmers, while male swimmers had a mean 2.0% (±2.5%) increase over the same period. Improvements from year to year were also observed in maximal time and speed at the 4-mM lactate. Female swimmers had a substantial decrease of 3.3 ± 2.9% in maximal time and a 5.3 ± 2.5% increase in speed at the 4-mM lactate over 5 y. In contrast, male swimmers showed only a small improvement of 1.1% (±1.5%) in maximal time over the first 2 y and then subsequently got slower. Males had less than 0.5% (±1.8%) improvement in speed at the 4-mM lactate over the 5 y period.

3.2.3. Correlations Between Test Measures and Competition Performance

Changes in individual test measures taken during the training season had moderate to large correlations with changes in end-of-season competition performance. Overall changes in step test and anthropometric measures tracked performance best in the taper phase. The correlation between step test and competitive performance, presented as % change in competitive performance/1% change in the test measure (modelled as a slope), are shown in Table 3-1. The range of the standard error of the estimate for these correlations in the taper phase was 0.9-1.1% for the female swimmers and 1.0-1.1% for the male swimmers. The relationships between changes in competition time and changes in stroke rate at 4-mM lactate in the taper phase are shown for both male and female swimmers in Figure 3-2. In earlier phases of the season, there were substantial correlations for the female swimmers between competition performance and maximal or 4-mM lactate time, peak heart rate, stroke rate and stroke length at 4-mM lactate and skinfolds (r = 0.31-0.55; 95% confidence limits ±0.35).
The male swimmers had a moderate to large correlation with competition performance in the pre and early phases for the lean mass index ($r = 0.39-0.51; \pm 0.23$).

**Table 3-1:** 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.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Adjusted Correlation ($r$)</th>
<th>Slope (%/1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female</td>
<td>Male</td>
</tr>
<tr>
<td>7 x 200-m Step Test:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal 200-m Time</td>
<td>0.37</td>
<td>0.08</td>
</tr>
<tr>
<td>Maximal Lactate</td>
<td>$\sim 0.00^a$</td>
<td>0.41</td>
</tr>
<tr>
<td>Time at 4-mM Lactate</td>
<td>0.31</td>
<td>0.21</td>
</tr>
<tr>
<td>Stroke Rate at 4-mM Lactate</td>
<td>0.46</td>
<td>0.41</td>
</tr>
<tr>
<td>Stroke Length at 4-mM Lactate</td>
<td>0.36</td>
<td>0.33</td>
</tr>
<tr>
<td>Anthropometry:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body Mass</td>
<td>0.32</td>
<td>0.13</td>
</tr>
<tr>
<td>Sum of 7 Skinfolds</td>
<td>0.53</td>
<td>0.15</td>
</tr>
<tr>
<td>Lean Mass Index</td>
<td>$\sim 0.00^a$</td>
<td>0.30</td>
</tr>
</tbody>
</table>

*a* adjusted $r^2 < 0$

*b* for a 10% change in blood lactate or sum of 7 skinfolds

Number of athletes (and total number of tests): females step test, 8 (30); males step test, 15 (48), females anthropometry, 10 (25); males 17 (76).

Approximate 95% confidence limits for correlations: female step test, $\pm 0.35$; male step test, $\pm 0.30$; female anthropometry, $\pm 0.35$; male anthropometry, $\pm 0.25$. 

76.
**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).

For female swimmers, the best combination for predicting changes in competition performance from changes in the taper phase was stroke rate at 4-mM lactate and maximal 200-m time (\( r = 0.52; \pm 0.32 \)). For male swimmers, peak lactate and stroke rate at the 4-mM lactate in the taper phase was the best combination of measures (\( r = 0.58; \pm 0.24 \)).
3.2.4. **Off-Season and Within-Season Correlations**

The question of whether swimmers lost sport-specific fitness during the off-season was also addressed. There were small to large correlations between fitness changes in the off-season (taper phase to next pre phase) with changes in competition performance from one season to the next. Poorer competitive performance was correlated with changes in maximal stroke length (increased) and stroke rate (decreased), peak heart rate (increased), and stroke length (increased) and stroke rate (decreased) at the 4-mM lactate \( r = 0.30-0.57; \pm 0.60 \). For the male swimmers, there were moderate to large correlations between competition performance and an increase in stroke length and a decrease in stroke rate at 4-mM lactate over the off-season \( r = 0.31-0.50; \pm 0.45 \). Overall there were only small changes within a season (the first half of the season to the second half: \( r < 0.30 \)), with changes in competition performance from the previous season to the current. The exception was a within-season decrease in maximal 200-m swimming time for male swimmers, which had a moderate correlation with faster competition performance \( r = 0.34; \pm 0.48 \).

3.3. **Discussion**

In this study, the longitudinal changes in competition performance, fitness tests, and body composition in elite swimmers were tracked. The swimmers monitored in this study typically displayed worthwhile improvements in competition performance each year. The typical magnitudes of change and variability in measures of maximal and submaximal training performance, as well as physiological, anthropometric, and biomechanical measures have been established. This study has established important reference or benchmark standards for the mean and typical individual changes in national and international representative swimmers. Furthermore, several key measures have been identified from testing within a
season that may assist the coach and sport scientist to effectively gauge an elite swimmer’s progression during the training season.

An important issue for coaches and athletes is the magnitude of meaningful or worthwhile performance improvements in training and competition. The smallest worthwhile enhancement in performance that will have a substantial effect on an athlete’s chance of winning a medal is approximately 0.5 of the within-athlete coefficient of variation (100). For top ranked Olympic-level swimmers, this magnitude of change has been established as 0.4% of competitive performance time (178) or ~0.25 s in 100-m events and ~0.5 s in 200-m events. A small but clinically (practically) worthwhile mean improvement (0.4%) in competition performance each year for the female swimmers was observed. The male swimmers initially had twice the rate of improvement of females (~1%) before starting to plateau after 4 y. Individual swimmers varied up to 1% from the mean change between competitions, which is similar to the magnitudes of within-swimmer variation previously reported (178, 206, 222). The within-athlete variation in performance between competitions reported for the elite senior swimmers in the present study was less than the 1.4% reported for elite junior swimmers (206), but greater than the 0.8% reported for Olympic swimmers both within and between competitions (178, 222). The smaller variation for the better standard of swimmer suggests that swimmers at the elite level are more consistent with their competitive performance from race to race.

A key outcome of this study was that the female swimmers showed continuing improvements in test performance in training and competition performance, whereas the testing performance of males remained stable despite improving competition performance. Over the 5 years, female swimmers were likely to have a 3-5% improvement in time for the maximal 200-m
effort and at the 4-mM lactate concentration. Although the long-term changes in test performance were greater in magnitude for female swimmers, the pattern of these improvements were consistent with the changes in competition performance over the same period. Conversely, while substantial improvements in the male swimmers’ competition performance were observed over the study period, there were only trivial changes in test performance measures of the maximal 200-m effort or the time at the 4-mM lactate. The differences observed between the male and female swimmers in the performance tests and the subsequent competitive performance could be related to sex-specific adaptations to similar training programs. The male swimmers showed a greater ability to develop power and utilise the anaerobic energy system while the female swimmers demonstrated a greater swimming efficiency. The present finding of different responses between the male and female swimmers is in contrast to previous research involving U.S. collegiate swimmers in which similar improvements were found between the sexes over a short 8-wk training period (36). One possible explanation that has been suggested for the larger relative gains in fitness in females compared with males is a lower initial level of fitness in the females (34, 67). This may partially explain the observed differences across the current cohort of elite swimmers where eight of the male swimmers were individual medallists at international competition compared with only two of the female swimmers. Nevertheless, coaches need to take into account the potential differences in the rates of adaptation between male and female swimmers, particularly over several seasons. Consequently, the training programs for male and female swimmers may need different emphases in content, volume, and intensity.

Previous longitudinal studies of the relationship between fitness assessment and competitive performance of athletes have invariably restricted their analysis to the mean changes in test measures and performance. A novel aspect of the study is the analysis of the changes in
individuals. The test measure most representative of competition performance is the maximal time derived from the 7th step in the step test. Time at the fixed 4-mM lactate is a marker of aerobic fitness, a physiological attribute important in swimming performance (196, 226). Maximal lactate was also a parameter common to the regression models for both male and female swimmers. Maximal lactate can arguably be used as an indicator of the underlying contribution of anaerobic energy contribution to swimming performance (136).

Biomechanical and stroke characteristics are important elements in competitive swimming. Our data shows that stroke rate at a 4-mM lactate as an important parameter especially for female swimmers. It appears that the manner in which female swimmers undertake their swimming at submaximal speeds is an excellent predictor of their subsequent competitive performance (59). Coaches are advised to monitor the stroke rate of swimmers in testing sessions and routine training sets at both submaximal and maximal speeds.

Tracking changes from the taper phase in one season to the taper phase in the next was clearly the period when the step test measures best tracked changes in competition performance. A possible explanation for the poorer predictive value of test measures in earlier phases may be that the coach and/or swimmer took action to correct discrete aspects of their training or body composition identified as deficient with the testing. For example, if a swimmer’s speed at the 4-mM lactate was slower than at the same phase of training in previous years, indicating poor fitness, the coach may have supplemented the training with additional endurance threshold training to rectify this limitation by the time of the end-of-season competition. Consequently the additional training through the season remedied the swimmer’s poor fitness and presumably maintained or improved end-of-season competition compared with the previous season. Given its proximity to the competition, the taper phase is presumably more representative of the physical state of the swimmers when they compete. However tests in
this phase were mostly 3-4 weeks from the competition and allowed one final opportunity for corrective action. It is also possible that the results of early- and mid-season testing is more variable due to the effects of accumulated fatigue in the earlier phases of training characterised by higher training volumes. The extent to which the coach may have acted on a poor test result for individual swimmers is not known in the current study, but it seems reasonable that any successful corrective action would reduce the magnitude of relationship between test measures in early phases and competition performance.

In addition to the changes in the same phase from season to season, the changes from the first to the second half of the season and over the off-season were also analysed. These may have practical importance for a swimmer’s training preparation and subsequent end-of season competition performance. However, given the limited number of observations in this study, there is a reasonable degree of uncertainty in the estimates. Further investigation is required into the role of the off-season or the rate of change of adaptation during the season on competition performance.

The anthropometric characteristics of world class swimmers are well established (1, 204). Surprisingly little has been published on the seasonal and long-term changes in elite swimmers particularly considering these measures are probably taken regularly throughout the training preparation in many high level swimming programs (174). Siders et al. (197) observed an increase in fat-free mass for female sprinters and a decrease in fat mass and body fat percentage for male sprinters as measured by hydrostatic weighing within a competitive season. In the present study, it was found that an increase in proportional lean mass in several phases of the season correlated highly with improved end-of-season competition performance in male swimmers. In contrast, for female swimmers, a decrease in body fat (skinfolds) in the
taper phase from one season to the next was highly correlated with improved competition
performance. Unfortunately, limited data in the pre and early phases for females in this
sample may have precluded any definitive assessment of the ability of skinfolds in these
phases to track competition performance. From observations made previously (5; Chapter 2),
training induces a loss of mass and body fat (skinfolds) in female middle-distance swimmers
with minimal changes in lean mass. In contrast, male middle-distance swimmers generally
respond to training with gains in mass and lean mass, but have minimal changes in skinfolds.

The within-athlete design used in the present study poses some unique challenges to
researchers. In the elite sport setting, it is often difficult to include a control group into the
experimental design. At this level of competition, athletes are managed in an individual
manner and so stringent experimental control is difficult to achieve. Factors such as the
psychology of dealing with competition stress or injury are also difficult to control and could
impact on an individual’s testing and competitive performance. One outcome of these factors
is that athletes who are less able to cope may exhibit greater variability in the test measures
and performance. Interpretation of test results for a given swimmer should account for a
number of factors: the magnitude of change in fitness and body composition measures under
examination, the smallest worthwhile change in performance, the typical error of
measurement, and the precision of the estimate (96). While there is value in establishing
short-term test-retest reliability over a few days, this may not be fully indicative of the
(typically greater) variability occurring over a season or several seasons. The value of
performance testing primarily lies in structured routine monitoring of individuals within and
between seasons to establish individual variability and seasonal changes. This approach
should facilitate more well-informed judgements on training adaptations than is possible with
ad hoc or one-off testing.
Of primary concern to coaches and sport scientists is how they can apply and interpret the relationships identified between testing and competition performance. In interpreting the prediction results of this study for practical situations, the percent estimated change in competition performance for a 1% change in test measure were modelled, and interpreted these estimates against the reference smallest worthwhile change for competition performance (0.4% for Olympic swimmers) (222), and the standard error of the estimate (~1.0% for female swimmers and ~1.1% for male swimmers) in the present study. For example, a 1% improvement in competition performance would require a ~4% decrease in swimming time at 4-mM lactate for female swimmers and a ~8% decrease for the male swimmers. The percentage slope of the relationship is useful for predicting changes in competition performance when there are large changes in step test or body composition measures. While the predictive analysis is less accurate with individuals with small changes in test performance, it is nevertheless useful for assessing the likelihood of a team’s performance outcomes at an upcoming competition (102).

3.4. Conclusion

The current study is the first to characterize the typical magnitude of mean and individual long-term progressions in competition performance of elite swimmers. A combination of step-test measures can predict mean and individual changes in competition performance. It is possible to accurately predict competition performance from certain tests measures in the taper phase; possibly as it is closest to the competition and in earlier phases coaches take corrective action. However, there is still some uncertainty in the predictive models that requires further research with other high-level swimmers. The combination of performance,
physiological and biomechanical predictors of performance highlights the importance of an interdisciplinary approach to assessing training and performance adaptations.
CHAPTER FOUR

DEVELOPMENT OF A SWIMMING MONITORING DEVICE - TRAQUA

4.0. Introduction

The evaluation of physiological and sport-specific performance measures provide fundamental information to the coach, athlete and sport scientist on the athlete’s response to the training program (200). The most practical methods of monitoring the performance of elite athletes are those that can be easily administered in the training environment. This is particularly the case for sports such as swimming where the physiological and movement demands cannot be easily replicated in a laboratory setting (183). As swimming competition and training is performed in a relatively closed and controlled environment of either a 50 metre or 25 metre pool, coaches frequently use standardised training sets to monitor the athlete’s physiological and biomechanical adaptations. Unfortunately these assessments are made infrequently and provide just a snapshot of how the athlete is performing in a particular training session. Furthermore, tools such as video or biomechanical race analysis systems are either time-consuming or very labour intensive and therefore only used intermittently.

Continual in-field monitoring of training may provide more a better approach for assessing the magnitude of adaptations or fatigue. Continual monitoring of training may provide better insight into both a swimmer’s acute and long-term training state as well forming the basis for training prescription. Initially, the continual monitoring of stroke characteristics may provide further information about stroke efficiency and swimming economy such as stroke rate and stroke length (40, 55). A primary focus of previous studies that have examined the factors
influencing elite swimming have been stroke rate and stroke length, which together determine velocity (velocity = stroke rate x stroke length) (9). To achieve a high level of performance, the swimmer must have tight control of the stroke rate and stroke length used during training over a range of speeds (45). A device that is able to automatically detect swimming-specific characteristics such as stroke type, start, stops, turning movements, stroke count and stroke frequency (stroke rate) would provide useful information to the coach. Those components which have a direct bearing on the outcome of a race should be trained and monitored.

Various devices have been proposed for systematically tracking movement of the human body. Much of this work has been in activity monitoring (158, 224) as well as in the context of sporting activities, with the goals of improving performances and reducing injuries (117, 167, 191). A major development in sports technology has been the application of tri-axial accelerometry. This involves mounting an accelerometer on the body to detect movement by sensing acceleration and deceleration. Within the scientific literature, the reliability and validity of uniaxial, biaxial and tri-axial accelerometers in general applications have been well established (30, 125, 158). However, the use of accelerometers within the sporting environment has been limited. In swimming, the current technology used to monitor and quantify stroke patterns is unsatisfactory. Manual or automated video-based biomechanical systems are both cumbersome and time consuming. Manual stroke counting or stroke rate provide limited accuracy because of the likelihood of human error.

Ohgi and co-workers in a series of study (105, 106, 165, 166, 168) have investigated the use of a tri-axial accelerometer device for the monitoring of swimming technique with a device attached to the wrist. These studies showed the device clearly discriminated every stroke and classified each phase of the arm movement (i.e. down-sweep, in-sweep, out-sweep and
Furthermore, during an intensive training session, they were able to detect changes in the accelerometer traces due to the fatigue of the swimmer (164). More recently, Roncaíez and co-workers (185), have proposed a similar device to measure whole-body repetitive movements may have applicability to swimming. These studies suggest that tri-axial accelerometry may provide an accurate and easily operated alternative to the existing methods of monitoring swimmer’s movements and training.

Continual pool-based monitoring may provide more accurate and detailed information about a swimmer’s training adaptation than current fitness tests and monitoring methods. A recent development which may assist in the area of improving the continual pool-based monitoring of swimmers has been a smart sensor known as the *Traqua*. The *Traqua* consists of a tri-axial accelerometer packaged within a microprocessor and is attached to the swimmer to monitor their movements while swimming. Therefore, the purpose of this chapter is to describe the development pathway of a swimming monitoring device (*Traqua*) that is used in the subsequent experimental studies in this thesis. In addition, the aim is to describe and evaluate the algorithms that have been created to detect the swimming-specific characteristics of the *Traqua* accelerometer device.

### 4.1. Swimming Monitoring Device - Prototype Considerations and Development

#### 4.1.1. Proof of Concept

The initial proof of concept of an accelerometer-based device originated from pilot studies of a uniaxial accelerometer device strapped to the back of a single swimmer. The device was placed such that the accelerometer was oriented to the forwards-backwards direction (*X* axis) of the swimmer’s motion. The device was hardwired to a data logger which the study investigator held and walked alongside the pool deck next to the swimmer. The
accelerometer trace from the initial trials of freestyle and breaststroke are shown in Figure 4-1. A trace of each distinct stroke was evident in the breaststroke but not freestyle. The distinctive trace in the forward-backwards axis was presumably attributable to the large fluctuations in velocity common to this stroke and similar traces of breaststroke have been previously shown (57). A working hypothesis that a stroke pattern, where each single stroke is recognisable, would be observed in the side-to-side axis for freestyle was established. Further preliminary trials were conducted in each of the four basic swimming strokes (freestyle, butterfly, backstroke, and breaststroke). The preliminary data indicated that the accelerometer-based device was able to discriminate between the four different swimming strokes. The data also demonstrated that the device could differentiate each individual stroke cycle.
**Figure 4-1:** Accelerometer traces from the proof of concept trial. The blue line is the acceleration trace; the green line indicates zero acceleration and the yellow lines indicate where a simple algorithm (not developed on swimming data) has identified a stroke occurring.

a) Freestyle trace in forwards-backwards axis

![Freestyle trace in forwards-backwards axis](image)

b) Breaststroke trace in forwards-backwards axis

![Breaststroke trace in forwards-backwards axis](image)
4.1.2. Location Considerations on Body

Unlike land-based sports, there are only certain locations on a swimmer's body where a device can be attached without causing major interference while swimming. The options explored were placement on the head, attachment to the goggle strap or under the swimming cap, between the shoulder blades, or the lower back.

