PERFORMANCE CHARACTERISTICS OF PARALYMPIC SWIMMING

By

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B. Arts (Human Movement) (Hons.)

This thesis is submitted in fulfilment of the requirements for the completion of the degree of Doctor of Philosophy

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Abstract

Margins of victory in elite swimming competitions are often small and are influenced by the performance characteristics of the athlete. The Paralympic Games is the highest level of competition for elite swimmers with a disability. The key performance characteristics of these athletes depend on training and technique, yet these have not been wholly quantified and documented. The purpose of this thesis was to enhance training and optimise competition outcomes for Paralympic swimmers by examining variability and progression in competition times, training characteristics, and the contribution of kicking to performance. The variability and progression of performance from competition to competition provides guidelines for the global improvements required for swimmers to succeed. To achieve this objective, the training programs used to prepare swimmers for competition must be effective. Kicking training is a key component of the training process prescribed by coaches however there is no simple method to measure the kinematics of the kick. Quantifying the patterns of kick count and kick rate was achieved by using inertial sensor technology. When net propulsive force of the kick is measured at race velocities and using different kicking amplitudes, coaches and sport scientists were able to identify key technical and training characteristics to increase kicking velocity.

Study one examined the magnitude of variability and progression in competitive performance in the 100 m freestyle event for elite swimmers with a disability. The major results of this study found that annual improvements in competitive performance of 1-2%, which account for variability (~1.3%), progression (~0.5%) and the level of a competition (~1.5%), are required for top-ranked Paralympic swimmers to substantially increase medal prospects. Improvements of this magnitude require an effective training program. In study two, training volume and intensity (load) were quantified for 16 Paralympic swimmers, in the 16 weeks prior to a World Championship to determine the weekly pattern of training load throughout a training block. Increases in main-set training volume (~24, ±19%: mean, ±90% confidence limits) and perceived exertion (~7, ±3%) were observed mid-season prior to substantial reductions in volume (~24, ±18%) and maintenance of intensity during the taper. There was no clear association (correlation coefficient) between training
volume and functional ability of the swimmers, or between training measures and performance. Kick sets were prescribed in the majority of the training sessions in study two though lap time was the only quantifiable variable.

The characteristics of a swimmer’s kick are unknown. The kick is partially obscured by turbulence and therefore difficult to measure. The aim of study three was to evaluate the application of inertial sensor technology, when attached to the legs, to quantify kick count and kick rate in freestyle swimming. The validity and reliability of this new method of quantifying kicking measures were evaluated. Kicking patterns were then measured in study four for 14 Paralympic swimmers in 100 m freestyle swimming time trials to determine changes and differences within and between a) swimming and kicking-only trials; b) Paralympic classes and disabilities; and c) 100 m distances. Kick count did not change within a trial, though substantial decreases in kick rate (~12, ±1%) were observed by the 3rd 25 m segment. The relationship between swimming and kicking-only kick rates in study four was substantial; $r = 0.67$ (0.55 to 0.76). Some swimmers have a better transfer of kick rate from kicking-only to swimming than others.

Study five examined the influence of kicking velocity and amplitude on net force and kick rate in 12 Paralympic swimmers using a dynamometer and force platform system. The net force naturally increased with a faster tow velocity (~24, ±5%), without a concomitant increase in kick rate that remained largely unchanged at ~150 kicks·min$^{-1}$ for all velocities. Deep amplitude kicking substantially decreased kick rate (~14, ±5%) and increased force (~10, ±5N). This relationship between kick rate, velocity, amplitude and net force provides insight into guidelines for the prescription of kick training. The key for Paralympic swimmers is to implement kick rates and amplitudes, complementary to the arm stroke, that elicit faster swimming velocities with a relative decrease in net towing force.

In conclusion, the results of this series of studies suggest that coaches and swimmers should address issues of variability and progression in competition times. These estimates can be used to set realistic performance goals when planning for major competitions and yearly training programs. Coaches, when planning the yearly training season for Paralympic swimmers, should follow similar periodised patterns to
Olympic swimmers. Contemporary training facilitates substantial improvements in freestyle velocity when kick rate is increased and kick amplitude is maintained. Integration of these key characteristics should enhance Paralympic swimming performance and increase chances of success in competition.
Declaration of Originality

This thesis is submitted to the University of the Sunshine Coast in fulfilment of the requirements for a Doctor of Philosophy.

The work presented in this thesis is, to the best of my knowledge and belief, original except where explicit reference is made in the text. I hereby declare that this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for, or been awarded another degree or diploma at this or any other university institution. No other person’s work has been relied upon or used without due acknowledgment in the main text and bibliography of the thesis.

This research was conducted under the supervision of Professor Brendan Burkett (Centre for Healthy Activities, Sport and Exercise, University of the Sunshine Coast) and Professor David Pyne (Department of Physiology, Australian Institute of Sport).

This thesis has been prepared to conform to the guidelines provided by the University of the Sunshine Coast and is based upon the style recommended in the Publications Manual of the American Psychological Association (5th edition: 2003). Where there are six or more authors, the first author only, followed by et al., is cited in all instances in Chapters 1, 2 and 8. Spelling is Australian English.

Sacha Kate Fulton
CANDIDATE

18th December 2008
Date
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‘Failure is never final. Forget the past, ignore the future, live for the present, the here and now, and the result will look after itself’
Publications from Doctoral Thesis

At the date of submission of this thesis, the following papers are ‘in press’ or have been submitted for publication:


Chapter 1: Introduction

Background
In elite swimming competitions the margins of victory are often small and the majority of swimmers in the final of an individual event have a realistic chance of winning. Consequently, coaches and sport scientists spend hours devising training techniques and racing strategies to gain sufficient advantage over the competition. An optimum level of performance to gain such an advantage requires integration of key physiological, biomechanical and technical characteristics. The pursuit of swimming excellence places great emphasis on integrating and developing these characteristics for performance. The key to success requires that a swimmer’s training and competition performance is planned and monitored.

The unique physiological and biomechanical demands of Paralympic swimmers provide challenges for coaches and sport scientists to enhance fitness, swimming technique and competitive performance. To provide an equal platform of competition for athletes with a disability, the International Paralympic Committee (IPC) has developed sports-specific groupings of disabilities. In Paralympic swimming there are two broad classifications: one for functionally impaired swimmers (Class S1-S10) and the other for the visually impaired (Class S11-S13) (International Paralympic Committee, 2008). The swimming functional classification system, which attempts to ameliorate the effects of impairment on competition and combines athletes with different disabilities but comparable ability and function, is continually in question. The classification system is based on a point system, which assumes a certain percentage contribution of arm and leg propulsion to the potential swimming speed. Swimmers with upper limb impairments are scored lower than those with lower limb impairments based on the belief that the upper body contributes maximally to swimming propulsion. Despite this scoring system the impairment profile of a swimmer does not guarantee that they will win or lose a race.

The Paralympic Games is the highest level of competition for elite swimmers with a disability. The disability profiles of Paralympic swimmers may depend on characteristics that are different from those of able-bodied swimmers and some of
which have not yet been recognised. The contemporary training programs and technical strategies used to prepare able-bodied swimmers for competition may therefore not be suitable for Paralympic swimming. The sample of subjects used in this series of research investigations was small and limited to swimmers from the same country. However the key performance characteristics that could enhance training and competitive performance identified in this study should apply to other national and international level Paralympic swimmers. This thesis examined variability and progression in competition times, training characteristics, and the contribution of kicking to Paralympic swimming performance.

In elite sport, the most important level of evaluation is performance itself. The race-to-race variation in performance of elite athletes yields the smallest worthwhile change or difference in performance time, which can substantially affect the final placing (Hopkins, 2004). Simply, the smallest worthwhile change is the magnitude an athlete must improve by to substantially increase their chance of success. For elite athletes competing in individual sports at international events, statistical simulations show that the smallest worthwhile change in performance is ~0.5% of the typical within-athlete random variation in the athlete’s performance from competition to competition (Hopkins et al., 1999). Magnitudes of variability and progression in performance have been established for Olympic swimmers with an improvement of ~1.0-1.4% in performance time necessary to account for both variability and progression in the pre-Olympic year (Pyne et al., 2004). Therefore, an improvement in performance of this magnitude should be relevant for all swimmers at this level of competition. However, Paralympic swimmers are different from Olympic swimmers and the estimates of performance improvements for elite able-bodied athletes may not be appropriate to account for athletes with physical and visual impairments. The nature of the impairment of Paralympic swimmers may limit their consistency of swimming performance from race to race; a key factor in determining the extent to which performance-enhancing strategies affect the chances of an athlete winning a medal (Hopkins et al., 1999). The magnitude of these estimates has not been derived for Paralympic swimmers. This information may allow athletes and coaches to set realistic performance goals for future competitions and assess the benefit of training interventions.
The improvement of competitive swimming performance necessary to medal in competition is achieved through a training process to automate motor skills and enhance fitness. The dynamics of swimming training involve the manipulation of the training load through the variables of volume (duration and frequency) and intensity (Faude et al., 2008; Thomas et al., 2008). Swimming coaches periodise training and recovery to elicit short-term responses and long-term adaptations that underpin improvements in performance (Pyne & Goldsmith, 2005). A systematic increase in training load during the season develops physical, technical and performance capacities prior to an adaptation phase, where volume is tapered and intensity maintained, in the weeks prior to major competition (Busso & Thomas, 2006).

Coaches currently prescribed training for Paralympic swimmers based on recommendations for able-bodied swimmers. However, it is possible that limitations associated with limb loss or motor control may influence the demands and response to training of Paralympic swimmers. Monitoring the training response and quantifying training load has not been characterised in Paralympic swimmers, and offers a practical means to help coaches develop effective training methods for the improvement of competitive performance. Consequently, these data may provide a framework to evaluate the efficacy of contemporary programs used to prepare Paralympic swimmers for competition.

Coaches routinely prescribe kick sets in training sessions for swimming. When kicking-only training forms a substantial part of a competitive swimmer’s program, it is effective in inducing training adaptations in musculature of the legs (Konstantaki & Winter, 2007). Measuring the kinematics of kick count and kick rate in kicking-only performance should identify those variables that elicit improvements in full-stroke freestyle swimming performance. However, the flutter kick in freestyle swimming for example, occurs predominantly below the water surface and it is difficult to measure the kinematics of the kick from video footage due to water turbulence (Ohgi et al., 2003). Lap time is the only current variable that coaches can measure in flutter kicking training sessions. Consequently, kick count and kick rate have not been quantified for swimmers at any level and neither have patterns of the kick within and between performance trials. For Paralympic swimmers with upper limb disabilities there may be a natural dependence on the kicking action for optimal performance, and
swimmers with lower limb disabilities may have to modify their pattern of kick to complement the arm action and optimise velocity. The difficulty in measuring the kick could be addressed with application of inertial sensor devices that systematically track movement.

Inertial sensor devices have been used successfully to evaluate the underwater phase of the arm stroke in swimming using wrist acceleration (Ohgi et al., 2003). When placed on the wrist or forearm, inertial sensors can discriminate this underwater phase, between swimming strokes and within stroke movement patterns (i.e. down sweep, in sweep, out sweep and recovery), through characteristics of acceleration (Ohgi et al., 2003). The ability of inertial sensor technology to discriminate the kicking action when attached to the legs of swimmers could assist coaches’ to design more effective training interventions and identify key performance characteristics of the kick.

Swimming velocity is governed by passive and active (net propulsive) forces. Towing a swimmer through the water in a rigid streamline position, with a tethering device that measures the force required to maintain equilibrium, is used to estimate the passive force of a swimmer (Maiello et al., 1998). Towing a swimmer through the water as they create propulsive movements such as stroking or kicking, is used to estimate the active, or net propulsive force (Toussaint & Hollander, 1994). Swimmers’ can therefore improve speed by either reducing the passive forces, or increasing the active forces, during free swimming. Kicking is one of the contributions to the active force. The contribution of the kick can be estimated by quantifying the difference between the force required when being towed at maximal swimming velocity while kicking only, and the force required when being towed without kicking.

Researchers have measured the net force produced by different underwater kicking techniques, and the optimal velocity for swimmers to initiate underwater kicking during the stroke resumption phase of the turn in able-bodied swimmers (Lyttle et al., 2000). Underwater kicking technique is important for all swimmers. However, for Paralympic swimmers, the free swimming phase, independent of the underwater phase, is the strongest segment of a race (Daly et al., 2001). Researchers should
therefore investigate techniques to enhance free-swimming velocity in these athletes. The net force produced when swimmers kick maximally on the surface is unknown. Given difficulties in measuring the kick, the kick rate used to produce net force at race velocities and different kicking amplitudes is also unknown. These data have implications for coaches and researchers wishing to develop techniques to enhance free-swimming velocity in Paralympic swimmers, while estimating the contribution of the kick.

The fundamental goal of any athlete is to develop all aspects of performance to maximise success during competition. The sport of Paralympic swimming is maturing globally and competition performance times for these athletes are now faster than ever. The physiological, biomechanical and technical performance characteristics of Paralympic swimmers may not be the same as their able-bodied counterparts and require investigation. The primary purpose of this research was to identify key characteristics of Paralympic swimmers that have direct implications for optimising training and competitive performance. The specific focal issues of this research include: the race-to-race variability and progression in performance of Paralympic swimmers to evaluate the benefits of training interventions, and the setting of realistic performance goals when planning for future competitions. The quantification of seasonal training loads in Paralympic swimmers prior to competition will enable evaluation of contemporary programs used to prepare swimmers for international competition. The application of inertial sensor technology will allow measurement of the kinematics of the kick to help clarify the contribution of the lower body to swimming propulsion. The measurement of net forces when swimmers are towed at race velocities and using different kicking amplitudes, will allow coaches to estimate the contribution of the kick by identifying methods for improving kicking-only velocity and swimming performance.

**Research Aims**

The aim of the present research was to identify some key performance characteristics of Paralympic swimming. To determine these characteristics, five investigations were conducted: variability and progression in competitive performance of Paralympic swimmers; training characteristics of Paralympic swimmers; measuring kick count
and kick rate in freestyle swimming; quantifying freestyle kicking patterns in Paralympic swimmers; and the influence of velocity and kicking amplitude on net force and kick rate in Paralympic swimmers.

**Study 1: Variability and progression in competitive performance of Paralympic swimmers**

Estimates of race-to-race variability and progression in competitive performance indicate the magnitude of improvement necessary for athlete’s to medal, that is, place in the final top three, at major competitions. These estimates would allow coaches of Paralympic swimmers to set realistic performance goals for future competitions. This study addressed the research question:

- What is the magnitude of variability and progression in competitive performance in the 100 m freestyle event for elite swimmers with a disability?

The variability and progression of a Paralympic swimmer’s performance from competition to competition will provide guidelines for the global improvements required to substantially increase their chance of success. To achieve this objective, the training program that prepares Paralympic swimmers for competition must be effective.

**Study 2: Training characteristics of Paralympic swimmers**

A key objective of training is to identify the physiological functions that underpin performance. Coaches typically divide a training block into shorter phases (specific macro-cycles of 2–4 weeks in duration) to manage the loading patterns of volume and intensity. A comprehensive evaluation of contemporary Paralympic swimming training throughout a 16-week season from Selection Trials to a World Championship will identify the key characteristics used to prepare elite swimmers with a disability for performance in international competition. This evaluation will allow researchers to make assertions on the effectiveness of the prescribed program and how it can be enhanced to maximise performance. This study addressed the research questions:

- What is the weekly pattern of training volume and intensity for Paralympic swimmers over a competitive season and how does this pattern of training change between training phases?
• Are changes in measures of training load associated with substantial improvements in competitive performance?

Kicking training is a key component of the training process and is prescribed by coaches in the majority of training sessions to enhance leg muscle endurance and leg kicking speed. Stroke count and stroke rates are commonly measured by the coach in training using a stopwatch and visual inspection. However, water turbulence and the high rate of the kick prevent easy measurement of the kinematics. To measure kick count and kick rate, technology must be developed that can overcome the water environment, yet does not interfere with a swimmer’s kick or swim technique.

Study 3: Measuring kick count and kick rate in freestyle swimming

The difficulties in measuring the kinematics of the kick may be overcome by using inertial sensor technology. Establishing the validity and reliability of this new technology is a critical step before routine use and practical applications. This study addressed the research question:

• Is the application of inertial sensor technology valid and reliable for quantifying kick count and kick rate in freestyle swimming and kicking, independent of their location on a swimmers’ leg?

Valid and reliable measurements of the kinematics of the kick using inertial sensor technology would then allow coaches and sport scientists to quantify kicking patterns in swimming and kicking-only training.

Study 4: Quantifying freestyle kick count and kick rate patterns in Paralympic swimming

Quantifying the patterns of kick count and kick rate and establishing the differences in these variables (with and without the arm stroke) may enable coaches to design more effective swimming training programs and enhance performance applications. This study addressed the research questions:

• What are patterns of kick count and kick rate over 100 m freestyle swimming and kicking-only trials in Paralympic Swimmers?
• What is the magnitude of change in kick count and kick rate between 25 m segments within a 100 m time trial?
• What is the magnitude of change or improvement in kick variables necessary to elicit an improvement in kicking and swimming velocity?

The kinematics of the kicking action generates a net propulsive force. Measuring the net propulsive force when swimmers are towed at race velocities and using different kicking amplitudes, may allow coaches and sport scientists to identify methods for improving kicking-only velocity and swimming performance.

**Study 5: Influence of velocity and kicking amplitude on net force and kick rate in Paralympic swimmers**

Identifying the net force produced when swimmers use a maximal surface kick has implications for enhancing free-swimming velocity and estimating the contribution of the kick. Investigations on the magnitude of change in surface kick rate and net force when swimmers are towed at race velocities and using different kicking amplitudes will allow sport scientists to identify key technical and training characteristics to increase kicking velocity. In this study the propulsive contribution to overall active force of the kick was estimated by quantifying the difference between the force required to maintain equilibrium (the force provided by a towing device) at maximal swimming velocity while kicking only and the force required to maintain equilibrium without kicking. This study addressed the research question:

• Is a modified dynamometer and force platform system valid and reliable for towing swimmers at predetermined velocities and for quantifying the net force produced?
• What is the influence of velocity and kicking amplitude on net force and kick rate?
Presentation of Research Thesis

The format for this research thesis is an introduction, literature review, journal articles, discussion, conclusion, and future directions. The outputs of this research include five peer-reviewed scientific journal manuscripts. To date, two manuscripts have been accepted for publication, one has been submitted with revisions, and two are under review.

A statement of intellectual contribution and the reference or publication status for each manuscript precedes each chapter. These manuscripts are presented in the submitted/accepted form and as a consequence, some repetition of background information occurs. The five experimental investigations are presented separately each with an abstract, introduction, methodology, results, discussion and reference section. Chapters 5 and 6 were submitted as companion papers to the Journal of Sports Sciences.
Chapter 2: Literature Review

This chapter examines the variability and progression of competitive athletic performance, the principles of training as they relate to swimming, methods for quantifying movement patterns using inertial sensor technology and the contribution of the freestyle kick to swimming performance. To begin, the race-to-race variability and progression in performance of individual athletes is explained, including the advantages of using these estimates to derive the magnitude of improvement necessary for an athlete to remain competitive. Next, the literature on swimming training is reviewed including training cycles and strategies, training variables and the influence of these variables on swimming performance. The routine methods used by swimming coaches to monitor physiological training responses including velocity, blood lactate concentration, heart rate and rate of perceived exertion are also discussed. The review then explores the applications of inertial sensor technology to swimming. The final sections of the review examine the contribution of the kick to swimming propulsion, net force production in swimming, and the influence of kicking forces on performance.

1.0 Variability and Progression in Performance

The variation in performance of individual athletes from race to race is an important determinant of an athlete’s chances of winning the race. In simple terms, the race-to-race variation in the athlete’s performance is the consistency or reliability of their performance in an event of the same distance and stroke. Nevertheless, other athletes may also improve their performance between competitions, so a given athlete will need to improve by an additional amount (progression) approximately equal to the mean progression of all the competitors to remain competitive.

1.1 Variability in Performance

The race-to-race variation of performance in elite athletes yields the smallest worthwhile effect in performance that substantially affects an athlete’s medal prospects (Hopkins et al., 1999). For elite athletes competing in individual sports, the smallest worthwhile effect in performance is ~0.5% of the typical within-athlete
random race-to-race variation in the athlete’s performance (expressed as a standard deviation) from competition to competition (Hopkins et al., 1999). An athlete in contention for a medal must improve their performance by this amount (or more) to substantially increase their chance of success (Hopkins, 2004). Hopkins and co-workers have assessed the variability of competitive performance in national-level swimmers (Stewart & Hopkins, 2000b), distance runners (Hopkins & Hewson, 2001), Olympic-level swimmers (Pyne et al., 2004), track and field athletes (Hopkins, 2005) and elite Olympic-distance triathletes (Paton & Hopkins, 2005). Some studies have examined the changes from heats to finals in the 100m freestyle events in nearly all classes at the Sydney 2000 Paralympic Games. Other studies quantified the evolution of performances between the 1996 Atlanta and the Sydney 2000 Paralympic Games in three freestyle events in both men and women (Daly et al., 2003; Djobova et al., 2002). To the author’s knowledge, no study has established meaningful estimates of variability between competitions at the Paralympic-level.

International 100 m track athletes have a coefficient of variation (CV) of performance of ~0.9% (Hopkins et al., 1999). In comparison, sub-elite distance runners exhibit a CV of 1.2-1.9% in cross country runs (3 km-10 km), 2.7-4.2% in half marathons and 2.6% in marathons (Hopkins & Hewson, 2001). Elite athletes in selected athletic track and field events and those in international Olympic-distance triathlons have also reported broadly similar results of ~1-3% for the typical race-to-race variability (Hopkins, 2005; Paton & Hopkins, 2005). The difference in the level of performance of the athlete or the competition itself is another variable to consider when deriving estimates of variability and progression. In swimming, the within-swimmer variability of performance represents the expected variation in a given swimmer’s performance between competitions. At the Olympic-level, swimmers show a 0.8% variability in performance (Pyne et al., 2004) which is substantially less than the 1.4% observed for junior national swimmers (Stewart & Hopkins, 2000b). The greater consistency of international swimmers may relate in part to maturity (junior versus senior swimmers) and a greater experience of racing. At the Paralympic-level, swimmers in lower functional classes might be more variable in the reproducibility of their results than those in higher classes. The challenge remains for all swimmers with high variability in race-to-race performance to achieve greater consistency of results.
1.2 Progression in Performance

Estimates of progressions in performance are less prevalent in the literature and researchers who only account for estimates of variability in performance fail to account for the improvements of other athletes between competitions. The issue of progression in performance times within and between races is fundamental to competitive swimming. Swimmers are generally required to improve their performance time from a heat swim to ensure they qualify for a semi-final or the final in a given event. Subsequently, swimmers must ensure that their peak performance is produced in the final, where the medals are decided. One study on Olympic-level swimmers has calculated estimates to account for both variability and progression in competitive performance at international competitions (Pyne et al., 2004). Over a 12-month period from the Pan Pacific Championships to the Sydney Olympic Games in 2000, Olympic swimmers from two nations improved performance by 0.9% between competitions. Additional enhancements of ~0.4% between competitions (one-half the between competition variability) would substantially increase the swimmer’s chances of a medal (Pyne et al., 2004). The estimates of variability and progression in competitive performance appear small though in closely matched races they have a substantial effect on the final outcome.

The unique physiological and biomechanical demands of Paralympic swimmers provide challenges for coaches and sport scientists to improve fitness, swimming technique, race tactics and pacing strategies. Estimates of variability and progression in competitive Paralympic swimming events will allow swimmers and coaches to evaluate the benefits of training interventions and set realistic performance goals when planning for future competitions.

2.0 The Training Process - Governing Principles of Training

Improved competitive performance is achieved through automation of motor skills, adaptive responses and enhancement of physiological capacities. Various systems govern the biochemical and physiological changes that take place within the body to enable growth and function. Exercise performance models and models of training load have been proposed by researchers to explain the relationships between exercise/training and performance. A contentious issue in the exercise and sports
sciences maintains that exercise and training is regulated by a complex system known as the central governor model of exercise regulation (Noakes, 2000; Crewe et al., 2008). This system is thought to integrate feedback sensory information based on the pre-exercise expectations of the training load. The researchers who developed this model propose that performance during exercise is limited by chemical factors acting either in the exercising muscles, or in the brain, that produce ‘peripheral’ or ‘central’ fatigue, respectively (Crewe et al., 2008). Other researchers have debated the validity of this model and proposed alternative physiological models based on motivational intensity theory (Marcora, 2008).

Another popular concept in the sport sciences is the use of training models to establish fatigue and fitness profiles in athletes (Banister et al., 1975; Busso & Thomas, 2006). In the training process for swimming, investigators have variously examined the effects of training load (Mujika et al., 1996c; Atlaoui et al., 2007; Faude et al., 2008), models of training and overtraining (Mujika et al., 1996b; Hohmann et al., 2000; Avalos et al., 2003; Hellard et al., 2006), the influence of the taper (Mujika, 1998; Bosquet et al., 2007; Papoti et al., 2007; Thomas et al., 2008) and swimmers compliance to training prescription (Stewart & Hopkins, 1997). Coaches continually monitor and adapt their training plans throughout a season via competition-specific time trials (Banister & Calvert, 1980) and physiological testing (Anderson et al., 2008). Optimising training programs for athletes is important, since failure to properly condition an athlete can result in poor performance or an increased risk of fatigue, injury and/or illness.

2.1 Training Variables

The dynamics of training involve the manipulation of the following training variables: volume (duration and frequency) and intensity (Mujika, 1998). This combination is dependent on the duration and therefore the metabolic requirements of discipline-specific competition. In swimming, the metabolic demands are mainly covered by anaerobic and aerobic glycolytic pathways (Trappe, 1996). Compared to the relatively short competition distances, training volume is usually very high but is performed at a low intensity (Mujika et al., 1996a). In view of the demands of competitive
swimming, particularly in the 50 m to 400 m events, a lower overall training volume with an emphasis on high-intensity training bouts seems to be an alternative.

2.1.1 Training Volume

The peak weekly training mileage of competitive elite swimmers is ~80-85 km-wk\(^{-1}\) for distance swimmers, 60-70 km-wk\(^{-1}\) for middle distance swimmers and 40-50 km-wk\(^{-1}\) for sprinters (Maglischo, 2002). During certain macro-cycles weekly totals may exceed 100 km, though these distances are rare (Maglischo, 2002). Seasonal training volume has only been quantified in a single study for top level swimmers with a disability (Pelayo et al., 1999). Training volume, quantified for male and female 100 m freestyle swimmers, ranged from 14 km.wk\(^{-1}\) (class S3) to 37 km.wk\(^{-1}\) (class S10). In comparison, the weekly training volume for top-level able bodied swimmers, quantified in the same study, was 64 km.wk\(^{-1}\) highlighting the substantial differences in volume between the two groups (Pelayo et al., 1999). Weekly training volume was assessed via a questionnaire. However, the researchers failed to report the reliability or validity of the methodology. There was also no mention of the length of the data collection period (training season). Consequently, to date there are few recommendations on training volume for elite swimmers with a disability. Further research needs to examine the training intensity of this cohort of swimmers. Understanding the relationships between training and competitive performance in elite swimmers with a disability may thus provide a framework for optimising training prescription.

High-volume training does not always elicit performance enhancements in trained athletes; however the scientific literature with regard to the design of training programs in swimming is limited. Two decades ago researchers manipulated training volume in groups of swimmers (Costill et al., 1988). When daily training volume was doubled to ~9 km-day\(^{-1}\) and training intensity maintained for ten consecutive days, maximal and sub-maximal blood lactate concentrations and heart rates were decreased after the high-volume training period, whereas swimming power, 22.9 m sprint performance, 365.8 m endurance performance and aerobic capacity were unchanged (Costill et al., 1988). Similar results were achieved when training volume in one group of swimmers was increased to twice that of a second group (9.5 km-day\(^{-1}\) vs. 5 km-day\(^{-1}\) for six weeks). However, the increase in training volume did not lead to
improved performance, particularly over short swimming distances (Costill et al., 1991). A limitation of these research designs was that measures of training intensity did not accompany the training volumes recorded. Nowadays researchers have identified training intensity as the principal component required to maintain training induced adaptations. Intensity should be a mandatory variable when quantifying training load for athletes.