Attaching the device to the head was initially an attractive option because it would cause minimal interference to the swimmer. However, while this option appeared appropriate for detecting the breathing pattern of the swimmer, the head movement was found to be independent of the body movement, particularly with swimmers of lower standards and when fatigued. Therefore, this placement of the device on the head was not considered the ideal position for detecting the primary features of the number of strokes (stroke count) and the frequency of strokes (stroke rate).

On the other hand, positioning the device between the shoulder blades was found to provide a clear signal of each single stroke cycle. The device has to be attached by either being taped to the back or a strap around the chest. Unfortunately, these two methods of attachment proved unpopular with the swimmers in the pilot testing because it inhibited their swimming movement.

A key aim of the development of this device was to track whole body movements. Consequently, given the limitations of the other possible attachment sites as well as its close proximity to the centre of gravity, the lower back (midline, top of the buttocks) was selected as the most suitable site of attachment (Figure 4-2). With the device located at the lower back, a clear and distinctive signal was evident for each type of stroke.
Initial prototype versions (prototypes 1 and 2) had the device attached to the swimmer via a strap sitting just below the iliac crest. Several problems were encountered with this method of attachment included the accelerometer not being perfectly centred as well as the belt coming loose and subject to extraneous movement. Feedback from the swimmers indicated the strap created significant drag and tended to slip upwards on the body, particularly when pushing off the wall. Some swimmers felt that the belt restricted their breathing as well as restricting their hip/trunk movement during butterfly in the wave action of the body during the butterfly stroke. Subsequent generations of the device overcame these problems by incorporating the device into the swimmer’s swimsuit.

**Figure 4-2:** Location of the accelerometer device on the lower back
4.1.3. Orientation

The swimming monitoring device contains two bi-axial accelerometers, one placed perpendicular to the other to obtain three orthogonal axes of acceleration ($X$, $Y$, and $Z$ axes). The accelerometer axes were aligned with the body so that the $X$ axis was parallel with the length of the body (forwards-backwards movements), the $Y$ axis parallel to the hips (sideways movements), and the $Z$ axis perpendicular to the back (up-down movements). The orientation of the device on the swimmer when swimming is shown in Figure 4-3. For future reference the $X$ axis will be referred to as forwards/backwards, the $Y$ axis as up/down and the $Z$ axis as sideways (left/right). Orientation of the device was kept constant for all subsequent experimental trials.

Figure 4-3: Accelerometer orientation when placed on the back of a swimmer while swimming and the 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.
4.1.4. Packaging

The primary requirements for packaging the system were a waterproof housing, an unobtrusive design that would not interfere with the swimmer or create additional drag, and a device that could be easily operated. In the early stages of this study, substantial time was spent developing a streamlined packaging within the limitations originally imposed by the size of the electronic components. As the development of the prototype progressed, the actual size of the electronics decreased allowing for the smaller and rectangular design used in the final prototype. From the trialing and experience of the first three prototypes, overall size of the device was the overriding consideration in making the device as unobtrusive to the swimmer as possible. The dimensions of each of the prototypes are shown in Table 4-1.

The device was waterproofed to withstand being submerged in water for periods in excess of 4 hours per day. In the initial prototype, a commercially available hard plastic case with rubber seals was used. In the following two generations of prototypes, waterproofing was achieved using a fully encapsulated silicone elastomer moulded device. The limitations of using this type of packaging included difficulties with repairing or servicing the electronics, the method of switching the device on and off, and degradation of the packaging materials associated with constant use in a chlorine-rich environment. The final prototype used a hard plastic case with in-moulded gold plated conductors (for charging and data transfer) and a soft over moulded on-off button. These design features allowed for an easy to use on/off button and the ability to access the electronics for repair if required.
Table 4-1: Dimensions of the four fully packaged versions of the swimming monitoring device

<table>
<thead>
<tr>
<th>Prototype Version</th>
<th>(Length x Width x Depth) (cm)</th>
<th>Mass (g)</th>
<th>Volume (cm³)</th>
<th>Percentage of volume of prototype 1 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.3 x 8.7 x 3.9</td>
<td>170</td>
<td>383</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>21.7 (incl. strap attachments) x 11.8 x 1.0</td>
<td>196</td>
<td>256</td>
<td>67%</td>
</tr>
<tr>
<td>3</td>
<td>8.4 x 5.4 x 1.6</td>
<td>100</td>
<td>73</td>
<td>19%</td>
</tr>
<tr>
<td>4</td>
<td>6.6 x 5.0 x 1.2</td>
<td>20</td>
<td>40</td>
<td>10%</td>
</tr>
</tbody>
</table>

4.1.5. Swimming Monitoring Device Evolution

The evolution of the device designed to monitor movements in swimming from the initial prototype to the final version is shown in Figure 4-4. The first prototype was fully encased in a waterproof box and placed in a fitted pouch attached to a strap. The second prototype was the first fully moulded and employed a heart rate strap to attach it to the swimmer. The third prototype was placed in a specifically made pouch in the back of the swimmer’s swimsuit and the final prototype was a smaller and waterproof version.
Figure 4-4: 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 Traqua4.

4.1.5.1. Prototype 1

After the initial proof of concept trials using the uniaxial accelerometer, a waterproof tri-axial accelerometer version was developed. This device was contained within a pouch attached to a belt which fitted around the swimmer's hips. This prototype was the first unit that could be used by swimmers to observe performance in the pool during a training session rather than in simulated conditions.

The primary problem with this the prototype was the overall size. In particular, swimmers found wearing this device during training to be quite inhibiting. The prototype was heavy and had a tendency to move around. It also created substantial drag for the swimmer, especially when pushing off the wall and in tumble-turns. This prototype was used to develop initial stroke identification algorithms, with the data collected from this device showing that each
stroke type had a unique signal across the three acceleration axes. Moreover, each individual stroke in a lap could also be clearly identified as well as an estimation of the timing of the start, turn, and finish of a lap or interval.

4.1.5.2. Prototype 2

The primary aim of the second prototype was to develop a more hydrodynamic shape that would not interfere with the swimmer’s stroke. Various prototype packaging designs were developed and trialled (Figure 4-5). The design that was eventually adopted is shown in Figure 4-6 together with its charging and download cradle. This prototype had an infrared download capability and utilised a fully enclosed charging coil. The coil could be placed on the cradle within a graphite bridge in order to complete a circuit to charge the device. The strap design was retained for this prototype as it was thought that this would make the device easier to attach to the swimmer.

Unfortunately this design encountered several major problems. First, even though the device was designed to be hydrodynamic with tapered edges, it tended to lift up and flip over particularly when the swimmer was turning or pushing off the wall. The lifting upwards and flipping generated additional drag (self-reported by the swimmers) and increased the signal noise in the accelerometer traces. Secondly, the strap design restricted some swimmers in their breathing and moved upwards when swimming. Thirdly, the infrared method of data transfer was unreliable and regularly lost connection mid-way through downloading a file. Finally, the relatively large size of the device made the device noticeable to the swimmer when swimming and violated a design aim of being unobtrusive to the athlete.
**Figure 4-5:** The various designs that were proposed for Prototype 2.

![Prototype 2 Designs](image1)

**Figure 4-6:** Final design for Prototype 2 (*Traqua*) sitting on its charging/download cradle.

![Final Design](image2)
4.1.5.3. **Prototype 3**

The third prototype was a device modified from another application in field sports and waterproofed so it could be used in the aquatic environment. The modular device utilised USB interfacing, allowing for a more reliable connection with the PC and a significantly faster download time. As the prototypes became progressively smaller, the use of a strap became more problematic.

An alternative to the strap using the swimmer’s swimsuit modified with a pouch sewn in the back was adopted for the third prototype to minimize drag interference. The pouch was sewn into the back of the swimsuit, centred, and positioned distally to the drawstring in the male swimmer’s swimsuit.

A major issue with this set-up was the need to individually size each swimmer’s swimsuit. If the swimsuit were too large for the swimmer then extra movement of the device when swimming created further noise in the accelerometer signal. For the female swimmers, bikini bottoms were used to ensure the device was located in the same anatomical place on the pelvis as the males.

Although the leading edges of this prototype were not tapered to provide a more hydrodynamic shape it worked very well, primarily due to the smaller size. The main limitations with this iteration of the device were the lack of permanent waterproofing and the need to individually size the swimming swimsuit for each individual.
4.1.5.4. Prototype 4 - Traqua4

The fourth iteration of the swimming monitoring device was a smaller and permanently waterproof version that addressed most of the problems encountered in the earlier versions. Like the previous version, this prototype utilised USB download and charging. However, to ensure the device was completely waterproof, gold bump connectors on the underside provided direct data connection to the cradle. The final version of this prototype, known as the ‘Traqua4’, is shown in Figure 4-7.

Figure 4-7: Final prototype version of the swimming monitoring device, the Traqua4 – 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.

4.1.5.4.1. Technical Specifications of the Traqua4

The technical specifications of the Traqua4 are listed in Table 4-2 and the electronic configuration is shown in Figure 4-8. The system was implemented with an onboard flash memory, which can store several hours of data across multiple sessions. In the final prototype version, the system can operate for more than 12 h on the internal rechargeable batteries and
is recharged using a wireless charging system. The system includes a cradle with USB interface to a PC for charging, download, and firmware upgrade. The recording system was configured for 100 Hz sampling rate on all three channels. The download time for an individual file is dependent upon the file size: typically ~2 minutes for a 30 minute file.

Table 4-2: Specifications for the final design of the sensor (Traqua4 device)

- ±2g piezoelectric tri-axial accelerometer (Kionix KXM52 series)
  - Sensitivity: 660 mV/g
  - Bandwidth: 0 to 3000 Hz max (x and y), 0 to 1500 Hz max (z)
  - Output Resistance: 32K Ω typical
  - Cross-Axis Sensitivity: ±2.0% typical (±3.0% max)
  - Mechanical Shock: 4600g
- 300 degree angular rate sensor – gyroscope (Analog Devices)
- USB interface for data download, firmware upgrade and feature selection
- 256 MB memory card
- Rechargeable battery with >6 h of operation
- Battery recharged in <3 h
- Dual colour LED for recording/battery charge

Figure 4-8: Electronic configuration of the final prototype of the swimming-monitoring device (Traqua4).
4.2. Swimming Monitoring Device - Software and Algorithm Development

4.2.1. Calibration

Each device was calibrated prior to initial use and was also periodically calibrated during research trials and routine field use. The calibration was achieved via a real-time connection to the software and required the unit to be oriented so that each of the axes (X, Y, and Z) was equal to +1g and −1g. Each unit’s accelerometer values were then recorded. The aim of the algorithms was to detect the swimming specific characteristics without having to calibrate to an individual’s swimming stroke.

4.2.2. Swimming-Specific Algorithms

Prior to any of the swimming-specific algorithms being run, a filter was applied to the raw accelerometer data. The raw accelerometer data was filtered using a Butterworth low pass filter (190) with a cut-off frequency of 1.5 Hz. The purpose of the filter was to limit the noise in the data and limit the dynamic accelerations. As a result, the changes in the accelerometer output in swimming were observed as characteristic stroke patterns related to changes in orientation or acceleration due to gravity (static acceleration).

4.2.2.1. Start Identification

During regular swimming training, the majority of laps/efforts are commenced with an in-water push start, compared with the dive starts from a block used in competitive racing. While the push start and dive start have similar features, the initial focus was to develop a reliable algorithm for the detection of push starts. An example of the characteristic trace for a push start is shown in Figure 4-9. A push start was typically characterised by:
i) A sudden increase in acceleration in the X (forwards/backwards) axis in the region of a large swing in the Y (up/down) axis in the 10 s before the first stroke,

ii) The start was defined as a peak >0 g proceeded by a trough of <0 g and with >1 g difference between the two

iii) The algorithm worked backwards after first locating the timing of the first three strokes in a row.

iv) To determine the start a fourth channel was used, which was the sum of square difference of adjacent accelerometer readings (Ac3Diff). The start, which is the point in time where the swimmer’s feet leave the wall, was determined as the highest peak in the Ac3Diff. The peak in the Ac3Diff channel had to be located within a 10 second window of the first stroke occurring.
Figure 4-9: 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).
4.2.2.2. Turn Identification

The turn was defined as the point where the swimmer’s feet touched the wall (lap finish) and subsequently left the wall on the way out of the turn. A characteristic turn is shown in Figure 4-10. The turn was identified by a number of events. The specific events included:

i) The absence of any swimming stroke,

ii) A peak (>1g) in the up/down accelerometer (Y axis) as the swimmer initiates the turn, followed by a trough (approximately equal to –1g) in this same axis when the swimmer has touched the wall, and

iii) A sudden increase in the forwards/backwards acceleration (X axis) over a short period of time (similar to the push-off lap start detection).
Figure 4-10: Accelerometer trace of a typical push 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).
4.2.2.3. Stroke Identification

Each of the four competitive swimming strokes was characterised by distinctive changes in one or more of the three accelerometer axes. Freestyle and backstroke were characterised by:

i) A wave pattern in the Z (sideways) axis (see Figure 4-11 for freestyle and Figure 4-12 for backstroke),

ii) Freestyle had minimal changes in the other two axes (X or Y axis). In contrast, backstroke was differentiated from freestyle by a large (-2g) change in the Y (up/down) axis, and the wave pattern observed in the Z (sideways) axis was of smaller magnitude than that observed in freestyle.

iii) Each peak and trough was indicative of one arm stroke, either a left or right arm stroke depending on whether it was a peak or trough.

Breaststroke and butterfly were characterised by:

i) Changes in both the X (sideways) axis and the Y (up/down) axis. An example of the accelerometer traces is shown in Figure 4-13 (breaststroke) and Figure 4-14 (butterfly).

ii) Breaststroke had two characteristic peaks in the X axis that constituted a stroke; a larger peak associated with the leg action, and a smaller peak related to the arm movement.

iii) Similarly butterfly had two characteristic peaks to the accelerometer trace: the first peak had the greater area under the curve and was related to the leg action while the smaller peak was due to the arm action.

For all the strokes, the algorithms detecting individual strokes were then used to derive a stroke count (the number of strokes taken each 50-m lap) and a stroke rate (the number of stroke cycles per minute).
Figure 4-11: 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
Figure 4-12: 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).
Figure 4-13: 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).
Figure 4-14: 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).
4.2.2.4. Lap Finish

The finish of a lap was the most difficult characteristic to detect since there was no discernable change in the accelerometer trace when a swimmer touched the wall. Part of the explanation for this difficulty is that swimmers, especially in training tend to glide into the wall.

Initially the finish of a lap was designated as the point in time when the following events occurred:

i) More than one second since the last detected stroke,

ii) There was a prolonged decrease in the \( X \) (forward/backward) axis, and

iii) Before a change in orientation of the swimmer where the up/down accelerometer (\( Y \) axis) showed a sudden decrease of >1g as the swimmer stands upright.

However, because this method failed to reliably and accurately detect the exact point for the lap finish, it was decided to arbitrarily designate the finish point as a constant value of one second following the last detected stroke. The appearance of the typical accelerometer trace of a lap finish is shown in Figure 4-15. With the ability to detect both the start of a lap and either a turn or end of the lap, an individual lap time could then be determined.
Figure 4-15: 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).
4.2.3. Validation of Swimming-Specific Algorithms with Video Synchronisation and a Global Positioning Device (GPS)

Digital video was used to validate those points of the acceleration traces used as markers for the detection of lap start/turn/finish and individual strokes. Several trials were conducted in which accelerometer traces were synchronised with digital video (filmed both above and underwater). Once the video was time-synchronised with the accelerometer traces, the video was advanced frame-by-frame along with the accelerometer data to observe and confirm the accuracy of the algorithms for the push-off, turn, finish, and individual stroke determination.

As the initial validation with video was manually time-synchronised with the accelerometer data, further trials were conducted using a similar accelerometer device that also had GPS capability. Two accelerometer/GPS devices were used. One unit was attached to the swimmer and the other was connected to the video source, allowing the video to be automatically time-synchronised with the accelerometer/GPS device via the accurate GPS clock. Once the video and accelerometer data were accurately synchronised, the video was advanced frame-by-frame together with the accelerometer data. From this process, it was confirmed whether the characteristic points used as markers for the various algorithms were appropriate or not (eg. had the turn been picked by the right trough/peak).

4.3. Error Frequency in the Algorithms Developed for Swimming

Data was visually inspected to determine whether the algorithms had correctly identified the lap, stroke count and stroke rate. The lap consisted of correctly identifying the start and/or turn and/or finish, with an error in any of these three components contributing to an error in the lap timing. Errors in stroke count could occur where additional strokes had been
identified (usually at the start or finish of a lap) or strokes had been missed. When strokes were missed within the lap, this contributed to errors in the stroke rate. Data from twenty-four elite and sub-elite swimmers was pooled and analysed for the frequency of errors in each of the three components (lap, stroke count and stroke rate). The data consisted of 200-m efforts spanning seven incremental intensities from easy to maximum for each swimmer (speeds swum were individual for each swimmer but all ranged ~30 seconds from the slowest to the fastest swim). Efforts of 200 m were chosen as this distance encompassed most of the different combinations of lap algorithms (eg. start-turn, turn-turn, and turn-finish). The start-finish combination is the exception that could be deduced from the other combinations, and therefore adjusted as part of the data analysis.

In total, 1260 laps were inspected to allow algorithms to be manually corrected and to check for errors in the automated methods of determining lap times and stroke characteristics. This exercise focused on freestyle and breaststroke as these are the only strokes which were used in the subsequent experimental studies. The breakdown of the analysis by stroke was: 1064 laps of freestyle from 21 swimmers (11 elite and 10 sub-elite) and 196 laps of breaststroke from 3 swimmers (all elite). In order to determine whether the errors were systematically due to speed or swimming standard, the frequency of errors in the algorithms were analysed by stroke type; and for freestyle by standard (elite vs. sub-elite) and speed (fastest 3 versus slowest 4, 200-m efforts).
4.3.1. Criteria for Manual Correction of Algorithms

Criteria were established to determine when the algorithms systematically failed to correctly pick the markers of the particular movements as outlined in Section 4.2.2. Each of the four 50-m laps, which make up the 200-m effort, was individually inspected. The investigator determined whether the algorithms had correctly picked the right movements using established criteria (Table 4-3). Examples of traces of the most common distinctive errors which required manual adjustment are shown in Appendix A.

Table 4-3: Criterion for manual correction of swimming-specific algorithms

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Distinctive errors made by the algorithm that required manual adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start</strong></td>
<td>• Early start – a sudden increase in the X (forward/backward) axis which on inspection is clearly not the start e.g., 5 s prior to the actual start, possibly caused by the swimmer getting into the water.</td>
</tr>
<tr>
<td></td>
<td>• Late start – missed actual start and picked first stroke or an underwater kick as start</td>
</tr>
<tr>
<td></td>
<td>• Early or late identification of turn i.e., within clearly defined swimming strokes</td>
</tr>
<tr>
<td></td>
<td>• Inexplicably determined turn mid lap</td>
</tr>
<tr>
<td></td>
<td>• Early finish – finish picked prior to the final stroke occurring</td>
</tr>
<tr>
<td><strong>Turn</strong></td>
<td>• Late finish – finish determined greater than 2 s after last stroke and where the Y (up/down) axis has changed &gt;1g indicating swimmer has changed orientation e.g., stood up after touching the wall.</td>
</tr>
<tr>
<td><strong>Finish</strong></td>
<td>• Missed stroke – stroke missed when there was obviously a stroke e.g., mid lap</td>
</tr>
<tr>
<td><strong>Stroke</strong></td>
<td>• Additional stroke - near turn or finish where there is no obvious stroke, or detected an underwater kick as a stroke</td>
</tr>
</tbody>
</table>
4.3.2. Results – Frequency of Errors

In the algorithms for the determination of a lap and consequently lap times, there was an overall error rate of 13% (165 out of 1260 laps) where the algorithms failed to correctly denote the lap. Approximately 5% of all laps required some manual change in stroke rate (62 out of 1260 laps) and 11% required manual changes in stroke count (137 out of 1260 laps). For breaststroke, there was a 22% error in lap detection (lap time), 4% in stroke rate and 17% in stroke count. For freestyle the frequency of errors was 12% for laps, 5% for stroke rate, and 10% for stroke count.

The percentage of an individual swimmer’s laps requiring manual changes is presented in Table 4-4 for freestyle. A minority of swimmers had unusually high error rates, possibly because of the unusual nature of their stroke characteristics (refer to Appendix A for examples).

The frequency of errors in the elite swimmers compared with the sub-elite was similar for the stroke rate (~5% for both groups) and stroke count (11% elite versus 14% sub-elite). However, for lap identification, the elite swimmers had a lower percentage of laps which required changes (12% for the elite compared with 17% for the sub-elite). In comparing the frequency of changes in slow swimming versus fast swimming, there was similar rate of error in the lap identification and therefore lap times (11% slow versus 9% fast). However, there were substantially more errors in the detection of stroke counts and stroke rate at the faster speeds. For stroke rate, there was only 2% error at the slow speeds in stroke characteristics compared with 7% at the faster speeds. Stroke count detection had a 3% error at the slow speeds compared with 14% at the faster speeds.
Table 4-4: Frequency of errors in swimming-specific algorithms for laps, freestyle stroke count and stroke rate by individual swimmer and summary (mean ± SD).

<table>
<thead>
<tr>
<th>Swimmer</th>
<th>Standard</th>
<th>Lap (Time)</th>
<th>Stroke Rate</th>
<th>Stroke Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Percentage (%)</td>
<td>Percentage (%)</td>
<td>Percentage (%)</td>
</tr>
<tr>
<td>1</td>
<td>Elite</td>
<td>5.4</td>
<td>0.0</td>
<td>3.6</td>
</tr>
<tr>
<td>2</td>
<td>Elite</td>
<td>28.6</td>
<td>14.3</td>
<td>14.3</td>
</tr>
<tr>
<td>3</td>
<td>Elite</td>
<td>1.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>Elite</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>Elite</td>
<td>3.6</td>
<td>0.0</td>
<td>3.6</td>
</tr>
<tr>
<td>6</td>
<td>Elite</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>Elite</td>
<td>17.9</td>
<td>21.4</td>
<td>21.4</td>
</tr>
<tr>
<td>8</td>
<td>Elite</td>
<td>21.4</td>
<td>14.3</td>
<td>17.9</td>
</tr>
<tr>
<td>9</td>
<td>Elite</td>
<td>10.7</td>
<td>7.1</td>
<td>10.7</td>
</tr>
<tr>
<td>10</td>
<td>Elite</td>
<td>3.6</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td>11</td>
<td>Elite</td>
<td>4.8</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>12</td>
<td>Sub elite</td>
<td>28.6</td>
<td>19.6</td>
<td>21.4</td>
</tr>
<tr>
<td>13</td>
<td>Sub elite</td>
<td>14.3</td>
<td>7.1</td>
<td>10.7</td>
</tr>
<tr>
<td>14</td>
<td>Sub elite</td>
<td>16.1</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>15</td>
<td>Sub elite</td>
<td>7.1</td>
<td>0.0</td>
<td>5.4</td>
</tr>
<tr>
<td>16</td>
<td>Sub elite</td>
<td>14.3</td>
<td>10.7</td>
<td>25.0</td>
</tr>
<tr>
<td>17</td>
<td>Sub elite</td>
<td>7.1</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>18</td>
<td>Sub elite</td>
<td>10.7</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>19</td>
<td>Sub elite</td>
<td>25.0</td>
<td>3.6</td>
<td>30.4</td>
</tr>
<tr>
<td>20</td>
<td>Sub elite</td>
<td>12.5</td>
<td>0.0</td>
<td>1.8</td>
</tr>
<tr>
<td>21</td>
<td>Sub elite</td>
<td>23.2</td>
<td>1.8</td>
<td>30.4</td>
</tr>
</tbody>
</table>

Mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Elite</th>
<th>Sub Elite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lap (Time)</td>
<td>12.2 ± 9.2</td>
<td>8.9 ± 9.6</td>
<td>15.9 ± 7.4</td>
</tr>
<tr>
<td>Stroke Rate</td>
<td>5.9 ± 6.8</td>
<td>6.3 ± 7.7</td>
<td>5.5 ± 5.9</td>
</tr>
<tr>
<td>Stroke Count</td>
<td>10.5 ± 10.1</td>
<td>7.6 ± 7.8</td>
<td>13.8 ± 11.7</td>
</tr>
</tbody>
</table>

4.4. Conclusion

The algorithms developed to automate the process of determining lap times, stroke rates and stroke counts were quite successful in correctly identifying the markers representing specific parts of a swimming lap in a range of swimmers across a spectrum of swimming speeds. The first iteration of the algorithms had a 12% error rate in detection of lap times, a 6% error rate in the detection of stroke rate, and an 11% error rate in the detection of stroke count. All the data presented in the subsequent studies have been visually inspected for errors in the
algorithms and corrected in accordance with the criteria presented here. The Traqua and the algorithms developed to detect the swimming-specific parameters are a novel and potentially useful tool for monitoring swimmers.
CHAPTER FIVE

RELIABILITY AND VALIDITY OF A NEW ACCELEROMETER-BASED SENSOR TO MEASURE LAP TIMES AND STROKE MECHANICS IN HIGHLY TRAINED SWIMMERS

5.0. Introduction

The evaluation and monitoring of swimming performance in the training environment is an important issue for swimming coaches and sport scientists. In elite swimming, race or competition analysis is widely used by many of the leading swimming nations to provide quantitative feedback on the major elements of a swimmer’s race performance. The primary elements of race analysis are the start, turn, finish and free swimming (200). Free swimming is further analysed in terms of time or velocity, stroke rate and stroke length (60), traditionally in 25-m segments. These measures also provide a race model for the evaluation of pool-based testing and the prescription of individualized training programs.

Contemporary methods of evaluating the in-pool movements of swimmers during racing and training are limited in comparison to the monitoring of other sports such as cycling and running. In these sports devices such as power monitors e.g., SRM cranks (77, 228), or global positioning devices have enabled systematic field monitoring of athlete movements (117, 191, 211). In swimming, video analysis and digitising are often too labour-intensive or cumbersome to be used daily in routine training or testing. Consequently swimming coaches generally rely on manual methods (viz, the hand-held stopwatch) for timing and stroke rate analysis, while swimmers’ self-reported stroke count is used as a surrogate measure for stroke
length. Although swimming is conducted in a highly reproducible environment, the ability to compare training performance is often confounded by the reliability and accuracy of timing by the coach. Manual timing is presumably highly variable and prone to errors particularly when coaching a large group of swimmers across several lanes of the pool.

The emergence of smart sensor technology in tracking sporting movements offers a number of potential solutions for improved monitoring of swimmers in training. The use of accelerometry in sporting applications is increasingly common, particularly in monitoring activity and movement patterns (25, 31, 167). Much of the initial interest in accelerometry has focussed on estimating the daily energy expenditure during lifestyle, industrial (employment) and/or recreational activities (30, 158, 224). The application of sophisticated technology should permit automated (and eventually real-time) feedback to the coach and swimmer. A group of Japanese researchers have investigated the use of an accelerometer-based system attached to the wrist to monitor technique and changes in swimming technique due to fatigue (105, 106, 165, 166, 168). Other investigators (185), have proposed a similar device to measure whole-body repetitive movements may have applicability to swimming. These promising investigations are still in their infancy, and a systematic examination of the reliability and validity of these devices must be established before they can be used confidently by coaches and researchers.

Despite the integral part that timing and stroke analysis plays in elite swimming, none of the published literature has directly compared the validity and reliability of the different methods used in swimming. Manual handheld timing is the traditional and most frequently used method in training, yet the variability compared with the more time-consuming video analysis, or the competition standard of electronic timing is unknown. With the evolution of
new technologies, it is important to establish whether these measures are comparable and/or interchangeable. Coaches need confidence in the measures taken in the different settings of competition, pool-based training, and routine training. To achieve an adequate level of confidence in timing measures, it is necessary to establish the noise or error of the method and whether there is any systematic offset bias (93). The methods also need to be reproducible particularly when trying to track changes for a given swimmer through a training season or from year to year. The implementation of a new practical measure often requires the incorporation of calibration equations established from linear regression to correct for any systematic over/underestimation (93).

The purpose of this study was to compare the validity and reliability of manual methods of timing and stroke rate determination (stopwatch) against criterion measures (electronic timing and video analysis). The reliability and validity of a new swimming accelerometry-based monitoring device that automates the timing, stroke rate and stroke count determination during testing and training was also sought. A third aim of the study was to establish regression and calibration equations for the new monitoring device so that it could be implemented immediately in high level swimming programs.

5.1. Method

5.1.1. Subjects

Twenty-four competitive swimmers volunteered to participate in this study. Fourteen of the swimmers were scholarship holders at the Australian Institute of Sport and competed at national and international level. The remaining ten swimmers were competitive sub-elite club-level swimmers. The elite swimmers consisted of 8 males (age 21.4 ± 0.9 y; mass 84.7 ± 5.8 kg, height 1.88 ± 0.05 m, sum 7 skinfolds 54.7 ± 10.8 mm, mean ± SD) and 6 females
(age 19.5 ± 2.5 y; mass 62.3 ± 7.5 kg, height 1.72 ± 0.07 m, sum 7 skinfolds 72.6 ± 16.7 mm). The sub-elite swimmers consisted of 7 males (age 17.6 ± 1.7 y; mass 71.9 ± 9.8 kg, height 1.82 ± 0.06 m, sum 7 skinfolds 49.8 ± 4.8 mm) and 3 females (age 15.1 ± 1.5 y; mass 63.2 ± 7.0 kg, height 1.70 ± 0.08 m, sum 7 skinfolds 80.3 ± 10.0 mm). Participation was voluntary and all swimmers provided written informed consent after explanation of the purpose of the study and the experimental procedures. All procedures undertaken in this study were routinely conducted within the training environment and had approval from the Ethics Committees of the University of Canberra and the Australian Institute of Sport.

5.1.2. Experimental Design and Procedures

To establish the validity of the new accelerometer-based sensor in timing and stroke analysis, swimmers swam a series of 200-m efforts with the device attached. Timing from the device was compared with contemporary methods of electronic timing (touch pads), hand-held stopwatch, and video-coded timing. Stroke rate was compared with hand-held stopwatch and video coding, while stroke count was evaluated against self-reported counts and video-coded data. The swimmers then repeated the testing under the same conditions 7-d later and the comparative data were evaluated for reliability using established analytic techniques.

The 7 x 200-m incremental step test was employed to establish validity and reliability of each of the four timing methods. Each swimmer was required to swim seven evenly paced 200-m efforts on a 5-min cycle, graded from easy to maximal (176). Swimmers completed the test using their main competitive stroke (21 freestyle and 3 breaststroke). Individualized target times based on each swimmer’s personal best time were calculated prior to testing. Swimmers were typically within 2 s of target times for the first 6 efforts, with the 7th and final swim a maximal effort. All testing was conducted in a 50-m pool and swims utilised a
push start. Speeds for the swims ranged ~30 s from slowest to fastest for each 200-m effort (e.g. 2:30 to 2:00 min). Swimmers were instructed when to push off to start each effort by a verbal count down and a buzzer synchronised with the start of the electronic timing system (OCP5, Omega, Bienne, Switzerland). Retest trials for reliability were repeated under the same conditions 7 d following the first test.

5.1.3. Timing and Stroke Information Instruments

Swimmers wore a miniaturised tri-axial accelerometer (the Traqua) device mounted in a pouch in the back of their swimsuit positioned on their lower back while swimming. The Traqua device (Prototype Version 4) contained a ±2g tri-axial accelerometer (KXM52, Kionix, Ithaca, USA) built into a small waterproof package (dimensions length 6.6 mm x breadth 5.0 mm x depth 1.2 mm, mass 20 g). A microcomputer consisting of a CPU, memory card, A/D converter and I/O functions was built into the device. The tri-axial accelerometer measured acceleration in three axes (X, Y, Z) using the principle of differential capacitance (114). Briefly, acceleration causes displacement of a silicon structure resulting in a change in capacitance which is then converted into an analog output voltage proportional to acceleration (114). The rate of change of acceleration was sampled at 100 times per second (Hz). Once collected, the device was attached to a custom-made cradle and the recorded information downloaded to a PC using a USB connection.

A calibration procedure was completed before initial use using custom-designed data acquisition software so that each axis at 90 degrees was calibrated to equal ±1g (Logan V9.6, Colin Mackintosh, Australian Sports Commission, Canberra, Australia). Signal outputs from accelerometry were captured with algorithms specifically designed for this data. These algorithms were applied to: i) which swimming stroke was used; ii) the time of the push-off
from the wall to begin a lap – *start*; iii) each individual stroke for estimation of the stroke count and stroke rate; iv) when a turn (either tumble or touch turn depending on the stroke) had occurred – *end/start of lap*; v) and the finish of an effort – *finish*. This software then provided a consolidated summary of 50-m and 100-m splits, 200-m total time, stroke rate and stroke count for each of the seven 200-m efforts.

Each swimmer was also individually videoed using a manually operated digital video camera (Models DCR-TRV900E and DCR-TRV950E, Sony, USA) from a side-on position. The camera was positioned at the half-way mark of the 50-m pool and elevated approximately 3-m off the ground in the public grandstand. The swimmer’s entire body and arm action were captured and followed for the full distance of the pool. These video tapes were subsequently viewed in real-time and individually coded using custom-designed software (*SwimTimer* version 1.0, Colin Mackintosh, Australian Sports Commission, Australia), which had specific keystrokes allocated to the start, turns and finish of a swim and each stoke. Keys were pressed at the following points: when a swimmer’s feet left the wall indicating the start of an effort, on hand entry of each stroke to specify a stroke had been taken, when the swimmer turned at the end of the lap and their feet hit the wall (hands in breaststroke) to indicate the end of the lap, and when the swimmer’s hand touched the wall to indicate the finish. A subset of 15 data sets was subsequently recoded to establish the tester’s retest (intra-tester) reliability for the video coding method of these measures. The typical error for each measure is presented in Table 5-1.
Timing was also assessed by electronic touch pads using the *Ares 21 Timing System* (OCP5, Omega, Bienne, Switzerland). Each swimmer swam in a separate lane with touch pads positioned at both ends of the 50-m swimming pool to obtain 50-m split information.

Each 100-m split and the total 200-m time were also timed manually. Stroke rate was measured on the third lap by manually timing three complete stroke cycles with a stopwatch (Seiko, Model S120-4020, Japan). The number of strokes taken per 50-m lap (stroke count) was counted by the individual swimmer on the fourth lap of each 200-m effort and self-reported to a study investigator at the end of each 200-m swim.

### 5.1.4. Statistical Analysis

Data are presented as mean ± 90% confidence limits and analysed for reliability and validity using standard techniques. Some data is alternatively presented as a mean and range where appropriate. Data from practical measures were analysed for validity against the criterion measure(s) by linear regression (93). The raw values of the *Traqua* data were initially plotted against the raw values of the criterion measure (electronic timing or video coded stroke rate and stroke count) to check for bias. The plots of the residuals versus the ‘predicteds’ were

<table>
<thead>
<tr>
<th></th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time – All 50-m Combined</td>
<td>0.22</td>
</tr>
<tr>
<td>Time – 200-m</td>
<td>0.08</td>
</tr>
<tr>
<td>Stroke Rate - All 50-m Combined</td>
<td>0.25</td>
</tr>
<tr>
<td>Stroke Count - All 50-m Combined</td>
<td>0.00</td>
</tr>
</tbody>
</table>
plotted and inspected for non-uniformity of the error. Inspection of plots revealed a relative uniformity of error. The value of the predictor measure was calculated by the following formula: \( \text{predictor} = \text{intercept} + \text{slope} \times \text{criterion} \). The residuals equated to the criterion minus the predictor. These steps were repeated for both the manual data (timing and stroke characteristics) and the video coded timing against the criterion. Timing data were compared for each of the four 50-m lap splits and 200 m total time. Stroke rate and stroke count were compared on each of the four 50-m laps and an overall measure stroke count or stroke rate with all four 50-m combined. A standard error of the estimate was established for each of the comparisons. The mean difference between the new measure and the criterion measure was calculated as the mean bias. A calibration equation \( Y = aX^b \) was also established for time, where \( Y \) is the criterion, \( X \) is the actual measure taken with new method, \( a \) represents the magnitude of the systematic percent bias of the predicted from the criterion, and \( b \) corrects the percent differences of \( X \) to equate to \( Y \). This calibration equation was used to give an estimate of the predicted time for a known criterion time or vice versa.

The between- and within-subject reliability was established by quantifying the typical error (98). The typical error was established for total 200-m time, all 50-m laps together, and then the 1\(^{st}\), 2\(^{nd}\), 3\(^{rd}\), and 4\(^{th}\) laps separately for 50-m time splits, stroke rate and stroke count. The reliability analyses for each subject gave the error of the measure (e.g. \( \text{Traqua} \) timing) plus the within-subject error, computed via the variances. The typical error from the reliability analysis squared is the sum of the technical error plus the within-subject typical error squared (the subject variability).
5.2. Results

5.2.1. Uniformity of Residual Errors

Uniformity of residual error was evident for all of the predicted measures examined: total time, split times, stroke rate, and stroke counts. An example of the residual versus ‘predicteds’ plot of the *Traqua* timing versus the criterion electronic timing for the total 200-m time is presented in Figure 5-1. This figure shows relative uniformity of error throughout the range of times achieved in 200-m swimming - from 120 s (2:00 min:sec), the fastest category of swimmer (male freestyle) to 180 s (3:00 min:sec), the slowest category of swimmer (female breaststroke).