2.1.2 Training Intensity
Training intensity relates to the overload of the metabolic, neuromuscular, biomechanical and physiological systems. The manipulation of training intensity is responsible for achieving a training effect and elicits responses in the body which become more pronounced as intensity increases (Mujika, 1998; Faude et al., 2008). Relative intensity can be quantified by the assessment of attributes such as power, work, energy, torque and velocity. Physiological quantification of intensity is derived from attributes such as VO$_2$ max, heart rate, respiration rate, sweating rate and muscular fatigue. Training intensity may also be evaluated from ratings of subjective intensity as perceived by the subject (Borg, 1998; Day et al., 2004). Training intensity is the principal component necessary to maintain a training-induced increase in VO$_2$ max, sub-maximal exercise endurance and muscle metabolic potential during periods of reduced training, despite prolonged periods of aerobic training (Neufer, 1989; Faude et al., 2008). Low-volume training including high-intensity bouts may be optimal to induce relevant training adaptations and improvements in discipline-specific performance more efficiently than high-volume programs (Laursen & Jenkins, 2002). This finding was confirmed recently when the high-volumes of training usually associated with competitive swimming produced similar performance outcomes when compared to high-intensity training of lower volume (Faude et al., 2008). Therefore, it seems plausible that training-induced increases in VO$_2$ max, sub-maximal exercise endurance and muscle metabolic potential may be reached more economically with lower volume high-intensity training, and time could be saved for other relevant training elements such as technique.

2.1.3 Training Models
The use of training models to establish fatigue and fitness profiles in athletes was first initiated by Banister and co-workers (Banister et al., 1975). Their original model has
elicited various extensions (Calvert et al., 1976; Busso et al., 1997; Busso, 2003; Hellard et al., 2005; Busso & Thomas, 2006). Training models estimate fatigue (negative) and fitness (positive) training impulses imposed on the body using TRIMP (TR = training, IMP = impulse) units. Profiles are computed from training to quantify the fluctuations of athletic performance throughout periods of heavy training separated by periods of relative rest (taper). After each training impulse, fatigue rises abruptly and athletes enter a recovery period. However, the performance capacity of the athlete will return to pre-training levels if a subsequent training load is not induced (Banister & Calvert, 1980). Athletes react and adapt to the imposed training and performance capability increases once fatigue effects have dissipated (Busso & Thomas, 2006). According to the models, the level of performance of an athlete, at any time during the training process, can be estimated from the difference between a negative function and a positive function (Banister & Hamilton, 1985; Busso et al., 1990). Modelling the training performance relationship provides pertinent information about intra-individual differences that underpin individualised training programmes.

Swimming training profiles have been quantified to investigate the effect of training on performance using the Banister model (Mujika et al., 1996b). The model accounted for the effects of training on performance; however, it did not embrace the practical implications of training regimens for individual swimmers, nor was the precision of the model high enough to explain the small variations in peak performance. Other researchers have used statistical analyses to verify the accuracy of the Banister model in competitive performances of elite swimmers with similar conclusions (Hellard et al., 2006). The essential concept of fatigue and fitness models to determine individual adaptation profiles for athletes is useful. However, the practicality of the models is questionable as they are rarely used in routine training monitoring outside a research project. The true robustness of fatigue and fitness models should be further examined, as training volumes are organised within time sequences (pluri-annual, annual, macro-cycle, micro-cycle), and relations between training volume and performance vary significantly from one year to the next (Hellard et al., 2002). Some researchers are sceptical of the modelling approach as they claim the original training data recorded by the coach should not have to be transformed into an arbitrary ‘training impulse’, or any other more or less artificial training load parameter (Hohmann et al., 2000). Further research is needed to determine whether
associating the qualities of the Banister model with other methods of modelling provide pertinent (practical) information to monitor training. Precise quantification of training load with regular performance assessment may be more beneficial for individual evaluation of training responses.

### 2.2 Training Cycles and Strategies

Periodisation involves alternating periods of sequential increases and decreases in training load, interspersed with recovery to avoid excessive fatigue (Bompa, 1999). Training-induced adaptations of various physiological systems occurs through gradual increases in training load as the athlete responds to the training (Busso & Thomas, 2006). Coaches may stress athletes at a higher level than previously tolerated, in a process known as overload training, to provide a stimulus for further adaptation and super compensation (Fry et al., 1992; Budgett, 1998; Steinacker & Lehmann, 2002). Over time the responses to training can enhance competitive performance (Faude et al., 2008). If training programs do not allow for adequate recovery, overtraining or a compromised immune system may ultimately result in decreased performance (Halson, 2008). Conceptually, coaches periodise training into macro-cycles, meso-cycles and micro-cycles, with the focus of these cycles changing throughout the season to account for overload and recovery (Pyne & Goldsmith, 2005). Quantifying patterns of training load may provide a framework for evaluating the effectiveness of contemporary programs used to prepare elite swimmers with a disability for international Paralympic-level competition.

#### 2.2.1 Tapering Strategies

Tapering is used to describe a reduction in training, after high-intensity and/or volume training, prior to competition to allow recovery and enhance performance (Hickson et al., 1982; Mujika & Padilla, 2003). The most important goals of the taper are to maximise the decrease of accumulated fatigue, retain and enhance physical fitness, and maximise recovery in preparation for optimal performance (Thomas et al., 2008). The period of recovery is where discrete physiological processes, mainly energetic, allow the muscle to restore capacity and generate force (Mercier, 2003). Characteristics that can be altered during tapering include training frequency, volume, intensity and the taper duration, are often dependent on the pre-taper level of training.
volume and intensity. Furthermore, various formats of the taper include: a single step reduction in training load (Hickson et al., 1982; Hickson et al., 1985; Neufer et al., 1987), an incremental stepwise reduction (Houmard & Johns, 1994; Martin et al., 1994) or a fast or slow exponential taper (Mujika, 1998; Banister et al., 1999; Mujika & Padilla, 2003; Bosquet et al., 2007; Papoti et al., 2007). No study on the tapering of swimmers with a disability has been published. Thus, whether these athletes can follow the general principles of able-bodied swimmers is unclear.

Exponential reductions in training volume of 50-90% coupled with maintained intensity and training frequency have been associated with significant performance improvements of 3-8% (D’Acquisto et al., 1992; Houmard et al., 1994; Mujika & Padilla, 2003). Conversely, substantial gains in performance have been obtained when training volume was reduced exponentially by 41-60% over 11-14 days and there were no alterations to training intensity or frequency (Bosquet et al., 2007; Papoti et al., 2007). Significant improvements in performance have also been reported for very short (< 7 days) (Neary et al., 2003) or very long tapers (> 28 days) (Mujika et al., 1996b). Tapering data from controlled experiments in non-athletes has provided useful data to test experimental models (Busso, 2003). However, in the Busso (2003) study the training situation was artificial and the low fitness levels of the subjects produced modelled outputs that are probably not representative of trained athletes’ responses to training. To extend the earlier work, non-linear models have been applied to athletes in real training conditions to determine the influence of pre-taper training characteristics on the optimal taper (Thomas et al., 2008). For elite swimmers, overload periods of ~20% increase in normal training prior to the taper, followed by a step reduction in training of ~65% over 3 weeks is recommended. Exponential tapers are preferable after prior overload training, but if implemented they should last nearly twice as long as the step taper.

In summary, the taper is widely used by athletes to gain a performance edge over the competition. Consequently, there are many different characteristics of an optimal taper for any given sport.
2.3 Monitoring the Training Response

Monitoring the training response in athletes is difficult given the number of factors, which affect how the body integrates various training stimuli. In swimming, training responses are predominantly monitored by direct routine physiological measures including training times (velocity), blood lactate, heart rate and the rate of perceived exertion. Monitoring these responses impacts little on training and requires relatively inexpensive equipment. Indirect methods of monitoring physiological parameters as they relate to the training response have also been the focus of discussion: diet and the immune system (Pendergast et al., 2003), metabolic demands (Michael et al., 2008), physiological responses to exercise at altitude (Mazzeo, 2008), inflammation, cytokines and hormones (Duclos, 2008; Peeling et al., 2008), maximal and sub-maximal physiological variables (Bentley et al., 2007) and blood volume (Schmidt & Prommer, 2008). These techniques predominantly entail performance efforts, longitudinal monitoring and blood tests that require specialised skills and equipment and are not normally endorsed by the coach.

2.3.1 Swimming Velocity and Blood Lactate Concentration

A fundamental challenge for coaches and sport scientists is the accurate determination of specific training velocities. In sports such as swimming that are performed in a relatively controlled environment the velocity-intensity relationship is not affected by factors such as surface, undulating terrain and ambient conditions (Jeukendrup & Van Diemen, 1998). Swimmers should therefore be able to reproduce race-pace velocities to target training zones with relatively high reliability. Critical swimming velocity corresponds to the exercise intensity at the onset of blood lactate accumulation, and is a relevant criterion for the physiological evaluation of aerobic training status and swimming endurance performance (Pyne et al., 2001). Blood lactate accumulation is another commonly used measure of exercise intensity and reflects the balance between lactate production and removal. The rate of accumulation of blood lactate depends upon the intensity of the exercise and the duration of the event. A characteristic rightward shift of the lactate-velocity curve is assumed to reflect training-induced improvements in endurance fitness (Madsen & Lohberg, 1987; Pelayo et al., 1996b; Pyne et al., 2001). There is an extensive body of work that has examined the utility of blood lactate concentration to monitor intensity during training.
and competition for able-bodied swimmers (Pyne et al., 2001; Baron et al., 2005; Anderson et al., 2006b; Faude et al., 2008; Psycharakis et al., 2008) and swimmers with a disability (Pelayo et al., 1995; Bentley et al., 2002; Garatachea et al., 2006). These relationships allow coaches to control the intensity of swimming during training so that they can focus on energy systems necessary to optimise performance in a chosen swimming event (Keskinen et al., 2007). As swimmers do not always compete on a regular basis, routine training monitoring allows coaches to gauge the progress in fitness through the training and competitive season.

Progressive incremental tests are commonly used to assess the physiological adaptations of swimmers, where blood lactate and heart rate are measured over a range of intensities culminating in a maximal effort (Hein et al., 1989). An example of a swimming-specific lactate profiling protocol currently used to assess sub-maximal blood lactate training responses in world-ranked able-bodied swimmers is the 7 x 200 m step test (Pyne et al., 2001; Anderson et al., 2006b). The heart rate and blood lactate responses measured during the test are sensitive indicators of endurance fitness, and can be used to detect training-induced adaptations occurring within the skeletal muscle. The identification of these responses provides researchers with reference values on the magnitude of typical changes expected for national and international swimmers within and between training seasons. However, training-induced adaptations from lactate profiling is only modestly associated with competition performance (Anderson et al., 2006b). The relationship between testing and competitive performance still remains uncertain and requires further investigation to determine the true utility of training monitoring. Establishing relationships between training patterns and competitive performance might be one step towards achieving this goal.

2.3.2 Heart Rate

Heart rate is a popular method of measuring, prescribing and regulating intensity during exercise. Given the nature of the training environment, monitoring heart rates in swimming is more practical than measuring oxygen consumption and is still a valid predictor of intensity given the close relationship between %VO₂ max and %HR max (Gilman & Wells, 1993; Swain, 2000). Procedurally, swimmer-specific target training zones can then be established with consideration of maximal and resting heart rate
variations (DiCarlo et al., 1991). Compared to resting heart rate, maximal heart rate changes little with increased or decreased fitness level and there is little need to perform multiple assessments. The fluctuations of resting heart rate require periodic re-assessments and a corresponding recalculation of target heart rate zones (Green, 2007). In swimming, maximum heart rate is often lower than other sports due to the cooler ambient environment of water and the smaller muscle mass of the upper body reducing cardiac demand compared with leg-dominated sports. The prone position adopted in swimming does not require the heart to pump blood against gravity as hard as sports where competitors are in upright positions (DiCarlo et al., 1991; Maglischo, 2002).

A large number swimming testing protocols to measure maximum heart rate have been proposed (Lavoie et al., 1981). However, few provide details of the underlying validity or reliability of the protocols. Heart rate, as an adjunct to prescribing and regulating intensity, is convenient, non-invasive, easy to apply and therefore remains an attractive option for coaches.

2.3.3 Rate of Perceived Exertion

Rate of perceived exertion (RPE) is a widely used method of quantifying exercise intensity (O’Connor et al., 2001; Day et al., 2004). While accurate perception of internal physiology seems unlikely, Swedish researcher Gunnar Borg developed a perceptual scale to estimate the degree of internal effort sensed while exercising. The scale enables simple, reliable and valid estimations of exercise intensity, effort and exertion, breathlessness and fatigue during physical work. High correlations between the scale values and physiological measures of heart rate, \( \text{VO}_2\max \), ventilatory minute volume, \( \text{CO}_2 \) production, lactate accumulation and body temperature, confirm the validity of the RPE scale for routine use (Noble & Robertson, 1996; Borg, 1998). The scale is based on a linear relationship between effort, sense and force production (Borg, 1998). The Borg RPE scale has been used successfully in many sports settings including resistance exercise (Gearhart et al., 2002; Day et al., 2004; Egan et al., 2006), running (Lamb et al., 1999; Garcin & Billat, 2001), rowing ergometry (Marriott & Kevin, 1996), swimming (Ueda & Kurokawa, 1995; Chatard et al., 1998; Green, 2007) and cycling ergometry (Eston & Williams, 1988; Potteiger & Weber, 1994; Buckley et al., 2000). Although this approach has shortcomings in some
situations involving different subjects, types of exercise and environmental conditions, the scale values remain intact and functional.

2.3.4 Compliance with Training Prescription

Monitoring the training response in swimmers depends on their level of compliance to the prescribed training program. Squad-based swimmers are expected to adhere closely to the prescribed training program from their coach regardless of level or experience. Compliance to the prescribed training distance is very high although there are small discrepancies in compliance to training intensity and rest intervals (Stewart & Hopkins, 1997). The predominant cause of lower compliance to training intensity arises when swimmers do not adhere to the training pace, and simply follow the swimmer in front of them, or when swimmers change places in a lane during an interval set. Coaches are advised to monitor intensity prescription more closely in training and ensure familiarity with gauging intensity levels for junior swimmers. Whether compliance to training applies to swimmers of all levels or whether elite Olympic- and Paralympic-level swimmers naturally have higher training intensity compliance due to training experience and commitment, requires further examination.

In summary, the training process for swimming performance is complex culminating in different energy systems and training strategies to elicit optimal performance. Coaches periodise training load and monitor training responses to determine an athlete’s adaptation to the prescribed program, and avoid excessive fatigue and peak athletes for competition. Monitoring seasonal training loads in Paralympic swimmers prior to competition will enable researchers to evaluate whether training is periodised and whether the patterns of change in training load elicit relationships with performance. A framework for evaluating the effectiveness of contemporary programs used to prepare elite swimmers with a disability for international Paralympic-level competition is needed to establish these relationships.

3.0 Inertial Sensor Technology

Inertial sensor technology has become a major focus of field-based research measurement and is used in research applications for monitoring posture and motion (VanAcht et al., 2007; Wong & Wong, 2008), ambulatory assessment (Salarian et al.,
2007; Cutti et al., 2008), physical activity (Nichols et al., 2000; Anderson et al., 2005) and even animal locomotion and behaviour (Venkatraman et al., 2007; Pfau et al., 2008). Inertial sensors use an analogue signal to decipher accelerations and decelerations for real-time analysis of movement patterns (Ichikawa et al., 1999; Ichikawa et al., 2003).

Inertial sensors are unobtrusive, lightweight, wireless, and relatively inexpensive making them an attractive option for sport-specific research projects. The technology allows researchers to systematically track movement of the human body in one or more planes (Nichols et al., 2000) and quantify and monitor training sessions, providing fundamental information to the coach on the athlete’s response to training (Anderson et al., 2006a). Ultimately the technology has applications for enhancing sports performance and discriminating movement patterns in the martial arts; karate and boxing (Ohgi et al., 1998), running (Herren et al., 1999) and swimming (Ohgi et al., 2003). Despite these research applications anecdotal evidence suggests that few programs use inertial sensor technology routinely in training and performance settings. The challenge for sport scientists is to devise research projects with specific performance outcomes, which engage the coach and athlete and demonstrate the practical advantages of the technology.

Hip-mounted accelerometer applications are a common method of monitoring physical activity and researchers have reported a mean bias of 0.8-1.1% in detecting walking steps at a range of different speeds (Le Masurier & Tudor-Locke, 2003). The mean bias is just one measure of the validity of a measurement tool and alone is not sufficient to quantify the agreement between an observed value and the true or criterion value of a measure. Other measures of validity should accompany the mean bias including: the standard error of the estimate (SEE), coefficient of variation (CV) and correlation coefficients (Hopkins, 2004) or limits of agreement (LOA) (Bland & Altman, 1995). Establishing the validity and reliability of a measurement tool is a critical step before routine use. The utility of using inertial sensor technology to quantify movement patterns means little unless the measurement error and reproducibility is sufficient for the technology to be used for practical applications and to report on small changes.
3.1 Inertial Sensor Application in Swimming

Practical and convenient methods of monitoring performance measures are especially important for sports such as swimming where physiological and movement demands cannot be easily replicated in the laboratory (Robertson & Hunter, 2004). A large proportion of swimming training is dedicated to optimising efficiency and technique in the water for elite performance. The discrimination of movement patterns in swimming has traditionally depended upon visual information from the coach, kinaesthetic information from the athlete, or joint digitisation by the scientist. The digitising process required to evaluate a swimmer’s stroke motion is time consuming and difficult to complete immediately after a race for prompt feedback to coaches and athletes. Underwater three-dimensional video analysis has been used to evaluate the underwater stroke paths of freestyle swimmers at the Olympic Games (Cappaert et al., 1995). Inertial systems are less time consuming than panning cameras to capture a whole swimming length and post-event digitising, and more practical for regular use or collection of large quantities of data. The technology can alleviate these potential problems and has been successfully used for the analysis of stroke mechanics.

Inertial sensor applications, using built-in monolithic acceleration sensors, are commonly directed towards evaluation of upper body or arm movements (Ichikawa et al., 2003; Ohgi & Ichikawa, 2003; Ohgi et al., 2003). When placed on the wrist or forearm, inertial sensors can discriminate this underwater phase, between swimming strokes and within stroke movement patterns (i.e. down sweep, in sweep, out sweep and recovery), through characteristics of acceleration (Ichikawa et al., 2003; Ohgi et al., 2003). Swimmer fatigue has also been quantified by analysing the accelerometer trace obtained during intensive swimming sessions (Ohgi & Ichikawa, 2003). More recently, uni-axial accelerometer inertial sensors have shown promise when strapped to a swimmer’s back for quantifying swimming-specific characteristics such as lap times, dives and turns, stroke rate, stroke length and intra-stroke acceleration (Anderson et al., 2006a).

The validity of wrist mounted inertial sensor technology applications in swimming is however limited and the mean bias again appears to be the only measure of validity reported (Anderson et al., 2006a). The mean bias for accelerometer axes for the
discrimination of freestyle and breaststroke strokes is 0.0-2.0%, respectively, where
the accelerometer typically missed a stroke detection by up to 2 strokes for every 100
taken (Ichikawa et al., 1999). For stroke count and stroke rate detection in freestyle
swimming, the mean bias of tri-axial accelerometry is ~5-10% (Anderson et al.,
2006a). Further studies are required to establish the validity and reliability of this
technology for assessment of whole body motion and specific body segments such as
the hand or legs. Another current limitation of the technology for swimming is that it
has not yet been developed to analyse and quantify the characteristics of the kicking
action such as count and rate.

Inertial sensor technology is used to systematically track movement of the human
body and has been used successfully to discriminate the different phases of the arm
stroke in swimming. Applications of inertial sensor technology could be developed to
address the difficulties in measuring the kinematics of the kick helping to clarify the
role of the lower body in swimming, and assist coaches’ to design more effective
training programs and enhance performance applications.

4.0 The Freestyle Kick

The flutter kick in freestyle occurs predominantly below the water surface and it is
difficult to measure the kinematics of the kick from video footage due to water
turbulence (Ohgi et al., 2003). Lap time is currently the only variable for coaches to
measure in kicking training sessions with ease and consequently, the kinematics of the
kick have not been quantified for swimmers at any level.

The flutter kick in freestyle consists of an upbeat and downbeat with the legs moving
in lateral and vertical directions to stabilise the body as it rolls from side to side
(O'Shea & O'Shea, 1991; Maglischo, 2002). Kicking consists of three common
patterns: the two-beat crossover kick, the straight two-beat kick and the six-beat kick.
Long distance swimmers tend to adopt a two-beat kick where as sprinters, who do not
need to conserve energy over a long time can benefit from a higher frequency kick
(Lepore et al., 1998). When leg-kicking training forms a substantial part of a
swimmer’s training program, leg muscle endurance and movement economy can be
improved. Additionally, leg kicking training significantly decreases 200 m kicking
time. However, there are no subsequent improvements in 400 m swimming performance (Konstantaki & Winter, 2007). Patterns of the kick count and kick rate may help coaches and researchers to better understand the role of the legs in swimming, and in the design and application of effective training programs.

Ankle flexibility and range of motion are other factors determining the effectiveness of kicking. In breaststroke, a substantial range of motion (ROM) of the lower-extremity joints is essential for a successful whip kick (Councilman & Councilman, 1994). More recent studies have substantiated these claims where researchers have investigated the range of lower-extremity joint angles exhibited during the execution of the whip kick and the influence of the active range of motion (aROM) of these joints of the effectiveness of the kick (Kippenhan, 2002). Swimmers of different skill levels were videotaped performing whip kick sprints and standard aROM assessment tests. The obtained three-dimensional coordinates of selected body landmarks were used to determine range of lower-extremity joint angles during the whip kick and the aROM of these joints. The results indicated that for swimmers with below average flexibility, many joint motions limit the effectiveness of the whip kick; the external knee rotation was the joint motion most likely to do so. Furthermore, improvements in kicking speed have to be accompanied by improvements in the ankle inversion aROM. Although no significant relationships were found between skill level and aROM, swimmers with below average flexibility may limit the effectiveness of the kick (Kippenhan, 2002).

4.1 Contribution of the Kick to Swimming Propulsion

In freestyle swimming, the relative contribution to velocity from the upper and lower limbs is unclear and there is conflicting evidence on how propulsion is generated (Chollet et al., 2000; Millet et al., 2002). In the early 1970’s and 80’s researchers claimed that the arm stroke alone enabled swimmers to obtain ~90% of maximal freestyle velocity, while the propulsive efficiency of the flutter kick was responsible for ~60% of freestyle velocity (Bucher, 1975; Dwivedi & Dubey, 1981). In these early studies, measuring the arm stroke and leg kick separately did not produce the velocity of the combined freestyle action. However, no attempt was made to measure the separate contribution of the upper and lower body during total body swimming.
When direct propulsion from the legs is removed completely, an unstable trunk position results in a decrease in velocity of ~9% between swimming with the arms only and legs supported compared to a full stroke condition (Watkins & Gordon, 1983). Subsequently, free swimming velocity increases of ~4% have been observed, with no affect on the power output of the arms, with the addition of leg kicking at maximal velocity (Hollander et al., 1988). Determining the differences in kick count and kick rate, with and without the arm stroke, in freestyle swimming may provide valuable insight into the potential of kicking to contribute to swimming velocity.

The influence of stroke count and stroke rate on swimming propulsion has been recently investigated (Kjendlie et al., 2006; Hellard et al., 2007). Swimming velocity is the product of stroke rate and stroke length. Assessment of these variables during competition via digital video technology from race footage provides feedback to the coach for training prescription, development of a race strategy and ultimately performance enhancement. Analysis of Paralympic 100 m freestyle swimmers has shown that stroke length is responsible for better maintenance of velocity at the end of races and for achieving long-term changes in speed. Conversely, improvements to stroke rate could lead to small increases in velocity at the beginning of a race without impacting negatively towards the end of the race (Daly et al., 2003). A recent examination of the kinematic changes in 100 m freestyle swimming for able-bodied swimmers revealed that faster swimmers were characterised by higher velocity, longer stroke length and higher stroke rate (Seifert et al., 2007). Irrespective of performance level, all swimmers in this recent study adopted a six-beat kick for the trial, indicating that the difference in inter-arm coordination between fast and slow swimmers was not related directly to the kick. An analysis of the kinematic variables of the leg kick coupled with research findings such as these might explain the stroke/kick relationship.

Through the decades, researchers have attempted to explain the contribution of the legs to swim velocity and the swimming motion (Alley, 1952; Counsilman, 1968; Lawrence, 1969; Onusseit, 1972; Counsilman, 1977; Watkins & Gordon, 1983; Hollander et al., 1988; Lyttle et al., 2000). It has been postulated that forward propulsion in freestyle swimming is predominantly accomplished through the arm stroke with minimal contribution from the legs (Ohkuwa & Itoh, 1992; Toussaint &
Beck, 1992). The sole function of the kick is to stabilise and streamline the body reducing resistance through the water and/or producing a more effective arm action (Lawrence, 1969; Councilman, 1977). Conversely, researchers have found substantial positive relationships between foot length and an increase in stroke length (Keskinen & Komi, 1992) and maximal velocity by ~10%, thereby enhancing propulsive force of the whole body (Deschodt et al., 1999). Although the flutter kick is thought to have a relatively low efficiency compared with the arm stroke for producing propulsive force, there is little difference between arms only and legs only peak oxygen consumption (VO₂ peak) in free and simulated swimming (Konstantaki et al., 2004). The leg kick also contributes indirectly to propulsion by organising arm-leg coordination (Persyn et al., 1983; Deschodt et al., 1999). The recent use of swimming simulation models suggests that although there is a large energy loss from the action of the flutter kick, the body position achieved by the kicking action is still beneficial to propulsion (Nakashima, 2007). The role of the legs in swimming is therefore an ongoing debate though a greater number of researchers support the notion of the kick positively contributing to propulsion than previously thought.

Paralympic swimmers with upper limb disabilities naturally have a great dependence on the kicking action. Swimmers with lower limb disabilities may have to modify their pattern of kick to complement the arm action and optimise velocity. For all swimmers, with or without a disability, the relationship between kicking and swimming performance is relatively unknown. The contribution of the legs to propulsion through the assessment of force production may help clarify this relationship.

4.2 Net Force Production in Swimming

In swimming, resistive forces are influenced by skin friction, wave making frontal resistance and eddy resistance (Sheehan & Laughrin, 1992). Skin friction is minimised by shaving body hair and wearing a cap to decrease skin surface area (Rushall et al., 1994). Wave making frontal resistance occurs when the body is positioned too low in the water with a large surface area increasing the frontal resistance. To reduce frontal resistance swimming techniques such as keeping the body flat and high in the water in an effort to hydroplane, or by rolling the body from
side to side can be employed (Colwin, 1992). Eddy resistance occurs from water turbulence associated with poor stroke technique and swimming too low in the water. When swimmers do not create propulsive forces of sufficient magnitude they decelerate as resistive forces act upon them (Rushall et al., 1994). The combination of the stroking and kicking actions generate a net propulsive force profile in swimming. This profile is typically classified as either streamline (passive) force or swimming (active) force. Towing a swimmer through the water in a rigid streamline position, with a tethering device transduced to measure the force required to maintain equilibrium, is used to estimate the passive force of a swimmer (Chatard et al., 1990a; Maiello et al., 1998; Lyttle et al., 2000). Towing a swimmer through the water as they create propulsive movements such as stroking or kicking, is used to estimate net propulsive force (Toussaint et al., 1988; Kolmogorov & Duplishcheva, 1992; Toussaint & Hollander, 1994; Lyttle et al., 2000). Swimmers’ can therefore improve speed by either reducing the passive forces, or increasing the active forces, during active swimming. In an effort to minimise resistance and improve velocity in swimming, researchers and coaches have developed methods of measuring swimming forces, and techniques to overcome these forces. The tension measured on the cable indicates the net force required to pull the swimmer through the water.

4.2.1 Measuring Net Force Production

Net force production in swimming was initially quantified using the Measurement of Active Drag (MAD) system where a series of submerged static pads, fixed to a force transducer, quantified the force exerted as a swimmer propelled themselves forward (Hollander et al., 1986). Limitations of this system were its restriction to the freestyle stroke and orientation of the static pads that only quantified force in a limited range of the underwater stroke. The MAD system was unable to evaluate kicking force as swimmers were required to hold a pool buoy between their legs to prevent injury when testing. In the early 1990’s another system was developed using the hydrodynamic body technique where force was calculated from the difference in velocity between two maximal swimming conditions (Kolmogorov & Duplishcheva, 1992). Net force was calculated from the difference in velocity between a maximal swimming condition and one where the swimmer towed a hydrodynamic body that created an additional, known resistance. However, the initial results were somewhat paradoxical with measured net active force greater than net passive force in most
strokes. In the late 1990’s Lyttle et al., (1998) designed a system to measure above-water and underwater forces created by swimmers. The towing device used a mechanical, velocity control unit and strain gauge amplifiers to quantify forces at predetermined velocities and depths. High intra-day reliability was reported for this system for measuring passive and active forces (Lyttle et al., 1999a). The Indirect Measurement of Active Drag (IMAD) system developed recently was capable of use with all strokes and the arms and legs separately. The system uses only a tape measure, stop watch and formulae extracted from mathematical modelling to quantify passive and active force (Shahbazi et al., 2006).