**Figure 5-1:** For 200-m time, the *Traqua* time is plotted against the residuals which are the difference between the criterion measure of electronic timing and the predicted measure of *Traqua* timing. Zero represents the point at which the electronic times equalled the *Traqua* 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.
5.2.2. **Validity and Reliability**

The validity of predicted measures was assessed using linear regression analysis of predicted versus residual measures. Figure 5-2 shows a representative plot of the relationship between *Traqua* timing and electronic timing for 200-m swim times for all subjects. The overall typical error of the estimate for 200-m times was 0.64 s (90% confidence limits: 0.60 to 0.69 s), which was similar to manual timing and marginally worse than video-coded timing (Table 5-2).

**Figure 5-2:** Plot of the raw values from the *Traqua* 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.
5.2.3. Stroke Counts and Stroke Rates

The estimates for validity and reliability for measuring stroke rate and stroke count are shown in Table 5-2. The stroke rate was assessed in the 3rd lap of the 200-m swim using both manual (stopwatch determined) and the Traqua. The Traqua had similar validity to manual stopwatch-determined stroke rate. However, the Traqua-determined stroke rate was approximately twice as reliable as that determined manually by the coach using a stopwatch. The magnitude of the standard error of the estimate (SEE) for validity comparison of stroke rate was <2 strokes min⁻¹ for both Traqua and manual timing. The stroke count was assessed in the 4th lap of the 200-m swim using both manual (self-reported by the swimmer) and the Traqua. The validity of the Traqua was also better for measurement of strokes per 50-m lap. The SEE for manual counting of strokes was approximately four times larger than that for stroke count derived from the Traqua. Similarly the Traqua was approximately twice as reliable as manually determined strokes counts.
Table 5-2: 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 ±90% confidence limits. Number of samples for the validity data: 200-m Time Video n = 282, Manual n = 286, Traqua n = 273; Stroke Rate and Count Manual n = 342, Traqua n = 325. Number of samples for the reliability data: 200-m Time Video n = 131, Manual n = 133, Traqua n = 131; Stroke Rate and Count Manual n = 133, Traqua n = 167.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Compared with Criterion</th>
<th>Validity Standard error of estimate</th>
<th>Reliability Typical error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.52 s (0.49 to 0.55)</td>
<td>1.99 s (1.80 to 2.22)</td>
</tr>
<tr>
<td>Time (200-m) Video</td>
<td></td>
<td>0.63 s (0.59 to 0.67)</td>
<td>2.03 s (1.85 to 2.27)</td>
</tr>
<tr>
<td>Manual</td>
<td></td>
<td>0.64 s (0.60 to 0.69)</td>
<td>1.99 s (1.80 to 2.22)</td>
</tr>
<tr>
<td>Traqua</td>
<td></td>
<td>1.52 strokes.min⁻¹ (1.43 to 1.63)</td>
<td>1.08 strokes.min⁻¹ (0.98 to 1.20)</td>
</tr>
<tr>
<td>Stroke Rate (lap 3) Manual</td>
<td></td>
<td>1.80 strokes.min⁻¹ (1.69 to 1.92)</td>
<td>1.97 strokes.min⁻¹ (1.79 to 2.19)</td>
</tr>
<tr>
<td>Traqua</td>
<td></td>
<td>0.55 strokes.50 m⁻¹ (0.51 to 0.58)</td>
<td>1.09 strokes.50 m⁻¹ (0.99 to 1.21)</td>
</tr>
<tr>
<td>Stroke Count (lap 4) Manual</td>
<td></td>
<td>2.32 strokes.50 m⁻¹ (2.18 to 2.47)</td>
<td>1.86 strokes.50 m⁻¹ (1.69 to 2.07)</td>
</tr>
</tbody>
</table>

The magnitude of error in the Traqua’s detection of stroke rate increased as the swimmer’s speed increased over the seven incrementally faster stages of the test. At the slowest speed, the SEE was 1.08 strokes.min⁻¹ (90% confidence limits 1.00 to 1.19 strokes.min⁻¹) compared with the second fastest effort where the SEE was 1.67 strokes.min⁻¹ (1.54 to 1.83 strokes.min⁻¹). There was no difference in the SEE for stroke count between the slowest and the fastest speeds (0.74 strokes.50 m⁻¹ versus 0.71 strokes.50 m⁻¹), however the magnitude of error decreased slightly over the same range (0.56 strokes.50 m⁻¹ for the moderate speeds at efforts 3 and 4).
5.2.4. Standard Error of Estimate and Mean Bias in Estimation of 50-m Split Times

Overall the mean typical error was 1.1% with a bias of 0.2% indicating the Traqua was generating times marginally slower than the criterion electronic timing system. Table 5-3 shows the error in the estimate between the criterion electronic and Traqua timing, the mean bias in the estimate and a predicted time derived from the calibration equation to magnitude of difference at a standard time. The first and last (4th) laps of each 200-m effort had a three-fold greater error than the 2nd and 3rd laps. Similarly the mean bias of the first and last laps was greater in comparison to the middle laps. The first lap had the largest average difference between the criterion and the Traqua time and the Traqua tended to overestimate the lap time. In contrast, the Traqua tended to underestimate the actual time on average for the final lap.

Table 5-3: Comparison of the Traqua 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 Traqua was different from the electronic timing. All estimates shown with ±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.

<table>
<thead>
<tr>
<th>Lap</th>
<th>Standard Error of Estimate (s)</th>
<th>Mean Bias of Estimate (s)</th>
<th>Estimate if Electronic Time for Lap was 30.00 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 50-m</td>
<td>0.40 (0.38 to 0.41)</td>
<td>0.05 (0.05 to 0.06)</td>
<td>30.11 (29.45 to 30.76)</td>
</tr>
<tr>
<td>1st 50-m</td>
<td>0.35 (0.33 to 0.38)</td>
<td>0.29 (0.27 to 0.31)</td>
<td>30.22 (29.63 to 30.80)</td>
</tr>
<tr>
<td>2nd 50-m</td>
<td>0.12 (0.11 to 0.13)</td>
<td>0.01 (0.01 to 0.01)</td>
<td>30.04 (29.84 to 30.24)</td>
</tr>
<tr>
<td>3rd 50-m</td>
<td>0.14 (0.13 to 0.16)</td>
<td>0.00 (0.00 to 0.00)</td>
<td>30.01 (29.77 to 30.25)</td>
</tr>
<tr>
<td>4th 50-m</td>
<td>0.65 (0.60 to 0.70)</td>
<td>-0.10 (-0.11 to -0.09)</td>
<td>29.84 (28.77 to 30.92)</td>
</tr>
</tbody>
</table>
Across the different swimming speeds from easy to maximal, the speed of the swimmer had no substantial effect on the Traqua’s ability to detect lap times. The standard error of the estimate for the individual seven incremental speeds in freestyle was 0.38 s (range: 0.32 s to 0.43 s), with the error at the slower speeds (0.43 s; 90% confidence limits 0.39 to 0.48 s) similar to that at maximal speed (0.38 s; 0.35 to 0.42 s).

5.2.5. Within-Athlete Error

For all of the 50-m laps combined, each swimmer was also analysed individually to give a within-athlete standard error of estimate. The mean within-athlete standard error of the estimate for all swimmers was 0.42 s ranging from 0.22 to 0.76 s in individual swimmers. For freestyle, only the mean error was 0.39 s and individual swimmers ranged from 0.22 to 0.56 s. The within-athlete standard error of the estimate equated to the technical error of the measurement for the measure used. The retest reliability represents a typical error of measurement of individual swimmers and is a combination of the technical error from the Traqua and the subject variability. The mean within-athlete typical error of all 50-m lap timing derived from the Traqua was 0.61 s, ranging from 0.39 s to 1.00 s. Consequently the typical swimmer error in the timing was 0.44 s.

5.3. Discussion

This study has established the validity and reliability of a new swimming-specific accelerometer-based smart sensor (the Traqua) to measure time and stroke mechanics. The Traqua was evaluated against contemporary methods used for timing, stroke rate and stroke count determination. The Traqua was found to be sufficiently valid and reliable to allow the sensor to be used for the automated analysis of performance information in routine training, organised testing, and possibly competitive racing.
The statistical approach in the current study examined measurement error, concurrent validity, and retest reliability of the *Traqua*. Measurement error is concerned with how the observed value differs from the true value. Determining the magnitude of the measurement error is essential when evaluating the value of a new technology for timing and stroke characteristic determination. Inspection of the plots of the residual error and the predicted values confirmed the relative uniformity of error underlining the goodness of fit of the modelling.

The novel statistical approach used in this study allows for a more practical assessment and application of the results. The actual unit of time (or stroke rate/count) is reported instead of the coefficient of variation (%), which should be more useful for coaches and sports scientists. Determining the validity of the new equipment involved establishing the agreement between the observed values from this equipment and the values from the criterion measures. The retest reliability represents a combination of the biological variation of the athlete and the technical error of measurement of the device used to measure (96). Over time, higher reliability will allow for better tracking of measurement changes. In this way, sports scientists can interpret the observed magnitude of changes associated with particular types of training or an intervention more confidently. The *Traqua* had similar reliability to other methods timing and substantially better reliability than manual determination of the stroke mechanics.

The standard error of the estimate for the different methods of timing, including the *Traqua*, was ~0.5 s different to the electronic timing over a 200-m effort. This magnitude of error is probably acceptable for the analysis of training sessions and of particular sets where repeat efforts of lengths more than 50-m are completed.
The timing and stroke characteristics determined from the Traqua rely on specifically developed software algorithms. The Traqua is clearly not as valid or reliable in quantifying the first and last laps compared with the middle laps. In the middle laps, the end of the lap is determined by large changes in the orientation of the swimmer during the tumble turn. The larger error in the start appears to be in part related to individual variations in the starting techniques from the push. Some swimmers started below the water and commenced the downward movement before pushing off, while others started above the water and moved horizontally rather than vertically. The magnitude of error in the start was further confounded by a limitation of the methodology of the study. When the swimmers were started from the gun on a push start, errors (swimmers leaving early or late) would be evident in the electronic timing but not the Traqua timing. The primary source of error for the Traqua timing occurred in the finish of an effort as a consequence of the lack of a definitive finishing point in orientation of the body (triaxial accelerometer output) when the swimmer touches the wall. Those laps which included a turn provided a more definitive marker, and this is evidenced in the better validity of the middle 50’s (~0.1 s) compared with the final 50-m (~0.7 s). In the finishing lap the swimmers glide into the wall and so there is no definitive change in orientation of the body at this point.

Timing is to the hundredth of a second in swimming competitions, simulated races, and time trials. In these situations, the magnitude of the error associated with the Traqua is probably too large for it to be used, and therefore if available, electronic timing is still the best choice for these situations. Our findings also imply that coaches/sport scientists should only use the Traqua to report swimming times to the tenth of a second rather than a hundredth until the device has been further refined to achieve greater accuracy.
Stroke characteristics are regularly used in training (and competition) as surrogate measures of efficiency to assess the technical elements of the swimming action. This information is complementary to lap split times and overall race time. However, when using a stopwatch in training, it is hard to obtain several stroke rates on more than one swimmer at a time. Furthermore, when a single stroke rate value per effort or lap is obtained from one to three stroke cycles (depending on the type of stopwatch), it may not be fully representative of the swimmer’s entire lap. Reducing variations in stroke rate within a given lap is a key issue for swimmers and coaches. The Traqua should overcome this limitation by recording every stroke in each lap. The inherent problem of getting athletes to self-report stroke counts particularly at maximal speeds are widely acknowledged by coaches and swimmers. In this study, the Traqua was better than the manual measurements for assessing both stroke rate and stroke count. While analysis via video remains the preferred choice for competition or time trial settings, the Traqua could be a useful tool for the gross analysis of training sets involving multiple intervals. Mean errors of the magnitude of ~1-2 strokes cycles per minute and 1-2 strokes per lap were found. The implication of this finding is that changes larger than these values are likely to be real whereas smaller changes may be due to measurement error. The algorithm used for the detection of stroke rate showed up substantial individual variation due to the subtle variations in technique from swimmer to swimmer. Consequently, for some individual swimmers, the algorithm was unable to reliably detect the stroke rate. The timing and stroke algorithms can be further refined and/or other sensors such as a gyroscope added to improve the precision of the estimates in the future.

The concept of noise in the routine measurement of swimming performance has been analysed in detail as part of this study. However, the pertinent question is how this relates to the signal or magnitude of typical changes in these measures within- and between-training
preparations. Previously, the typical within-season changes for performance time in a maximal effort, and at a 4-mM fixed lactate, were established as ~1.5-2%, whereas the typical changes between seasons was ~0.7% per year (4). In this study the typical error of the Traqua in measuring performance time was ~0.5% compared with electronic timing, coupled with a coefficient of variation for reliability of ~1%. Given that the typical error is substantially smaller than the expected change during a season, it is concluded that the Traqua can be used to confidently monitor worthwhile changes and differences in swimming performance time. The typical within-season changes in stroke rate were ~2-4%, with only females having substantial changes between seasons (~1%) (4). The magnitude of typical changes observed in the stroke rate was smaller than the error observed in this validity and reliability study. Consequently, caution is required when interpreting changes in stroke rate recorded either manually with a stopwatch or with the Traqua.

It is apparent that there is systematic bias in some of the methods used to measure timing and stroke characteristics. The calibration equation provides a practical method of accounting for uniform bias and should be permanently incorporated into the Traqua algorithms to improve their precision. For instance, the consistent overestimation of the first 50-m lap time can be corrected through use of a calibration equation. For example, a first 50-m time of 25.0 seconds determined from the Traqua would be corrected to 24.87 seconds using the calibration equation in the current version of the software.

While this approach should correct the typical bias, it will not account for the error due to individuals. The substantial individual range in the error of measurement in stroke rate cannot be corrected until calibration equations for individuals are established. In the case of
monitoring certain individuals on a long-term basis establishing individual calibration equations to reduce the technical noise may be a useful approach.

5.4. **Conclusion**

In conclusion, this study has demonstrated that the automated tri-axial accelerometry-based sensor device, the *Traqua*, is comparable to current methods for determining swimming lap time and stroke rate, and better than current methods for quantifying stroke count. A substantial source of error in the *Traqua* timing was additional noise in the detection of the start and finish actions (laps). This shortcoming should be addressed in future development of the *Traqua* or similar accelerometry-based devices in swimming. The *Traqua* is useful for the monitoring of routine training sets, but electronic timing and video analysis are preferred for racing and time trials.
CHAPTER SIX

VARIABILITY IN SWIMMING PERFORMANCE MEASURES IN JUNIOR AND SENIOR SWIMMERS

6.0. Introduction

A major role of the coach is coordinating the long-term progression of a junior swimmer into the senior ranks. State, national, and international programs need a well-structured developmental pathway to promote junior swimmers into competitive senior swimmers. The performance characteristics that discriminate between these levels of swimmers are not well established in the scientific literature, and coaches have traditionally relied upon their own experiences. One of the major differences between junior and senior swimmers reported by coaches is the ability to pace both submaximal (training) and maximal (competitive) swimming speeds. Given that the vast majority of a swimmer's time in the sport is spent in training rather than competition, a detailed analysis of the relative pacing ability of junior and senior swimmers would provide valuable information for the coach and swimmer.

Athletes adopt various pacing strategies to delay fatigue and optimise performance in competitive events (227). Pacing strategy is defined as the conscious or subconscious regulation of work output according to a predetermined plan in order to maximise performance without causing irreparable harm to physiological systems (7). In higher level swimming, coaches routinely advise swimmers to adopt a particular pacing strategy during races (216). Swimmers tend to use one of three different pacing strategies: fast-slow pacing, slow-fast pacing (or negative splitting), and even splitting (136). Swimmers must concentrate
on distributing their efforts evenly over the length of paced swims to swim at the correct speed in the most economical manner (136). In training sets, athletes are often required to descend or swim each subsequent effort faster than the previous one. The ability to pace and descend efforts evenly is presumably a characteristic of elite swimmers that must be learned and practiced by junior swimmers.

Another important issue for coaches and swimmers is the magnitude of worthwhile improvements (and impairment) in stroke rate and stroke count. While experienced coaches get a feel for these numbers over many years of trial and error, no previous study has systematically quantified these values. Estimation of these values, coupled with interpretation of the typical error, permits the coach, sports scientist and researcher to evaluate the effectiveness of various training interventions or strategies aimed at improving stroke rate and stroke count (100, 178). The purpose of this study was to quantify the magnitude of differences and the variability between senior and junior swimmers in their ability to pace a series of incremental 200-m efforts, both within an effort and across the entire set.

6.1. Method

6.1.1. Subjects

Twenty-one athletes, comprising of eleven elite senior swimmers and ten competitive junior swimmers, participated in this study. The senior swimmers were scholarship holders at the Australian Institute of Sport and competed at national and international level. The junior swimmers were competitive junior club-level athletes. The senior group consisted of 6 males (age 21.3 ± 0.7 y; mass 83.9 ± 7.1 kg, height 1.87 ± 0.05 m, sum 7 skinfolds 57.5 ± 11.9 mm, mean ± SD) and 5 females (age 18.8 ± 2.2 y; mass 60.3 ± 6.4 kg, height 1.70 ± 0.07 m, sum 7 skinfolds 70.2 ± 17.4 mm). The junior group consisted of 7 males (age 17.6 ± 1.7 y; mass
71.9 ± 9.8 kg, height 1.82 ± 0.06 m, sum 7 skinfolds 49.8 ± 4.8 mm) and 3 females (age 15.1 ± 1.5 y; mass 63.2 ± 7.0 kg, height 1.70 ± 0.08 m, sum 7 skinfolds 80.3 ± 10.0 mm). The age difference between the senior and junior swimmers was deemed to be acceptable, considering age group swimming goes up to 18 y and the average age of national team swimmers in recent years has been ~21 y (personal communication, Dr David Pyne, Australian Institute of Sport). Participation was voluntary and all swimmers provided written informed consent. All procedures undertaken in this study were routinely conducted within the training environment and had approval from the Ethics Committees of the University of Canberra and the Australian Institute of Sport.

6.1.2. Experimental Design and Procedures

Following a standardised 1500-m in-pool warm-up, the swimmers were required to perform a 7 x 200-m incremental step test. The protocol for the 7 x 200-m incremental step test was described in detail in Chapter 2 (refer to Section 2.1.3). Briefly, the 7 x 200-m test consisted of seven even-paced swims on a 5-min cycle, graded from easy to maximal (176). All swimmers completed the test using the freestyle stroke. The speeds for each 200-m effort were predetermined based on the individual’s personal best time for 200-m freestyle. All testing was conducted in a 50-m pool and swims utilised a push start. Speeds for the swims ranged ~30 s from slowest to fastest for each 200-m effort (e.g. 2:30 to 2:00 min), with the seventh and final swim a maximal effort. All swimmers had completed at least one familiarisation trial on the test prior to the formal data collection session.

An accelerometer-based sensor (Traqua4, CRC for Microtechnology, Melbourne, Australia; refer to Chapter 5 for specifications) was attached to the swimmer via a specifically-designed pouch in their swimsuit. The miniaturised sensor was worn for the duration of every pool test.
set for lap-by-lap (50 m) timing and stroke analysis (stroke rate and stroke count). Each test set was downloaded into a specially designed software program (Logan V9.6, Colin Mackintosh, Australian Sports Commission, Canberra, Australia; refer to Chapter 5 for algorithm information). The signal outputs were captured with algorithms specifically designed for this data. The customised software provided a consolidated summary of 50-m and 100-m splits, 200-m total time, and lap-by-lap stroke rate and stroke count for each of the seven 200-m efforts.

6.1.3. Statistical Analyses

Data was analysed for differences in the progression between each of the 200-m efforts, and between each of the four 50-m laps which comprise a 200-m effort for both the junior and senior swimmers. Data was analysed initially as raw numbers and then log transformed in order to report percentage changes and differences. Each 200-m time was analysed against the target times which were individually set for each swimmer by linear regression using an Microsoft Excel spreadsheet developed by Hopkins (92). The lap-by-lap analysis of time, stroke rate and stroke count was analysed by standard reliability analysis techniques to establish the typical error (98). A pairwise comparison was conducted for each combination of the four 50-m laps. A coefficient of variation was also calculated for each of the groups for all the variables. All differences and change scores are presented as mean ± 90% confidence limits.

To examine differences in variability between the senior and junior swimmers additional within-swimmer random effects were included. The ratios of coefficients of variation (CV) (senior/junior) were calculated. A ratio of CV between groups greater than 1.15 was considered substantially different, because the effect of such a difference on sample size in a
controlled trial of competitive performance is a factor of $1.15^2$, or change in sample size of 32\% (101, 178).

6.2. Results

The senior swimmers were better able to pace and descend each of the 200-m efforts. The incremental increase in speed meant the actual times of the senior swimmers were closer to their target times for each of the 200-m efforts. The junior swimmers were almost twice as variable as the senior swimmers. The typical variation in actual performance time from the predetermined target time was 1.5\% (90\% confidence limits: 1.4 to 1.8\%) or 2.1 s (1.9 to 2.4 s) for the senior swimmers, and 2.5\% (2.2 to 3.0\%) or 3.6 s (3.1 to 4.2 s) for the junior swimmers. Figure 6-1 illustrates the change in 200-m time for the senior and junior swimmers compared with the predetermined target times over the seven incremental stages of the step test.
Figure 6-1: 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 ± 90% confidence limits.

Overall, the senior swimmers were ~2-3 s per 50-m faster than the junior swimmers. As shown in Figure 6-2, both groups were typically fastest in the first 50-m lap due to the push start, with the senior swimmers 7.0% (6.9 to 7.5%) and the junior swimmers 8.9% (8.8 to 9.7%) faster in the first lap compared with the second. The senior swimmers then built speed through the subsequent laps, getting ~0.5 s faster per lap (~1.4%), with the final lap the fastest. While the junior swimmers swam the third lap 0.4s (1.1%; 0.7 to 1.5%) slower than the second, and the fourth lap in a similar time to the second lap and 0.3s (0.8%; 1.3 to 0.3%) faster than the third lap. On the whole, the junior swimmers were more variable in their 50-m times (~2.0%) compared with the senior swimmers (~1.8%).
Figure 6-2 also illustrates the mean stroke rate and stroke count of each of the four laps for the senior and junior swimmers. The senior swimmers on average took approximately 3 strokes less per 50-m than the junior swimmers. For both groups, they took 1-2 fewer strokes on the first lap compared with the second and third laps and on the last lap took ~1 stroke more than the middle laps. Both groups had a similar magnitude of variability on the first three laps (~2%), however from the third to the fourth lap the senior swimmers were more variable (3.5%; 3.1 to 4.1%) than the junior swimmers (2.2%; 2.0 to 2.6%) in the number of strokes they took. Overall, the swimmers had a stroke rate of approximately 36 strokes min⁻¹, however this varied depending on the different incremental stage in the test. The swimmers typically had a higher absolute stroke rate in the first lap compared with the other laps (~1.5-2.0 strokes min⁻¹ greater in the first lap). In second to fourth lap there was, minimal changes in the stroke rate (<0.6 strokes min⁻¹). The junior swimmers tended to be more variable in their stroke rate (~1.2%) compared with the senior swimmers (~0.7%).
**Figure 6-2:** 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 ± 90% confidence limits.
6.3. Discussion

The main finding of this study is that the junior swimmers were twice as variable as the senior swimmers in their ability to pace the increases in speed required for the progressive incremental 7 x 200-m swimming step test. The senior swimmers in this study were also 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 junior swimmers were also less efficient in their swimming, taking ~2 strokes more per lap than the senior swimmers for a similar stroke rate. Consequently, a key difference between highly trained junior and senior swimmers is the accuracy and variability of pacing both within and between swimming efforts.

Swimmers need to be able to control their pacing in both training and competition. While the competition pacing strategies of a select number of elite performers has been published in popular swimming textbooks (49, 136), there is limited peer-reviewed research examining pacing strategies in swimming. In competition, pacing strategies are required to conserve energy for the final stages of the race. Inexperienced swimmers tend to swim too hard in the first section of a race and are then unable to maintain sufficient speed in the closing stages. More experienced swimmers have the ability to control their pace and have ‘easy speed’ in the first part, allowing them to finish without a large decrement in time from the first half to the second half of the race. They are characterised by having a high level of performance and a greater consistency in velocity and stroke parameters (i.e. stroke rate and stroke length) (44). In training, swimmers need to control their pace in different training sets and accurately adjust their speed to swim at a range of submaximal to maximal intensities. For a swimmer, the ability to control their swimming pace is important during training to ensure the appropriate physiological adaptation and technical refinement, while for competition it is important to
ensure effective race tactics in order to improve the likelihood of success. Senior swimmers are presumably able to judge their swimming speed substantially more accurately than junior swimmers. The more experienced swimmers were able to swim closer to their prescribed individual target times, typically within 1.5% over a range of submaximal and maximal speeds. The swimmers were substantially less variable in their pacing time at each of the seven intensities and particularly at maximal speed than that observed between the junior swimmers. In contrast, the junior swimmers in the present study demonstrated that they were not as skilled at judging their pace, particularly in maximal efforts when already under a certain amount of fatigue. The junior swimmers appeared to have a three stage pattern as to how they paced the incremental 7x200-m step test compared to their target time. The first step was at an easy intensity and was highly variable, the next three efforts (steps 2-4) were at an easy to moderate pace, which the junior swimmers were able to pace reasonably compared to their target times. In the high to maximal intensity efforts (steps 5-7) the junior swimmers have a greater variability in their swimming. The findings of the current study confirms earlier work by Thompson and co-workers (215), who reported that accomplished breaststroke swimmers self-paced within ~1.6% of their target time (±2.4 seconds over a swim duration of ~150 seconds). The implication of these findings is that in training the senior swimmers are more aware of their range of pacing speeds and therefore are able to attain their required training intensities more often and conversely the juniors are not able to.

Pacing in athletic events is underpinned by the different central and peripheral physiological mechanisms of fatigue (74, 76, 159). Fatigue is a complex multifactorial phenomenon and the type of fatigue, and consequently the pacing strategy chosen, is determined by the duration and the intensity of the event. In longer duration events, substrate depletion will have a primary limiting role (47, 58, 70). However, in the short events that occur in
competitive pool swimming, with durations ranging from 22 seconds (Men’s 50-m freestyle) to 16 minutes (Women’s 1500-m freestyle), it is believed that fatigue results from a myriad of contributing factors. The proposed cellular muscle fatigue in short-term exercise results from the inability to generate ATP sufficiently rapidly to sustain a high power output for the duration, metabolite accumulation, the loss of excitability within the transverse tubules, impaired rate of calcium ions released, impaired function of the sodium-potassium pump and reduced cross bridge force development (70, 74, 75, 146, 160). On the other hand, in swimming training, which is usually at least 2 hours per session and up to 3 sessions per day in some training phases, substrate depletion may be an overall limiting factor. Within the individual training sets, the mechanisms of fatigue operating for the shorter duration exercise will play a role. The pacing considerations in training will most likely be different to competition due to underlying fatigue from other work done that session or from a block of heavy training. The effect of the progressively faster previous efforts may affect less skilled (and less fit) junior swimmers more substantially.

Past experience subconsciously influences the pacing strategies adopted in an exercise effort in a feed-forward manner or by teleoanticipation, so that the exercise is completed within the biomechanical and metabolic constraints of the body (2, 83, 116, 225). In a feed-forward manner, the analysis of past experiences performing an exercise task will preset the exercise intensity for future efforts (225). However, teleoanticipation associates a power output and pacing strategies with the end point of the exercise task and takes into account not only the prior knowledge, but also feedback from afferent changes linked with peripheral metabolic structures and the external environment (116). Although both the junior and senior swimmers were familiar with the step test protocol, the additional experience of the senior swimmers in pacing during training and competition may have improved their ability to meet the target
times. Furthermore, even during a maximal 200-m effort the velocity is preset in order to reach a predetermined finishing point, and part of the experience of the senior swimmers has been to increase their overall maximum velocity (i.e. 50 and 100-m velocity), which will in turn adjust the internally preset swimming velocity for the 200-m effort.

In exercise bouts lasting longer than 80 to 100 seconds, even pacing strategies (first half to second half split times) have been recommended (227). Many investigators have examined different pacing strategies employed in competition in a range of sports (59, 124, 170) yet swimming has not been systematically studied. In the current study, there were striking differences between the junior and seniors in pacing within the 200-m efforts. The senior swimmers were closer to evenly splitting the first and second half of the 200-m step test efforts with a mean increase in time of 0.9 seconds. In contrast the junior swimmers had a marked slowing of second half speed with 3.6 seconds increase in the 2nd 100-m split time. It appears that the junior swimmers swam at a pace that was beyond the level of physiological control in the first half and were therefore unable to maintain this speed for the entire distance.

In swimming competitions, the first lap is usually slightly faster due to the dive start where the swimmer is moving through the air, in comparison with the push start or turns where the swimmer must overcome the higher resistance of the water. Moreover, a higher stroke rate and stroke length in this first lap elicits a greater power output (124, 170, 192). Previously in homogenous groups of elite swimmers, Letzelter and Freitag (124) and Pai et al. (170) have shown that the velocity of less skilled swimmers decreased during a competitive race more than the velocity of the better swimmers. In the current study, a push start was employed which would have negated some of the differences in time between the first lap and the
subsequent laps, yet a greater decrease in velocity was observed in the less skilled junior swimmers.

Swimming is a highly technical sport and since the time spent stroking (i.e. the so-called free swimming that excludes the start, turns and finish) accounts for approximately 60-70% of swimming time (212), the stroke rate and distance per stroke are important elements in competitive swimming. In simple terms the swimming velocity is the product of the stroke rate and the distance travelled each stroke (60). Swimmers normally increase their swimming speed using a combination of increasing stroke length and/or stroke rate (200). These variables are frequently used by coaches and sport scientists to assess the technical elements of a particular training or competitive swimmer, and make objective judgements as to whether or not the swimmer is swimming efficiently. The regular monitoring of stroke rates and stroke counts is important information, given that the efficiency of a swimmer’s stroke technique impacts substantially on the energy cost of swimming and subsequently performance (39). In groups of heterogenous swimmers, stroke length is the primary distinction across a range of performance levels (59, 64). At fixed stroke rates, stroke length was also substantially lower for non-expert swimmers when compared with expert swimmers (172). In contrast, Chatard and co-workers reported that skilled freestyle swimmers were characterised by among other things a higher stroke rate and shorter stroke length (39). Stroke rate was reported to be a better indicator of swimming technique than stroke length because it explained a greater part of the variability of the swimming performance (39). In the present study, the senior swimmers took substantially fewer strokes per lap than the junior swimmers, with a similar stroke rate, indicating the greater stroke length of the senior swimmers. From previous work (Chapter 5), it has been established that the smallest worthwhile change in stroke counts is approximately 1 stroke 50 m\(^{-1}\), therefore suggesting that
the ~3 strokes per lap difference between the junior and senior swimmers was a substantial difference. The senior male swimmers were ~5 cm taller and with longer limbs were able to take fewer strokes than the younger shorter male swimmers. Indeed, Grimston and Hay (82) suggested the combination of stroke rate and stroke length used to attain a given swimming velocity is a function of body size. However, there were no anthropometric differences between the junior and senior female swimmers in the current study, so it would appear that the senior female swimmers in this study had a better stroke length and greater efficiency.

Interpretation of the magnitude of the change in performance measures of athletes in competition, testing or training, involves several factors. These factors include the observed magnitude of change, the precision of the estimates, and the smallest worthwhile change or reference value (95, 100). Several previous studies have reported the variability of competitive performance and established threshold values for the smallest worthwhile change in junior (206) and elite swimmers (178, 222). In addition, Anderson et al. (5; Chapters 2 and 5) reported the typical variability of elite swimmers expected in training in swimming test performance and the typical errors in associated performance and physiological measures. For example, the typical error for swimming performance is ~0.6%, the smallest worthwhile change ~0.4%, and with an observed change or improvement of 1.2%, it can be confidently asserted that the swimmer or intervention has/is likely to have made a worthwhile improvement in performance. Whereas for a specific physiological variable, such as blood lactate, the typical error is ~16% and the smallest worthwhile change is ~7%, as a result a change in blood lactate of 5% would not be considered a worthwhile change.
6.4. Conclusion

The more experienced senior swimmers are better able to control their swimming speed over a range of intensities in comparison to lesser experienced junior swimmers. Junior swimmers making the transition to senior ranks should be taught (and practice) a higher degree of consistency in pacing and improve the technical aspects of their swimming. A greater exposure to pacing efforts in training and competition both in a fresh and fatigued state will assist the development of swimming pacing abilities in both junior and senior swimmers. Furthermore technology such as the Traqua can be utilised as tools to help coaches and swimmers assess and devise pacing routinely.
CHAPTER SEVEN

THE EFFECT OF AN INTENSIVE TRAINING PHASE ON THE
REPRODUCIBILITY OF SUBMAXIMAL SWIMMING PERFORMANCE IN
ELITE SWIMMERS

7.0. Introduction

Submaximal testing is commonly used in many sports to monitor improvements in training fitness that presumably transfer to improved competitive performance. Submaximal VO$_2$ in the laboratory testing of recreational and highly trained athletes has been shown to correlate with competitive swimming performance (115, 182, 201). In the field with competitive athletes, the focus has been traditionally on simple measurements of heart rate and blood lactate. The blood lactate profile is recognised as an important tool for evaluating endurance capacity, assisting in the control of training and predicting endurance performance (68, 72, 87). Although these methods have been widely used, few published studies have systematically evaluated the variability in these measures, and the influence of fatigue during intensive training.

Progressive incremental tests in both the laboratory and in the field have been used to quantify the direction and magnitude of changes in physiological variables in response to training programs or experimental interventions. In practice however, single effort submaximal efforts are commonly used by coaches in swimming as a method of checking an athlete’s current adaptive status. Generally, a more complete picture of a swimmer’s status in training involving parallel measurement of performance time, heart rate, blood lactate and
self-reported perceived exertion is considered a better approach than any single measure (202). Swimming researchers have also recognised that stroke mechanics play a critical role in the fatigued/training state of the swimmer. Various methods of identifying changes in stroke rate, distance per stroke or other derived indexes have been proposed (54, 121).

Several studies have examined the physiological and performance changes before and after a training phase or season, however this has not been undertaken on a daily basis. While it is difficult to monitor all the training and physiological responses occurring within a phase of training, simple submaximal testing may be useful in assessing how swimmers are responding to the training program. Although coaches and scientists are interested in how swimmers respond from session-to-session within a day, and from day-to-day in a training week, the sheer volume of performance data makes it logistically difficult to collect information using (traditional) manual methods. The development of smart-sensor technologies and their application to sport science will create the opportunity for the non-invasive and automated collection of training and performance data in the field. A waterproof smart-sensor, known as the **Traqua**, was developed to allow for the continual monitoring of swimmers’ stroke and time information during training and test sessions.

Although most swimming coaches and swimmers acknowledge the effects of fatigue in high volume and high intensity programs, these relationships have not been examined systematically in the published literature. To overcome this deficiency, the current study monitored swimmers during an intensive 14 day training camp in preparation for the national championships. The purpose of this study was to characterise the intra-session, daily and training block variability of elite swimmers in their submaximal performance, physiological responses, and stroke mechanics. A secondary aim of the study was to examine whether an
accelerometer-based smart sensor (the *Traqua*) was a useful tool in detecting meaningful changes in the swimming performance and stroke mechanics over an extended period.

### 7.1. Method

#### 7.1.1. Subjects

Seven elite swimmers (3 male and 4 female) participated in the study. The male swimmers physical characteristics were as follows (mean ± SD): age 21.9 ± 1.0 y; height 1.88 ± 0.02 m; mass 80.5 ± 7.5 kg; sum of 7 skinfolds 48.2 ± 4.2 mm. The female swimmers physical characteristics were as follows: age 17.8 ± 2.1 y; height 1.76 ± 0.07 m; mass 63.1 ± 5.8 kg; sum of 7 skinfolds 76.9 ± 19.0 mm. The swimmers mostly do middle distance events and generally trained 48 weeks each year. The swimmers’ training consisted of typically ~50-60 km of swimming each week, and several swimming-specific and resistance training sessions. All procedures undertaken in this study were routinely conducted within the training environment and had approval from the Ethics Committee of the Australian Institute of Sport. All athletes provided written informed consent for sports science and sports medicine testing at the commencement of their scholarship.

#### 7.1.2. Training Structure

The swimmers participated in an intensive 14-day training camp conducted one month prior to the national championships. All swimming training and testing was conducted in an outdoor 50-m swimming pool. Training consisted of 10 pool sessions and three resistance training sessions per week. Daily training consisted of either one or two in-pool training sessions of ~2 h conducted between 7-9 am and between 4-6 pm. Approximately 30 min of dry-land training consisting of stretching, abdominal and body weight exercises was conducted prior to morning sessions. To provide a measure of training intensity a 1 to 5
Likert scale was used with the following criteria: 1 was low intensity recovery/aerobic swimming and a rating of 5 was for very intense/race pace swimming. Ratings of intensity were assigned by the study investigator in conjunction with the coach at the completion of each day’s training. Swimming training sessions were 7.1 ± 1.0 km (mean ± SD) in volume and consisted of a warm-up of ~1.5 km, a main set, and a cool-down. Resistance training in the gymnasium was completed on days 1, 3, 5, 8, 10, and 12, and comprised ~1-1.5 h of weights, abdominal exercises, and stretching.