4.2.2 Net Passive Force
Hydrodynamic studies of streamlined objects indicate that net passive force increases with an increase in velocity. The research by Clarys (1985) was fundamental to the work performed in this area. Net passive force is greatest immediately below the water surface and decreases with depth (Maiello et al., 1998; Lyttle et al., 2000). Positive force is also influenced by changes in body position and is minimised when a swimmer adopts a passive prone (front) streamline compared to a lateral (side) streamline regardless of velocity (Lyttle et al., 2000). Somatic measurements are another determinant of net forces in swimming and are influenced by external characteristics, including the shape and size of a swimmer and internal characteristics such as body composition (Van Tilborgh et al., 1983; Huijing et al., 1988). The relationships between mechanical characteristics, somatic variables, swimming velocity and performance might be attributed to body characteristics that cannot be altered with training, thus providing a basis for orientation and selection.

The greatest influence on net passive force for a group of Paralympic swimmers was the ratio of body mass to body height (Chatard et al., 1990b). Conflicting evidence has been reported for able-bodied swimmers where passive force is more dependent on technique and less so on individual anthropometry (Kolmogorov & Duplishcheva, 1992). Net passive force is also thought to be a good indicator of general aptitude for swimming performance (Chatard et al., 1990a). Researchers must therefore ensure that when net passive force is measured, swimmers maintain a prone streamlined body position throughout the data collection. Anthropometric variables of stature and body mass must also be measured at the time of testing.
4.2.3 Net Active Force

Net active forces are influenced by the physical strength and fitness of the swimmer, and the technique and stroke mechanics employed (Toussaint & Beck, 1992). To maximise velocity, swimmers’ must either reduce passive force or increase active force during active swimming (Rushall et al., 1994). The propulsive forces for swimmers of different strokes and different race distances have been investigated (Magel, 1970; Toussaint et al., 1988; Kolmogorov & Duplishcheva, 1992; Toussaint & Hollander, 1994). Little information is available on the kicking forces of swimmers; how these kicking forces change at competitive velocities and when kicking characteristics are changed.

In an early research study of kicking forces, the propulsive force for a typical freestyle surface amplitude kick was greater than a reduced amplitude kick for a single elite swimmer at a velocity of around 1.3 m·s\(^{-1}\) for (Alley, 1952). When velocity was increased, there was no substantial difference in active force between the typical and reduced amplitude kick. These results were supported by another researcher who studied three competitive male swimmers (Thrall, 1960). Unfortunately both of these studies provided only descriptive analysis of the net forces as inferential statistical analysis may have been difficult given the small sample sizes. Counsilman (1968) measured maximal kicking at towing velocities less than 1.5 m·s\(^{-1}\) and showed a net force benefit when compared to maximal kicking at higher velocities. Subsequently, when velocity was increased there was no additional contribution to forward propulsion and in some instances resistance was created as a result of the kicking. These kicking studies were conducted almost half a century ago and since this time significant changes have occurred in the measurement and technology of propulsive forces. More recently, researchers have measured kicking forces and determined no advantage over using a prone dolphin kick, lateral dolphin kick or prone flutter kick during the underwater phase of the start and turn, though all kicking styles were substantially faster than swimming on the surface (Lyttle & Mason, 1997; Lyttle et al., 1999b). Swimmers should initiate underwater kicking following the dive entry, or resume kicking after a turn at velocities between 1.9 m·s\(^{-1}\) and 2.2 m·s\(^{-1}\) to minimise deceleration caused by drag forces (Lyttle et al., 2000). While these studies have implications for the underwater phase of the start and turn, the force profile of the free-swimming component of freestyle where the leg kick is performed on the water
surface is unknown. Investigations of the influence of velocity and kicking amplitude on net force may identify training methods for improving swimming velocity.

The utility of inertial sensor technology to discriminate the kicking action will assist coaches’ to design more effective training programs. Measuring the net propulsive force when swimmers are towed at race velocities and using different kicking amplitudes, will allow coaches and sport scientists to identify methods for improving kicking-only velocity and swimming performance.

5.0 Literature Review Conclusion

This chapter has reviewed classic and recent research studies to synthesise and evaluate the literature on variability and progression of competitive athletic performance, principles of swimming training, quantification of movement patterns using inertial sensor technology and contribution of the freestyle kick to swimming performance. The race-to-race variability and progression in performance of individual athletes, and the magnitude of improvement necessary for athletes to remain competitive, are important determinants of an athlete’s chances of winning a race. For Paralympic swimmers these estimates will allow coaches to evaluate the benefits of training interventions and set realistic performance goals when planning for future competitions. The review of literature on swimming training highlights the training cycles, training strategies and routine training variables necessary to elicit optimal competitive swimming performance. Coaches periodise training load and monitor the response to training to prepare athletes for competition. Monitoring seasonal training loads in elite swimmers with a disability prior to competition will enable researchers to evaluate the effectiveness of contemporary programs used to prepare swimmers for international Paralympic-level competition.

Inertial sensor technology has been used to systematically track movement of the human body and discriminate the different phases of the arm stroke in swimming. Further developments of this technology are need to address the difficulties in measuring the kinematics of the kick, and help clarify the contribution of the lower body to swimming propulsion. To enhance propulsion and minimise resistance in swimming, researchers have developed methods of measuring swimming forces, and
developing techniques to overcome these forces. Measuring the net forces when swimmers are towed at race velocities and using different kicking amplitudes, will allow coaches to identify methods for improving kicking-only velocity and swimming performance. Evaluation of the literature shows that sufficient gaps exist to warrant further investigation of the performance characteristics of Paralympic swimmers, and the development of these characteristics to enhance success in competition’.
Chapter 3: Variability and Progression in Competitive Performance of Paralympic Swimmers

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Statement of Intellectual Contribution

I, Sacha Kate Fulton, have made substantial independent intellectual contributions to the research paper ‘Variability and Progression in Competitive Performance of Paralympic Swimmers’. I consider that intellectual contribution is the substantial, direct, intellectual contribution to the conception and/or design of a research paper. Intellectual contribution is different from technical services, which although essential to the work, are not in themselves sufficient contributions to justify intellectual contribution. I consider that examples of intellectual contributions include, but are not limited to, significant input in the development of the study hypothesis, design of the study, development of study protocols, identification of study methodology, development or modification of methodology used in the project, or development of new applications, unique settings for use of existing methodology, or responsibility for independent analysis and interpretation of results.

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Chapter 3: Variability and Progression in Competitive Performance of Paralympic Swimmers

Abstract

Analysis of variability and progression in performance of top athletes between competitions provides information about performance targets that is useful for athletes, practitioners and researchers. In this study 724, official finals times were analysed for 120 male and 122 female Paralympic swimmers in the 100-m freestyle event at 15 national and international competitions between 2004 and 2006. Separate analyses were performed for males and females in each of four Paralympic subgroups: S2-S4, S5-S7, S8-S10 (most through least physically impaired), and S11-S13 (most through least visually impaired). Mixed modelling of log-transformed times, with adjustment for mean competition times, was used to estimate variability and progression. Within-swimmer race-to-race variability expressed as a coefficient of variation, ranged from 1.2% (male S5-S7) to 3.7% (male S2-S4). Swimming performance progressed by ~0.5%·y⁻¹ for males and females. Typical variation in mean performance time between competitions was ~1% after adjustment for the ability of the athletes in each competition, and the Paralympic Games was the fastest competition. Thus, taking into account variability, progression and level of competition, Paralympic swimmers who want a substantial increase in their medal prospects should aim for an annual improvement of at least 1-2%.

Keywords: athletes with disabilities, reliability, reproducibility, swimming
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Introduction

Estimates of variability and progression in competitive performance are useful for researchers and sport scientists interested in factors that affect medal prospects of elite athletes. Statistical simulations show that the smallest important effect in performance at an international event is \(~0.5\) of the typical within-athlete random variability between events (Hopkins, Hawley, & Burke, 1999; Hopkins, 2004). The variability of swimming performance within and between national and international competitions has been quantified (Stewart & Hopkins, 2000; Pyne, Trewin, & Hopkins, 2004). In an Olympic year, potential Olympic medal swimmers need to improve performance by \(~1\)% within competitions, and \(~1\)% within the year leading up to the Olympics (Pyne et al., 2004). Additional enhancements of \(~0.4\)% between competitions would substantially increase a swimmer’s chance of a medal (Pyne et al., 2004). Other studies have assessed the variability of competitive performance in distance runners (Hopkins & Hewson, 2001), track and field athletes (Hopkins, 2005) and elite Olympic-distance triathletes (Paton & Hopkins, 2005).

Swimming has been one of the major sports of the Paralympic Games since their inception in Rome in 1960. To provide an equal platform for competition, classification systems have been developed and used at competitions sanctioned by the International Paralympic Committee (IPC). In swimming there are two sections: one for the physically impaired swimmers (S1-S10) and one for the visually impaired (S11-S13) (Green, 1991). The unique physiological and biomechanical demands placed on these swimmers provide challenges for coaches and sport scientists to improve fitness, swimming technique, race tactics and pacing strategies. There have been several studies of competitive Paralympic swimming performance (Pelayo et al., 1999; Daly, Malone, Smith, Vanlandewijk, & Steadward, 2001; Daly, Djobova, Malone, Vanlandewijck, & Steadward, 2003). Other investigators have studied Paralympic swimming performance criteria to evaluate the classification system and the effectiveness of the current system for generating fair competition (Daly & Vanlandewijck, 1999; Wu & Williams, 1999). Specifically swimmers in higher classes generally out-perform those in lower ones, although there is sometimes little difference between adjacent classes (Wu & Williams, 1999). To the authors’ knowledge, no study has established meaningful estimates of variability and progression between competitions.
Quantifying the smallest important effect in competitive Paralympic swimming events allows swimmers and coaches to set realistic performance goals for future competitions. The 100-m freestyle is one of the most competitive and widely swum events at IPC-sanctioned competitions and one of only two events available to all classes at world championships and the Paralympic Games. The aim of this study was to quantify the magnitude of variability and progression in competitive performance in the 100-m freestyle event for elite swimmers with a disability.

Methods
The competitions were 15 major national and international IPC swimming events over a 3-y period. The competitions analysed included: Australian, British, German and American National Championships, the 2004 Paralympic Games and 2006 World Championships. All swimming pools met official Federation Internationale de Natation Amateur (FINA) accreditation requirements for 50-m competitions (www.fina.org). All data were downloaded from publically accessible official swimming websites, including www.paralympic.org, www.swimming.org.au, www.paralympics.teamusa.org and www.britishswimming.org; therefore, informed consent was not obtained from athletes for use of this information.

At each competition, times of only the top eight finalists in each class were used for analysis. Swimmers who entered only one competition (161 males and 125 females) were excluded from the analysis. Insufficient data for swimmers in the S1 class (22 official race times from seven males and four females) prevented their inclusion. Eleven race times were identified as outliers (see below) and excluded from the analysis. The race times included for analysis were from 120 males and 122 females, representing 32 countries. A total of 724 100-m freestyle races were analysed in four subgroups: S2-S4, S5-S7, S8-S10 (most through least physically impaired), and S11-S13 (visually impaired), for males and females. The subgroups were formed to reduce sampling variation and allow reasonably accurate estimation of the competition random effects and the progression effects.

A repeated-measures mixed linear modelling procedure (Proc Mixed) was used in the Statistical Analysis System (SAS, version 9.1.3, SAS Institute, Cary, NC). Race times were log transformed to yield changes and differences in performance as percents of
the mean and variability as coefficients of variation (Hopkins, 2000). The only fixed effect was competition date, to estimate annual mean progression. The random effects were swimmer identity (to estimate between-swimmer variance), swimmer identity interacting with competition year (to estimate within-swimmer year-to-year variance), competition identity (to estimate and adjust for differences in mean competition time), and the residual (within-swimmer race-to-race variance). Using this approach we can compute separate estimates of variability, progression and the level of a competition. As with all linear models each estimated effect is adjusted for all other effects. In the modelling we allowed for negative variance and reported any as negative standard deviations. Separate analyses were performed for each sex in each of the four disability subgroups. Plots of residual versus predicted values were examined in each analysis to check for outliers (via the t statistic) whose observed final time was greater than 3.5 standard deviations from the predicted value. In the preliminary analysis 11 official race times were identified as outliers and deleted. Uniformity of error was also confirmed by visual inspection of the log-transformed plots of the residual versus the predicted values.

Measures of centrality and dispersion are presented as mean ± s. Uncertainty in true (population) values of effects was expressed as 90% confidence limits. We employed an approach using magnitude-based inferences and precision of estimation to interpret the practical/clinical meaningfulness of effects (Hopkins, 2004). An effect was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold (effect size of ± 0.2). To interpret the observed magnitude of differences of coefficients of variation, a default for the smallest important ratio of 1.15 was used (Stewart & Hopkins, 2000; Hopkins & Hewson, 2001). The smallest important effect on performance time was calculated as half the within-swimmer race-to-race variability (Hopkins et al., 1999). This value was used to interpret the magnitude of the typical variation in mean time between competitions and the mean annual progression in performance time.

Intra-class correlation coefficients were calculated to assess the reproducibility of performance. The expression used was (between – within)/between, where between is the observed between-swimmer variance in a race and within is the within-swimmer race-to-race variance. For between we derived the mean between-swimmer variance
in the competitions by taking the mean of variances weighted by their degrees of freedom. Correlations <0.40 represented poor, 0.40-0.70 fair, 0.70-0.90 good, and >0.90 excellent reliability (reproducibility) (Fleiss, 1986).

Results

Race performances

Table 1 summarises the number of races and the mean 100-m freestyle competition time for each Paralympic swimming class. For all but one class, an increase in class number (i.e., an increase in physical function or vision) was associated with faster mean performance times. Table 2 summarises the total number of swimmers and the mean number of races per swimmer in each subgroup. The mean time between swimmers’ consecutive races ranged from 8.3 to 12.9 months.

Variability

The within-swimmer race-to-race variability expressed as coefficients of variation (CV) had a mean of ~2.2% in both sexes (Table 2). The S2-S4 male swimmers were substantially more variable than S5-S7 male swimmers (ratio of CV 3.1, 90% confidence interval 1.9 to 4.8); the difference between the S5-S7 and S8-S10 male swimmers was unclear (ratio of CV 1.1, 0.7 to 1.6). The S5-S7 female swimmers were substantially more variable than the S8-S10 female swimmers (ratio of CV 1.5, 1.1 to 2.1); the difference between the S2-S4 and S5-S7 female swimmers was unclear (ratio of CV 1.1, 0.7 to 2.0). Some differences in the within-swimmer race-to-race variability between physically impaired and visually impaired swimmers were clearly substantial. There were substantial differences in variability between male and female swimmers in each subgroup. However, the pattern of difference was variable presumably an artifact of substantial differences in the numbers of swimmers in the various subgroups. The smallest important effect on performance time for Paralympic swimmers, estimated as half the within-swimmer race-to-race variability, was ~1.1%, with a range of 0.6% to 1.9% across the subgroups.

Combined with the mean between-swimmer standard deviation in each race, the within-swimmer variability yielded race-to-race intra-class correlation coefficients from 0.77 to 0.97. There was no obvious pattern in the difference between subgroups and sexes for intra-class correlations (Table 2). Additional within-swimmer year-to-
year variability (not shown in the table), had considerable uncertainty (up to ±2.9%), but all the estimates were consistent with a true value of ~1-2%. When combined with the within-swimmer race-to-race variability, the mean within-swimmer variability increased to ~2.7% for races a year apart, and the corresponding smallest important effect on performance time increased only slightly to ~1.3%.

**Differences in performance between competitions**

The typical variation in mean performance time between competitions ranged from 0.8% (90% confidence limits ±0.7%) for S8-S10 males to 2.5% (±2.9%) for S2-S4 males and had an overall mean of ~1.5%. The fastest competition in each subgroup was the 2004 Paralympic Games, ~1.7% faster than the mean competition time. Performance times were generally slowest at national competitions, by ~1.4% relative to the mean competition in each subgroup.

**Mean progression in performance**

The change in mean performance time per year is also shown in Table 2. Most subgroups experienced reasonably clear trivial to small mean improvements in performance of ~0.5%·y⁻¹. One subgroup (female S2-S4) showed a decrement in mean performance time, but the magnitude was trivial. Comparisons between subgroups were unclear.

**Discussion**

The typical within-swimmer race-to-race variability in performance in Paralympic swimmers was ~2%, which is substantially larger than the 1.4% for junior national swimmers (Stewart & Hopkins, 2000) and the 0.8% for Olympic swimmers (Pyne et al., 2004). The greater variability in Paralympic swimmers probably relates to the nature of their disabilities, more limited international race experience and the slower evolution of the sport compared with Olympic swimmers (Daly & Vanlandewijck, 1999). Swimmers with the most physical impairment (S2-S4 subgroup) showed greater variability in performance than swimmers with less physical impairments. The day-to-day fluctuations in movement and function, based on the experience of one of the researchers (SKF) of this study, make consistent performances harder to reproduce. Swimmers who race in these classes are predominately confined to a wheelchair; have little to no use of their hands, legs or trunk, moderate to severe
coordination problems, and/or a degree of limb loss in all four limbs (Green & Jaubert, 2005). It is likely that S8-S10 swimmers with greater functional ability have fewer musculoskeletal limitations and benefit more substantially from traditional strength and conditioning sets, skill drills and pacing strategies. Swimmers in these higher classes typically out-perform swimmers in lower classes (Daly & Vanlandewijck, 1999; Wu & Williams, 1999). The challenge remains for swimmers with high variability in race-to-race performance to achieve greater consistency by managing disability-related stressors. Various therapeutic modalities, including physical therapies and/or strength and conditioning could help achieve greater consistency in performance.

In this study within-swimmer race-to-race variability in performance differed substantially between male and female swimmers in each subgroup. The lack of consistency in these differences was probably attributable to variation in the numbers of disability classes in each subgroup. At international competitions fewer swimmers are represented in some classes than others, which affect performance time in some classes. In other international competitions substantially fewer women than men compete in the same events. Additionally, in some events, low numbers of swimmers means that there are not enough competitors to warrant heats, so swimmers often advance directly to finals (Wu & Williams, 1999). Any clear difference in variability between the sexes is therefore marginal. Authors of previous studies have found that sex had little effect on race-to-race variability in performance time (Stewart & Hopkins, 2000; Pyne et al., 2004), even though differences in swimming speed were substantial.

The differences in mean time between competitions after adjustment for all other factors presumably reflect differences in preparation or motivation. These differences in mean time between competitions are of a magnitude similar to the smallest important effect and hence, are important both for swimmers and coaches. In this study the Paralympic Games was the fastest competition for all subgroups. National competitions were generally the slowest competitions presumably because of a lack of depth of competition and less preparation.
The mean annual progression in performance time of ~0.5% was not substantial but should still be considered when advising coaches of the necessary improvements in performance. As training methods evolve, year-to-year progression probably increases. In Olympic swimmers, the yearly progression in performance time between international competitions was somewhat larger ~0.9% (Pyne et al., 2004). This estimate could have been influenced by better performances at the Olympic Games, the final competition in the analysis.

Estimates of variability and progression provide useful information about the smallest important changes in performance. These estimates are worth considering by swimmers and coaches for planning yearly training programs and analyzing competition outcomes. For Olympic swimmers, improvements in performance attributable to variability and progression were ~1.4% in a pre-Olympic year (Pyne et al., 2004). In this study, the smallest important effect on performance time of ~1.3% accounts for the variability of a swimmer from race-to-race as well as the additional variability from year-to-year. Estimation of additional year-to-year variability is important because athletes’ improvements in competition times fluctuate from year-to-year as well as from race-to-race.

Conclusions
Paralympic swimmers who want to increase their medal prospects should aim for an annual improvement of at least 1-2%. This improvement takes into account variability (~1.3%), progression (~0.5%), and the effect of level of competition (~1.5%). For example, a freestyle swimmer with a 60 second personal best time will increase their medal prospects, accounting for variability, progression and level of a competition, with an improvement in performance time of just 0.60 seconds per year. At all classifications, these estimates will allow swimmers and their coaches to set realistic performance goals when planning for major national and international competitions.
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References


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### Table 1. Number of races and race time (mean ± s) for each Paralympic swimming class.

<table>
<thead>
<tr>
<th>Class</th>
<th>Male Swimmers</th>
<th>Female Swimmers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Races</td>
<td>Race Time (s)</td>
</tr>
<tr>
<td>S2</td>
<td>22</td>
<td>160.9 ± 11.1</td>
</tr>
<tr>
<td>S3</td>
<td>28</td>
<td>127.4 ± 14.5</td>
</tr>
<tr>
<td>S4</td>
<td>18</td>
<td>99.4 ± 10.4</td>
</tr>
<tr>
<td>S5</td>
<td>26</td>
<td>83.2 ± 10.1</td>
</tr>
<tr>
<td>S6</td>
<td>26</td>
<td>74.1 ± 7.9</td>
</tr>
<tr>
<td>S7</td>
<td>38</td>
<td>67.3 ± 3.5</td>
</tr>
<tr>
<td>S8</td>
<td>46</td>
<td>65.7 ± 4.5</td>
</tr>
<tr>
<td>S9</td>
<td>48</td>
<td>60.4 ± 1.8</td>
</tr>
<tr>
<td>S10</td>
<td>42</td>
<td>57.3 ± 2.0</td>
</tr>
<tr>
<td>S11</td>
<td>25</td>
<td>65.9 ± 5.1</td>
</tr>
<tr>
<td>S12</td>
<td>14</td>
<td>57.7 ± 2.2</td>
</tr>
<tr>
<td>S13</td>
<td>28</td>
<td>60.2 ± 3.9</td>
</tr>
</tbody>
</table>

Class S2-S10 (most through least physically impaired), Class S11-S13 (most through least visually impaired).
Table 2. Sample size and effect statistics for within-swimmer race-to-race variability (as a coefficient of variation), race-to-race reproducibility (as an intra-class correlation) and yearly percent progression in the four disability subgroups.

<table>
<thead>
<tr>
<th>Subgroups&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Swimmers</th>
<th>Races per swimmer</th>
<th>Variability&lt;sup&gt;b&lt;/sup&gt; (%)</th>
<th>Reproducibility</th>
<th>Progression&lt;sup&gt;b&lt;/sup&gt; (%·y&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Males</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2-S4</td>
<td>25</td>
<td>2.7</td>
<td>3.7 (2.9 to 5.3)</td>
<td>0.82</td>
<td>0.8 (-1.9 to 3.5)</td>
</tr>
<tr>
<td>S5-S7</td>
<td>28</td>
<td>3.2</td>
<td>1.2 (0.9 to 1.9)</td>
<td>0.97</td>
<td>0.9 (-0.2 to 1.9)</td>
</tr>
<tr>
<td>S8-S10</td>
<td>41</td>
<td>3.3</td>
<td>1.3 (1.1 to 1.7)</td>
<td>0.83</td>
<td>0.5 (-0.1 to 1.0)</td>
</tr>
<tr>
<td>S11-S13</td>
<td>26</td>
<td>2.6</td>
<td>2.4 (1.7 to 4.2)</td>
<td>0.77</td>
<td>1.2 (0.0 to 2.3)</td>
</tr>
<tr>
<td><strong>Females</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2-S4</td>
<td>19</td>
<td>2.7</td>
<td>2.9 (2.0 to 5.0)</td>
<td>0.91</td>
<td>-0.8 (-2.7 to 1.1)</td>
</tr>
<tr>
<td>S5-S7</td>
<td>36</td>
<td>2.9</td>
<td>2.6 (2.1 to 3.4)</td>
<td>0.81</td>
<td>0.2 (-1.3 to 1.7)</td>
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<tr>
<td>S8-S10</td>
<td>43</td>
<td>3.1</td>
<td>1.7 (1.4 to 2.1)</td>
<td>0.84</td>
<td>0.9 (0.1 to 1.8)</td>
</tr>
<tr>
<td>S11-S13</td>
<td>24</td>
<td>3.2</td>
<td>1.5 (1.2 to 2.1)</td>
<td>0.91</td>
<td>0.5 (-0.5 to 1.4)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Class S2-S10, most through least physically impaired; Class S11-S13, most through least visually impaired.

<sup>b</sup>Data in parentheses are 90% confidence intervals.
Chapter 4: Training Characteristics of Paralympic Swimmers

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Chapter 4: Training Characteristics of Paralympic Swimmers

Statement of Intellectual Contribution

I, Sacha Kate Fulton, have made substantial independent intellectual contributions to the research paper ‘Training Characteristics of Paralympic Swimmers’. I consider that intellectual contribution is the substantial, direct, intellectual contribution to the conception and/or design of a research paper. Intellectual contribution is different from technical services, which although essential to the work, are not in themselves sufficient contributions to justify intellectual contribution. I consider that examples of intellectual contributions include, but are not limited to, significant input in the development of the study hypothesis, design of the study, development of study protocols, identification of study methodology, development or modification of methodology used in the project, or development of new applications, unique settings for use of existing methodology, or responsibility for independent analysis and interpretation of results.

...............................................  18th December 2008

Sacha Kate Fulton, CANDIDATE

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David B Pyne, CO-AUTHOR

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William G Hopkins, CO-AUTHOR

...............................................  18th December 2008

Brendan Burkett, CO-AUTHOR
Chapter 4: Training Characteristics of Paralympic Swimmers

ABSTRACT

The ability to monitor training is critical to the process of quantifying training periodisation plans, yet weekly patterns of volume and intensity for Paralympic swimmers prior to competition have not been reported. Sixteen swimmers were monitored prospectively over a 16-week training block constituting four training phases (Early, Mid, Late, Taper), prior to a World Championship. Training volume (total and main-set distance) and intensity (percentage of peak heart rate, swimming velocity and rate of perceived exertion) were quantified using an on-line training diary and changes in training load were examined over the four training phases. For a sub-group of swimmers (n = 12), with similarities in underlying disability, change in performance between Selection Trials and World Championships was also quantified. Substantial increases in total training volume (29.6%) were observed late phase and main-set volume was reduced substantially (24.1%) during the taper phase. Small to moderate increases in training intensity (heart rate 2.4%, velocity 4.5%, rate of perceived exertion 6.7%) were observed late phase and maintained through the taper. There were no clear associations between discrete training measures and competition performance. Swimmers competing at the Paralympic-level appear to follow traditional periodised patterns of training, similar to those of swimmers at the Olympic-level, prior to competition. Coaches of elite swimmers with a disability should review their prescribed patterns of training prior to major competition: a more substantial taper (larger reduction in volume) could elicit a greater improvement in performance. Training prescription should account for different disabilities and classes, and individual circumstances of elite swimmers with a disability.

Keywords: volume, intensity, taper, Paralympic, competition, swimming
INTRODUCTION

In swimming, training volume is traditionally prescribed on the basis of distance swum or frequency of training sessions. These parameters do not however adequately reflect the physiological stress produced by different forms of training [24]. Training intensity is related to both exertion and fatigue and can be quantified in absolute terms such as maximal oxygen consumption (VO$_2$ max), velocity and heart rate, or from subjective rate of perceived exertion (RPE) by the athlete [3, 9]. The balance of training volume and intensity, otherwise known as training load, elicits both short-term responses and long-term adaptations that underpin training effectiveness and improved competitive performance [6, 10, 13, 15]. Training loads have been monitored and quantified in competitive able bodied swimmers [6, 17, 26]. These details have only been reported in one published study for Paralympic swimmers [21], though several studies have analysed competitive performance in these athletes [7, 8, 23]. Monitoring training and quantifying training load will provide a framework for evaluating the effectiveness of contemporary programs used to prepare elite swimmers with a disability for international Paralympic-level competition.

Swimmers at the Olympic-level typically follow variable (periodised) pattern of training load [13]. Coaches typically divide a training block into shorter phases (specific macro-cycles of 2-4 weeks duration) to manage the loading patterns of volume and intensity [19, 22]. A systematic increase in training load develops physical, technical and performance capacities prior to an adaptation phase where volume is tapered and intensity maintained in the weeks prior to major competition [4, 6, 13, 14]. Monitoring training volume and intensity throughout a training block provides a framework to enhance training and competitive performance [2, 5, 15].

The relationship between training and competition in swimming is a complex issue and several factors influence performance outcomes at international competitions. The training-performance relationship depends on an individual athlete’s long-term training background, current level of fitness, and capacity for physiological and technique improvement [2, 25]. Mathematical models have evaluated this relationship by estimating fatigue and fitness profiles from training to interpret fluctuations of performance during periods of heavy load [2, 5, 14]. Quantifying the training-
performance relationship generates essential information necessary to enhance the prescription of group and individualised training programs [1, 15, 20].