7.1.3. Experimental Design and Procedure

The swimmers performed a submaximal 200-m test in most sessions, after the warm-up (pre) and at the end of the session (post) following the main set for both morning (am) and afternoon (pm) sessions (a total of 23.1 ± 3.8 submaximal 200-m tests over the camp duration). Figure 7-1 shows a schematic representation of the testing in relation to the training sessions. Each swimmer was instructed to swim the 200-m effort at a submaximal pace equating to their lactate threshold pace (~3-4 mM blood lactate). The swims were self-paced and on completion of the effort the swimmers were informed of their time for the swim. These tests were conducted intermittently through the training year, so the swimmers were broadly familiar with the experimental procedures of the study.
Figure 7-1: Schematic of the daily training and the timing of the submaximal testing in relation to the morning (AM) and afternoon (PM) training sessions: ↑ indicates the location of the 200-m submaximal testing in relation to training session.

During the submaximal 200-m effort, each 100-m split and the total 200-m time was timed manually (Seiko, Model S120-4020, Japan) by the coach. The number of strokes taken per 50-m lap (stroke count) was self-reported by the swimmer and determined on the fourth lap of each 200-m effort. On completion of each effort, heart rate (HR) was measured using a portable heart rate monitor (Polar Electro Oy, Kempele, Finland). A rating of perceived exertion (RPE) was also taken on completion of the swim using the Borg Scale (28). The swimmer then exited the pool and a 5-µl blood sample taken from the earlobe or fingertip, with the location standardised for each subject. The sample was analysed immediately for lactate concentration using a portable hand-held blood lactate analyser (Lactate Pro, Arkray, Japan).
An accelerometer-based sensor (*Traqua4*, CRC for Microtechnology, Melbourne, Australia; refer to Chapter 4 for specifications) was attached to the swimmer inside a specifically-designed pouch in the back of their swimming suit. The sensor was worn during every pool training session to allow lap-by-lap (50-m) timing and stroke analysis (stroke rate and stroke count) during the session. Each session was downloaded into a specifically designed data acquisition software program (*Logan V9.6*, Colin Mackintosh, Australian Sports Commission, Canberra, Australia; refer to Chapter 5 for algorithm information). Signal outputs from accelerometry were captured with algorithms specifically designed for this data. The specific algorithms allowed for the identification of the swimming stroke used; quantified the time taken to swim a 50-m lap and the total time for the 200-m effort; and also detected each individual stroke for the estimation of stroke count and stroke rate for each 50-m lap.

An overview of the daily training volume and a rating of the daily training intensity is shown in Figure 7-2. The mean training volume per session was 7.1 ± 1.0 km. The mean intensity, out of a 1 to 5 rating scale, with 1 being a low intensity recovery/aerobic swimming and a rating of 5 as very intense/race pace maximal swimming, was a rating of 3.2 ± 1.1 as determined by the investigator and the coach.
Figure 7-2:  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.

7.1.4.  Statistical Analyses

Log transformation and repeated measures mixed linear modelling (Proc Mixed) using Statistical Analysis System software (Version 8.1, SAS Institute, Cary, NC) provided estimates of percent change in the mean (fixed effects) and within-swimmer coefficient of variation (CV) (random effects) for pre and post; morning and afternoon sessions; and overall for each sex. The effect of the previous session as well as the effect of the previous day’s volume or intensity on each of the measures was estimated as a standard deviation. Data are
shown as mean ± 90% confidence limits. Predicted values for each of the measurements were also estimated.

Magnitudes of the change scores were assessed by calculating the probability that the true value of the effect was beneficial in practice, trivial, or harmful (99). To calculate these probabilities, it was assumed that the smallest worthwhile change was $0.5 \times$ within-athlete coefficient of variation (CV) for competitive performance, equating to 0.4% for elite swimmers (222). For all the non-performance measures (e.g. heart rate and blood lactate), the smallest worthwhile change was calculated indirectly as Cohen’s smallest effect size of $0.2 \times$ the between-athlete CV (48). Thresholds for assigning qualitative terms to chance of a substantial increase or decrease were as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely or probably not; <50%, possibly not; >50%, possibly; >75%, likely or probable >95%, very likely; >99%, almost certain (99).

To examine differences in variability between the sexes, additional within-swimmer random effects were included. The ratios of coefficients of variation (CV) (male/female) were calculated to compare variability between the sexes. A ratio of coefficients of variation between groups greater than 1.15 was considered substantially different, because the effect of such a difference on sample size in a controlled trial of competitive performance is a factor of $1.15^2$, or a change in sample size of 32% (101).

7.2. Results

7.2.1. 200-m Time

Swimmers were very likely to be faster (0.7%; 90% confidence limits ±0.7%) in the afternoon sessions compared with the morning sessions. Encouragement by the coach in the initial 2
days of the training camp elicited a faster submaximal 200-m time (1.4%; ±1.0%). There was minimal change day-to-day (<0.1%) in the 200-m time. However, excluding the initial effect of the coach, the swimmers were moderately slower (1.4%; ±1.4%) over the 14 day training camp. Figure 7-3 shows the submaximal performance times for the pre and post session, and am and pm, over the duration of the 14 day training camp. Overall, the males were substantially faster (3.7%; ±3.3%) than the females in their 200-m efforts. The females were more variable in their self-paced submaximal performance times than the male swimmers (CV = 2.6 ±0.8% versus 1.7 ±0.7%). Individual swimmers could also vary from these mean trends for 200-m time by 2.0% (±1.7%).

The training volume and intensity had variable effects on submaximal performance within the session and on the following training session. The effect of higher volume of the previous session on performance time in the current session was trivial (0.1%; ±0.6% slower), however increased intensity of the session before had a negative effect on the speed of the submaximal 200-m efforts (both pre and post) (0.7%; ±0.5% slower). Increased volume and intensity of that particular session elicited slower performances in the post session 200-m effort (~0.8%; ±1.2%).
Figure 7-3: 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±4 (mean±SD); AM Pre n = 11±2; AM Post n = 7±1; PM Pre n = 5±1; PM Post n = 1±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).
7.2.2. Blood Lactate, Heart Rate and RPE

An increase in blood lactate of 7.5% (±2.0%) accompanied the 1% decrease in 200-m time. Estimated blood lactate concentrations following the submaximal 200-m efforts for the swimmers were ~2.8 mM for the males and ~3.4 mM for the females. There were only trivial changes in blood lactate from the morning to the afternoon session and over the 14 day duration of the training camp. Within a session, there was a 25% (±17%) increase in blood lactate concentration from the pre to post submaximal effort. The coach’s motivational efforts had a substantial effect on the initial 2 days, resulting in a 31% (±27%) higher blood lactate or ~5.1 mM for days 1 and 2 compared with ~3.5 mM for the rest of the camp. In contrast, blood lactate was substantially lower following high volume training during the previous session (~23%; ±10%). However, a higher intensity workout during the previous session elicited a higher lactate (21%; ±15%) in the current session. The coefficient of variation in the swimmers’ blood lactate concentrations overall was 25% (±16%).

Mean heart rate was related to swimming velocity. A 1% decrease in 200-m time was associated with an increased heart rate of 1.1 beats min⁻¹ (±0.6 beats min⁻¹). The typical heart rate for the swimmers immediately after the 200-m submaximal test was ~160 beats min⁻¹. A 0.5 beats min⁻¹ increase in heart rate each day was observed, which resulted in a 6.2 beats min⁻¹ increase over the whole camp. Swimmers’ mean heart rates typically varied by 9% (±3%). The influence of the coach in the initial 2 days of training was associated with a substantially higher heart rate (6.6 beats min⁻¹; ±4.5 beats min⁻¹) than other days. The influence of the coach also elicited a 1.7 units (±0.7 units) increase in the RPE. The RPE self-reported by the swimmers increased over the duration of the training camp (1.6 units; ±0.9 units). The male swimmers rated the submaximal test swim ~12 or between ‘light’ and ‘somewhat hard’,
whereas the female swimmers rated the efforts ~14 or between ‘somewhat hard’ and ‘hard’ on a 6-20 point RPE scale.

7.2.3. Stroke Characteristics

Swimmers’ stroke characteristics at a submaximal speed were largely unchanged over the total 14-day training camp (stroke rate: 0.1 ±0.8 strokes.min⁻¹; stroke count: -0.8 ±0.8 strokes.50 m⁻¹). However, over the 12 d of training there was a decrease in stroke count in the 3rd and 4th laps of the 200-m effort (-0.8 ± 0.7 strokes.50 m⁻¹ and -2.4 ± 2.2 strokes.50 m⁻¹ respectively). For a 1% increase in the 200-m swimming time, there was an increase of 0.1 strokes.50 m⁻¹ and a decrease of 0.3 strokes.min⁻¹. The female swimmers had a substantially higher stroke rate (7.7 ± 3.8 strokes.min⁻¹) and stroke count (6.5 ± 4.0 strokes.50 m⁻¹) than the male swimmers. The typical stroke rates were 38 strokes.min⁻¹ for the males and 45 strokes.min⁻¹ for the females, and stroke counts were 35 strokes.50 m⁻¹ for the males and 43 strokes.50 m⁻¹ for the females. Individual swimmers could typically vary from the mean trends in their stroke rate and stroke count by ~2.5% (±1.8%).

The stroke rates of the female swimmers were slightly more variable than the male swimmers (CV 0.8% versus 0.7%). However, the male swimmers had a substantially greater variability in their stroke counts than the females (CV 1.1% versus 0.7%; >1.15 ratio). All swimmers tended to be more variable in the 4th lap of the 200-m effort compared with the other laps in both their stroke rate and stroke count (CV ~1.5% versus ~1.0%). The effects of the time of day, previous session as well as the volume and intensity on the stroke characteristics are shown in Table 7-1. A higher volume or high intensity in the previous training sessions, primarily affected stroke characteristics on the 2nd to 4th laps of the 200-m, rather than the 1st 50-m lap.
Table 7-1: 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 50 m\(^{-1}\) or strokes min\(^{-1}\) ± 90% confidence limits. The qualitative likelihood of the effect being substantial in magnitude is indicated.

<table>
<thead>
<tr>
<th></th>
<th>Stroke Count (strokes 50 m(^{-1}))</th>
<th>Stroke Rate (strokes min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate (±90% confidence limits)</td>
<td>Likelihood of a substantial change</td>
</tr>
<tr>
<td>Time of day (Afternoon-Morning)</td>
<td>-0.5 ± 0.3</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Before or after session (post-pre)</td>
<td>0.1 ± 0.3</td>
<td>Possible</td>
</tr>
<tr>
<td>High previous session’s volume</td>
<td>-0.6 ± 0.2</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Greater previous session’s intensity</td>
<td>0.3 ± 0.2</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>High current session’s volume</td>
<td>0.0 ± 0.3</td>
<td>Possibly</td>
</tr>
<tr>
<td>Greater current session’s intensity</td>
<td>0.3 ± 0.3</td>
<td>Very Likely</td>
</tr>
</tbody>
</table>

7.3. Discussion

This investigation examined the magnitudes of change in submaximal performance, physiological measures, and stroke mechanics in elite swimmers over a 14 day intensive training camp. Novel accelerometer-based smart sensor technology was utilised to obtain the majority of the timing and stroke information, and observed measurable changes in performance and physiological measures from session to session and from day to day. The degree of typical intra-session and daily variability was established, as well as the variability in these measures during an intensive 14 day training period in a group of elite swimmers.
The findings of this study indicate that a single submaximal effort in the warm-up should be useful for obtaining pertinent information on the training status of the swimmers, without invoking substantial fatigue prior to their main set.

In the current study, minimal day-to-day changes in a swimmer’s submaximal performance were observed. There was, however, a cumulative effect of fatigue which elicited a slower self-paced effort over the duration of the 14 day training camp. The main fluctuations in submaximal speed were generally observed after a preceding high intensity session or a rest day. Increasing fatigue was also reflected in changes in physiological measures and stroke mechanics of elite swimmers. The magnitude of changes for these elite swimmers were relatively small (<1%). Nonetheless, a change of 0.4% of performance time is considered the smallest worthwhile change (178, 222), consequently many of the effects reported in this study are likely to be meaningful for elite swimmers preparing for national and international competition.

Clearly the coach can have a major motivational influence on how an athlete performs in a test situation. The effect of the coach on the submaximal times in the initial days was approximately the same magnitude of the accumulative fatigue effects observed over the training camp. Although the swimmers were instructed to swim at a submaximal pace equivalent to set times, the coach’s presence and feedback influenced the swimmers’ perception of their submaximal pacing. The positive influence of direct supervision on performance has been previously shown in resistance training where directly supervised training resulted in greater maximal strength gains compared with unsupervised training (145).
Researchers have previously modelled how swimmers are trained in order to try and understand the training-performance relationship (16, 86, 153). They found that the nature of the magnitude of performance and physiological responses to training depend on volume, intensity and frequency of training sessions (153, 207). The relationship between training load and performance varies according to the periodisation and implementation of discrete training phases and training loads (86). Furthermore, adaptation to training is known to be a highly individual phenomenon (16, 86, 153). In a study of two Olympic level swimmers competing in similar duration events, Hellard et al. (86) reported that the two swimmers responded quite differently to the same high training loads. In the present study, there was large individual variation in how the swimmers respond to the training load despite only small mean changes.

The current study examined the acute effects of training volume and intensity on subsequent training sessions. A greater volume in the previous session resulted in lower blood lactate concentration, stroke rate, and stroke count in the subsequent training session. Presumably the decreased blood lactate concentration is related to an exercise-induced decrease in muscle glycogen or some other (unknown) blunting of anaerobic metabolism. Conversely, high intensity training during the previous session elicited a slower self-paced effort, higher blood lactate concentration, as well as an increase in stroke count and stroke rate. For these reasons, it is important when interpreting blood lactate concentration following a training set, to consider the training volume and intensity of the previous session (when conducted within the preceding 12 hours). These data show for the first time the magnitude of the cumulative effects of swimming training volume and intensity from session to session.
This study also examined the within-session and between-session effects of training on the submaximal performance, physiological measures, and stroke mechanics. Previous research has investigated the effects of diurnal variations on swimmers’ ability to perform maximal time trial efforts, with several investigations reporting faster maximal swimming times in the afternoon (19, 184, 198). However, while Arnett (10) reported initial diurnal variations in 100 yard swim time, favouring better performances in the afternoon, the effect was substantially reduced after the swimmers completed four months of morning and afternoon training sessions. However, in the present group of elite swimmers who had trained consistently twice daily for several years, they were markedly faster in their submaximal swim times during the afternoon session than in the morning session. Anecdotally, coaches report that swimmers can find it difficult to perform at their best in early morning workouts. After observing higher perceived effort in the morning compared with the afternoon in a series of submaximal swims, Martin and Thompson (140) suggested that extra motivation may be required for swimmers to achieve target times in morning training sessions. As the present study was self-paced, the additional perceived exertion in the mornings was associated with slower swimming for the same perceived effort. Consequently, when comparative performance and testing is conducted, it should be done at the same time of day in order to ensure standardisation.

In previous studies, the mean swimming velocity during stroking, the mean stroke rate and the mean stroke length have been used to characterise biomechanical performance while swimming. These parameters are practical and convenient for coaches to assess the effectiveness of stroke technique (110). For example, increases in velocity are typically characterised by an increase in stroke rate with a slight decrease in stroke length (60). In an applied setting, it is difficult to collect direct measures of stroke length and so this parameter
is usually inferred from the simple number of strokes taken per lap. The changes that were observed in the swimmer’s stroke rate and stroke count were quite subtle and typically less than the typical variation of the swimmer and the measurement error. For this reason, video-based analysis of the swimming action is suggested when more precise measures of stroke length or rate are sought by the coach.

It is essential for an elite swimmer to be able to self-pace their efforts in training. A substantial proportion of the training undertaken by competitive swimmers requires them to pace each lap of an effort as well as multiple laps across the training set. This study required the swimmers to self-pace their own submaximal 200-m test swims. The limitations of using self-paced efforts and the consequent effects of the coach’s encouragement on the swimming performance in the initial days are acknowledged. Nevertheless, with the exception of the performance in these initial days of the training camp (which was subsequently controlled for in the statistical analysis), the physiological, performance, and stroke responses observed in the submaximal swims form a useful picture of the swimmer’s fatigue status. Tools such as programmable pacing lights or the Aquapacer™ (a device which attach to the goggles and emit audible beeps at set intervals) could be useful for control of stroke rating.

The use of accelerometer-based smart sensor technology in swimming enables the continuous monitoring of a swimmer’s movements. The signal from the device can be used to derive information such as lap times, stroke rates, and stroke counts, with this data comparable to that taken manually (Chapter 5). In this study, the swimmers wore the sensor for all their swimming training sessions for the full duration of the training camp. However, this study only details the longitudinal responses on a single submaximal effort. Nevertheless, the potential to monitor the entire team throughout a full training session represents a valuable
opportunity for researchers and practitioners to quantify the different performance and physiological aspects of the training. Other researchers have also shown that this type of technology can provide information on swimming technique and the influence of fatigue (164). Devices such as the Traqua have the potential to revolutionise the monitoring of routine swimming training sessions.

7.4. Conclusion

Submaximal performance and physiological testing is useful for the coach and swimmer to monitor the swimmers day-to-day training status. Testing can also be used to monitor a swimmer’s training status when there is a change in the training program (e.g. altitude training, an intensive training camp, and tapering). Furthermore, this type of testing should be useful for the researcher interested in the time course, underlying physiology, and the effects of cumulative fatigue. Considered as a whole, these results indicate that a 200-m submaximal test can be used confidently to monitor changes in submaximal physiological and performance measures, and the negative effects of cumulative fatigue. The Traqua device has been shown to be a useful tool for detecting changes in swimming stroke within a training set, a single training session, and over an extended period.
CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

Monitoring and evaluating the performance of a swimmer is important for the coach and sport scientist to allow them to assist the swimmer’s progression and improvement. While it is a necessary and important aspect of the sports science program to monitor competition and training times, it is also essential to examine the various technical and physiological components that contribute to those performances. Parallel measurement of performance times, heart rate, blood lactate, stroke mechanics and self-reported perceived exertion, should establish a more complete picture of a swimmer’s status in training than from any single measure.

At the elite level of sport, the laboratory and field tests used in monitoring the various technical and physiological components need to be as minimally disruptive and invasive to the athlete as possible. Furthermore, studies of individual responses to training will be particularly useful. Although there is widespread understanding in the swimming community that swimmers respond differently to similar training loads, these individual differences are rarely considered in the peer-reviewed scientific literature. Consequently it is not sufficient in contemporary research to monitor only the mean effects of training and interventions in a group of swimmers or athletes. Researchers should also be encouraged to quantify the magnitude of the individual response in both peer-reviewed publications and in lay reports for coaches and the swimming community. Moreover, in order to interpret change in
performance appropriately, the coach and sport scientist must account for the precision and reliability of the tests they employ in routine practice and in research studies.

Although pool-based monitoring of swimmers has been conducted for many years the peer-reviewed evidence for its benefits are lacking. The experimental findings in this thesis provide additional justification for the inclusion of performance and physiological testing in high-level swimming programs.

The experimental approach used in this study 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 an examination of the effects of an intensive 14-day training program on submaximal physiological and performance measures. The findings of this thesis have immediate application for junior and senior level swimmers in a variety of settings. These include cross-sectional settings such as talent selection or identification camp, performance assessment of elite swimmers within a training phase and across a season, and for the interpretation of long-term changes in performance and fitness from season to season.