The International Paralympic (IPC) for swimming incorporates, with amendments, the rules and laws of the Federation International de Natation Amateur (FINA). Paralympic swimming events are conducted over distances of 50-400m in freestyle and the form strokes (breaststroke, backstroke, and butterfly. The functional classification system in Paralympic swimming (class S1-S10, most through least impaired, respectively) is a sanctioned method of the IPC for grouping swimmers with similar function and ability for competition. Classification is based on several factors including muscle strength, movement coordination, joint range of motion and/or limb length, and encompasses a broad range of physical disabilities including amputation and cerebral palsy. Swimmers are also required to perform practical water sessions, performing all strokes and are assessed accordingly on ability. The unique physiological and biomechanical characteristics of these swimmers provide a challenge for coaches and sports scientists.

Contemporary approaches to swimming training prescription in Paralympic swimmers have largely evolved through trial and error. An objective evaluation of training patterns and relationships with competitive performance is needed to enhance the development of the sport. The aim of this study was to quantify the weekly pattern of training volume and intensity for Paralympic swimmers throughout a training block prior to competition. We sought to characterise the pattern of change in training load measures in the phases prior to World Championships and determine whether these measures were associated with substantial improvements in competitive performance.

METHODS

Experimental approach to the problem

This study used data collected over a 16-week training block between Selection Trials and World Championships. Swimmers recorded specific details of their daily training sessions using an online training diary. The training block constituted of four training phases each of four weeks duration: early (weeks 1-4), mid (weeks 5-8), late (weeks 9-12) and taper (weeks 13-16) phase. Discrete training load measures including weekly training volume (frequency of training sessions, main set and total training
distance) and intensity (time, HR and RPE) were quantified for each phase. There was no experimental intervention and individualised training programs were prescribed by the swimmer’s home coach, based on age, training background, fitness and stroke speciality. The magnitude of changes in training load was quantified between training phases. Relationships were observed between the training load measures and competition performance at Selection Trials prior to the training block and World Championship competition following the training block for the S8-S10 sub-group only. The performance time for a swimmer’s single best event at both competitions was determined based on world ranking.

Subjects
Sixteen elite swimmers (nine males 21.0 ± 4.0 years, seven females 17.3 ± 2.6 years; mean ± SD) who all qualified for the 2006 IPC World Swimming Championships participated in the study. Subjects were informed of the experimental risks and signed an informed consent document prior to the investigation. The investigation was approved by the University of the Sunshine Coast and the Australian Institute of Sport Institutional Review Board for use of human subjects. Parental/guardian consent was obtained for any subject under the age of 18. An S8-S10 sub-group (n = 12) with similarities in underlying disability was formed for subsequent analysis. Training measures were quantified by class (S8 n = 5, S9 n = 3 and S10 n = 4) and disability (cerebral palsy n = 5, arm amputee n = 3 and leg amputee n = 4) for swimmers within the sub-group. Three swimmers who were the sole representatives for their class (S3, S6 and S7) and one swimmer who specialised in distance events (S10) were excluded from the sub-group. Their results are presented as case studies to provide reference data for coaches, practitioners and researchers.

Procedures
Prior to the start of the study, two training camps were used to familiarise swimmers with procedures for recording training information within sessions. Individually, swimmers were shown how to use a heart rate monitor, record details of training sets using a laminated poolside training diary, and transfer this information to a web-based training diary. During camp ten training sessions for all swimmers were closely monitored by the principal investigator to ensure compliance to the prescribed training and the actual training completed was the same information recorded on the laminated
diaries and into the website. The swimmers were blinded to the researcher’s role during these preliminary monitoring sessions and little difference was observed between the prescribed training, compliance to the training and the training information recorded.

An on-line training diary was established on a password protected website to record training details. Swimmers recorded training frequency, total session and main-set training volume (kilometres) and main-set training intensity (heart rate, time and RPE) for all training sessions. A ‘no training this session’ tick box was included online and coaches provided researchers with the planned number of weekly sessions for comparison. All training information was recorded poolside by the swimmers on laminated diaries and later transferred to the website.

Training volume was quantified in absolute terms i.e. the mean number of sessions completed each week, the mean number of kilometres swum each session and the mean total kilometres swum each week. Coaches used a stopwatch to measure interval times of 100-m repetitions for all strokes (to the nearest one hundredth of a second) during the main-set. Velocity was calculated from the recorded times. 50-m training velocities were used for the single swimmer who competed in the S3 class. Main-set velocity was calculated as a percentage of personal best time for each individual stroke and averaged for the training week. All swimmers were allocated a heart rate monitor (Polar FS1, Pursuit Performance Pty Ltd, Adelaide, Australia) for the duration of the study. Heart rate was recorded immediately upon completion of each repetition, as instructed during the familiarisation camps. Peak heart rate was established in the first training phase as the peak value recorded by swimmers. Main-set heart rate values were calculated as a percentage of peak heart rate and averaged for the training week. A laminated copy of the Borg RPE scale was also provided for swimmers to record RPE scores alongside repetition times and heart rates [3]. RPE scores were calculated as a percentage of 20 (peak RPE score) and averaged for the training week. All swimmers completed 2-3 sessions per week of coach directed dryland training which typically involved resistance training, stretching and swimming-specific exercises.
For the S8-S10 sub-group, performance between Selection Trials and World Championships was determined for a swimmer’s single best event based on world ranking. The events included 50-m to 200-m events and covered all strokes. The change in performance was calculated as a percentage decrease or increase in performance time. A decrease in performance time (a faster swim) corresponded to a positive percentage improvement in performance. Relationships were observed between the change in performance and the discrete training measures recorded during the training block. A substantial positive correlation indicated that training load was associated with a better performance (time) at World Championships. Performance in the same event was also calculated as the differential to the world record at the time of World Championships. Relationships were observed between competition the percentage differential to the world record and the discrete training recorded during the training block. A substantial positive correlation indicated that training load was associated with a better performance (closer to the world record).

**Statistical analysis**

Descriptive statistics (mean ± SD) for training load measures were used to characterise the sample group. The standard deviation was calculated as the week-to-week variability in each swimmer for all measures of training, averaged across individuals and training blocks. To reduce the likelihood of heteroscedasticity (non-uniformity of error i.e. the longer the distance the greater the variance) training volume (total and main-set kilometres) was log-transformed before analysis, the means were then back-transformed [18]. Training intensity (percentage of peak heart rate, velocity and RPE) was kept in its raw form. Standardised changes in training volume and intensity were reported and 90% confidence intervals were used to represent the uncertainty in the true value. The magnitude of change (effect size) was interpreted as: trivial 0.0-0.20, small 0.20-0.60, moderate 0.60-1.2, and large >1.2 [11]. An effect was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold (effect size of ± 0.2).

The relationships between mean training loads and changes in competitive performance were expressed as Pearson correlation coefficients. The magnitude of correlations was interpreted as: trivial <0.1, small 0.1-0.3, moderate 0.3-0.5 and large...
A relationship was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold (r value of ± 0.1) [11].

RESULTS

Table 1 depicts weekly training volume and intensity by Paralympic class and disability. A 90% compliance rate for recording training volume and a 60% compliance rate for recording training intensity were established for the sixteen swimmers. For swimmers in the S8-S10 sub-group, weekly training frequency was 5.8 ± 1.6 (mean ± SD) sessions and total volume swum was 22.3 ± 8.0 km·wk⁻¹ including 10.9 ± 4.9 km·wk⁻¹ of main-set volume. Individual training sessions averaged 3.8 ± 0.6 total km including 1.9 ± 0.5 main-set km. Weekly training intensity averaged 90.3 ± 2.5% for peak heart rate, 88.2 ± 4.0% for peak training velocity and 88.0 ± 4.0% for peak RPE levels. In the case studies weekly training volume was lower for the swimmer who competed in the S3 class. The swimmer who competed in the S10 class and specialised in distance events had ~66% greater total volume and ~62% greater main-set volume than the sub-group. Conversely, the swimmer who competed in the S3 class averaged one fifth of the training volume of the sub-group. Training intensities were broadly similar between the sub-group and case study swimmers.

Figure 1 shows weekly training volume and intensity for each phase of the training block. For the S8-S10 sub-group the greatest volume of total (24.6 km·wk⁻¹) and main-set (12.6 km·wk⁻¹) training was completed in the late training phase. Training volume reduced during the taper phase (~3 km·wk⁻¹) for total and main-set kilometres. Main-set training intensity increased throughout the training block and values peaked at 91.0% for heart rate and 90.6% for velocity during the taper phase. RPE peaked late phase (91.7%) and remained steady in the taper phase (89.4%). In the case studies, the swimmer who competed in the S10 class and specialised in distance events had greater volume in each phase and the individual swimmers who competed in class S3, S6 and S7 had less volume in each phase. Patterns of training volume and intensity were broadly similar between the sub-group and case study swimmers.

Table 2 reports the percent and standardised effects of change in key training load measures between the early-mid, early-late and late-taper training phases for the S8-
S10 sub-group of swimmers. There was a moderate increase in total volume and a small increase in main-set volume by the mid and late training phases. Small decreases in total volume and main-set volume were observed in the taper phase. Trivial-small, but unclear, increases in heart rate intensities were observed between phases throughout the training block. There were moderate increases in training intensity by the late training phase for velocity and RPE. Unclear changes in intensity for velocity and RPE were observed between the early-mid and late-taper training phases.

Relationships were established between discrete training measures for the training block and individual changes in competition performance between Selection Trials and World Championships for the S8-S10 sub-group. Improvements of 1.0 ± 1.5% (mean ± SD) were observed between Selection Trials and World Championships. A positive correlation indicated that training load was associated with a better performance (time) at World Championships. There was no clear association between training volume and improved competition performance $r = -0.32$ (90% confidence interval -0.71 to +0.21). A large negative association was observed between training intensity, indicated by percentage peak heart rate, and a change in competition performance $r = -0.59$ (-0.86 to -0.05).

When compared to the world record, performance times at World Championships were 5.1 ± 3.1% (mean ± SD) slower. A positive correlation indicated that higher training volumes and intensities were associated with a better performance (closer to the world record). No substantial association was observed between training volume and performance relative to the world record $r = 0.03$ (-0.47 to 0.52). There was however a large association between training intensity, indicated by percentage of peak training velocity, and the differential to the world record $r = -0.57$ (-0.85 to -0.02).

**DISCUSSION**

Paralympic swimmers follow traditional periodised patterns of variable training volume prior to important competitions. These patterns are similar to those observed in competitive swimmers competing at the Olympic-level. For the swimmers in this study, training volume is increased mid to late phase before a decrease in volume
indicative of a taper phase occurs in the final weeks. Training intensity is largely maintained throughout the training block with small increases in race pace intensity coinciding with the taper phase. Swimmers who had the greatest improvements in performance between competitions trained at lower volumes and intensities than swimmers with smaller improvements. This counter-intuitive finding raises questions about contemporary training programs and provides justification for exploring alternative training strategies and methodologies.

The majority of swimmers observed in this study trained substantially less weekly mileage than typical swimmers competing at the Olympic-level. Training volume for the swimmer who competed in the S10 class and specialised in distance events was comparable to that of swimmers who compete at the Olympic-level in the 400-m event [12]. During a competitive training phase swimmers who compete at the Olympic-level in the 200-m and 400-m events train on average 60-70 km·wk^{-1} while swimmers who compete in the 50-m and 100-m events average closer to 40-50 km·wk^{-1} [12]. Anecdotal evidence suggests that there is considerable individual variation in training mileage between swimmers who compete at the Olympic-level and no published study has clearly established the relationship between training mileage and success in competition. Some researchers have assessed the value of periods of increased volumes of training on swimming performance. High training volumes have shown a decline in sprinting velocity and training intensity rather than volume has been shown as a key factor for performance improvement [6, 16].

Training volume for Paralympic swimmers has only been quantified in one previous study. Consequently there are few recommendations on training volume for class-specific or disability-specific swimmers [21]. The previous study reported training volumes of 13.9 km·wk^{-1} (S3), 16.1 km·wk^{-1} (S4), 20.0 km·wk^{-1} (S5), 24.5 km·wk^{-1} (S6), 28.9 km·wk^{-1} (S7), 30.5 km·wk^{-1} (S8), 35.4 km·wk^{-1} (S9) and 37.0 km·wk^{-1} (S10) [21]. In our study training volume was ~70% lower for swimmers in classes S3-S7, ~20% lower for class S8, ~54% for class S9 lower and ~34% lower for swimmers in class S10. All swimmers in the study by Pelayo et al., 1999 were 100-m male and female freestyle swimmers and there was no statement on the reliability or validity of the methodology used to quantify training volume. Average weekly training volume and weekly training time were assessed via a questionnaire. The ~10-year time-frame
between the studies, suggests that coaches may now have adopted less volume orientated strategies in the preparation of elite swimmers with a disability at Paralympic-level competition. International performances at the Paralympic-level are faster now than they have ever been, consistent with the possibility that contemporary training programs elicit better performances.

We anticipated a gradual decrease in training volume with descending class number from S10 through S8. The failure to observe this association conflicts with an earlier study [21] and suggests that either training volume in Paralympic swimmers is not directly related to classification, or the classification system needs refining. Training volume was lower for the individual swimmers representing classes S3, S6 and S7 than for the other swimmers observed in the study, as expected. Further research is needed to develop prescriptive guidelines for training volume in each swimming class, accounting for the type of disability.

A key finding of this study was the periodised pattern of training volume followed by all swimmers throughout the training block. The greatest amount of volume was completed mid to late phase before a decrease in volume indicated the taper phase as swimmers prepared for competition. Olympic swimmers train at varying intensities throughout training blocks when preparing for competition, but the magnitude of change in intensity measures is much smaller than those for training volume. In most training sessions coaches include variable levels of intensity, particularly during the main-set, where the highest heart rates and swimming velocities are observed. When training volume decreases during the taper phase, intensity is maintained and ‘race pace’ and time-trial efforts become more prominent. In our study, training intensity varied little between classes and disabilities in the S8-S10 sub-group during the taper, indicating similar levels were adopted by the majority of swimmers. This observation is consistent with earlier research that found no modification of training intensity during the taper phase [4]. The sub-group followed a traditional periodised pattern of variable volume through to World Championships, increasing training volume in the mid phase and peaking 4-8 weeks from competition. The most substantial increases in volume were between the early and late phase for total and main-set training, before substantial decreases during the taper phase. Performance benefits of 14 and 28 day tapers have been associated with 40-60% reductions in training [4, 14], substantially
greater reductions than observed for swimmers in the current study. The smaller reductions in taper volume in this study might be related to the lower overall training volumes undertaken by the Paralympic swimmers compared with their able-bodied counterparts.

Detailed training information for swimming research projects is collected and recorded by coaches, support staff or researchers and some studies use self-administered questionnaires sent to coaches to quantify coaching programmes and training methods [15, 20, 27, 26]. These methods do not involve athlete interaction and athletes are not involved in the recording process. In this study the swimmers themselves were responsible for the recording process using novel methods. When provided with adequate resources and given the necessary support, swimmers can record their own training information for subsequent download, analysis and evaluation. This system encourages swimmer accountability, education and a greater understanding of the prescribed training program. Methods in other research studies have been devised to capture and quantify data from swimming training programs and determine the extent to which swimmers comply with coaching prescription [27]. Swimmers in this earlier study complied with prescribed distances and rest intervals but were less effective in judging the intensity of swimming training. Recommendations were made for coaches to monitor training intensity more closely. To the author’s knowledge no study has evaluated the validity and reliability of self reported data in swimming training programs. In this study there was a high degree of compliance for recording training volumes throughout the training block, but recording a time, heart rate and RPE for every main-set repetition was a substantial task and compliance for recording training intensity was not as high. Future studies might examine how many repetitions can be reported within a training set that is representative of the entire set.

Understanding the relationships between training and competitive performance in elite swimmers is important for optimising training prescription [1, 17, 20]. Traditionally, coaching styles have been based on a ‘more is better’ philosophy and previous studies that have reported high correlations between performance and training distance [26] and between performance and training intensity [17]. Here we found an opposite trend: swimmers who had the greater improvements in performance between
competitions trained at lower volumes and intensities, and swimmers who raced closer to the world-record time trained at lower intensities. These findings could be a consequence of inflation of the chance of finding effects that are clearly substantial when a large number of trivial effects are estimated with a small sample size. Consequently we hesitate to make any recommendations on training intensity pending further research with greater numbers of Paralympic swimmers.

In conclusion, we have quantified the training characteristics of a unique squad of Paralympic swimmers using rigorous scientific methods of data collection. Paralympic swimmers follow a traditional periodised pattern of training. Increases in training volume are apparent throughout the training block, with the highest volume in the late training phase, 4-8 weeks out from an important competition. Coaches follow this period of increased volume with substantial decreases in training volume, particularly main-set volume, in the taper phase 0-4 weeks from competition. Training intensity levels remain much the same throughout the training block, with small increases in the taper phase as swimmers practice race-pace intervals immediately prior to important competitions.

PRACTICAL APPLICATIONS
This study has established novel methods for self-reporting training data encouraging swimmer accountability, education and a greater understanding of the prescribed training program. One limitation of this approach is the potential for participants to report what they believe the researcher expects to see, or report what reflects positively on their own abilities, knowledge, beliefs, or opinions. Coaches and researchers will need to instruct athletes on the importance of providing accurate self-reported training data. Coaches should adopt a periodised approach to prescription of training programs for Paralympic swimmers prior to major competition. The main set and total volume of training can be increased by ~30% during the mid to late phases via manipulation of the frequency and volume of sessions. Similarly, an increase of ~5% in training intensity during the late phase and taper of a training block is indicated. A more substantial taper (larger reduction in volume) could elicit greater improvements in performance.
REFERENCES


Chapter 4: Training Characteristics of Paralympic Swimmers

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the swimmers and coaches who gave their consent for training data to be recorded.
Table 1. Weekly training volume and intensity (mean ± SD) for the 16 swimmers for the 16-week training block by class and disability.

<table>
<thead>
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<th>Session Volume</th>
<th>Weekly Intensity</th>
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<td>Sessions (n)</td>
<td>Total (km.wk⁻¹)</td>
<td>Main-set (km.wk⁻¹)</td>
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<tr>
<td>S8-S10 sub-group by class (n = 12)</td>
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<td></td>
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</tr>
<tr>
<td>S10 (n = 4)</td>
<td>6.3 ± 1.7</td>
<td>24.6 ± 8.8</td>
<td>10.8 ± 4.7</td>
</tr>
<tr>
<td>S9 (n = 3)</td>
<td>4.2 ± 1.9</td>
<td>16.3 ± 8.4</td>
<td>8.7 ± 5.0</td>
</tr>
<tr>
<td>S8 (n = 5)</td>
<td>6.2 ± 1.3</td>
<td>24.6 ± 7.0</td>
<td>12.6 ± 4.9</td>
</tr>
<tr>
<td>S8-S10 sub-group by disability (n = 12)</td>
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</tr>
<tr>
<td>CP (n = 5)</td>
<td>6.4 ± 1.4</td>
<td>27.1 ± 8.3</td>
<td>13.4 ± 5.1</td>
</tr>
<tr>
<td>AA (n = 3)</td>
<td>5.3 ± 1.5</td>
<td>21.6 ± 7.9</td>
<td>10.7 ± 4.9</td>
</tr>
<tr>
<td>LA (n = 4)</td>
<td>5.0 ± 1.9</td>
<td>17.4 ± 7.6</td>
<td>8.3 ± 4.5</td>
</tr>
<tr>
<td>Individual class (n = 4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S10 (CP n = 1)</td>
<td>10.1 ± 1.0</td>
<td>65.8 ± 9.3</td>
<td>28.9 ± 5.1</td>
</tr>
<tr>
<td>S7 (CP n = 1)</td>
<td>3.1 ± 1.6</td>
<td>8.1 ± 4.5</td>
<td>3.4 ± 2.4</td>
</tr>
<tr>
<td>S6 (SS n = 1)</td>
<td>3.6 ± 1.5</td>
<td>7.3 ± 3.9</td>
<td>2.5 ± 1.5</td>
</tr>
<tr>
<td>S3 (LC n = 1)</td>
<td>3.9 ± 1.1</td>
<td>4.6 ± 1.3</td>
<td>1.9 ± 0.6</td>
</tr>
</tbody>
</table>

Note: CP = Cerebral Palsy, AA = Arm Amputee, LA = Leg Amputee, SS = Short Stature, LC = Lower Class
Class S1-S10 = swimming classes used in IPC-sanctioned competition as most through least impaired, respectively.
Chapter 4: Training Characteristics of Paralympic Swimmers

- S8-S10 sub-group n = 12 (mean ± SD)
- † S3 - △ S6 - ○ S7 - □ S10

- Volume (total km·wk⁻¹)
- Volume (main-set km·wk⁻¹)
- Intensity (% heart rate)
- Intensity (% velocity)
- Intensity (% RPE)

Training Phases: Early, Mid, Late, Taper
Figure 1. Patterns of training volume and intensity between training phases for the 16-week training block by Paralympic class. Class S1-S10 represents the swimming classes used in IPC-sanctioned competition as most through least impaired respectively.
Table 2. Change in training volume and intensity between training phases for the S8-S10 sub-group (n = 12) expressed as percent effect (with 90% confidence interval) and standardised units.

<table>
<thead>
<tr>
<th>Training Phases</th>
<th>Weekly Volume</th>
<th>Weekly Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total (km·wk⁻¹)</td>
<td>Main-set (km·wk⁻¹)</td>
</tr>
<tr>
<td>Early-Mid</td>
<td>33.2% (19 to 49)</td>
<td>22.9% (13 to 34)</td>
</tr>
<tr>
<td></td>
<td>0.73*</td>
<td>0.44*</td>
</tr>
<tr>
<td>Early-Late</td>
<td>29.6% (13 to 49)</td>
<td>24.0% (4 to 47)</td>
</tr>
<tr>
<td></td>
<td>0.66*</td>
<td>0.46*</td>
</tr>
<tr>
<td>Late-Taper</td>
<td>-10.5% (-19 to -1)</td>
<td>-24.1% (-36 to -11)</td>
</tr>
<tr>
<td></td>
<td>-0.28*</td>
<td>-0.59*</td>
</tr>
</tbody>
</table>

Standardised changes were interpreted as: trivial 0.0-0.20, small 0.20-0.60, moderate 0.60-1.2, and large >1.2

*Clear effects (90% confidence interval does not include substantial positive and negative values).
Chapter 5: Measuring Kick Count and Kick Rate in Freestyle Swimming

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JCR ranking: 24/72 (sport science discipline)
Impact factor: 1.4
ARC tier ranking: B
Statement of Intellectual Contribution

I, Sacha Kate Fulton, have made substantial independent intellectual contributions to the research paper ‘Measuring Kick Count and Kick Rate in Freestyle Swimming’. I consider that intellectual contribution is the substantial, direct, intellectual contribution to the conception and/or design of a research paper. Intellectual contribution is different from technical services, which although essential to the work, are not in themselves sufficient contributions to justify intellectual contribution. I consider that examples of intellectual contributions include, but are not limited to, significant input in the development of the study hypothesis, design of the study, development of study protocols, identification of study methodology, development or modification of methodology used in the project, or development of new applications, unique settings for use of existing methodology, or responsibility for independent analysis and interpretation of results.

Sacha Kate Fulton, CANDIDATE

David B Pyne, CO-AUTHOR

Brendan Burkett, CO-AUTHOR
Abstract
In freestyle swimming the arm action is routinely quantified by stroke count and rate, yet no method is currently available for quantifying the kick. This study evaluated validity and reliability of inertial sensor technology (gyroscope) to measure kick count and rate. Twelve Paralympic swimmers completed both a 100 m freestyle swimming and kicking-only time trial six times within a season. An algorithm was developed to detect the upbeat and downbeat of individual kicks from the gyroscope trace. Underwater video analysis was the criterion measure. The standard error of the estimate (validity) for kick count, expressed as a coefficient of variation, was 5.9% (90% confidence interval 5.5 to 6.4) for swimming, and 0.6% (0.5 to 0.6) for kicking-only trials. The mean bias for kick count was -1.7% (-2.4 to -1.1) for swimming, and -0.1% (-0.2 to -0.1) for kicking-only trials. Correlations between the sensor and video for kick count were 0.96 (0.95 to 0.97) for swimming, and 1.00 (1.00 to 1.00) for kicking-only trials. The typical error of the measurement (reliability) between trials was ~4% for kick count and rate. The inertial sensor technology and associated software used in this study generated valid and reliable estimates of kick count and rate in freestyle swimming.

Keywords: swim, kick, inertial sensor technology, measurement error
Introduction

The evaluation of sport-specific performance measures provides fundamental information to the coach, athlete and sport scientist on an athlete’s response to training (Smith, Norris, & Hogg, 2002). Practical and convenient methods of monitoring performance measures are especially important for sports such as swimming where physiological and movement demands cannot be easily replicated in the laboratory (Robertson & Hunter, 2004). Until recently, discrimination of movement patterns in swimming was dependent upon visual information from an observer, kinaesthetic information from the athlete, or the lengthy process of joint digitisation from video footage making it difficult to evaluate a swimmer’s stroke motion promptly after a trial. Inertial systems are less time consuming than panning cameras to capture a whole swimming length and post-event digitising, and more practical for regular use or collection of large quantities of data.

Sports scientists who use the application of inertial sensor technology to systematically track movement of the human body are pioneering sports research. Inertial sensors are unobtrusive, lightweight, wireless, relatively inexpensive and commercially available which makes them an attractive option for field-based research measurement (Montoye, Kemper, Saris, & Washburn, 1996). Outside of sport, inertial sensor technology is currently a major focus of posture and motion (VanAcht, Bongers, Lambert, & Verberne, 2007; Wong & Wong, 2008), ambulatory assessment and monitoring (Salarian, Russmann, Vingerhoets, Burkhard, & Aminian, 2007; Cutti, Giovanardi, Rocchi, Davalli, & Sacchetti, 2008) and animal locomotion and behaviour (Venkatraman, Long, Pister, & Carmena, 2007; Pfau, Ferrari, Parsons, & Wilson, 2008). Other sports that have successfully implemented this technology include the martial arts; karate and boxing (Ohgi, Mokuno, Yamagishi, & Miyaji, 1998) and running (Herren, Sparti, & Aminian, 1999). In swimming, the influence of stroke count and stroke rate on propulsion has been investigated (Kjendlie, Haljand, Fjørtoft, & Stallman, 2006; Hellard et al., 2007); however, kicking occurs at an unknown faster rate and the relative contribution to velocity from the upper and lower limbs is unclear (Deschodt, Arsac, & Rouard, 1999; Millet, Chollet, Chalies, & Chatard, 2002)
Inertial sensor technology was first piloted a decade ago in swimming. Analogue signals from the accelerometer trace of inertial sensors discriminated stroke cycles from a swimmer’s forearm acceleration (Ichikawa, Ohgi, & Miyaji, 1999). Wireless inertial sensors worn on the wrist identified the different phases of the arm stroke, such as the down sweep, in sweep, out sweep and recovery (Ichikawa, Ohgi, Miyaji, & Nomura, 2003; Ohgi, Ichikawa, Homma, & Miyaji, 2003). Swimmer fatigue has also been quantified by comparing the accelerometer traces obtained during intensive swimming sessions (Ohgi & Ichikawa, 2003). Uni-axial accelerometer inertial sensors have shown promise when strapped to a swimmer’s back and used to detect swimming-specific characteristics such as lap times, dives and tumbling movements, stroke rate, stroke length and intra-stroke acceleration (Anderson, Pyne, & Hopkins, 2006). However, no published research has investigated the utility of inertial sensor technology to discriminate the kick action and further understand the complex process of human swimming.

Lap time is currently the only variable quantified when coaches prescribe kicking-only drills in swimming training sessions (Konstantaki & Winter, 2007). Inertial sensor technology could be useful for quantifying kick count and kick rate variables in kicking-only performance, and to identify those variables that elicit improvements in full-stroke freestyle swimming performance. The aim of this research was to evaluate the application of inertial sensor technology to quantify kick count and kick rate in freestyle swimming. As a new method of measurement, the evaluation involved quantifying the validity and reliability of these kicking measures.
Methods

Participants
Twelve Paralympic swimmers (eight males 20.9 ± 4.2 yr, four females 16.5 ± 2.1 yr; mean ± s) participated in the study. The disabilities of the swimmers were cerebral palsy n = 5, leg amputee n = 5 and arm amputee n = 2. Ethics approval was obtained prior to commencement of the study from the Ethics Committee of the University of the Sunshine Coast and the Australian Institute of Sport and all swimmers provided written informed consent.

Study design and procedures
Swimmers repeated two maximal effort 100 m freestyle swimming and freestyle kicking-only time trials on three occasions, approximately five weeks apart. In every trial swimmers wore an inertial sensor device taped to each available lower limb segment (thigh and shank). A total of 226 swimming trials and 217 kicking-only trials were included in the analysis for validity and reliability. The criterion measure for validity was underwater video analysis. One-day reliability was reported between trials one and two within each testing session and five-week reliability was reported for trials one and two between each testing session.

On each testing occasion there was typically 10-15 min active recovery between the 100 m freestyle swimming and 100 m freestyle kicking-only time trials and ~24 h recovery between the first and second testing sessions. The order of the swimming and kicking-only trials was reversed each session. Swimmers started in the water and all trials timed with a handheld stopwatch. Swimmers were given equal verbal encouragement during each trial to ensure a maximal effort. Swimmers were instructed to swim to their normal race plan for the swimming trials and keep both hands on the kick board for the duration of the kicking-only trials. The inertial sensors were worn for each trial: one each on the left and right thigh and shank segment. Trans femoral amputees (n = 3) wore two sensors on the unaffected side. For two swimmers a single sensor was worn on the thigh of the affected side and for one swimmer no sensor was worn on the affected side, as the amputation was high.
The inertial sensors (MiniTraqua™, version 5, Cooperative Research Centre for Microtechnology, Australian Institute of Sport) are housed in a semi waterproof plastic casing with external dimensions 5.2 x 3.3 x 1.1 cm, mass of 20.7 g and volume of 18.9 cm³ (Figure 1). The device includes a ±2G tri-axial accelerometer, one perpendicular to the other to obtain three orthogonal axes of acceleration (Kionix; Model KMXM52, New York, USA); a single > 600 rad·s⁻¹ angular rate sensor (gyroscope); a 256 MB memory for data storage; USB interface for charging, calibrating, firmware upgrade and downloading data; a rechargeable battery (~3 h of operation); and an LED screen for operational status indication. The device was charged and calibrated via gold-plated conductors and a USB cradle. The recording system was configured for 100 Hz sampling rate on all three accelerometer channels and the gyroscope channel. The gyroscope functionality was utilised to detect kick patterns given the absolute measure of angular velocity. Gyroscope calibration involved rotating the sensor from horizontal to vertical through the roll axis to calibrate for 90° of movement.

An ‘in-house’ software program (Logan, Version 21.9, Australian Institute of Sport) was developed to operate the inertial sensor, extract and process the data. A kick detection algorithm was written specifically to identify a downwards trough in the 100 Hz gyroscope signal, filtered with a 4 Hz cut-off frequency Butterworth filter (Schaumann & Van Valkenburg, 2001), using a 0.2 s sampling window. The beginning of a trough was set as zero rad·s⁻¹ and the lowest point in the trough defined as the point of maximum angular velocity of the leg during the downbeat. A subsequent zero rad·s⁻¹ crossing identified the start of a new trough and the end of a previous trough. Three troughs in a row were required before a kick was identified a minimum of 0.15 s was required between each trough. A complete kick was defined as starting at zero rad·s⁻¹, and finishing when the upbeat and downbeat of the limb segment returned to zero rad·s⁻¹. A typical image of the gyroscope trace is shown in Figure 2. A kick count was registered as the upbeat and downbeat of a single leg, and kick rate was derived as the number of kicks per unit time (k·min⁻¹).

All sensors were calibrated prior to use. The sensors were attached at the segmental centre of gravity of the thigh (trochanterion-tibiale laterale length) and shank (tibiale mediale-sphyrión tibiale length) and orientated vertically on the muscle belly by a
A qualified Level 3 anthropometrist. The accelerometer axes were aligned as follows: X-axis parallel to length of leg (forwards/backwards movements), Y-axis parallel to muscle belly (medio-lateral movements) and Z-axis perpendicular to the limb segment (up/down movements). This orientation ensured that the gyroscope functionality was utilised in its intended ‘roll’ mode for kick detection and kept constant for all experimental trials. The sensors were placed in clear plastic zip lock bags for further waterproofing and attached using tape for comfort and security. No swimmer reported restriction of movement.

On completion of a swimming or kicking-only trial, data from each inertial sensor were downloaded via a USB interface. A cluster of vertical lines (kicks) on the gyroscope trace clearly identified each trial and each 25 m segment manually identified to determine a count and rate. Raw data were exported to a spreadsheet to calculate average kick rate for each segment. Underwater video footage was manually inspected to validate the sensor’s kick count. The same researcher completed the video inspection, download and data compilation process for all trials. The first and last kick of each lap was complex to identify, even with inspection of video footage. To estimate the magnitude of the first kick and last kick error we conducted a short simulation. A probability, set at 33.3%, was used to evaluate each scenario; the sensor under counting, over counting or counting correctly the first and last kick of each lap, by estimating the typical error and bias as the mean and standard deviation of a (arbitrary) large number of laps (over 1200).

Statistical analysis
Kick count validity was established between the inertial sensor and kicks counted from underwater video footage. The standard error of the estimate was reported in raw and standardised (coefficient of variation) units. The mean bias was reported in raw units and as a percent. The precision of estimates was indicated with 90% confidence intervals. Pearson correlation coefficient was used to examine the relationship between the inertial sensor and underwater video analysis for swimming and kicking-only trials. The magnitude of correlation was interpreted as: trivial <0.1, small 0.1-0.3, moderate 0.3-0.5 and large >0.5. A relationship was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold (r value of ± 0.1) (Hopkins, 2004).
One-day and five-week reliability for kick count and kick rate was reported as the typical error of the measurement and expressed in raw and standardised (coefficient of variation) units with 90% confidence intervals. Intra-class correlation coefficients (ICC) were calculated to interpret the reliability of the repeated measures. ICC values <0.40 represented poor reliability, 0.40-0.70 fair, 0.75-0.90 good, and >0.90 excellent reliability (Fleiss, 1986). To determine the signal (the magnitude of a worthwhile change or difference in kick characteristics) to noise (the typical error or test-retest reliability) ratio the smallest worthwhile effect was calculated as 0.2 of the between-subject variability in accordance with existing methods (Hopkins, 2000). To reduce the likelihood of heteroscedasticity (non-uniformity of error) data were log-transformed before analysis (Paton & Hopkins, 2005). Log-transformed data were back transformed to obtain changes and differences as a percentage (Stewart & Hopkins, 2000b). To interpret the observed magnitude of differences of coefficients of variation, we used a threshold ratio of 1.15 (Hopkins & Hewson, 2001).

Results
The standard error of the estimate between the inertial sensor and underwater video footage for kick count is shown in Table 1. The coefficient of variation (CV) between the sensor and video footage was 5.9% (90% confidence interval 5.5 to 6.4) for swimming trials and 0.6% (0.5 to 0.6) for kicking-only trials. In raw units the standard error of the estimate was 6.4 (5.9 to 6.9) and 1.4 (1.3 to 1.5) kicks for swimming and kicking-only trials respectively. The estimate of kick count in swimming trials was substantially more variable than kicking-only trials (ratio of CV 9.8, 8.8 to 11.0). Within swimming trials kick count of the right leg was substantially more variable than the left leg (ratio of CV 3.6, 3.1 to 4.2). Within kicking-only trials the kick count of the left leg was substantially more variable than the right leg (ratio of CV 2.3, 2.0 to 2.7). In swimming (ratio of CV 1.2, 1.0 to 1.4) and kicking-only (ratio of CV 4.0, 3.4 to 4.7) trials the kick count of the shank was substantially more variable than the thigh. From computer simulation an additional typical error of ~1.1% was calculated for every 100 kicks.

The mean bias of the inertial sensor for detecting kick count in freestyle swimming and kicking-only trials for each individual swimmer is shown in Table 2. The inertial
sensor typically recorded a lower kick count than the video with a mean bias of -1.7% (90% confidence interval -2.4 to -1.1) for swimming trials and -0.1% (-0.2 to -0.1) for kick count in kicking-only trials. In raw units the inertial sensor typically recorded -2.0 (-2.7 to -1.3) and -0.3 (-0.5 to -0.2) kicks per 100 m less than the underwater video footage for swimming and kicking-only trials respectively. In freestyle swimming trials the bias was -7.2% (-12.5 to -1.6) for swimmer 2 and -7.2% (-11.0 to -3.1) for swimmer 8 where the inertial sensor underestimated kick count by -7.3 (-12.6 to -2.0) and -9.3 (-14.6 to -4.0) kicks per 100 m respectively. The Pearson correlation coefficient between the inertial sensor and underwater video measures are shown in Figure 3.

One-day and five-week estimates of the reliability of kick count and kick rate for swimming and kicking-only trials are shown in Table 3. The reliability of quantifying kick count (ratio of CV 1.8, 1.6 to 2.2) and kick rate (ratio of CV 1.3, 1.1 to 1.5) from day to day was substantially lower in swimming compared with kicking-only; no substantial differences were observed for five-week reliability. Trials five weeks apart were slightly less reliable than trials one-day apart for swimming for kick count (ratio of CV 1.2, 1.0 to 1.4); there was no substantial difference for kick rate. For kicking-only trials, day-to-day reliability was substantially less reliable than trials five weeks apart for kick count (ratio of CV 1.2, 1.0 to 1.4) and kick rate (ratio of CV 1.4, 1.2 to 1.6).

Within swimming trials, kick count on the right was slightly less reliable than the left (ratio of CV 2.5, 1.7 to 2.7); there was no substantial difference for kick rate. The thigh was less reliable than the shank for kick count (ratio of CV 1.4, 1.1 to 1.7); was no substantial difference for kick rate. The correlation between sensor data and video analysis for kick count rate over one day and five weeks ranged from 0.90 to 0.95. The magnitude of the smallest worthwhile effect for one-day reliability was 3.5 kicks for kick count and 2.4 k·min⁻¹ for kick rate per 100 m. Magnitudes for five-week reliability were 3.3 kicks for kick count and 2.5 k·min⁻¹ for kick rate per 100 m.

Within kicking-only trials there were no substantial differences in kick count or kick rate between left and right or between the thigh and shank. The correlation between sensor data and video analysis for kick count rate over one day and five weeks ranged
from 0.86 to 0.98. The magnitude of the smallest worthwhile effect for one-day reliability was 4.1 kicks for kick count and 2.4 k·min\(^{-1}\) for kick rate per 100 m. Magnitudes for five-week reliability were 4.1 kicks for kick count and 2.5 k·min\(^{-1}\) for kick rate per 100 m.

**Discussion**

This research measured the kick count and kick rate in freestyle swimming using inertial sensor technology, and found this new method valid and reliable. Kicking movements that are time consuming and to detect, can now be identified with this technology. In this study, the standard error of the measurement for kick count validity was substantially greater in swimming trials, approximately six kicks per 100 m, than kicking-only trials, approximately one kick per 100 m presumably attributable to the more pronounced biomechanics of the kicking-only action that elicits more clearly defined troughs for kick detection. Variation in the first and last kicks of a lap had little effect on the overall estimates of kick count and rate. Large correlations between the inertial sensor and underwater video confirm the suitability of kick count detection for swimming and kicking-only trials.

In the current study the inertial sensor detected kicks from a series of troughs from a gyroscope trace. The sensor slightly underestimated kick count for swimming trials with a mean bias of -1.7% and for kicking-only trials this reduced to only -0.1%. On average, the inertial sensor underestimated kick count by no more than two kicks for every 100 m trial swum. Other research using wrist mounted inertial sensor technology applications in swimming reported a mean bias of 0.0% to 2.0% for accelerometer axes for the discrimination of freestyle and breaststroke strokes (Ichikawa et al., 1999). Similarly, hip mounted accelerometer applications in physical activity research reported a mean bias of 0.8% to 1.1% in detecting walking steps at a range of different speeds (Le Masurier & Tudor-Locke, 2003). A mean bias of 1-2% in kicking characteristics is favourable given a preliminary report that in arm stroke count and stroke rate detection in freestyle swimming using triaxial acclerometry the mean bias was ~5-10% (Anderson, Pyne, & Hopkins, 2006). The reason for the greater bias in arm stroke detection compared with leg kick detection in the current study is the movement pattern of the kick. The action of the kick is confined to a single, vertical plane, making kick detection relatively simple. Substantially greater
errors were calculated in the stroke detection at faster swimming speeds and similar to the current study, high errors were specific and limited to a few individual swimmers (Anderson et al., 2006). In this study, closer inspection of the kicking patterns of swimmer 2 and swimmer 8 during swimming trials from the underwater video footage could not identify any definitive explanation for the skewed results. With a kick count variation of only 1-2% this technology and software new method is an effective measure of kick count.

The evaluation of semi-automated kick count and kick rate detection using inertial sensor technology yielded small differences between swimming and kicking-only trials, and between the one-day and five-week time frames. Coaches are now able to utilise this technology to identify changes in kicking patterns between training sessions and for seasonal changes between major competitions. Semi automated inertial sensor technology orientated on the lower limbs for kick count and kick rate detection also yielded small differences between the left and right side and between the thigh and shank segment. Future studies and testing sessions may consider placement on a single lower limb segment. The shank of a swimmers dominant leg, more applicable for Paralympic swimmers, should be the location of choice. In terms of the signal to noise ratio, the sensor is best suited for identifying moderate to large changes in kick patterns. The inherent noise in sensor output makes it problematic to identify small changes or differences in kicking. Improvements to the technology and software, coupled with duplicate measures or repeat trials, would increase the likelihood of detecting small changes in kick patterns, which may influence swim performance and ultimately medal chances.

Researchers have orientated inertial sensors on various parts of the body to enable identification of movement patterns. For monitoring physical activity sensors have been worn on the hip area held against the body in velcro pouches secured with a waist strap (Nichols, Morgan, Chabot, Sallis, & Calfas, 2000; Le Masurier & Tudor-Locke, 2003; Anderson, Hagstromer, & Yngve, 2005). In swimming and martial arts sensors have been attached to the wrist by a wrist band (Ohgi, Mokuno et al., 1998; Ichikawa, Ohgi, & Miyaji, 1999; Ohgi, Yasumura, Ichikawa, & Miyaji, 2000; Ichikawa et al., 2003; Ohgi & Ichikawa, 2003; Ohgi et al., 2003). The inertial sensor devices used in this study were orientated on a swimmer’s lower limbs and attached
without discomfort or restriction of movement. Future studies could investigate modifying racing suits to incorporate this type of sensor device and eliminate the attachment process. Inertial sensor technology could be further developed to quantify multi-segmental limb displacement, which could be used by coaches and swimmers to optimize kicking range of movement. Quantifying angular velocity and linear acceleration patterns, and the propulsive role of the legs for future research, should provide useful information for researchers, coaches and athletes.

The inertial sensor technology and associated software used in this study is sufficiently valid and reliable for quantifying kick count and kick rate in freestyle swimming. The technology can be used by coaches and researchers interested in quantifying kick patterns in swimming to guide training regimes and for biomechanical and performance enhancement applications. In a single timed effort coaches and researchers can expect strong agreement between the sensor and video analysis for detecting kick count in freestyle swimming. Refinements to the current system are needed to fully automate the kick detection process, reduce associated measurement error and increase reproducibility when reporting small changes in kicking patterns.
Chapter 5: Measuring Kick Count and Kick Rate in Freestyle Swimming

References


Chapter 5: Measuring Kick Count and Kick Rate in Freestyle Swimming


Acknowledgements

The authors gratefully acknowledge the swimmers who gave their consent for participation in the study. The assistance of Swimming Australia Ltd is also acknowledged.
Figure 1. Inertial sensor device (MiniTraqua™) used for quantifying kick count and kick rate. The image is orientated as it appears on the thigh and shank during testing.
Figure 2. A typical gyroscope trace for one second of data capture from the inertial sensor. A single complete kick, indicated by the vertical black lines, consists of a combined downbeat and upbeat starting from zero rad·s$^{-1}$ and finishing when the limb segment has returned back to zero rad·s$^{-1}$.
Table 1. The standard error of the estimate (SEE) expressed in raw units and as a coefficient of variation (CV) with 90% confidence limits (90% CL) for validity.

<table>
<thead>
<tr>
<th>Side/Segment</th>
<th>Swimming Trials</th>
<th></th>
<th>Kicking-only Trials</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SEE (raw units)</td>
<td>CV (%)</td>
<td>SEE (raw units)</td>
<td>CV (%)</td>
</tr>
<tr>
<td>Left Side</td>
<td>2.5 (2.2 to 2.8)</td>
<td>2.1 (1.9 to 2.3)</td>
<td>1.7 (1.5 to 1.9)</td>
<td>0.7 (0.6 to 0.8)</td>
</tr>
<tr>
<td>Right Side</td>
<td>8.1 (7.2 to 9.2)</td>
<td>7.5 (6.7 to 8.5)</td>
<td>0.8 (0.7 to 0.9)</td>
<td>0.3 (0.3 to 0.4)</td>
</tr>
<tr>
<td>Thigh Segment</td>
<td>4.7 (4.2 to 5.3)</td>
<td>5.3 (4.8 to 6.0)</td>
<td>0.4 (0.4 to 0.5)</td>
<td>0.2 (0.1 to 0.2)</td>
</tr>
<tr>
<td>Shank Segment</td>
<td>7.5 (6.8 to 8.4)</td>
<td>6.4 (5.7 to 7.2)</td>
<td>1.9 (1.7 to 2.1)</td>
<td>0.8 (0.7 to 0.9)</td>
</tr>
<tr>
<td>Mean</td>
<td>6.4 (5.9 to 6.9)</td>
<td>5.9 (5.5 to 6.4)</td>
<td>1.4 (1.3 to 1.5)</td>
<td>0.6 (0.5 to 0.6)</td>
</tr>
</tbody>
</table>
Table 2. Mean bias of inertial sensor for kick count detection in freestyle swimming and kicking-only trials, expressed in raw units and as a percent with 90% confidence limits (90% CL), by individual swimmer.

<table>
<thead>
<tr>
<th>Swimmer</th>
<th>Swimming</th>
<th>Kicking-only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw Bias</td>
<td>% Bias</td>
</tr>
<tr>
<td>Swimmer 1</td>
<td>-0.1 ± 0.1</td>
<td>-0.1 ± 0.1</td>
</tr>
<tr>
<td>Swimmer 2</td>
<td>-7.3 ± 5.3</td>
<td>-7.2 ± 5.4</td>
</tr>
<tr>
<td>Swimmer 3</td>
<td>-0.9 ± 1.1</td>
<td>-1.0 ± 1.2</td>
</tr>
<tr>
<td>Swimmer 4</td>
<td>-0.7 ± 2.2</td>
<td>-0.8 ± 1.1</td>
</tr>
<tr>
<td>Swimmer 5</td>
<td>-1.1 ± 0.7</td>
<td>-1.1 ± 0.7</td>
</tr>
<tr>
<td>Swimmer 6</td>
<td>-1.8 ± 1.6</td>
<td>-1.5 ± 1.3</td>
</tr>
<tr>
<td>Swimmer 7</td>
<td>-0.1 ± 0.1</td>
<td>-0.1 ± 0.1</td>
</tr>
<tr>
<td>Swimmer 8</td>
<td>-9.3 ± 5.3</td>
<td>-7.2 ± 4.0</td>
</tr>
<tr>
<td>Swimmer 9</td>
<td>-1.3 ± 1.3</td>
<td>-1.0 ± 1.0</td>
</tr>
<tr>
<td>Swimmer 10</td>
<td>-0.0 ± 0.0</td>
<td>-0.0 ± 0.0</td>
</tr>
<tr>
<td>Swimmer 11</td>
<td>-0.2 ± 0.4</td>
<td>-0.2 ± 1.0</td>
</tr>
<tr>
<td>Swimmer 12</td>
<td>-0.1 ± 0.1</td>
<td>-0.0 ± 0.1</td>
</tr>
<tr>
<td>Mean</td>
<td>-2.0 ± 0.7</td>
<td>-1.7 ± 0.7</td>
</tr>
</tbody>
</table>
Figure 3. Scatter plot showing the kick count relationship between the inertial sensor and underwater video methods for quantifying kick in swimming and kicking-only trials. The open symbols show two swimmers whose kick count during swimming trials skewed results.
Table 3. The standard errors of the measurement (SEM) expressed in raw units and as a coefficient of variation for kick count and kick rate in swimming and kicking-only trials (CV) with 90% confidence limits (90% CL) for reliability.

<table>
<thead>
<tr>
<th>Kick Variable</th>
<th>Swimming Trials</th>
<th>Kicking-only Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SEM (raw units)</td>
<td>CV (%)</td>
</tr>
<tr>
<td>Count (one-day)</td>
<td>5.7 (5.1 to 6.4)</td>
<td>4.6 (4.0 to 5.6)</td>
</tr>
<tr>
<td>Count (five-week)</td>
<td>10.2 (9.3 to 11.3)</td>
<td>3.9 (3.5 to 4.5)</td>
</tr>
<tr>
<td>Rate (one-day)</td>
<td>4.2 (3.8 to 4.8)</td>
<td>3.5 (3.1 to 3.9)</td>
</tr>
<tr>
<td>Rate (five-week)</td>
<td>4.8 (4.4 to 5.3)</td>
<td>3.9 (3.6 to 4.4)</td>
</tr>
</tbody>
</table>

*One-day reliability was reported between two trials at each testing session.

*Five-week reliability was reported for two trials between each testing session.
Chapter 6: Quantifying Freestyle Kick Count and Kick Rate Patterns in Paralympic Swimming

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Statement of Intellectual Contribution

I, Sacha Kate Fulton, have made substantial independent intellectual contributions to the research paper ‘Quantifying Freestyle Kick Count and Kick Rate Patterns in Paralympic Swimming’. I consider that intellectual contribution is the substantial, direct, intellectual contribution to the conception and/or design of a research paper. Intellectual contribution is different from technical services, which although essential to the work, are not in themselves sufficient contributions to justify intellectual contribution. I consider that examples of intellectual contributions include, but are not limited to, significant input in the development of the study hypothesis, design of the study, development of study protocols, identification of study methodology, development or modification of methodology used in the project, or development of new applications, unique settings for use of existing methodology, or responsibility for independent analysis and interpretation of results.

Sacha Kate Fulton, CANDIDATE 18th December 2008

David B Pyne, CO-AUTHOR 18th December 2008

Brendan Burkett, CO-AUTHOR 18th December 2008
Chapter 6: Quantifying Freestyle Kick Count and Kick Rate Patterns in Paralympic Swimming

Abstract

Swimming velocity is a function of the propulsion generated from arm strokes and leg kicks. Kicking is partially obscured underwater making the kinematics of the kick difficult to analyse. This research quantified freestyle kick count and kick rate variables for 14 Paralympic swimmers using inertial sensor technology to determine changes and differences within and between a) swimming and kicking-only trials; b) Paralympic classes and disabilities; and c) 100 m distances. Swimmers took 145 ± 39 kicks (mean ± s) for swimming trials and 254 ± 74 kicks for kicking-only trials. Kick rate was 124.9 ± 20.3 kicks·min⁻¹ for swimming trials and 129.6 ± 14.0 kicks·min⁻¹ for kicking-only trials. Between 25 m segments there were no substantial changes in kick count within swimming trials. However a substantial increase of 10.6% (90% confidence interval 7.3 to 14.0%) in the number of kicks was observed for kicking-only trials by the 4th 25 m segment. There was a substantial decrease in kick rate by the 3rd 25 m segment for swimming of -12.0% (-12.8 to -11.1%) and kicking-only of -7.3% (-8.6 to -5.9%) trials. The relationship between swimming and kicking-only kick rates was \( r = 0.67 \) (0.55 to 0.76). The temporal patterns of the kick in kicking-only were different from swimming; improvements in kick rate are identified as a potential means of eliciting improvements in freestyle swimming performance.

Keywords: swimming, freestyle kick, disability, inertial sensor technology
Chapter 6: Quantifying Freestyle Kick Count and Kick Rate Patterns in Paralympic Swimming

Introduction

In swimming the contribution of kicking to overall swim velocity has yet to be clearly quantified. The influence of stroke count and stroke rate on swimming propulsion has been investigated (Kennedy, Brown, Chengalur & Nelson, 1990; Arellano, Brown, Cappaert et al., 1994 & Hellard et al., 2007); however, kicking is partially obscured by turbulence and presumably occurs at an unknown faster rate. In freestyle swimming the relative contribution to velocity from the upper and lower limbs is unclear (Persyn, Daly, Vervaecke, Van Tilborgh, & Verhetsel, 1983; Watkins & Gordon, 1983; Hollander, DeGroot, Jan van Ingen Schenau, Kahman, & Toussaint, 1988; Deschodt, Arsac, & Rouard, 1999; Chollet, Chalies, & Chatard, 2000; Millet, Chollet, Chalies, & Chatard, 2002) and there is conflicting evidence on how propulsion is generated. Information on kick count and kick rate patterns in swimmers may enable coaches to ensure training programs are conditioning the legs appropriately to meet kicking demands during competition.

The optimal length of time and the type of kick used during the underwater phase of the start and turn has been measured using underwater cameras (Lyttle, Blanksby, Elliot, & Lloyd, 2000). The underwater dolphin kick, a simultaneous upbeat and downbeat of the legs used in butterfly swimming, is substantially faster than swimming on the surface in the start and turn phase (Lyttle & Mason, 1997; Lyttle, Blanksby, Elliott, & Loyd, 1999). The optimal time to resume kicking after a turn, and the different gliding and kicking styles that can be adopted to minimise deceleration caused by drag forces, have also been examined (Lyttle, et al., 2000). In freestyle the flutter kick is generally thought to have relatively low efficiency compared with the arm stroke for producing propulsive force. There is little difference between arms only and legs only peak oxygen consumption (VO2 peak) in free and simulated swimming (Konstantaki, Winter, & Swaine, 2004). Determining the differences in kick count and kick rate with and without the arm stroke in freestyle swimming would give valuable insight into the potential of kicking to contribute to swimming velocity.

In Paralympic competition, swimmers with functional disabilities compete in 10 classes: S1 (most severe disabilities) to S10 (least severe disabilities). Within these classes there are swimmers with upper limb disabilities (e.g. arm amputee), lower limb disabilities (e.g. trans-femoral amputee or spinal cord injury), and disabilities
that may affect the whole body (e.g. cerebral palsy). Swimmers with upper limb disabilities naturally have a great dependence on the kicking action and for optimal performance it is vital these swimmers enhance their kick. Swimmers with lower limb disabilities may have to modify their pattern of kick to complement the arm action and optimise velocity. For all swimmers, with or without a disability, there is a relationship between kicking and swimming performance though the magnitude of the contribution of the kick is still an open question. For swimmers with a disability, the contribution of arms and legs to freestyle performance is fundamental to the present classification system.

Coaches prescribe kicking-only drills in the majority of swimming training sessions however until now the lap time has been the only variable quantified (Konstantaki & Winter, 2007). The difficulty in measuring the kick can be overcome with recent technological developments, such as inertial sensor technology (see Chapter 5). Using this technology the assessment of kick count and kick rate variables in kicking-only performance could identify the kick variables that elicit improvements in full-stroke freestyle swimming performance. These findings could then assist coaches to design more effective swimming training programs and enhance performance applications. The aim of this study was to quantify freestyle kick count and kick rate variables over race distances in Paralympic swimmers to determine a) changes between swimming and kicking-only trials; b) differences between Paralympic classes and disabilities; and c) changes within and between 100 m distances. The relationship between freestyle swimming kick rate and kicking-only kick rate was investigated as well as the influence of kick rate on time for swimming and kicking-only trials.

**Methods**

**Participants**

Fourteen Paralympic swimming finalists (eight males: age 20.9 ± 4.2 yr, stature 179.0 ± 6.8 cm, body mass 74.4 ± 12.1 kg; six females: age 18.0 ± 2.9 yr, stature 154.1 ± 20.9 cm, body mass 55.2 ± 6.4 kg; mean ± s) participated in the study. Kick variables were quantified by Paralympic class and disability (Table 1). Ethical approval was obtained prior to commencement of the study through the University of the Sunshine Coast and the Australian Institute of Sport Ethics Committees and all swimmers provided written informed consent. The participants were primarily sprint distance (50
m and 100 m) trained swimmers. The class S6 and S7 swimmers trained ~3-4 sessions (total volume ~8 km) per week and class S8-S10 swimmers trained ~4-6 sessions (~20 km) per week. All swimmers completed 1-2 weekly dry land training sessions involving resistance training, stretching and swimming-specific exercises. At the time of the study the participant’s 100 m world ranking for their class were: three participants ranked 1-5, five participants ranked 6-10, five participants ranked 11-15 and one participant ranked 16-20.

**Study design and procedures**

Swimmers performed both a 100 m freestyle swimming and 100 m freestyle kicking-only time trial at nine weeks (Trials 1 and 2) and five weeks (Trials 3 and 4) prior to a World Championship and two weeks after the competition (Trials 5 and 6). All trials were performed in a certified short-course (25 m) pool. Kick count and kick rate patterns were quantified and averaged for each 25 m segment using inertial sensor technology. Standardised changes in kick patterns within and between trials were also reported. Kick rate relationships were examined within and between swimming and kicking-only trials.