Swimmers do not always compete on a regular basis, which has necessitated the use of fitness tests to evaluate and monitor progress in training. The swimming specific incremental test required a combination of performance, physiological and stroke parameters measured at submaximal and maximal intensities. Substantial improvements in performance in training were demonstrated during a season and across several seasons. The associated physiological and stroke fluctuations were also quantified, which established magnitude and direction of the
longitudinal changes in commonly measured parameters in training in elite swimmers. Importantly there were also substantial associations between the changes observed in competitive performance and the changes in a number of these performance, physiological and stroke parameters in training. These data provide experimental evidence of moderate connections between testing and competitive performance, and therefore justification for the inclusion of incremental testing in the testing program of high level swimmers.

This thesis has employed rigorous quantitative analysis that encompasses mean effects, individual responses, magnitude of effects, precision of estimation, and real-world practical significance. This approach allows coaches and scientists to confidently distinguish those improvements that are worthwhile in a real-world sense from changes that are attributable to random fluctuations of measurement or individual performance. A more traditional analytical approach that focuses solely on statistical significance, has both theoretical and practical limitations (18, 95, 99). This thesis has systematically analysed the typical mean changes and variation in performance and physiological measures expected in elite swimmers both within and between seasons. The magnitudes of changes were small but meaningful, with swimmers likely to achieve an increase in speed of 1-2% at maximal and 4-mM lactate levels during a season. Moreover the changes established are meaningful in a real-world sense. To do so, the magnitudes of changes and differences were interpreted in light of the smallest worthwhile change in competitive swimming performance. The smallest worthwhile change is 0.4% for elite swimmers and the typical error of performance is 0.8%, while individual swimmers may vary up to 2% on the mean changes. The magnitude of mean changes and variability in key physiological and performance measures established in this thesis can be immediately applied to the training and testing of elite swimmers.
The use of technology to monitor human performance is an exciting and evolving area in sports research. New technologies such as miniaturised and wearable smart sensors can provide greater and non-invasive insight into an athlete’s performance and adaptation to training. This thesis evaluated the utility of a prototype triaxial accelerometer sensor \textit{(Traqua)} to provide comprehensive information on swimmer’s performance times and stroke mechanics. In the future, further refinement of this technology may also provide the swimming and research communities with additional information on the swimmer’s physiology in a non-invasive manner (such as a telemetered real-time blood lactate/glucose information).

The validation of new equipment or a new technique against a previously established criterion is an important aspect of science and sport science. The methods used to measure key performance and physiological parameters in athletes certainly warrant careful evaluation before implementation. The \textit{Traqua} was evaluated for validity and reliability against the manual methods currently used by coaches on the pool-deck and a criterion. The \textit{Traqua} was comparable with current methods for determining lap time and stroke rate, and was better than manually determined stroke count. Consequently, the \textit{Traqua} shows promising results as an improved and standardised means of measuring these components in testing and training situations. The \textit{Traqua} was subsequently utilised to evaluate the pacing differences and variability in stroke measures between elite senior swimmers and competitive junior swimmers. This study of pacing clearly demonstrated the typical magnitudes in differences that coaches could expect in performance and split times, and stroke measures, across a range of swimming intensities. This study also demonstrated that the more experienced senior swimmers were better able to control their swimming speed over a range of intensities in
comparison to less experienced junior swimmers. The study demonstrated the capability of the Traqua to be sensitive enough to distinguish between the different standards of swimmers.

The phase by phase and seasonal adaptations of the swimmers were monitored using fitness testing, which involved maximal and submaximal components. In an elite level program, when trained swimmers are in a physically challenging high volume or high intensity training phase, or in the later stages of the training season preparing for competition, it is often only practical to use a submaximal test. This is the first study to systematically track performance over 14-day study period and quantify the cumulative effects of training volume and training on performance and physiological measures in swimming. A principal outcome of this study was the magnitude of effect that the preceding session’s volume or intensity could influence the performance and physiological responses. High intensity and high volume sessions have a demonstrable effect on the performance and physiological responses in the subsequent training session. When evaluating test results, these findings need to be taken into consideration. Furthermore, the effects of cumulative fatigue and the daily fluctuations in training performance and the associated physiological and stroke responses can be confidently monitored using a standardised submaximal test.

The current smart sensor device provides relatively accurate measurement of timing, stroke rate, and stroke count, that is, for the most part an improvement on conventional methods of obtaining this information. However, the device has shortcomings that need to be addressed in future refinements of the technology. The areas most in need of improvement are the detection of the start and finish times. In the current series of studies, a rudimentary algorithm (adding one second to the last stroke) was used to determine the finish point. More accurate determination of both start and finish points in future iterations of the Traqua device
will also improve other limiting factors, particularly the accuracy of quantifying a swimmer’s velocity and stroke length, which are both significant pieces of information in a swimmer’s performance ability. Further developments to the technology should extend the current work to examine the other competitive swimming strokes (butterfly, backstroke, and breaststroke), quantify stroke-by-stroke changes in stroke mechanics, establish real-time transmission of data, develop software for full feature extraction, more accurate synchronisation with video, and improve data basing of results and related video.

In conclusion, these studies demonstrate that routine physiological and performance testing can provide measurable benefits for both elite swimmers and their coaches. As stroke characteristics are a primary component of performance in competition, the monitoring and feedback on these components in training, in conjunction with performance and physiological testing, is beneficial. The ability to pace efforts in training in both fresh and fatigued states is a characteristic which distinguishes elite senior swimmers from their junior counterparts. Swimmers should be taught and rehearse a high degree of consistency in pacing times and the technical aspects of their swimming. The thesis also provides a quantitative framework for interpreting the magnitude of changes and differences in test measures within a training phase, between phases within a season, from season to season, and between males and females. This information can be directly applied to similar elite level swimmers preparing for major competition. Finally, evaluation of the automated smart sensor known as the *Traqua* highlights the potential for new technologies to provide more accurate and detailed information on a swimmer’s training adaptation than current methods.
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Example of the Accelerometer Traces Where the Algorithms Failed to Correctly Detect the Start, Finish, and Stroke Rate

(Most common accelerometer errors which required correction)
An example of where the *Traqua* algorithms failed to correctly identify all the strokes, the correct stroke rate and incorrectly added a turn in the middle of a lap.
An example of where the *Traqua* algorithm has failed to correctly identify the finish – the correct finish is shown by the dotted red line and the algorithm-identified finish shown by the full red line.
APPENDIX B

Published Peer-Reviewed Articles and Abstracts
Monitoring seasonal and long-term changes in test performance in elite swimmers

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Abstract
The purpose of this study was to characterize changes and variability in test performance of swimmers within and between seasons over their elite competitive career. Forty elite swimmers (24 male, 16 female) performed a 7 × 200-m incremental swimming step test several times each 6-month season (10 ± 5 tests, spanning 0.5–6.0 y). Mixed linear modeling provided estimates of percent change in the mean and individual responses (within-athlete variation as a coefficient of variation) 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 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 ±0.80%. Step test and anthropometric measures can be used to confidently monitor progressions in swimmers in an elite training program within and between seasons.

Keywords: Lactate, reliability, skinfolds, stroke, testing and evaluation

Key points
- We analyzed the progression of 40 elite swimmers in anthropometric and performance tests for up to 5 years.
- Mean swimming speeds improved by ~2% within a season, but progression between seasons was smaller, and for males eventually plateaud.
- Lean mass increased in males and body fat decreased in females over several seasons.
- Most tests had short-term measurement error small enough to permit tracking of individual swimmers’ changes within and between seasons.

Introduction
The evaluation of physiological and sport-specific performance measures provides fundamental information to the coach, athlete and sport scientist on the athlete’s response to the training program (Smith, Norris, & Hogg, 2002). Given that performance in swimming is closely related to the physiological adaptations induced by the athlete’s training program (Edelmann-Nusser, Hohmann, & Henneberg, 2002), the assessment of various components of performance can provide important information on training progress and likely competition potential. The most practical tests for elite athletes are generally those that can be easily administered in the training environment. Ease of testing is especially the case in swimming where the demands cannot be easily replicated in a laboratory setting (Costill, Maglischo, & Richardson, 1992).

Progressive incremental tests are commonly used to assess the physiological adaptations of swimmers, measuring blood lactate and heart rate over a range of intensities culminating in a maximal effort (Hein, Kelly, & Zeballos, 1989; Pyne, Lee, & Swanwick,
2001). Incremental swimming tests can also provide feedback on performance measures such as pacing and stroke/movement characteristics at increasing speeds. Relationships between lactate and velocity have been widely used as a means to monitor the training state of swimmers by identifying an intensity (velocity) at a fixed blood lactate or lactate threshold (Hein et al., 1989; Maglischo, Maglischo, & Bishop, 1982). The main premise for this type of testing is that the lactate threshold is a useful measure of submaximal endurance fitness and assumed to reflect training-induced adaptations occurring in the skeletal muscle (Pyne et al., 2001). The changes in the lactate threshold through a training season have been previously documented in swimmers (Pyne et al., 2001), but there is limited information available on international level swimmers or on any swimmers taken consistently within and between seasons. Furthermore, parallel monitoring of maximal and submaximal physiological and performance measures has not been systematically addressed in previous longitudinal studies of collegiate (Maglischo et al., 1982; Renoux, 2001; Sharp, Vitelli, Costill, & Thomas, 1984) or elite (Bonifazi, Sardella, & Lupo, 2000; Pelayo, Mañàs, Sidney, & Chatard, 1996; Pyne et al., 2001) swimmers within a training phase or over several phases, although some investigators have attempted to develop models of training and performance in elite swimmers (Avalos, Hellard, & Chatard, 2003; Hellard et al., 2005).

The implementation of systematic training and performance diagnostic testing facilitates the analysis of changes in fitness and performance elicited through training (Smith et al., 2002). Analysis of these trends allows for reference values of changes in performance and physiological measures to be developed to assist coaches and swimmers in the preparation of annual plans and the prescription of training programs. Assessing the responses of individual swimmers should also provide more useful information to the coach and scientist. The progression and variability of individual responses in these physiological measures and performance, rather than purely reporting the mean trends, has not been previously addressed in other studies. Therefore the purpose of this study was to model the within-swimmer changes in the progression in test performance of swimmers and characterize the changes and variability within and between seasons over their elite competitive career.

Methods
Subjects
The subjects were forty national and international representative middle distance swimmers, all scholarship holders at the Australian Institute of Sport. The study sample consisted of 24 male (age at commencement 19±2 years; mean age 22±3 years, mass 80±6 kg and height 185±5 cm for time in program, mean±SD) and 16 female (age at commencement 18±3 years; mean age 20±3 years, mass 64±6 kg and height 174±7 cm) swimmers. During the study period three swimmers were ranked number one in the world in their specialist event and 11 others were ranked Top 10 in the world at some stage during the 6-year period. Fifteen of these swimmers (38%) had won an individual or relay medal at a major international competition. All procedures undertaken in this study were routinely conducted within the training environment and had approval from the Ethics Committee of the Australian Institute of Sport. All athletes provided written informed consent for sports science and sports medicine testing at the commencement of their scholarship.

The swimmers generally trained 44–48 weeks each year with pool and dry land training typically reaching a total of 20 hours per week. Typical weekly average training distance was ~50–60 km. Dry land training typically involved short 20–30-minute circuits of calisthenics, body weight exercises, stretching before training and three 1–1.5-hour gymnasium sessions per week consisting of traditional resistance training and swimming-specific exercises. Male and female swimmers were in mixed training groups and essentially completed the same training programs.

Study design and procedures
During the study period the swimmers performed a 7 × 200 m incremental step test several times each season (n = 396 tests, 10±5 per swimmer; spanning 1 season to 6 years). Each season was arbitrarily divided into four phases according to the training plan: pre-season (tests conducted >16 weeks to competition), early-season (10–16 weeks to competition), mid-season (4–10 weeks to competition), and taper (<4 weeks to competition), with swimmers usually performing at least one test in each phase.

Body composition measurements were taken regularly throughout a season (~ once per month). One anthropometrist recorded the body mass and sum of seven skinfold thicknesses on each occasion over the 6-year period. Measurements of body mass and skinfolds were generally made between 0800 and 0900 h with the athletes presenting after training in a fasted state. Body mass was measured to the nearest 0.1 kg with digital standing scales (Model DS-410, Teraoka Seiko, Tokyo, Japan). Skinfold thickness was measured using calibrated Harpenden skinfold calipers (Model
HSK-BI, Baty International, West Sussex, UK) in accordance with recommended methods of the International Society for the Advancement of Kinanthropometry (Norton et al., 1996). The seven sites used were: triceps, subscapular, biceps, supraspinale, abdomen, thigh, and calf. The anthropometrist's typical error of measurement for the sum of seven skinfold thicknesses was 1.3 mm or 2.8%. A derived lean mass index described by Hopkins, Anderson, Lee, Turovetski, & Pyne (2002) was used to track changes in lean mass controlled for changes in skinfolds.

7 × 200-m testing procedure

The 7 × 200-m test consisted of seven even-paced swims on a 5-minute cycle, graded from easy to maximal (Pyne et al., 2001). Swimmers usually completed the test using the stroke of their main competitive event and used the same stroke for all tests during the study period. Individualized target times based on each swimmer's personal best time were calculated prior to testing. Swimmers were typically within 2 seconds of target times for the first six efforts, with the final effort maximal. All testing was conducted in a 50-m pool and swims utilized a push start. Speeds for the swims ranged ~30 seconds from slowest to fastest for each 200-m effort (e.g. 2:30 to 2:00 min), with the seventh and final swim a maximal effort.

Each 100-m split and the total 200-m time were timed manually. Stroke rate was measured on the third lap by manually timing three complete stroke cycles with a stopwatch (Seiko, Model S120-0420, Japan). The number of strokes taken per 50-m lap (stroke count) was determined on the fourth lap of each 200-m effort. Given that speed is the product of stroke length and stroke rate, we determined stroke length as the quotient of speed and stroke rate (Craig & Pendergast, 1979). On completion of each effort, heart rate (HR) was measured using a heart rate monitor (Polar Electro Oy, Kempele, Finland). The swimmer then exited the pool and a 5-μl blood sample taken from the earlobe or fingertip, with the location standardized for each subject, and analyzed for lactate concentration using a portable hand-held blood lactate analyzer (Lactate Pro, Arkray, Japan). Blood samples were taken within 1 minute of completion of the swim for the first six efforts and 3 minutes after for the final maximal effort.

Derived values at a fixed 4-mM blood lactate were determined using a modification of the log-log model originally described by Beaver, Wasserman, and Whipp (1985). A straight line was fitted to the log-log transformed plots of the last five steps for blood lactate and swimming speed. To establish the criteria for the linear regression analysis, we plotted 20 representative data sets. Only the last five steps of log-transformed values for speed and blood lactate were used to improve the linear fit of the lactate-speed curve (correlation of r = 0.92 for the representative data sets) and on the basis that the first two steps were generally less than 2 mM. The speed at a fixed blood lactate concentration of 4-mM was determined using the 4-mM y-intercept on the blood lactate-time curve. This procedure was then repeated for the other measures, with the log of time plotted against the log of heart rate, stroke rate, stroke count and stroke length. However, on the basis of initial inspection of the 20 representative data sets the first two steps of these measures were included, the seventh step excluded for heart rate, stroke rate and stroke length, and the last two steps excluded for stroke count. A straight line was fitted to the log–log plots (r > 0.80 from the representative 20 plots) and the submaximal values at a fixed 4-mM lactate determined for heart rate, stroke rate, stroke count and stroke length by linear regression.

Reliability testing

Test–retest reliability of the 7 × 200 m incremental step test was assessed prior to analysis of the longitudinal data. Twenty-two competitive swimmers (12 male, 10 female) completed the incremental 7 × 200-m test twice ~72 hours apart under similar conditions. All subjects were familiar with the testing protocol and undertook a standardized warm-up. Typical error of measurement (Hopkins, 2000) was determined on maximal and 4-mM lactate measures of time, lactate, heart rate, stroke rate, stroke count, and stroke length.

Statistical analyses

Log transformation and repeated measures mixed linear modeling (Proc Mixed) using Statistical Analysis System software (Version 8.1, SAS Institute, Cary, NC) provided estimates of percent change in the mean (fixed effects) and within-swimmer coefficient of variation (CV) (random effects) for maximal and derived 4-mM lactate step test measures and body composition between phases and years for each sex. The fixed effects in the model were Phase, ProgTime, ProgTime*ProgTime, AgeRel, ProgTime*AgeRel, AgeRel*AgeRel. Phase was a within-subject effect with values for pre, early, mid and taper representing the effect of the training phase at the time of each assessment. ProgTime was a numeric within-subject effect representing the duration the swimmer had been in the program at the time of each assessment. AgeRel was a within-subject effect representing the age of the swimmer relative to the reference age of 19 years. The random effects were
Athlete (estimating pure between-athlete variation), Athlete*Season (estimating within-athlete variation additional to the residual arising between tests performed in different seasons), and the residual (estimating within-athlete variation for tests within a season). Expressed as coefficients of variation, within-athlete variation represents typical variation in an athlete’s test scores; for typical variation in an athlete’s change score between two tests, the typical variation needs to be multiplied by \( \sqrt{2} \).

Data are shown as a mean or range ±95% confidence limits. Magnitudes of the change scores were assessed by calculating the chance that the true value of the effect was practically beneficial, trivial, or harmful (Hopkins, 2002). To calculate these chances we assumed that the smallest worthwhile change in measures which could have a direct relationship with performance (speed and stroke characteristics) was 0.5 \( \times \) within-athlete coefficient of variation (CV) for competitive performance, equating to 0.4% for elite swimmers (Trewin, Hopkins, & Pyne, 2004). For all the non-performance measures (heart rate, blood lactate and body composition) the smallest worthwhile change was calculated as Cohen’s smallest effect size of 0.2 \( \times \) the between-athlete CV (Cohen, 1988). Thresholds for assigning qualitative terms to chance of a substantial increase or decrease were as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely or probably not; <50%, possibly not; >50%, possibly; >75%, likely or probable; >95%, very likely; >99%, almost certain (Hopkins, 2002).

**Results**

Representative mean data for male and female freestyle swimmers in the group are shown for all the 7 × 200-m test measures in Table I. The typical error of measurement for each of the maximal and 4-mM lactate measures in the 7 × 200-m step test, derived from the reliability testing are shown in Table I.