Swimmers had ~24 h recovery between trials at each testing period, and as much active recovery as required between the swimming and kicking-only trials on each day of testing. Swimmers wore a single inertial sensor, orientated on the calf of the dominant leg, to quantify kick count and kick rate. Each sensor had the following specifications; a ±2G tri-axial accelerometer; a single > 600 rad·s⁻¹ angular rate sensor (gyroscope); a 256 megabyte memory for data storage; USB interface for charging, calibrating, firmware upgrade and downloading data; a rechargeable battery; and an LED screen for operational status indication. The recording system was configured for 100 Hz sampling rate on all three accelerometer channels and the gyroscope channel.

A kick count was registered as the upbeat and downbeat of a single leg, and kick rate was derived as the number of kicks per unit of time. The gyroscope functionality was utilised to detect kick patterns given the absolute measure of angular velocity. Briefly, the standard error of the estimate for kick count validity, expressed as a coefficient of variation (CV), was 5.9% (90% confidence interval 5.5 to 6.4%) for swimming and
Swimmers completed their own pre-race warm up and post-race swim down for each time trial performance. Trials were started from a push and timed manually using a hand-held stopwatch (Seiko, Tokyo, Japan) for 25 m split times and final time. Swimmers were given equal verbal encouragement before and during each trial to ensure a maximal effort. Swimmers were instructed to swim to their normal race strategy for the swimming trials and keep both hands on the kick board for the duration of the kicking-only trials.

**Statistical analysis**

Descriptive statistics (mean ± s) for time and kick variables were used to characterise the sample group by Paralympic class and disability. Standardised changes in time and kick variables within and between 100 m freestyle swimming and kicking-only trials were reported. Confidence intervals (90%) were used to make inferences about clear effects. To reduce the likelihood of heteroscedasticity (non-uniformity of error) kick variables were log-transformed before analysis, the means were then back-transformed (Nevill, 1997). Log-transformed changes in performance were converted into standardised changes in the mean. The smallest standardised change was assumed to be 0.20 (Cohen, 1988). The magnitude of change (effect size) was interpreted as: trivial 0.0-0.20, small 0.20-0.60, moderate 0.60-1.20, and large >1.20 (Hopkins, 2004). An effect was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold (effect size of ± 0.2).

The relationship between swimming and kicking-only trials for kick rate was expressed as a Pearson correlation coefficient. The magnitude of correlation was interpreted as: trivial <0.10, small 0.10-0.30, moderate 0.30-0.50 and large >0.50 (Cohen, 1988). A relationship was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold ($r$ value of ± 0.1) (Hopkins, 2004). Correlations were calculated by 25 m lap segment and averaged across segments and trials.
To quantify the relationship between kick rate and the contribution of each 25 m segment to final time, within-athlete correlation coefficients ($r$) between kick rate and 25 m segment time were derived for swimming and kicking-only trials. The practical implication of the correlations was assessed by estimating the magnitude of the within-athlete standard deviation ($s$) to predict a swimmer’s change in a correlated dependent variable (25 m time) from a change in a predictor variable (kick rate). From statistical first principles, the relationship between the change in a predictor ($\Delta x$) and a dependent ($\Delta y$) variable is $\Delta y/s_y = r\Delta x/s_x$, where $s_y$ and $s_x$ are the standard deviations of $x$ and $y$, and $r$ is the correlation coefficient. Assuming the predictor and performance scores were normally distributed, this relationship was used to calculate changes in $x$ (as a factor of $s_x$) needed to change final time. Mixed modelling was used to fit straight lines to kick rate and associated 25 m time. The slope of the line was expressed as an $x$% change in kick rate for a $y$% change in 25 m time (%/%). The model provided estimates of the effect of changes in kick rate on lap time and these estimates were averaged across all four laps. A change in kick rate of two standard deviations was deemed appropriate (Hopkins, 2006). Subjective interpretations were made regarding changes in final time with the threshold for the smallest worthwhile enhancement (0.5 x within athlete coefficient of variation) (Hopkins, Hawley, & Burke, 1999) in Paralympic swimming performance in international competitions.

**Results**

Time, kick count and kick rate (mean ± $s$) for 100 m swimming and kicking-only time trials are shown in Table 2. For all disabilities and classes, time, kick count and kick rate variables were substantially higher in kicking-only trials than in swimming trials. Freestyle swimming trials were ~40% faster than kicking-only trials and similarly kick count was ~40% higher in kicking-only trials. Conversely, only small differences of ~4% were observed for kick rate between freestyle swimming and kicking-only trials. Swimmers in the S6 class had the slowest velocity for swimming and kicking-only trials with the highest kick count. Swimmers in class S9 and S10 exhibited the highest kick rate for swimming and kicking-only trials. The arm amputee swimmers had the fastest velocity and the lowest kick count, almost half that of short stature swimmers, for swimming and kicking-only trials. Leg amputee swimmers had the highest kick rates in swimming and kicking-only trials.
All swimmers used a four-beat or six-beat kick, which remained unchanged within and between all swimming trials, revealing stable leg kick. The relationship between swimming and kicking-only kick rate was \( r = 0.67 \) (90% confidence interval 0.55 to 0.76) for all swimmers. In Paralympic competition swimmers from several impairment groups compete in the same class. The relationship between swimming and kicking-only kick rate for Paralympic disabilities was: leg amputee \( r = 0.89 \) (0.80 to 0.94); short stature \( r = 0.46 \) (-0.04 to 0.46); cerebral palsy \( r = 0.27 \) (-0.04 to 0.53) and arm amputee \( r = -0.38 \) (-0.73 to 0.14).

The kick patterns for 25 m segments within 100 m time trials for Paralympic swimmers are shown in Figure 1. Table 3 depicts the magnitude of change in kick variables between the 1st to 2nd, 1st to 3rd and 1st to 4th 25 m segments of 100 m time trials. Magnitudes of change in kick variables between the 2nd to 3rd and 3rd to 4th 25 m segments were examined, however, no substantial differences were observed. Velocity decreased substantially by the 3rd and 4th 25 m segments for swimming and kicking-only trials as swimmers fatigued. The short stature swimmers had the largest decrease in velocity by the 3rd 25 m segment for swimming trials of 16.2% (90% confidence interval 14.3 to 18.2); all other swimmers decreased swimming velocity by ~12% by the 3rd 25 m segment. For kicking-only trials, arm amputee swimmers substantially decreased velocity by 16.8% (13.5 to 20.1) by the 3rd 25 m segment; all other swimmers decreased swimming velocity by ~20%.

There was no substantial difference in kick count between 25 m segments in swimming trials though arm amputee swimmers had small increases of 3.9% (2.2 to 5.6) by the 3rd 25 m segment. Small increases in kick count were observed in kicking-only trials by the 3rd and 4th 25 m segments for all swimmers. In the 3rd and 4th 25 m segment for swimming and kicking-only trials, all swimmers observed moderate decreases in kick rate. Between consecutive segments the most substantial decrease in kick rate occurred between the 1st and 2nd 25 m segment. There were no substantial differences observed for kick count or kick rate between testing sessions. There was no substantial change in relationships between swimming and kicking-only kick rate between 25 m segments.
The effect of kick rate on 100 m freestyle swimming and kicking-only time was modelled via a within-athlete correlation coefficient for each 25 m segment of all trials. For a given increase in kick rate there was an associated improvement in final time for swimming and kicking-only trials. There was no substantial difference in the relationship between kick rate and lap time between all four segments. An increase in kick rate of 9.1 ± 5.0% (mean ± s) equated to an overall improvement in freestyle swimming final time of 3.3 ± 2.6% (~2.5 s). An increase in kick rate of 7.9 ± 3.1% (mean ± s) equated to an overall improvement in freestyle kicking-only final time of 2.8 ± 4.6% (~3.5 s).

**Discussion**

The measurement of kicking dynamics of Paralympic swimmers showed that small to moderate decreases in kick rate were associated with a reduction in swimming velocity during the latter stages of a 100 m time trial. Kick rate was identified as an important factor for freestyle swimming time trial performance. Correlations between swimming and kicking-only kick rate suggest that kick rate is under utilised in Paralympic freestyle swimmers. Substantial improvements in final time for freestyle swimming trials are achievable when kick rate is increased. Coaches need to prescribe training programs that minimise the reduction in kick rate during a 100 m freestyle event. Coaches and swimmers can utilise these findings to guide their training regime and kick strategy for enhancing the kick contribution to swimming performance during competition.

Kick count is substantially greater in kicking-only compared to swimming, where the combined action of the upper body and legs allow swimmers to cover the same distance using only half the number of kicks, and in around two-thirds of the time. Arm amputee swimmers with relative ‘able-bodied’ lower limbs recorded the fastest kicking-only times and used the least number of kicks to cover the 100 m distance. These values increased for cerebral palsy swimmers, given the inherent poorer motor control of the lower body in athletes with this disability. An even greater number of kicks were taken by leg amputee swimmers presumably reflecting an adaptive response to compensate for amputation. Short stature swimmers, took twice as many kicks as other disabilities, consistent with slower times. Swimmers in the S9 and S10 classes exhibited the highest kick rate values for swimming and kicking-only trials.
suggesting that swimmers with greater functional ability have sufficient motor control to produce higher kick rates. By disability, leg amputee swimmers had the highest kick rates in swimming and kicking-only trials suggesting a natural adaptive response to help stabilise the body and increase forward propulsion. The current classification system used to group swimmers with functional disabilities for Paralympic competition has been assessed for its robustness and found effective to generating fair competition for most swimmers (Daly & Vanlandewijck, 1999; Wu & Williams, 1999). Our data indicate that freestyle kicking ability is not directly related to classification but may be more attributable to disability. As the degree of lower limb musculoskeletal limitation increases kick count values also increase. This evidence could be useful for refining the classification system.

Paralympic swimmers adopt and maintain natural kick count and kick rate patterns for race pace efforts, which remain largely unchanged during a season. Within swimming trials, however, substantial changes are apparent. Decreases in velocity by the 3rd 25 m segment are indicative of competitive 100 m freestyle swimming performance where velocity is high in the early stages of a race before velocity decreases in the latter stages as swimmers fatigue (Daly, Djobova, Malone, Vanlandewijck, & Steadward, 2003; Seifert, Boulestelx, Carter, & Chollet, 2005). Within the current study, freestyle kicking-only trials followed a similar pattern of changes in velocity. However, decreases in velocity were substantially higher than swimming trials suggesting that swimmers were less experienced with pacing these trials. Furthermore, there were no substantial changes in kick count between segments for swimming trials and swimmers maintained a stable kick-beat, suggesting that the majority of swimmers adopt consistent kick count and kick beat patterns. This pattern is consistent with data showing that stroke length is maintained throughout a swim race (Daly et al., 2003; Seifert et al., 2005). The small increases in kick count throughout segments for kicking-only trials of the current study most likely reflect leg fatigue and swimmers becoming less efficient (less distance travelled for each kick) towards the end of trials. The changes in kick rate and velocity were similar to changes observed in competitive freestyle swimming where stroke rate and velocity decline in the latter stages of a race, indicative of swimmer fatigue (Daly et al., 2003). A reduction in kick rate may be one of several factors associated with reduced swimming velocity and may not be the most powerful influence. Coaches should
however train swimmers to control kick rate in the early stages of a race and maintain kick rate in the latter stages of a race to ensure performance is not jeopardised.

There is a general debate that changes in kick rate can only be brought about by corresponding changes in stroke rate (Chollet, Pelayo, Tourny, & Sidney, 1996). However, the precise contribution of stroke rate and kick rate to swimming velocity is still to be determined and there is no conclusive evidence to suggest that changes in one variable are a result of changes in another (Hollander et al., 1988; Deschodt et al., 1999; Seifert, Chollet, & Chatard, 2007). Kick rate was typically higher in kicking-only trials when compared with swimming trials for all swimmers. Given the large correlation coefficients between swimming and kicking-only kick rates for all swimmers, the current study suggests that some swimmers have a better transfer of kick rate from kicking-only to swimming trials than others. That is, some swimmers are better able to match the typically higher kicking-only kick rates with swimming kick rates. Kick rate may therefore be an important variable for coaches to measure during kick training to help guide training regimes and kick strategies for enhancing whole stroke competition performance.

Quantifying kick variables has important implications for training prescription and competition sprint performance. The leg kick in swimming allows for a 10% increase in maximal 25 m sprint speed, when compared to swimming with the arms alone (Deschodt et al., 1999). A key question in the present study was the relationship between kick and swim performance. The estimated change in kick rate required to change final time was modelled from correlations between kick rate and swimming or kicking-only 25 m segment times. The predicted enhancements in swimming time from changes in kick rate varied substantially between swimmers suggesting that some swimmers will benefit more than others from increasing kick rate. This may also reflect the different impairments of the swimmers. A similar enhancement was also observed between all 25 m segments across all swimmers suggesting that for a given change in kick rate there was a corresponding change in 25 m time, independent of fatigue. This relationship is not however causal, as mentioned above and the effect of confounding variables such as kick amplitude should be considered. Recent findings have however suggested that kick training improves leg conditioning and is effective for inducing training adaptations (Konstantaki & Winter, 2007). Combined with the
achievable increases in kick rate, coaches could use this knowledge to design kicking training programs to increase swimming velocity.

The current study is the first to characterise kick count and kick rate patterns in freestyle swimming and kicking-only performance trials for Paralympic swimmers. Substantial improvements in final time may be achievable when kick rate is increased and maintained over 100 m freestyle swimming and kicking-only distances. Nevertheless, further studies are needed to account for possible confounding variables such as kicking amplitude. Implementing inertial sensor technology should enable coaches to monitor kick variables in kicking-only training and design test protocols to measure performance improvement. Conditioning programs that allow swimmers to maintain a continuous kick and use the kick as a surge tactic in competition are required. Further studies are needed to thoroughly investigate training, stroking and kicking strategies and 100 m freestyle performance in elite swimmers.
References


Chapter 6: Quantifying Freestyle Kick Count and Kick Rate Patterns in Paralympic Swimming


Acknowledgements

The authors gratefully acknowledge the swimmers and coaches who gave their time to participate in the testing sessions.
Table 1. The breakdown of classes included within each disability.

<table>
<thead>
<tr>
<th>Disability</th>
<th>Number of swimmers (n)</th>
<th>Class breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebral Palsy</td>
<td>5</td>
<td>S7, n = 1; S8, n = 3; S10, n = 1</td>
</tr>
<tr>
<td>Leg Amputee</td>
<td>5</td>
<td>S9, n = 3; S10, n = 2</td>
</tr>
<tr>
<td>Arm Amputee</td>
<td>2</td>
<td>S8, n = 1; S9, n = 1</td>
</tr>
<tr>
<td>Short Stature</td>
<td>2</td>
<td>S6, n = 2</td>
</tr>
</tbody>
</table>
Table 2. Kick variables (mean ± s) for freestyle swimming and kicking-only 100 m trials, by disability and class.

<table>
<thead>
<tr>
<th>Disability</th>
<th>All Swimmers (n = 14)</th>
<th>Swimming</th>
<th>Kicking-only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (s)</td>
<td>Count (n)</td>
<td>Rate (k·min⁻¹)</td>
</tr>
<tr>
<td>Disability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cerebral Palsy (n = 5)</td>
<td>71.5 ± 8.8</td>
<td>136 ± 13</td>
<td>123 ± 11</td>
</tr>
<tr>
<td>Leg Amputee (n = 5)</td>
<td>70.0 ± 4.1</td>
<td>142 ± 38</td>
<td>132 ± 30</td>
</tr>
<tr>
<td>Arm Amputee (n = 2)</td>
<td>63.1 ± 1.2</td>
<td>112 ± 7</td>
<td>117 ± 8</td>
</tr>
<tr>
<td>Short Stature (n = 2)</td>
<td>107.5 ± 4.4</td>
<td>208 ± 36</td>
<td>124 ± 18</td>
</tr>
<tr>
<td>Class</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class S10 (n = 3)</td>
<td>70.1 ± 4.4</td>
<td>132 ± 111</td>
<td>123 ± 8</td>
</tr>
<tr>
<td>Class S9 (n = 4)</td>
<td>66.6 ± 4.5</td>
<td>135 ± 45</td>
<td>128 ± 34</td>
</tr>
<tr>
<td>Class S8 (n = 4)</td>
<td>67.1 ± 2.7</td>
<td>133 ± 13</td>
<td>128 ± 8</td>
</tr>
<tr>
<td>Class S7 (n = 1)</td>
<td>88.0 ± 1.8</td>
<td>146 ± 3</td>
<td>110 ± 1</td>
</tr>
<tr>
<td>Class S6 (n = 2)</td>
<td>107.5 ± 4.4</td>
<td>208 ± 36</td>
<td>124 ± 18</td>
</tr>
</tbody>
</table>
Chapter 6: Quantifying Freestyle Kick Count and Kick Rate Patterns in Paralympic Swimming

Figure 1. Kick patterns between 25 m segments for 100 m freestyle trials by Paralympic disability.
Table 3. Percent change in kick patterns between 25 m segments for 100 m freestyle trials for Paralympic swimmers ±90% confidence interval and standardised effect size (ES).

<table>
<thead>
<tr>
<th></th>
<th>1st to 2nd Segment</th>
<th>1st to 3rd Segment</th>
<th>1st to 4th Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>ES</td>
<td>%</td>
</tr>
<tr>
<td><strong>Swimming</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>9.5 ±1.4</td>
<td>0.89*</td>
<td>13.0 ±1.5</td>
</tr>
<tr>
<td>Count</td>
<td>-1.9 ±2.3</td>
<td>-0.09</td>
<td>0.2 ±1.9</td>
</tr>
<tr>
<td>Rate</td>
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<td>-6.4 ±1.2</td>
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*Clear effect (±90% confidence interval does not include substantial positive and negative values).
Chapter 7: Influence of Kicking Velocity and Amplitude on Net Force and Kick Rate in Paralympic Swimmers

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Statement of Intellectual Contribution

I, Sacha Kate Fulton, have made substantial independent intellectual contributions to the research paper ‘Influence of Kicking Velocity and Amplitude on Net Force and Kick Rate in Elite Swimmers’. I consider that intellectual contribution is the substantial, direct, intellectual contribution to the conception and/or design of a research paper. Intellectual contribution is different from technical services, which although essential to the work, are not in themselves sufficient contributions to justify intellectual contribution. I consider that examples of intellectual contributions include, but are not limited to, significant input in the development of the study hypothesis, design of the study, development of study protocols, identification of study methodology, development or modification of methodology used in the project, or development of new applications, unique settings for use of existing methodology, or responsibility for independent analysis and interpretation of results.

Sacha Kate Fulton, CANDIDATE

David B Pyne, CO-AUTHOR

Brendan Burkett, CO-AUTHOR
Abstract
Kicking is a key component of swimming, yet the influence of kicking velocity and amplitude on net force and kick rate remains unknown. For Paralympic swimmers, where the kicking action is fundamental to swimming, particular for the upper limb disabilities, the contribution of the kick is an important question. The purpose of this study was to determine the influence of towing velocity and kick amplitude on net force and kick rate. A secondary purpose was to establish the validity and reliability of a modified dynamometer and force platform system to measure net passive force and net active force. Twelve Paralympic swimmers (aged 19.8 ± 2.9 years; mean ± SD) were towed at their individual peak freestyle velocity using a modified dynamometer and force platform system. The experimental conditions were as follows: i) a prone streamline glide position, with the arms fully extended, the legs unsupported and no kicking action and ii) maximal freestyle kicking in a prone streamline position. Kick rate was quantified using inertial sensor technology. A prone streamline was adopted for passive trials. Maximal freestyle surface kicking was adopted for active trials for different velocities and kick amplitudes as prescribed by researchers. The towing speed of the dynamometer was checked for validity and overhead video was the criterion measure for velocity. The standard error of the estimate (validity) expressed as a coefficient of variation was 0.6 (±0.1%, ±90% confidence interval). Net force was measured using a Kistler force platform system. The test-retest reliability of measuring net force was ~6%. Active force increased 24.2% (±5.3) when peak velocity was increased 5%. However, the kick rate remained at ~150 kicks·min⁻¹. Larger amplitude kicking increased the net active force by 25.1% (±10.6), although kick rate decreased substantially by -13.6% (±5.1). Speed-assisted kick training may help swimmers increase kick rate velocity.

Keywords: swim, towing force, passive, active, dynamometer
Chapter 7: Influence of Kicking Velocity and Amplitude on Net Force and Kick Rate in Paralympic Swimmers

Introduction

The combination of kick and arm stroke generate a net propulsive force in swimming. These forces are typically classified as either the streamline (passive) force or swimming (active) force. Towing a swimmer through the water in a rigid streamline position, with a tethering device transduced to measure the force required to maintain equilibrium, is a method used to estimate the passive force of a swimmer (Chatard et al., 1990a; Lyttle et al., 1998; Maiello et al., 1998; Lyttle et al., 2000). Towing a swimmer through the water as they create propulsive movements such as stroking or kicking, is used to estimate active force (Toussaint et al., 1988; Kolmogorov & Duplishcheva, 1992; Toussaint & Hollander, 1994; Lyttle et al., 2000). The leg kick, when a part of the full stroke, increases maximal swimming velocity when compared to swimming with the arms alone (Deschodt et al., 1999). However net kicking forces have received little attention in the peer-reviewed research literature. Therefore, investigation of the influence of velocity and kicking amplitude on net force and kick rate may identify potential training methods for improving swimming velocity.

Net force production in swimming has been described using various methods. The Measurement of Active Drag (MAD) system used a series of submerged static pads, fixed to a force transducer which quantified the force exerted as a swimmer propelled themselves forward (Hollander et al., 1986). While this early system was the first to provide an objective measure of the forces generated during swimming, it is restricted to freestyle swimming and only a limited range of the underwater stroke. The MAD system was also unable to evaluate the contribution of the kick, as swimmers were required to hold a pool buoy between their legs to prevent injury when testing. The Indirect Measurement of Active Drag (IMAD) system followed the MAD system using only a tape measure, stop watch and formulae extracted from mathematical modelling (Shahbazi et al., 2006). In contrast to the MAD system the IMAD method is capable for use with all strokes and the arms and legs separately. Other systems use the hydrodynamic body technique developed in the early 1990s (Kolmogorov & Duplishcheva, 1992), where the force is calculated from the difference in velocity between two maximal swimming conditions. However, initial results were somewhat paradoxical with measured net active force greater than net passive force in most strokes.
In the late 1990s Lyttle et al., (1999) designed a system to measure above-water and underwater forces created by swimmers. A towing system was performed using a variable-control, motorized winch with a control unit adjustable to 0.1 m·s\(^{-1}\). Net force was recorded using a unidirectional load-cell. The load-cell was calibrated before testing using static weights (Lyttle et al., 1999). The towing device was able to quantify forces at predetermined velocities and depths using a mechanical, velocity control unit and strain gauge amplifiers. High intra-day reliability was reported for this system for measuring passive and active forces (Lyttle et al., 1999). To confidently determine the small changes in net force a valid and reliable measurement system must be used when quantifying passive and active forces.

Net forces in swimming are influenced by skin friction, wave-making frontal resistance caused by the swimmers’ movements and cross-sectional surface area, and eddy resistance caused by water turbulence from poor stroke technique (Sheehan & Laughrin, 1992). Net passive force is a good indicator of general aptitude for swimming and depends on the performance level of a swimmer (Chatard et al., 1990b). The velocity and depth of the tow influences the net passive force profile (Maiello et al., 1998; Lyttle et al., 2000). An exponential increase in the net passive force is elicited with an increase in velocity, as force is a function of velocity squared (Lyttle et al., 1998; Lyttle et al., 2000). Hydrodynamic studies of streamlined objects at different depths show that net passive force is greatest immediately below the water surface and decreases with depth (Maiello et al., 1998), although velocity is also a factor. At a depth of to 0.6 m there is no significant difference in passive force when swimmers are towed at velocities between 1.6 and 1.9 m·s\(^{-1}\). Between 2.2 and 3.1 m·s\(^{-1}\) the passive force at 0.2 m is significantly higher than 0.4 or 0.6 m (Lyttle et al., 2000). For different streamlining positions, a prone position consistently shows higher passive force than a lateral position at velocities between 1.6 m·s\(^{-1}\) and 3.1 m·s\(^{-1}\) (Lyttle et al., 2000). Overall, reducing resistance is more important to a swimmer than increasing propulsion through extra effort or exaggerated movements (Rushall et al., 1994).

The influence of stroke and/or velocity on active force has been measured (Toussaint et al., 1988; Kolmogorov & Duplishcheva, 1992; Toussaint & Hollander, 1994). Research on the influence of manipulated freestyle kicking amplitude on net force is
conflicting (Alley, 1952; Counsilman, 1968). At a towing velocity of ~1.3 m·s⁻¹ net active force is greater when swimmers use a typical amplitude kick compared with a reduced amplitude kick. When velocity was increased, there was no difference in towing force between the kicking amplitudes (Alley, 1952). Conversely, maximal kicking at a low towing velocity increases active force when compared with maximal kicking at higher velocities, however amplitude was not measured (Counsilman, 1968). In underwater kicking there is no advantage over using a prone dolphin kick, lateral dolphin kick or prone flutter kick (Lyttle & Mason, 1997; Lyttle et al., 2000). Swimmers should initiate underwater kicking at velocities between 1.9 m·s⁻¹ and 2.2 m·s⁻¹ to minimise deceleration caused by drag forces (Lyttle et al., 2000). While these studies have implications for the underwater phase of the start and turn, the force profile of the free-swimming component of freestyle where the leg kick is performed on the water surface is unknown. Given that researchers can now measure kick characteristics such as kick rate, the influence of changes in velocity and kicking amplitude on kick rate when swimmers are towed at competitive velocities, can be investigated in a research setting.

The contribution of the kick can be estimated by quantifying the difference between the force required to maintain equilibrium at max swimming velocity while kicking only and the force required to maintain equilibrium without kicking. Together these measurements will allow researchers to address issues of kicking velocity and amplitude. In Paralympic competition, swimmers with functional disabilities compete in 10 classes: S1 (most severe disabilities) to S10 (least severe disabilities). Swimmers with upper limb disabilities naturally have a great dependence on the kicking action. For optimal performance and swimmers with lower limb disabilities may have to modify their pattern of kick to complement the arm action and optimise velocity. For all swimmers, with or without a disability, the contribution of the kick is an important question. The influence of kicking velocity and amplitude on force may have performance implications for coaches and researchers wishing to develop techniques to enhance free-swimming velocity in Paralympic swimmers while concurrently estimating the contribution of the kick.

The purpose of this study was twofold. Part 1 of the study established the validity of a modified dynamometer to measure velocity, and the reliability of a modified
dynamometer and force platform system to measure net passive and active force for streamlining and kicking conditions. In this study the propulsive contribution to overall active force was estimated by determining the difference between active force when kicking and passive force when gliding. Part 2 of the study measured net force and kick rate at three separate velocities, and for different kicking amplitudes, to determine the influence of velocity and kicking amplitude on net force and kick rate.

**Methods**

**Participants**

Twelve elite Paralympic swimmers (nine males, aged 20.7 ± 2.6 yr; stretch stature 1.81 ± 0.1 m; body mass 76.2 ± 10.1 kg; and three females aged 17.3 ± 2.5 yr; stretch stature 1.66 ± 0.1 m; body mass 58.3 ± 0.9 kg; mean ± SD) volunteered to participate in this study. The disabilities of the swimmers were cerebral palsy n = 5, leg amputee n = 3, arm amputee n = 3 and visually impaired = 1. All swimmers were classified by the International Paralympic Committee (IPC) and had competed at the World Championships. Participants were informed of the experimental risks and signed an informed consent document prior to commencing the investigation. An institutional review board for experimentation using human subjects approved the investigation. Parental/guardian consent was obtained for those subjects under the age of eighteen.

**Study design and procedures**

To establish the validity and reliability of modified dynamometer and force platform system, four swimmers completed five trials over 30 m for two experimental conditions on three consecutive days. The experimental conditions were as follows: i) a prone streamline glide position, with the arms fully extended, the legs unsupported and no kicking action and ii) maximal freestyle kicking in a prone streamline position. Swimmers were towed at their individualised peak freestyle swimming velocity established over the 7 m data collection distance. The mean peak velocities of the four swimmers were 1.1 m·s⁻¹, 1.7 m·s⁻¹, 1.7 m·s⁻¹, and 1.9 m·s⁻¹. The criterion measure of velocity was determined with frame-by-frame analysis from an overhead video camera (SAMSUNG digital colour camera, type: SCC-C4301P, capturing at 50 Hz) on a single day of testing. The reliability of the modified dynamometer and force platform system to measure net force was established between trials within one day, and between trials conducted daily for three consecutive days. The motorized drum
around which the towline was coiled had a 66.4 cm internal groove; the distance for one complete revolution of the drum. A speed of 1.0 m·s⁻¹ was equal to 89.5 revolutions. A simple calculation therefore determined the number of revolutions programmed into the dynamometer.

Net passive force was determined using a prone streamline glide position, with the arms fully extended, the legs unsupported and no kicking action. To measure net active force the same streamline position was adopted, coupled with a maximal freestyle surface kick as used during free (mid pool) swimming. Swimmers were tested individually during a single two-hour session complete with a number of passive and active tows to familiarize the subjects prior to the formal data collection. Net passive force was measured at the swimmer’s individual peak velocity, and net active force was measured using five separate kicking conditions. Swimmers maintained their typical swimming amplitude kick for three velocities: i) 5% below peak velocity, ii) peak velocity, iii) 5% above peak velocity. Two different kicking amplitudes were then measured at peak velocity; i) larger amplitude kick, ii) smaller amplitude kick. Verbal instructions were given to the swimmers to increase or decrease their kick amplitude for the latter two conditions. Swimmers performed three trials for each experimental condition, for a total of eighteen trials, with ~60 s recovery between trials. The passive trials always preceded the active trials and the order of the three different velocity trials was randomized between swimmers. The larger amplitude kicking trials always preceded the smaller amplitude kicking trials.

Prior to data collection the peak towing velocity was determined from three maximal freestyle swimming trials over the 7 m data collection distance. The mean between-athlete velocities were: i) 5% below peak velocity 1.6 ± 0.1 m·s⁻¹ (mean ± SD); ii) peak velocity 1.7 ± 0.1 m·s⁻¹; iii) 5% above peak velocity 1.8 ± 0.1 m·s⁻¹. The net passive force \( F \) for the adjusted velocities was calculated as:

\[
F = \frac{1}{2} \cdot C \cdot \rho \cdot S \cdot v^2
\]

Where \( C \) is the body shape constant, \( \rho \) is the density of the water, \( S \) is the surface area perpendicular to the direction of motion, and \( v^2 \) is the observed swimming velocity (Kolmogorov & Duplishcheva, 1992). For a given velocity, a net active force smaller than a net passive force indicated that less force was required to tow a swimmer through the water, and thus a net force benefit was obtained from the kicking action.
This relationship between passive and active forces is the opposite of what happens during free swimming when an increase in net force elicits an increase in swimming velocity.

Net force was measured using a modified dynamometer and force platform system (Figure 1). All trials were completed in the same 50 m, certified indoor, Olympic swimming pool with water temperature kept constant at 27ºC. The towline was swum out to ~30 m without the dynamometer motor running. The towline was made from non-stretch mylar with an end loop. Swimmers held the end loop in both hands in the prone position with the arms fully extended. Swimmers had ~15 m to adopt the streamline position prior to the 7 m data capture. Force (N) was measured using a 0.9 x 0.6 m model Z12697 force platform (Kistler Instruments, Winterthur, Switzerland). The force platform was validated against a known calibrated mass prior to data collection. A flux vector direct drive dynamometer (custom built, Australian Institute of Sport, Canberra, Australia) was positioned directly on top of the force platform to measure rotational velocity (rpm). The force platform contained four piezometers in each corner of the plate. When the horizontal towing force was applied on the plate, a strain was developed in the piezometers. This strain was measured as an electrical signal and amplified to increase the sensitivity. The amplified signal (analogue) was converted to a digital signal and sent to a mainframe computer (Vax), for data collection. The mean net force was expressed in Newtons. Data were collected at 500 Hz for a 7 s sampling period during each trial. A low pass Butterworth filter (10 Hz) was applied to the data.

Each swimmer wore a single inertial sensor (MiniTraqua™, Version 5, Cooperative Research Centre for Micro-technology, Australian Institute of Sport) orientated on the calf of their dominant kicking leg to measure kick rate during all kicking trials. Each sensor had the following specifications; ±2G tri-axial accelerometer; single > 600 rad·s⁻¹ angular rate sensor (gyroscope); 256 megabyte memory for data storage; USB interface for charging, calibrating, firmware upgrade and downloading data; rechargeable battery; and an LED screen for operational status indication. The recording system was configured for a 100 Hz sampling rate on all three accelerometer channels and the gyroscope channel. The gyroscope functionality was
utilised to detect kick rate given the absolute measure of angular velocity. The typical error of the measurement for kick rate reliability of the sensors was 2.8% (±0.5%) (±90% confidence interval) measured within a single day of testing. Kick rate was derived as the number of kicks per unit time (k·min⁻¹). Hence, the criteria measure for kick rate was kick count. The standard error of the estimate between the inertial sensor and underwater video footage for kick count expressed as a coefficient of variation was 5.9% (±0.5%).

**Statistical analysis**

Validity was reported as the standard error of the estimate in raw and standardised (coefficient of variation) units. The mean bias was reported in raw units and as a percent. The precision of estimates was indicated with 90% confidence limits. The relationship between the dynamometer and video analysis was also characterised with the Bland-Altman estimate for limits of agreement and Pearson correlation coefficient. A correlation of r >0.95 was deemed an appropriate magnitude for validity (Hopkins, 2004). A relationship was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold (r value of ± 0.1) (Hopkins, 2004).

Reliability was reported as the typical error of the measurement, expressed as a coefficient of variation. Intra class correlation coefficients (ICC) were calculated to interpret the reproducibility of the repeated measures. ICC values <0.40 represented poor, 0.40-0.70 fair, 0.70-0.90 good, and >0.90 excellent reliability (reproducibility) (Fleiss, 1986). To evaluate the signal (the magnitude of change; non-random or systemic change in the mean that applies to all participants) to noise (the typical error or test-retest reliability; random change in the mean value due to sampling error) ratio the smallest important effect was calculated as 0.2 of the between-subject variability (Hopkins, 2000). When the signal is greater than the noise and the smallest important effect, the test is deemed good enough to identify those worthwhile changes. To reduce the likelihood of heteroscedasticity (non-uniformity of error) data were log-transformed before analysis. The means were then back transformed to obtain changes and differences as a percentage (Paton & Hopkins, 2005). A threshold ratio of 1.15 was used to interpret the observed magnitude of differences of coefficients of variation between velocities and kicking amplitudes (Hopkins & Hewson, 2001).
Net force and kick rate were presented as mean ± SD and standardised changes between trials were reported. The magnitude of change (effect size) was interpreted as: trivial 0.0-0.20, small 0.20-0.60, moderate 0.60-1.20, and large >1.20 (Hopkins, 2004). An effect was considered unclear if the 90% confidence interval overlapped both the substantial positive and negative threshold (effect size of ± 0.2).

**Results**

The net force was averaged over the period of towing through the 7 m. The standard error of the estimate (validity) between the dynamometer and overhead high-speed video for towing velocity, expressed as a coefficient of variation was 0.6% (±0.1, ±90% confidence interval) and in raw units 0.01 m·s⁻¹ (±0.00). The mean bias between the methods was -1.1% (±0.2) or -0.02 m·s⁻¹ (±0.0) with the dynamometer consistently underestimating velocity. The 95% limits of agreement between the dynamometer and overhead high-speed video were 0.02 m·s⁻¹ (Figure 2). The Pearson correlation coefficient between the methods was r = 1.00 (±0.00).

Within a testing day (intra) the typical error of net force (swimmer reliability) measured was 5.2% (±1.0) for streamlining (passive) and 4.9% (±0.9) for kicking (active). The magnitude of the smallest important change or difference in net force was 11.2% for streamlining and 9.6% for kicking. The comparative values for inter-day swimmer reliability were 7.2% (±1.5) for streamlining and 6.6% (±1.3) for kicking. The magnitude of the smallest important effect for inter-day swimmer reliability was 11.0% for streamlining and 9.4% for kicking. Testing between days was slightly less reliable (ratio of CV 1.4, 1.1 to 1.8) than testing within a single day for streamlining and kicking. Inter and intra-day ICC values for net force ranged between 0.97 (±0.03) and 0.99 (±0.02) for both streamlining and kicking.

There was no substantial difference in mean net force between any of the three trials for each experimental condition. The net forces and kick rates for each velocity and experimental condition (mean ± SD) are shown in Table 1. All swimmers recorded a smaller net active force during the kicking trials than the net passive force during the streamline trials at any given velocity.
Tables 2 and 3 present the results of the difference in force during active kicking and streamlined gliding used to indicate the contribution of the kick. The standardised difference in net force between streamlining and kicking for each velocity are shown in Table 2. Net passive force was substantially greater than net active force at any given velocity. The standardised net force differences between velocities and kicking amplitudes are shown in Table 3. For the typical amplitude kick, net force increased with an increase in towing velocity. Net force increased by 24.2% (±5.3) when peak velocity was increased by 5% and decreased by -16.4% (±5.5) when peak velocity was reduced by 5%. In contrast, there was no difference in kick rate when peak velocity was increased by 5% or decreased by 5%. Net force increased substantially with the larger amplitude kick. A large decrease of -13.6% (±5.1) in kick rate was observed when swimmers adopted a larger amplitude kick. A small increase of 3.1% (±3.5) in kick rate was observed when swimmers adopted a smaller amplitude kick.

**Discussion**

The modified dynamometer and force platform system used in this study for measuring net force and towing velocity was found to be valid and reliable. The dynamometer measured velocity to within 1% of that measured from the high-speed video camera. The test re-test reliability in measuring net force from the dynamometer and force platform system was ~6% for passive and active (kicking) conditions within and between days of testing. The coefficient of variation (CV) for intra-day reliability of net passive force for different velocities and depths (CV 1.1% to 2.7%) have been reported previously (Lyttle et al., 1999). The differences in the test re-test reliability observed between this study and that by Lyttle et al., (1998), most likely relate to the different towing conditions (surface versus ~0.5 m below the surface). When measured on the water surface net force is substantially more variable than when measured 0.5 m under the surface (Maiello et al., 1998). In this study, given a typical test re-test reliability error of ~6%, a worthwhile difference in net force of ~10-12% and an intra class correlation coefficient of ~0.97, researchers can be confident that the dynamometer and force system used in this study should detect important differences in net force between swimming velocities and kicking conditions. The current study is the first to reliably quantify net forces for kicking conditions on the water’s surface. The modified dynamometry system described here is capable of measuring small (and important) changes in net force in elite swimmers.
At peak freestyle velocities between 1.6-1.8 m·s\(^{-1}\), elite Paralympic swimmers produce net passive forces of \(~50-65\) N and net active forces of \(~30-50\) N when using a typical amplitude maximal freestyle surface kick. These net forces are \(~5-10\) N greater than those observed using a similar system and towing velocities for experienced adult male able-bodied swimmers (Lyttle et al., 2000). The differences in net force observed between the studies most likely relate to differences in water depth at which force was measured (surface versus \(~0.5\) m below the surface). Net force is greatest when measured closer to the water surface and decreases with depth (Larsen et al., 1981; Maiello et al., 1998). Measuring net kicking forces below the surface of the water is useful for evaluating the effectiveness of the underwater phase of the start and turn. However a different paradigm is required to interpret net kicking forces generated in the free-swimming component of freestyle. Free swimming is not influenced by the start and turn and the leg kick is performed on the water surface. For Paralympic swimmers, free swimming velocity correlates highly with final race time, (Daly et al., 2001). The challenge for Paralympic swimmers and their coaches is to increase free-swimming velocity via relative increases in net force production. The differences in net force observed between the studies may also relate to the difference in the absolute performance level of the swimmers compared to those in Lyttle et al., 2000. The greater net forces observed for Paralympic swimmers and the associated disability profiles of these athletes suggest that Paralympic swimmers may have a greater dependence on the kicking action and for optimal performance than able-bodied swimmers. The potential for Paralympic swimmers to utilise the kick to optimise performance may therefore be much greater than once previously thought.

A notable finding of the present study was that kick rate remained constant between the three kicking velocities suggesting that increases in towing velocity alone were responsible for the increases in net force. The parallel change in net force as a function of a change in velocity has been confirmed previously (Toussaint et al., 1988; Lyttle et al., 1998). One explanation for this parallel change is the associated change in stroke rate or kick rate, most often responsible for a change in swimming velocity (Rushall et al., 1994). A second explanation for a change in towing velocity is the increased contribution of wave making frontal resistance when velocity is increased. While it is difficult to determine the contribution of kick rate to net force
production it appears that kick rate is not responsible for increasing resistance. Future research in this area should examine the influence of anthropometric and range of motion characteristics of the lower limbs including the size and flexibility of swimmer’s feet.

In the current study there was a substantial decrease in net force between streamlining and kicking at each velocity indicating the propulsive effect of the kick. This phenomenon has been observed previously for net forces between streamlining and kicking underwater (Lyttle et al., 2000). Similarly in this study, at a slower towing velocity the net active force was ~16% less than at peak velocity, and at a higher towing velocity the net active force was ~24% greater than at peak velocity. Despite this increase in net force the kick rate remained unchanged. The inability of swimmers to increase kick rate to match increased velocity contradicts other data showing a significant increase in stroke rate during speed-assisted training for swimmers (Girold et al., 2006). By training swimmers to match higher kick rates at faster velocities there is a theoretical potential for an increase in swimming velocity. Future research is needed to confirm that the failure to match kick rate with velocity is not a consequence of some intrinsic neural control mechanism limiting kick rate to a predetermined maximal level.

The amplitude of a swimmer’s kick affects the magnitude of force production in kicking. In the present study swimmers completed kicking trials using a larger or smaller amplitude kick than their typical amplitude kick. A greater net force was observed from the larger amplitude kick than the typical or smaller amplitude kick. The swimmers were asked to maintain a maximal kick yet change their kicking amplitude. We attribute the increase in net force, an increase in the force produced by kicking as a result of a larger amplitude kick, to the lower observed kick rate. However we are hesitant to draw conclusions from the smaller amplitude kick as the net force increase was trivial and the kick rate increase was small. It would appear that a swimmer’s self-selected kicking amplitude is optimal for minimizing the potentially negative consequence of increasing net force and should not be changed. An increased or decreased amplitude kick increases the resistive force relative to self-selected amplitude, i.e. these conditions reduce the contribution of the kick. A swimmer’s self-selected amplitude kick, that is the preferred amplitude that
corresponds closely to optimal amplitude, rather than a larger or smaller amplitude kick, should help them achieve optimal velocity without increasing resistance. However, more work needs to be done to establish whether this is the case for all experienced swimmers.

The coaching of swimming technique should focus on actions that increase swimming velocity via speed-assisted kick training. Despite increases in net force when towing velocity increased, kick rate remained stable. Kick rate is therefore not directly responsible for increasing resistance but could be increased to match towing (or free swimming) velocity. Paralympic swimmers should implement speed-assisted kick training to increase physiological (strength and power) and technical (kick rate) parameters of swimming to maximise net force and increase the contribution of the kick. The typical kicking amplitude that swimmers adopt at peak velocities appears appropriate for optimising net force.
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Acknowledgements

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Figure 1. Dynamometer and force platform system.
Figure 2. Bland-Altman plot for the difference in velocity between the dynamometer and overhead video. The plot shows four swimmers at their individual peak freestyle velocities (1.1 m·s⁻¹, 1.7 m·s⁻¹, 1.7 m·s⁻¹, and 1.9 m·s⁻¹).
Table 1. Net force and kick rate for each experimental condition (mean ± SD) (n = 12).

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<th>Experimental condition</th>
<th>Velocity (m·s⁻¹)</th>
<th>Net force (N)</th>
<th>Kick rate (kicks·min⁻¹)</th>
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<td>Streamline (-5% peak velocity)</td>
<td>1.6 ± 0.1</td>
<td>53.8 ± 2.7</td>
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<td>Streamline (peak velocity)</td>
<td>1.7 ± 0.1</td>
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<td>0</td>
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<tr>
<td>Streamline (+5% peak velocity)</td>
<td>1.8 ± 0.1</td>
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<tr>
<td>Kicking (-5% peak velocity)</td>
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<td>33.1 ± 3.3</td>
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<td>Kicking (peak velocity)</td>
<td>1.7 ± 0.1</td>
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<td>150.6 ± 3.0</td>
</tr>
<tr>
<td>Kicking (+5% peak velocity)</td>
<td>1.8 ± 0.1</td>
<td>49.2 ± 3.3</td>
<td>150.8 ± 4.2</td>
</tr>
<tr>
<td>Kicking (typical amplitude)</td>
<td>1.7 ± 0.1</td>
<td>39.5 ± 3.3</td>
<td>150.6 ± 3.0</td>
</tr>
<tr>
<td>Kicking (larger amplitude)</td>
<td>1.7 ± 0.1</td>
<td>49.5 ± 5.4</td>
<td>130.1 ± 5.2</td>
</tr>
<tr>
<td>Kicking (smaller amplitude)</td>
<td>1.7 ± 0.1</td>
<td>42.1 ± 2.3</td>
<td>155.5 ± 6.2</td>
</tr>
</tbody>
</table>
Table 2. Difference in net force between streamlining and kicking at each velocity (±90% confidence interval). The standardised effect size (ES) is also shown (n = 12).

<table>
<thead>
<tr>
<th>Velocity (m·s⁻¹)</th>
<th>Net force (N)</th>
<th>Net force (%)</th>
<th>ES</th>
<th>Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5% Peak velocity</td>
<td>20.7 (±6.3)</td>
<td>65.3 (±16.2)</td>
<td>1.32*</td>
<td>Large</td>
</tr>
<tr>
<td>Peak velocity</td>
<td>20.0 (±6.6)</td>
<td>53.2 (±14.8)</td>
<td>1.14*</td>
<td>Moderate</td>
</tr>
<tr>
<td>+5% Peak velocity</td>
<td>16.5 (±5.8)</td>
<td>36.0 (±10.5)</td>
<td>0.81*</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

*Clear effect (±90% confidence interval does not include substantial positive and negative values).
Table 3. Difference in net force between peak velocity and velocity 5% above and below peak velocity for a typical amplitude kick and difference in net force between a typical amplitude kick and a larger and smaller amplitude kick at peak velocity (±90% confidence interval). The standardised effect size (ES) is also shown (n = 12).

<table>
<thead>
<tr>
<th>Kicking condition</th>
<th>Velocity (m·s(^{-1}))</th>
<th>Net force (N)</th>
<th>Net force (%)</th>
<th>ES</th>
<th>Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical amplitude</td>
<td>-5% Peak velocity</td>
<td>-6.4 (±2.2)</td>
<td>-16.4 (±5.5)</td>
<td>-0.47*</td>
<td>Small</td>
</tr>
<tr>
<td>Typical amplitude</td>
<td>+5% Peak velocity</td>
<td>9.6 (±3.1)</td>
<td>24.2 (±5.3)</td>
<td>0.57*</td>
<td>Small</td>
</tr>
<tr>
<td>Larger amplitude</td>
<td>Peak velocity</td>
<td>10.0 (±4.8)</td>
<td>25.1 (±10.6)</td>
<td>0.59*</td>
<td>Small</td>
</tr>
<tr>
<td>Smaller amplitude</td>
<td>Peak velocity</td>
<td>2.6 (±2.6)</td>
<td>6.4 (±6.1)</td>
<td>0.16*</td>
<td>Trivial</td>
</tr>
</tbody>
</table>

*Clear effect (±90% confidence interval does not include substantial positive and negative values).
Chapter 8: Discussion, Conclusions and Future Directions

Discussion

The pursuit of swimming excellence places great emphasis on the integration and implementation of effective training programs to prepare swimmers for competition. The evaluation of both the contemporary training programs and technical aspects of Paralympic swimmers has identified key performance characteristics to enhance training techniques and competition outcomes of these athletes. Paralympic swimmers require annual improvements in performance of at least 1-2% to substantially increase chances of success in competition. The training regimes for Paralympic swimmers to achieve these improvements incorporate periodised volumes and intensities throughout the training season, broadly similar to Olympic swimmers, with the exception of the taper where the relative reduction in volume is much smaller. In kick training programs, once guided by lap times alone, coaches can now quantify the kinematics of the kick and monitor the effect of various training interventions. Kicking training drills to substantially improve freestyle velocity should focus on maintaining or increasing kick rate. Integration of these key performance characteristics into contemporary training programs of Paralympic swimmers will facilitate improvements in training prescription and technique.

The aim of study one was to quantify the magnitude of variability and progression in competitive performance in the 100-m freestyle event for elite swimmers with a disability. Estimates of variability and progression in performance provide useful information about the smallest important changes (magnitude of improvement) necessary to medal at major competitions. In the first study of this current series, retrospective evaluation of 724 official 100 m freestyle times were analysed for 242 Paralympic swimming finalists at major national and international competitions. The typical within-swimmer race-to-race variability in performance in Paralympic swimmers of ~2%, was substantially larger than the variability observed in previous research for junior national swimmers (1.4%) (Stewart & Hopkins, 2000b) and Olympic swimmers (0.8%) (Pyne et al., 2004). The difference in performance
consistency between Olympic and Paralympic swimmers may be attributed to the evolution of Paralympic swimming (Daly & Vanlandewijck, 1999a) and the greater racing experience of Olympic swimmers. As all aspects of Paralympic swimming continue to evolve, the consistency in performance from race-to-race of these athletes may improve to near Olympic standard. Improved consistency should elicit lower race-to-race variability with the global aim to facilitate improvements in performance. Greater performance consistency may result from more systematic application of effective training interventions.

The typical race-to-race variability in performance for Paralympic swimmers with less functional ability (S2-S4 subgroup) of ~3% was twice that of swimmers with fewer musculoskeletal limitations (S8-S10 subgroup) of ~1.5%. The depth of competition for Paralympic swimmers in lower classes is less than higher classes, probably due to the lower total number of swimmers participating in competition (Daly & Vanlandewijck, 1999a). Low numbers often mean that swimmers in adjacent classes are merged for competition or advance directly to finals, and therefore do not have the same racing opportunity as swimmers in higher classes (Wu & Williams, 1999). Fewer racing opportunities transpire to less race experience and a reduced likelihood of reproducing consistent performance. The greater musculoskeletal limitations and the day-to-day fluctuations in movement and function associated with swimmers in lower classes (DePauw, 1986) may also make consistent performances harder to reproduce. The observed greater consistency in performance of swimmers in higher classes suggests that greater racing opportunities and fewer musculoskeletal limitations may contribute to lower race-to-race variability. Coaches who train swimmers in lower classes can now consider the magnitude of variability in these athletes when planning for competition.

Progression in performance is fundamental to competitive swimming. Swimmers must progress within and between competitions to ensure peak performance when medals count. The variability in performance for a given swimmer alone does not account for the improvements of other athletes between competitions: thus estimates of race-to-race variability in performance should always be accompanied by mean annual progressions in performance. The mean annual progression in performance time of Paralympic swimmers in this study of ~0.5% was substantially less than that
of ~0.9% of Olympic swimmers (Pyne et al., 2004). Although these estimates of progression appear small, in closely matched races they can have a substantial effect on the final outcome and should therefore be considered by swimmers and coaches when planning for competition. The performance progression of Paralympic swimmers in this study will also be of interest to researchers interested in performance prediction and evaluation. As Paralympic swimming performances continue to improve, the rate of year-to-year progression in performance for these athletes will probably increase and warrant ongoing investigation.

The differences in the level of a competition are also important for both swimmers and coaches when considering worthwhile improvements in performance. The differences in mean performance time between competitions in the first study were of similar magnitude to the smallest important effect. Performances at the Paralympic Games were faster for all subgroups and substantially faster than any other competition by ~1.7%. National-level competitions were slowest by ~1.4%, presumably reflecting less preparation, lower motivation and a lack of depth of competition. Paralympic swimmers wishing to substantially increase their medal prospects should aim for annual improvements in performance of ~1-2% to account for race-to-race variability and progression in performance. Comparatively, improvements in performance attributable to variability and progression of Olympic swimmers is ~1.4% (Pyne et al., 2004). Although similar in magnitude the composition of variability and progression varies between Paralympic and Olympic swimmers. Annual improvements in performance for Olympic swimmers combine low-variability and high-progression estimates. For Paralympic swimmers, annual improvements combine high-variability, low-progression estimates. To account for estimates of variability and progression when planning for competition the contemporary training programs used to prepare Paralympic swimmers should be examined.

The magnitude of improvement necessary for success in competition provides a reference value for coaches to develop and refine training programs to elicit these improvements. Contemporary training programs for Paralympic swimmers reflect those prescribed for able-bodied swimmers but at a lower overall volume. Functional impairments such as those associated with limb loss or motor control may influence
the demands and response to training such that able-bodied programs do not cater for differences in training volume and intensity. Until now, detailed quantitative evaluation of training programs for Paralympic swimmers has been limited, and the degree these training programs were associated with competitive performance is unclear. Quantifying training load and monitoring the training response in Paralympic swimmers may offer a practical means to help coaches develop training methodology specific to the requirements of these athletes.

Study two monitored the longitudinal pattern of change in training load measures for 16 Paralympic swimmers to determine associations between training and substantial improvements in competitive performance. Swimmers were provided with access to a novel web-based training diary for 16 weeks from their selection at a National Championship through to competition at a World Championships. The key finding of study two was the periodised pattern of training volume followed by Paralympic swimmers, which was similar to those adopted by Olympic swimmers (Pyne & Goldsmith, 2005). The greatest volume of training for Paralympic swimmers was completed in the four weeks prior to competition (an increase of ~30% from phase one) before a decrease in training volume (of ~11% from phase three) in or during the taper. The greatest change was an increase in intensity of ~5% in the late training phase. Intensity was maintained during the taper, consistent with previous results (Bosquet et al., 2007). The key difference in the periodised training of Paralympic swimmers was the relatively small decrease in training volume in the taper phase. The reductions in training volume were ~30-50% less than those associated with performance improvement in competitive able-bodied swimmers (Papoti et al., 2007; Thomas et al., 2008). The smaller reductions in taper volume observed might be related to the lower overall training volumes undertaken by the Paralympic swimmers compared with their able-bodied counterparts. The substantial improvements in performance associated with taper strategy in competitive able-bodied swimmers suggest similar taper strategies may also elicit improvements for Paralympic swimmers. More research is required to develop effective and optimal taper strategies for Paralympic swimmers.

Understanding the relationships between training load and competitive performance in elite swimmers is important for optimising training prescription (Avalos et al.,

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Traditionally, coaching styles have been based on a ‘more is better’ philosophy. Some studies have reported high correlations between performance and training distance (Stewart & Hopkins, 2000) and between performance and training intensity (Mujika et al., 1995). The training volumes for Paralympic swimmers were substantially lower (~20-70% depending on the class) than those recorded previously (Pelayo et al., 1999). The ~10-year time-frame between the current study and Pelayo (1999), suggests that coaches may have changed their perspective on the prescription of training for elite swimming. The current convention is a low-volume high-intensity strategy in the preparation for competition. Researchers have confirmed that the high volumes of training, usually associated with competitive swimming, are not advantageous compared to high-intensity training of lower volume (Faude et al., 2008). Training adaptations may therefore be reached more economically with lower-volume high-intensity training. In study two we found that swimmers who had the greater improvements in performance between competitions trained at lower volumes and intensities, and swimmers who raced closer to the world-record time trained at lower intensities. This counter-intuitive finding raises questions about the training prescription of contemporary training programs for Paralympic swimmers. High training volume may not necessarily elicit the improvements in performance once thought.

The third study employed the novel use of inertial sensor technology to evaluate the validity and reliability of a gyroscope algorithm to identify the upbeat and downbeat of individual flutter kicks. One facet of training that was observed, but not quantified in study two throughout the training season, was the kicking-specific training sets prescribed by coaches in the majority of sessions. Coaches provided swimmers with feedback on training stroke rates during swimming sets. However, when kicking sets were performed lap time was the only quantifiable variable. Up until now kick count and kick rate characteristics in freestyle swimming were relatively unknown, primarily due to the difficulty in measuring the kick which is partially obscured by turbulence (Ohgi et al., 2003).

In study three 12 Paralympic swimmers repeated two maximal effort 100 m freestyle swimming and freestyle kicking-only time trials on three occasions, approximately five weeks apart. The criterion measure for validity was underwater video analysis.
The correlation between the sensor and criterion video footage was nearly perfect for all swimming ($r = 0.96$) and kicking-only ($r = 1.00$) trials. The standard error of the estimate expressed as a coefficient of variation between the sensor and video footage was ~6% for swimming trials and ~1% for kicking-only trials. The sensors typically underestimated kick count by no more than two kicks for every 100 m. Similar mean bias values have been recorded for other inertial sensor applications (Ichikawa et al., 1999; Le Masurier & Tudor-Locke, 2003). A mean bias of 1-2% in kicking characteristics is favourable given a preliminary report that stroke count and stroke rate detection in freestyle swimming using similar technology had a mean bias of ~5-10% (Anderson et al., 2006a). Despite high validity, the inherent noise in the sensor output for reliability makes it problematic to identify small changes or differences in kicking within trials. Coaches can utilise the technology to identify moderate to large changes and differences in kicking patterns between training sessions, and for seasonal changes between major competitions. Repeat trials, may reduce associated measurement error and increase reproducibility when reporting small changes. Kick count and kick rate movements that were otherwise difficult to detect in training sessions, can now be identified using valid and reliable inertial sensor technology. The unique application of inertial sensor technology to quantify kick count and kick rate could assist coaches’ to design more effective training interventions and identify key performance characteristics of the kick.