**Within-season changes**

Improvements of 1.5–2.0% were generally observed in submaximal 4-mM swimming speeds during a training season. The within-season mean changes in 4-mM lactate speed, stroke rate and stroke length are shown in Figure 1. Typically mean increases of 2–4% were observed in stroke rate accompanied by a corresponding decrease in stroke length. The swimmers showed similar mean changes in maximal performance to those seen at 4-mM lactate within a season. At maximal speeds, female swimmers improved from the pre to taper phase by 2.3% (95% confidence limits [CL] ±1.2%), with most of the gains in the mid (1.6%, CL ±1.2%) and taper (1.5%, CL ±1.0%) phases. Conversely, at maximal speed, male swimmers were very likely to get faster over the season but only in the mid phase (1.4%, CL ±1.1%). Individual swimmers varied ~±2.6% in their maximal performance and ~±2.2% in their 4-mM lactate speed between tests within a season. Accompanying the changes in maximal speed were indications of 2–5% changes in the stroke characteristics. Individual variations of ±4–6% were observed in maximal and 4-mM lactate stroke characteristics between tests within a season.

Physiological changes in submaximal (4-mM fixed lactate) and maximal fitness were represented by changes in blood lactate and heart rate in the step test. Mean peak blood lactate after the final and maximal 200-m effort was ~10 mM, although a large degree of within-athlete variation (±28%) was evident from between tests. Only trivial changes in mean blood lactate concentration were seen between each phase within a season. The mean peak heart rate

| Table I. Descriptive statistics (mean ± SD) of the 7 × 200-m step test measures for the male and female freestyle swimmers and the re-test typical error of measurement expressed as a coefficient of variation from the reliability study |
|-----------------------------------------------|-----------------|-----------------|
| Maximal (final 200 m step):                   | Male (n = 17)   | Female (n = 11) |
| 200 m time (s)                               | 120.9 ± 4.5     | 130.1 ± 2.2     | 0.8 |
| Stroke rate (strokes.min⁻¹)                   | 40.5 ± 2.2      | 40.5 ± 3.5      | 2.1 |
| Stroke length (m)                             | 2.47 ± 0.15     | 2.29 ± 0.16     | 2.3 |
| Stroke count (strokes.50 m⁻¹)                 | 36.2 ± 2.6      | 40.7 ± 2.7      | 2.9 |
| Lactate (mM)                                  | 10.5 ± 2.1      | 9.2 ± 1.9       | 16  |
| Heart rate (beats.min⁻¹)                      | 182.9 ± 6.9     | 179.7 ± 8.5     | 2.3 |
| Submaximal (Fixed 4-mM lactate):              |                 |                 |
| Time per 100 m (s)                            | 65.2 ± 1.8      | 68.5 ± 1.6      | 0.8 |
| Stroke rate (strokes.min⁻¹)                   | 34.3 ± 2.9      | 36.1 ± 3.9      | 3.3 |
| Stroke length (m)                             | 2.70 ± 0.21     | 2.44 ± 0.20     | 2.9 |
| Stroke count (strokes.50 m⁻¹)                 | 32.6 ± 2.5      | 37.2 ± 3.1      | 3.5 |
| Heart rate (beats.min⁻¹)                      | 166.7 ± 7.0     | 166.0 ± 9.9     | 3.2 |

210.
Male and female swimmers both had trivial changes in body mass between phases in a season. The sum of skinfolds of the female swimmers progressively decreased in each phase during a season, characterized by a 5.3% (CL ±4.1%) decrease from early to mid season and a substantial 8.0% (CL ±4.6%) decrease from the mid to the taper phase. During the pre-season there was a substantial 14.6% (CL ±4.4%) decrease in skinfolds throughout a season. In comparison, male swimmers typically lost 8.5% (CL ±4.5%) throughout the season, with the majority of the decrease occurring in the latter phases of the season. Superimposed on the changes in mean skinfolds were typical variations in an individual's skinfolds between tests within a season of ±5.8% for females and ±7.0% for males. All changes in lean mass within a season were trivial.

**Progressive yearly changes**

The progression in maximal test performance, stroke rate and stroke length from year to year are presented in Figure 2. The mean increase in maximal speed was typically 0.6–0.8% each year for male and female swimmers, but plateaued in males after 2 years. At maximal speed, increases in stroke rate and decreases in stroke length of typically 1–2% each year were observed for the male swimmers. Female swimmers typically had a marginal decrease in stroke rate and an increase of ~0.9% each year in stroke length over 5 years. Female swimmers almost certainly improved their 4-mM lactate speed with a mean improvement of 1.2% each year (CL ±1.0%), while males had only trivial changes. Sex differences were also evident in the stroke characteristics at the 4-mM lactate speed over extended periods of time. Each year female swimmers increased stroke rate ~1.0% and decreased stroke count ~2.5% at 4-mM lactate speeds. In contrast, male swimmers had only trivial changes in stroke characteristics at 4-mM lactate speeds over 5 years. The typical individual variation in an individual's stroke characteristics between tests in different seasons was: ~±5.0% for stroke rate, ~±4.8% for stroke count and ~±4.7% for stroke length (CL ±1.1%). The progressive changes from year to year for peak lactate and heart rate are shown in Figure 3. Despite little change within a season, male swimmers showed a progressive increase in peak lactate concentration from year to year, while females had only trivial changes over 5 years. Peak heart rate for the males was relatively stable during the first 3 years in the program before decreasing in subsequent years. Females had a ~1.1% decrease in peak heart rate each year. Only trivial changes were observed in 4-mM lactate heart rate from year to year for male
and female swimmers. However the heart rate typically varied from these mean trends by $\pm 3.5\%$ for 4-mM lactate heart rate, and females by $\pm 2.0\%$ and males by $\pm 3.2\%$ for peak heart rate.

Sex differences were apparent in the long-term changes in body composition over several years. The typical within-athlete changes in body mass, skinfolds and lean mass over 5 years are shown in Figure 4. Male swimmers showed progressive increases in body mass and lean mass after the first 2–3 years in the program, with little change in skinfolds. Female swimmers had substantial decreases in body mass and skinfolds but only trivial changes in lean mass over 5 years. Individual female swimmers tended to vary more in the mean trends between tests in different seasons for body mass ($\pm 2.2\%$) and skinfolds ($\pm 11.0\%$) than between tests within a season. The skinfolds of male swimmers varied more from year to year ($\pm 9.2\%$) than from test to test within a season.
Monitoring test performance in elite swimmers

Figure 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.

Discussion

In this study we examined seasonal and long-term changes in a group of elite-level swimmers and characterized performance, anthropometric, physiological and stroke characteristic changes. The present study is the first to analyze such changes in elite athletes within and between seasons systematically and estimate the magnitude of individual responses superimposed on these mean changes. Maximal performance tests in training are commonly used to gauge the progress in fitness through a training and competitive season. Swimmers do not always compete on a regular basis, and incremental testing has emerged as common practice in many high level programs. We used the 7 × 200-m step test to ascertain the changes in performance and physiological measures in swimmers competing in sprint, middle-distance and distance events and basic anthropometric measures to characterize body composition changes.

We reported the magnitude of the effects using likelihoods and examined the precision of the estimate with 95% CIs. Standard statistical significance testing provides only a limited interpretation of the meaningfulness of changes and differences in performance for the elite level athlete (Atkinson, 2003; Strooë & Andersen, 2003). No previous study of swimming performance by elite competitors has examined the individual responses to training. We have estimated the individual variability as well as the mean changes to give an indication of the typical variations that would be expected when monitoring a randomly selected group of elite swimmers. Several sources may have contributed to the magnitude of individual variations observed in test performance, physiological and stroke parameters. The training groups were of mixed sex and had male and female swimmers undertaking the same or different training depending on their individual squad. Innate differences in the response to training may have contributed to the individual differences in progression. Variability in test measures may also have been influenced by factors such as levels of hydration, muscle glycogen, illness, recovery from injury and any acute fatigue.

The ability to monitor swimmers' adaptations to the training program within a season is probably the most critical element of testing for the coach and athlete. Quantifying improvements or decrements in performance can be used to determine whether the coach needs to make corrective actions in the training program. Furthermore, speed at a fixed 4-mM blood lactate has been used extensively to determine training speeds for swimmers (Maglischo et al., 1982) and correlates highly with 400-m maximum swimming speed (Wakayoshi et al., 1993). We found that elite swimmers were likely to become 1–2% faster at maximal and 4-mM lactate speeds during the season. Most of the improvement occurred in the mid and taper phases of the season. The improvements in fitness over a training season in the present study confirm earlier investigations.
(Ryan, Coyle, & Quick, 1990; Sharp et al., 1984) and the magnitude of these small but meaningful increases are similar to that of prior observations (Pyne et al., 2001). It should be noted that the information provided from the step test and body composition measurements was considered by the coach and athlete in subsequent preparation and modifications made to the training program entirely at the coach’s discretion.

Although within-season changes in fitness are important for immediate coaching feedback, it is also important to monitor longer term changes. The yearly progression in both maximal test performance and 4-mM lactate speed were considerably less than that observed within a season. It is apparent that improvements are generally cyclical in nature, whereby swimmers lose some or all their fitness gains in the transition from one season to the next. The importance of maintaining a degree of fitness during the off-season has previously been highlighted (Mujika et al., 1995). Mujika et al. (1995) found that lost form at the beginning of the season can be detrimental to performance during the season. In the present study we compared test performance and found a substantial decrease in speed from the end of one season to the beginning of the next. However, the effect of the lower test performance and therefore fitness at the start of the season on competition performance at the end >20 weeks of full-time training was not elucidated in the present study.

Differences in the direction and magnitude of changes in fitness between the male and female swimmers were apparent. Sex-specific differences in the adaptation to similar training programs may explain the discrepancies between the groups in test performance in the long term. In general, the males became stronger and more powerful whereas the females became leaner and more efficient. The male swimmers tended to increase in mass and lean mass, and developed their anaerobic qualities as indicated by the increase in peak lactate concentration after the maximal 200-m effort. Collectively with an increase in stroke rate and a decrease in stroke length over time, the increase in lean mass and lactate could possibly translate into improved power applied to the water for the male swimmers. In comparison, the female swimmers showed a decrease in mass and a decrease in skinfolds over time in agreement with previous observations (Meleshki & Malina, 1985). However, only trivial changes occurred in lean mass and peak lactate for the females. An increase in maximal stroke length and stroke rate at 4-mM lactate for the females was also observed and indicative of a possible improved swimming efficiency. The substantial loss of mass and skinfolds and the greater improvement in maximal and 4-mM lactate speed could also be due to the female athletes coming into the program initially in a lower state of training and fitness than the males.

Greater consistency in competitive performance is evident in Olympic-level swimmers compared with age group and national standard swimmers. Trewin et al. (2004) reported a variation of 0.8% for Olympic swimmers in major competitions from one year to the next, while Stewart and Hopkins (2000) reported for elite junior swimmers a coefficient of variation of 1.4% between competitions. Consequently, the variability in training performance appears to be substantially larger than that of competition performance in elite swimmers. In the present study, the within-subject between-test variability was 2.6% for maximal test performance and 1.9% for 4-mM lactate speed. The greater variation in performance in the training environment could relate to the individual differences in progression between tests during the season. Other possibilities for the greater variation could be related to variations in motivation and fatigue from one test to the next. The notion of greater variability in training is consistent with our earlier report where typical changes in test performance of 2–3% were observed (Pyne et al., 2001).

Stroke technique plays an important role in the variation of energy cost and efficiency of performance during competitive swimming (Chatard, Collomp, Maglischo, & Maglischo, 1990). Stroke rate and stroke length are useful parameters to monitor in swimming as indicators of swimming technique (Craig & Pendergast, 1979; Keskinen, Tili, & Konu, 1989). Keskinen et al. (1989) reported that stroke length was the predominate factor in producing high swimming velocity. However, Chatard et al. (1990) found that stroke rate was a better indicator of swimming technique than stroke length since it explained a greater proportion of the variability in swimming. In the absence of biomechanical or video-based analysis in the present retrospective study we reported manually recorded stroke count and stroke rate and a derived stroke length. We observed a substantial mean increase in stroke rate through the early and mid phases of the season with a slight decline in the taper phase. The magnitude of measurement error is quite large, but this is most likely owing to the manual methods used which will have contributed additional variation from test to test when monitoring an individual swimmer. The development and implementation of more sophisticated accelerometry-based systems to measure this characteristic in the future may assist with more confidently tracking changes in the individual.
Blood lactate measurements have provided the basis for estimating changes in aerobic fitness at a fixed blood lactate value as a function of velocity or power output to monitor training-induced changes or for prescription of training sets (Billat, 1996; Maglischo, Maglischo, & Bishop, 1982). Previous reports in elite speed skaters (Foster, Fitzgerald, & Spatz, 1999) and cyclists (Lucia, Hoyos, Perez, & Chicharro, 2000) have shown that heart rate remains stable at reference blood lactate and ventilatory thresholds during the course of a training year despite significant training-induced improvements in fitness and performance. The present study confirms the stability of heart rate at a fixed lactate value in elite swimmers. Changes in heart rate at the 4-mM lactate within a season and over several years were less than the typical error of measurement and the smallest worthwhile change. However, the earlier studies did not address the variation of individuals, which can provide more information than the stability of the mean. In the present study the mean heart rate and 4-mM lactate showed only trivial changes, whereas individual swimmers could actually vary quite substantially (±3.5%).

There are several practical implications arising from this study for coaches and sport scientists wanting to employ similar tests to monitor changes in fitness and performance of highly trained swimmers. First, testing should be conducted periodically throughout the season to establish baseline values (early season), assess progress (mid-season), and finalize the preparation (taper). In a mixed group setting, coaches will need to manage the testing and training of swimmers on a sex-specific basis with individualized training prescription. Secondly, given the evidence that the performance and physiological measures for an international swimmer tend to plateau over a longer competitive career, coaches will need to modify long-term training programs accordingly. Thirdly, scientists should administer a comprehensive battery of tests involving a combination of performance (total time and split times), stroke (stroke rate and stroke count), physiological (heart rate and blood lactate) and body composition (mass and skinfolds) measures. Finally, both the mean changes and individual responses of the swimmers to training should be considered.

Conclusions

Coaches and sport scientists can be confident in identifying real changes in performance, physical and physiological measure of individual swimmers using pool-based lactate testing and anthropometric testing. The identification of mean trends within a season and the progression over several years provides reference values on the magnitude of typical changes expected for national and international level swimmers. Scientists and coaches should also consider the degree of individual variation around these mean effects when assessing fitness and prescribing training. While routine testing offers insight into the training process, the relationship between testing and competitive performance in international swimmers remains uncertain and needs to be addressed.

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References


LONG TERM CHANGES IN FITNESS AND COMPETITIVE PERFORMANCE IN
ELITE SWIMMERS

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Auckland, New Zealand; University of Canberra, Australia.

PURPOSE: To evaluate the ability of incremental pool testing to track seasonal changes in
training performance and predict competitive performance in elite swimmers. METHODS: Nineteen elite Olympic representative swimmers (10 male; 9 female) completed the 7 x 200
m incremental swimming step test several times a season in the period from 1998 to 2002. Each swimmer completed 8-19 tests (259 in total). Tests were conducted in the pre, early, mid, and taper phases of each season. Repeated measures mixed linear modeling was used to derive estimates of within-athlete variability between phases and seasons for 200-m time, blood lactate, and heart rate (HR_LT), stroke count (SC_LT), stroke rate (SR_LT), and estimated swimming velocity at the lactate threshold (V_LT). Change in performance in national and international competitions between seasons was also modeled as a linear function of change in each of the step test measures.

RESULTS: Competitive performance improved marginally by 0.2% each year, with a within-athlete between-competition coefficient of variation (CV) of 1.0%. However there was no real change in test performance in training from one preparation to the next (0.0%; CV = 2.8%). Within a preparation a cyclical pattern in test performance was evident in the means of the four phases, with a 1.9% decrease in 200-m time from pre to taper phase. Within a season HR_LT, SR_LT and SC_LT were all relatively stable from phase to phase. V_LT was unchanged early in the season, before improving by 1.2% from the early to mid phase and then a further 0.4% from mid to taper phase. Swimmers improved 200-m time by 0.5% (CV = 2.4%), and V_LT by 0.3% in the taper phase between each preparation (CV = 1.7%). 200-m time, maximal lactate, HR_LT, SC_LT and SR_LT were poor predictors of competitive performance with large within-athlete variability (~2-4%). In contrast competitive performance improved by 0.4% for every 1% improvement in V_LT in the taper phase. CONCLUSION: The 7 x 200 m incremental swimming step test appears to be useful in tracking training responses but is a weak predictor of competitive performance.
Monitoring seasonal and long-term changes in test and competitive performance in elite swimmers

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Purpose: To evaluate the utility of an incremental swimming test for monitoring seasonal changes in performance of elite swimmers. Methods: 40 elite swimmers (24 M, 16 F) performed a 7 x 200-m incremental swimming test several times throughout each 6-month season during 1998-2003. Each season concluded with a major competition. Log transformation and repeated measures mixed linear modeling were used to derive estimates of percent change in mean and within-swimmer coefficient of variation for swim times between seasons and for the following test measures between phases and seasons: speed, stroke rate, stroke count, and HR at lactate threshold; time for the maximal (last) 200-m step; and maximal lactate. Ability to predict competition time changes was estimated as a within-subject correlation between each measure and performance. A reliability study of 12 swimmers also provided 3-d retest typical error of test measures. Results: Test measures directly related to swimming performance showed cyclical improvement (mean ~2%) from early to taper phases within each season. Within-swimmer variation had similar magnitude. These changes can be monitored confidently in individuals, because the typical error of the test measures was substantially smaller (e.g., lactate-threshold speed, 0.7%; 200-m time, 0.6%). Competition times improved slightly each season (0.7%) against a 1.1% within-swimmer variation between competitions. Only threshold speed, stroke rate and maximal lactate in the taper were moderately correlated (~0.4) with improvements in competition time. Conclusion: The swimming test tracks changes in training performance during a season, but is at best a moderate predictor of competitive performance only during the taper.
Ability Of Performance-Test Measures To Predict Competitive Performance In Elite Swimmers

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Purpose: To evaluate the efficacy of regular testing and identify the ability of changes in test measures to predict changes in competition performance in elite swimmers. Methods: The swimmers (24 male, 16 female; age 21±3 y, mean±SD) raced in a major competition at the conclusion of each 6-month season (3.6±2.2 competitions). A 7x200-m incremental swimming step-test was conducted in up to four training phases each season to monitor changes in 4-mM lactate threshold and maximal (the seventh step) performance. For each phase, simple and multiple linear regressions of swimmers’ change scores between seasons in step-test measures were correlated with competition performance. Results: Females’ mean competition performance improved by 0.4%/y (95% confidence limits ±0.7%); males improved initially at 1.0%/y (±0.7%) but plateaued at ~3% after 4 y. These mean changes were tracked well by submaximal stroke rate for females and maximal lactate for males. Changes in individual competition performance were best tracked by step-test measures in the taper phase, with single measure correlations (r) up to 0.49; the best combination for females (maximal time and lactate, submaximal time and stroke rate) produced a r=0.62 (confidence limits: 0.31–0.81) and for males (submaximal time, maximal time and lactate) r=0.66 (0.45–0.80). Conclusion: A combination of step-test measures can predict mean and individual changes in competition performance. The best prediction occurred in the taper, possibly as it is closest to the competition and in earlier phases coaches take corrective action. The step-test is apparently a valuable adjunct in a swimmer’s training preparation.