In study four kicking patterns were measured for 14 Paralympic swimmers in 100 m freestyle swimming time trials to determine changes and differences within and between a) swimming and kicking-only trials; b) Paralympic classes and disabilities; and c) 100 m distances. The quantification of kick count and kick rate in study 4 has important implications for training prescription and competition sprint performance. A controlled trial design was adopted in the fourth study to measure the kinematics of kick count and kick rate in fourteen Paralympic swimmers (with and without the arm stroke) using the inertial sensor technology established in study three. Swimmers maintained a stable kick count throughout swimming trials though substantial decreases in kick rate and velocity of ~12% were observed as swimmers fatigued. Kick rate was typically higher in kicking-only trials by ~4% when compared with swimming trials suggesting that kick rate is under utilised in freestyle swimming. Future research is needed to confirm that the failure to match kick rate with velocity is
not a consequence of some intrinsic neural control mechanism limiting kick rate to a predetermined maximal level. The relationship between swimming and kicking-only kick rate was $r = 0.67$. Some swimmers have a superior transfer of kick rate from kick-only to swimming; however others are unable to maintain the same rate between trials. Swimmers who are not able to replicate kicking-only kick rate in swimming reduce their chance of enhancing performance. Substantial improvements in freestyle velocity are achievable when kick rate is increased. As the kick rate has previously not been measured in swimming the difference between swimming and kick-only trials is a unique finding. Contemporary training programs for swimmers may not incorporate adequate kicking-only training that develops speed and stamina associated with maintaining a high kick rate. When leg-kicking training forms a substantial part of a swimmer’s training program, leg muscle endurance and movement economy can be improved (Konstantaki & Winter, 2007). Training Paralympic swimmers to adopt a high but controlled kick rate in the early stages of a race and maintain kick rate in the latter stages, should ensure that velocity is maintained.

The substantial differences in kick rate between swimming and kicking-only trials prompted exploration of the relationship between kick rate and freestyle velocity and whether this relationship was a key characteristic for performance. When the performance data was modelled for all swimmers, achievable increases in kick rate of ~9% (across all 25 m segments of a 100 m freestyle time trial) equated to substantial improvements in time of ~3% (~2.5 sec). The predicted enhancements in time varied substantially between swimmers suggesting that some swimmers will benefit more than others from increasing kick rate. Although a theoretical model was used, overall improvements of this magnitude are substantially greater than the magnitude of improvement necessary to medal at major competitions, and therefore have real performance implications.

Study five determined the influence of towing velocity and kick amplitude on net force and kick rate. Changes in net force production may result when kick rate is manipulated and these changes may not be optimal for enhancing race velocity. Measuring the net propulsive force and kick rate when swimmers are towed at race velocities, would allow coaches and sport scientists to determine the influence of velocity and amplitude on these parameters. In study five, 12 Paralympic swimmers
were towed over 30 m and a maximal freestyle surface kick was adopted. Net force was measured using a modified dynamometer and force platform system. The dynamometer measured velocity to within 1% of that measured by high-speed video cinematography. The test re-test reliability error of ~6% in measuring net force was substantially higher than the reliability reported in previous studies (Lyttle et al., 1999a). This difference was attributable to the differences in towing depth (surface versus ~0.5 m below the surface) which have been observed elsewhere (Maiello et al., 1998). Given a typical test re-test reliability error of ~6% in this study, a worthwhile difference in net force of ~10-12% and an intra class correlation coefficient of ~0.97, researchers can be confident that the system described here is capable of measuring small (and important) changes in net force in elite swimmers.

In swimming competition, the free-swimming segment of a race is where the arm stroke and leg kick are performed on the water surface and not influenced by an underwater phase. Measuring net kicking forces underwater is useful for evaluating the effectiveness of the underwater kicking phase of the start and turn. However, a different paradigm is required to interpret net kicking forces during free swimming. Net force is greatest when measured closer to the water surface and decreases with depth (Larsen et al., 1981; Maiello et al., 1998). Hence, kicking forces that have previously been measured underwater will be different from those measured on the water surface. For Paralympic swimmers, free swimming velocity is the most discriminating segment of a race (Daly et al., 2001) and researchers should explore techniques to optimise net force production of this phase. The challenge for Paralympic swimmers and their coaches is to increase free-swimming velocity via relative increases in net force production.

To maximise velocity swimmers must reduce passive force, increase active force, or do both to enhance swimming performance. In study five, net force naturally increased, from ~33-49 N, with an increase in velocity, from 1.6-1.8 m·s⁻¹, during the maximal kicking trials. However, kick rate remained constant at ~150 kicks·min⁻¹ suggesting that increases in towing velocity alone were responsible for the increases in net force. The inability of swimmers to increase kick rate to match the increased velocity contradicts other data showing a significant increase in stroke rate during speed-assisted training for swimmers (Girold et al., 2006). As there has been no
previous method to measure kick rate, any change in this parameter with regard to kicking force is a unique finding. This finding also confirms that contemporary conditioning programs for kicking may not be sufficient for facilitating increases in kick rate or there may be some intrinsic neural control mechanism limiting kick rate to a predetermined maximal level. By training swimmers to match higher kick rates at faster velocities there is a theoretical potential for an increase in swimming velocity.

The amplitude of a swimmer’s kick is another facet of swimming that may change net force production when increased or decreased and subsequently influence race velocity. When swimmers in study five adopted a maximal deep amplitude kick and velocity was kept constant, net force increased substantially by ~25% compared to the self-selected amplitude typical of normal racing. A substantial decrease in kick rate of ~14% accompanied the increase in net force. Subsequently, for a smaller amplitude kick, increases in net force of ~6% were observed and accompanied by small increases of ~3% in kick rate. It would appear that a swimmer’s self-selected kicking amplitude, rather than a larger or smaller amplitude kick, is optimal for enhancing race velocity without increasing resistance and should not be changed. The coaching of swimming technique should focus on actions that increase swimming velocity via increases in net force. Integration of these key performance characteristics to contemporary training programs will enhance improvements in training prescription, technique and competition outcomes of Paralympic swimmers.

Conclusions
The series of studies in this body of research has analysed some important performance characteristics of Paralympic swimming and the application of these characteristics to enhance success in competition. Five investigations were conducted to identify key characteristics that could be used by coaches and sport scientists interested in the competitive performance of Paralympic swimmers. Paralympic swimmers wishing to substantially increase their medal prospects should aim for an annual improvement in competition performance of at least 1-2% to account for race-to-race variability and additional year-to-year variability (~1.3%), progression in performance (~0.5%) and the effect of different levels of competition (~1.5%). The variability in performance of Paralympic swimmers with less functional ability is
twice that of swimmers with greater functional ability, hence these athletes should aim for improvements in competition performance closer to 2%. Estimates of variability and progression reported here should be considered by coaches to set realistic performance goals when planning for major competitions and yearly training programs.

The periodised patterns of training programs of Paralympic swimmers prior to major competitions follow similar patterns to Olympic swimmers and coaches, when planning the training season, should adopt these patterns. The main set and total volume of training can be increased by ~30% during mid- to late-season training phases via manipulation of the distance and frequency of sessions. The smaller reductions in taper volume observed by Paralympic swimmers compared with their able-bodied counterparts might relate to lower overall training volumes.

Swimming coaches are now able to quantify kick count and kick rate in freestyle swimming and kicking-only training through the use of inertial sensor technology and associated software. Coaches and researchers can use this unique technology to identify moderate to large changes in kicking patterns. However, the inherent noise in the current iteration of the sensor output makes it problematic to confidently quantify small changes or differences in kicking. Substantial decreases in kick rate within swimming trials are associated with reductions in swimming velocity suggesting that velocity decreases as a result of a decrease in kick rate. The temporal patterns of kick rate are different between kicking-only and swimming trials. Some swimmers are unable to maintain the same kick rate between swimming and kicking-only trials, reducing their chance of enhancing performance. Substantial improvements in freestyle velocity should be achievable when kick rate is increased and kick amplitude is maintained. Intervention of contemporary training programs may be sufficient to facilitate this increase and improve velocity.

In the measurement of net force production most swimmers are unable to increase their kick rate to match increases in towing velocity. Aside from some intrinsic neural control mechanism that may limit kick rate to a predetermined maximal level intervention programs to facilitate increase in kick rate may achieve increased velocity. However, an increase in kick rate would increase the energy expenditure of
the swimmer. Further research is required to determine whether or not an increase in kick rate is worthwhile. Given that the kick contributes ~20 N and the force of towing in the streamline position is ~ 60 N then the contribution of the kick at constant top velocity must be ~1/3 of the impulse required to overcome the basic minimum drag experienced in swimming to maintain that velocity. A swimmer’s chosen/natural kicking amplitude elicits an optimal net force and kick rate when compared with a deeper or shallower amplitude kick and should be retained.

The work described in this series of research projects has investigated some important performance characteristics of Paralympic swimmers. New approaches for guiding training and enhancing physiological, biomechanical and technical characteristics of Paralympic swimming have been identified. Annual improvements in performance of at least 1-2% should substantially increase medal prospects in Paralympic swimmers. The training regimes for Paralympic swimmers should follow similar periodised patterns to those of Olympic swimmers; however larger reductions in training volume should be followed in the taper. Kicking training drills should focus on maintaining or increasing kick rate, while maintaining kick amplitude, to substantially improve freestyle velocity. Integration of these key characteristics should enhance Paralympic swimming performance and increase chances of success in competition.

Future Directions
The work described in this current research has raised questions regarding contemporary training of Paralympic swimmers. Intervention studies are needed to investigate various therapeutic modalities that may achieve greater consistency in performance and reduce race-to-race variability. Refinements to training programs and improvements to the technical and tactical aspects of racing may identify why the rate of progression in performance of Paralympic swimmers is half that of Olympians. Future training programs for Paralympic swimmers should be class- and disability-specific to account for the substantial individual differences in training volume. The counter-intuitive finding for the association between training and performance needs exploring, and alternative strategies and methodologies for enhancing a swimmer’s performance identified. A more substantial taper (larger reduction in volume) is one
strategy that could be adopted by coaches to elicit greater improvements in performance.

Refinements to inertial sensor firmware are needed to fully automate the kick detection process in training sessions. Future improvements to the technology and software, coupled with duplicate measures or repeat trials, may result in an error small enough to allow adequate assessment of the effect of small changes in kick patterns on performance. Improvements to the sensor hardware are required to limit the need for additional waterproofing. A single inertial sensor placed on a single lower limb segment should only be required for future researchers wishing to quantify kicking patterns. Future studies could also investigate modifying racing suits to incorporate this type of sensor device and eliminate the time-consuming attachment process. When implementing new technology into the training setting sport scientists must devise research projects with specific performance outcomes, which engage the coach and athlete and demonstrate the practical advantages of the technology. The downloading of data must therefore be a fully automated process and user friendly for all parties. User-friendly technology with clear practical applications is more likely to be adopted by a coach and used in routinely in training sessions. Evaluating the underwater phase of the kick using leg acceleration could identify technical aspects of the kicking action currently unknown. Other projects could employ multiple sensors on the body to replicate the natural movement of whole-body acceleration patterns for deriving three-dimensional kinematics in swimming.

Future training intervention studies are needed to identify optimal kicking patterns and strategies for Paralympic swimmers wishing to enhance performance during competition. Conditioning programs that improve the muscular endurance of the kick are required to ensure Paralympic swimmers with upper and lower limb disabilities can maintain a continuous kick rate throughout races. Studies are needed to resolve the debate on the stroke/kick relationship for training, stroking and kicking strategies for 100 m freestyle performance in elite swimmers. When measuring kicking forces at race velocities, future research is needed to confirm that failure to match kick rate and velocity is not a consequence of some intrinsic neural control mechanism limiting kick rate to a predetermined maximal level. Researchers could tow swimmers over a wider range of velocities, substantially faster and slower than race velocity, to
determine whether towing velocity was a limiting factor. Speed-assisted kick training could be employed as an intervention to gauge whether this type of training can increase kick rate and ultimately kicking velocity.
References


# Appendix A: The Classification System for Swimming

Table 1. The functional classification system.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1, SB1, SM1</td>
<td>Swimmers with very severe coordination problems in four limbs or have no use of their legs, trunk, hands and minimal use of their shoulders. Swimmers in this class are typically wheelchair bound and usually only swim on their back.</td>
</tr>
<tr>
<td>S2, SB1, SM2</td>
<td>Swimmers able to use their arms though they have no use of their hands, legs or trunk, or have severe coordination problems in four limbs.</td>
</tr>
<tr>
<td>S3, SB2, SM3</td>
<td>Swimmers with reasonable arm strokes but no use of their legs or trunk. Swimmers may have severe coordination problems in all limbs or severe limb loss in four limbs.</td>
</tr>
<tr>
<td>S4, SB3, S4</td>
<td>Swimmers who use their arms and have minimal weakness in their hands but have no use of their trunk or legs. Swimmers may have coordination problems affecting all limbs but predominantly the legs. Swimmers with limb loss to 3 limbs.</td>
</tr>
<tr>
<td>S5, SB4, SM5</td>
<td>Swimmers with full use of their arms and hands but no trunk or leg muscles. Swimmers with coordination problems.</td>
</tr>
<tr>
<td>S6, SB5, SM6</td>
<td>Swimmers with full use of arms and hands, some trunk control but no useful leg muscles. Swimmers with coordination problems. Swimmers with loss of 2 limbs. Short stature swimmers (&lt; 130 cm).</td>
</tr>
<tr>
<td>S7, SB6, SM7</td>
<td>Swimmers with full use of arms and trunk with some leg function; Swimmers with coordination or weakness problems on the same side of the body. Swimmers with loss of 2 limbs.</td>
</tr>
<tr>
<td>S8, SB7, SM8</td>
<td>Swimmers with full use of arms and trunk and some leg function. Swimmers with coordination problems mainly in the lower limbs. Swimmers with both legs amputated just above or below knees. Swimmers with single amputation above elbow.</td>
</tr>
<tr>
<td>S9, SB8, SM9</td>
<td>Swimmers with severe weakness in one leg only. Swimmers with very slight coordination problems. Swimmers with one limb loss.</td>
</tr>
<tr>
<td>S10, SB9, SM10</td>
<td>Swimmers with very minimal weakness affecting the legs. Swimmers with restriction of hip joint movement. Swimmers with both feet deformed. Swimmers with one leg amputated below the knee. Swimmers missing a hand.</td>
</tr>
</tbody>
</table>

Adapted from Green & Jaubert, (2005).
The contemporary classification system for swimming was established by the IPC and has been used in international swimming competitions since 1989. The swimming classification system attempts to ameliorate the effects of impairment on competition and combines athletes with different disabilities, but comparable ability and function, to generate fair competition (International Paralympic Committee, 2008). The system combines swimmers with functional disabilities into ten classes (Class S1-S10) (Table 1) and swimmers with visual impairments into three classes (Class S11-S13) (Table 2) for competition (International Paralympic Committee, 2008). The prefix ‘S’ denotes the class for freestyle, backstroke and butterfly, the prefix ‘SB’ denotes the class for breaststroke and the prefix ‘SM’ denotes the class for individual medley. The class range is from swimmers with the most impairment or severity of disability (S1, SB1 and SM1; S11, SB11 and SM11) to those with the least impairment, or minimal disability (S10, SB9 and SM10; S13, SB13 and SM13) (International Paralympic Committee, 2008). Functional classification involves a medical test to establish whether an athlete meets minimal disability or criteria for that sport. Bench tests evaluating range of motion, strength, coordination and limb length and/or level of amputation precede functional swimming analysis and observation during competition (International Paralympic Committee, 2008). The International Blind Sports Association (IBSA) created the class system for swimmers with a visual impairment.

Classification is often filled with controversy and a swimmer’s classification status can be protested at IPC competitions. The classification status can change if it appears that a swimmer’s functional ability is outside his or her original classification (Richter et al., 1992). The relationships between performance, impairment and the classification system show that the current system is effective for generating fair competition for most, but not all, swimmers (Daly & Vanlandewijck, 1999a; Daly & Vanlandewijck, 1999b; Wu & Williams, 1999). Swimmers must be in a structured swimming training program for four years, before being given a permanent status classification. Any improvement that the swimmer makes via training should not change their classification status. Swimmers must be classified by the IPC before they are eligible to compete on a national or international level.
Table 2. The visual impairment classification system.

<table>
<thead>
<tr>
<th>Class</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11, SB11, SM11</td>
<td>An athlete in this class will either have no light perception in either eye, or some light perception but an inability to recognise the shape of a hand at any distance or in any direction. For swimming, athletes must wear blackened goggles and require someone to tap them when they approach a wall.</td>
</tr>
<tr>
<td>S12, SB12, SM12</td>
<td>The athlete has the ability to recognise the shape of a hand and the ability to perceive clearly up to 2/60. The visual field of the athlete is less than 5 deg. There is a large range of vision ability within this class.</td>
</tr>
<tr>
<td>S13, SB13, SM13</td>
<td>The athlete has the ability to recognise the shape of a hand and the ability to perceive clearly above 2/60 and up to 6/60. The visual field of the athletes varies between more than 5 deg and less than 20 deg.</td>
</tr>
</tbody>
</table>

Key: 2/60 is the distance ratio a person with a visually impairment can see compared to that of an able-bodied person. For a distance of 60 m seen by an able-bodied person, a visually impaired athlete can only see 2 m.

Adapted from Green & Jaubert, (2005).
Appendix B: Consent to Participate in Research

I, .............................................................................

- Understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time without penalty or the need to provide an explanation.

- Understand that if I do choose to withdraw from the research at any time, any information received from me or pertaining to me that was obtained during the research will not be used unless I provide written approval for its use.

- Have elected to partake in this physical assessment of my own free will and I have not been coerced in anyway to participate.

- Have been given an opportunity to ask questions about the research project and all my questions and inquiries have been answered to my satisfaction.

- Understand that I will be provided with a summary of the results of the research.

- Understand that all information obtained from me or pertaining to me will be kept strictly confidential to the research team and that there will be no means of identifying me personally as a research participant in any publication, presentation or other means arising from the research.

- Understand the contents of the Research Project Information Sheet and this Consent to Participate in Research form. I agree to participate and give my consent freely:

- Understand that the study will be carried out as described on the Research Project Information Sheet, a copy of which I have kept.
Appendix B: Consent to Participate in Research

- Realise that whether or not I decide to participate is my decision and will not impact on me in any negative way.

- Also realise that I can withdraw from the study at any time and that I do not have to give any reasons for withdrawing.

- Am aware that data obtained from or about me for this study may be used for future related research projects and I consent to their use for that purpose.

Any questions I have about this research project and my participation in it have been answered to my satisfaction.

Signature of Participant:__________________________ Date:_____/_____/_______

Signature of Parent or Guardian of minor:______________________________ Date:_____/_____/_______

I, the undersigned was present when the test procedures were explained to the participant in detail and to my best knowledge and belief it was understood.

Signature of Researcher:__________________________ Date:_____/_____/_______
Appendix C: Pre Screening Questionnaire

Personal
Date: ___________________________
Name: ___________________________ F / M (Please circle)
Address: _________________________ Post Code: _______
Suburb: __________________________ State: _______
Telephone (H): ___________________ (W): ________________
Mobile: __________________________
Occupation: _______________________
Date of Birth: ________________ Age: _______
Email Address: ____________________

Emergency Contact
Name: ___________________________ Telephone: _______
Relationship: _______________________

Family Doctor
Name: ___________________________
Address: _________________________ Post Code: _______
Telephone: _______________________
Date of last full medical check up: ______________________

Health Information
Known Medical Conditions (Please circle the correct response)
1. Do you have Diabetes? No Yes
   If yes, please indicate Type 1 Type 2
      a) How many years have you been diagnosed? ______years
2. Have you had a stroke? No Yes
Appendix C: Pre Screening Questionnaire

3. Has your doctor indicated you have heart trouble or a heart condition? No Yes

4. Do you have Asthma/Respiratory Problems? No Yes

5. Do you have a Chronic Illness or Condition? No Yes
   a) If yes, please specify: ___________________________________________

6. Do you have any Lung diseases? No Yes
   a) If yes, please specify: ___________________________________________

7. Do you suffer from a Thyroid Disorder? No Yes

8. Do you have any Renal or Liver Diseases? No Yes

9. Do you have any other conditions/disease not mentioned above? No Yes
   a) If yes, please specify: ___________________________________________

10. Is there any other reason that would prevent you from participating (eg. Mental illness, severe arthritis, osteoporosis, or cancer)? No Yes
    a) If yes, please specify: ___________________________________________

11. Are you pregnant? No Yes

---

**Signs and Symptoms**

12. Do you ever have pain or discomfort in your chest or surrounding area? No Yes

13. Do you ever feel faint or experience dizzy spells during exercise? No Yes

14. Do you ever find it difficult to breathe when lying down or sleeping? No Yes

15. Do you experience swelling or fluid accumulation, around the ankles? No Yes

16. Do you ever have heart palpitations or periods of rapid heart rate? No Yes

17. Do you regularly feel pain in your calves or lower legs that isn’t due to soreness or stiffness? No Yes

18. Has your doctor ever told you that you have a heart murmur? No Yes

19. Do you get unusually fatigued or have breathing difficulty at rest or with mild exertion? No Yes

---

**Cardiac Risk Factors**

20. Have you smoke cigarettes within the last 6 months? No Yes
    a) If yes how many per day? ______

21. Has your doctor ever indicated that you have High Blood Pressure? No Yes

22. Do you take any Blood Pressure, Asthma or Diabetic Medication? No Yes
    a) If yes, what type ___________________________________________

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23. Has your Father, Mother, Brother or Sister had a heart attack, stroke or suffered from Cardiovascular disease before the age of 55?  
   No  Yes  
   If yes, at what age did he or she have the attack or stroke?  

24. What is your Blood Pressure?  
   ____/___mmHg  

25. What are your triglyceride levels?  
   _____________  

26. What is your Resting Heart Rate?  
   _______ bpm  

27. What is your Total Cholesterol?  
   _______ mmol/L  

28. What are your Glucose levels?  
   _______ mmol/L  

29. What is your Height?  
   _______ metres  

30. What is your Weight?  
   _______ kg  

31. What is your Waist girth?  
   _______ cm  

32. Do you have any bone or joint problem such as arthritis or a past injury that might become aggravated with exercise?  
   No  Yes  
   If yes, please explain:  

33. Have you had any injuries or surgery in the past five years?  
   No  Yes  
   If yes, please specify:  

34. Do you have a cold or flu, or any other infection at present?  
   No  Yes  

35. How many years have you been swimming for?  
   _______ years  

36. How many years have you been competitively swimming for  
   _______ years  

37. Outline your current training regime?  
   a) Frequency  
   b) Duration  
   c) Duration  
   d) Duration  

What phase of training are you currently in? (please circle)  
Preseason  Competition  Taper  Recovery  

36. Please outline a current and typical training week by filling in the table below.
Appendix C: Pre Screening Questionnaire

<table>
<thead>
<tr>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
<th>Sunday</th>
</tr>
</thead>
<tbody>
<tr>
<td>am</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DECLARATION

I declare that the above information is true and correct, and authorise the USC Health Program to rely on this information for the purpose of this consultation and all subsequent training programs, services and tests recommended, provided or conducted for me. I acknowledge that USC Health Program does not give any advice of a medical nature.

Signature ___________________________ Date ____________

Signature ___________________________ Date ____________

(To be signed by a parent or guardian for persons under the age of 18)

Office Use Only

Letter to Doctor for Clearance Needed: No Yes
Letter sent to client No Yes
Appendix D: ASCTA Journal Article (Ross & Fulton, 2006)

A Day in the Office!
AT THE PARALYMPIC PROGRAM P2 CAMP

After a successful P2 Camp in Darwin, Northern Territory in March it was time to head to Queensland in May.

P2 athletes are priority 2-level athletes in the Paralympic Preparation Program and are at SWD (Swimmers with a Disability) Teqstra Delphies. The priority 1 (P1) athletes in the Paralympic Preparation Program is our highest-level squad and takes All Australia scholarships as well as being SWD Techste Delphies. This elite domestic camp sees all P2 athletes come together from all states across Australia for a week-long camp. Selected Coaches are also selected to attend & assist with the camp. This was the first time that the P2 program had a female & Male team with head coaches appointed to the teams, as well as staff for that team.

Training Sessions:
Both Men’s & Women’s teams had various training schedules. The head coach of both teams worked with appointed coaches to determine the main focus for each group & training programs were set. The theme of the camp was “Working towards Beijing”. The sessions were a vital opportunity for the Head Paralympic Coach, Brendan Keogh, to see at just what point the P2 Athletes were in their training process.

Swimming & Massage:
Warm-up stretch sessions were conducted for both teams prior to each training session or pool deck. This was good for coaches to observe, regular stretching by each athlete and assisted athletes who need more focus in this area.

Massage was also available to athletes who were not familiar with regular massage. Each swimmer was encouraged to book in for a massage.

Gym Sessions:
At the Super Sperm Centre at Runaway Bay there was an opportunity for P2 athletes to utilise the outdoor covered gym. From head coaches took advantage of this. Each team was appointed a gym instructor to work with the group & all team members participated. Adaptation requirements were made with each athlete where necessary. Boxing, gym classes & fitness tests were included in the daily activities. Many P2 athletes have a regular gym program in their training program.

Pilates/Yoga/Relaxation sessions:
These sessions were very popular with all athletes. Core strength exercises continued and work by athletes & these sessions assisted with this. Flexibility without exercise & relaxation were on the agenda. There were a few days with male coaches who used relaxation in the mix & went to sleep.

Activities:
At each camp it is important to have activities that are fun for athletes, coaches & staff. Both male & female teams had various activities throughout the week. These activities included visits to the beach, shopping, movies, etc. An activity that was great success on this camp was the female team competing with the male team in an activity similar to the “great race”. Each team travelled the sights of Gold Coast obtaining requirements at different landmarks points.

Still other days the teams had to present their finds & be creative about it. The male team held a video & the female team held a power point presentation. The female team was awarded honours by a panel of judges. Both coaches & athletes had fun.

Tour Orientation & Communication:
Gill Paralympic Head Coach – Brendan Keogh has a motto of “A fast team is a happy team.” & this for all teams & all events is important to work together as a team. Embrace each personality & communicate well. Having the Male & Female teams separated meant that each team could work together to achieve this. Both teams showed good team athletics & activities within each group.

Coaching:
This was very important to the coaches who attended the camp. Each evening the coaches would get together with the Head Paralympic Coach & talk about swimmers on the team. Strategies & coaching techniques to assist with improvement. All coaches had their say. The experience & knowledge that was gained by this forum proved very valuable.
Appendix D: ASCTA Journal Article

Pull test uses a pull buoy and loose rubber band around the ankles with no paddles. A pull force line, stroke count and stroke rate may also be recorded. With these tests conducted at regular time intervals it has been interesting to track the relative contribution of kicking or pulling to an individual swimmer’s velocity when the arms or legs are excluded. During the Runaway Bay training camp the PPSU swimmers completed the kick and pull tests for both freestyle and their turn stroke and performed these tests on the final and the last day of the camp.

Alongside swimming speed as a measure of intensity, a swimmer’s Peak Heart Rate (HR) is the anchor point around which HR zones are set. Peak HR can be determined for a swimmer by a peak HR test or by monitoring maximal efforts during a training phase while HR values are recorded. Values can then be assessed over time to estimate a peak swimming HR. The Runaway Bay training camp provided an ideal opportunity to educate the PPSU swimmers about HR during training. The swimmers were exposed to a Peak HR test at the beginning of the week and were taught how to monitor their own HR both manually and through the use of a HR monitor. Swimmers were then asked to check their HR periodically during their training sets and report back to staff. Based off values from their Peak HR test they could then customize for themselves whether or not they were working in the correct training zone as prescribed by their coach.

Finally, underwater video was available for all swimmers during the course of the camp in order for underwater technique to be assessed. From these, an underwater video camera software that allows swimmers to analyze their technique on their own as well as seeing the moves projected onto a live screen of a late stage. Underwater video footage can analyze each swim technique, and vital skills such as the streamline positioned adopted in the underwater phase of the dive, the position of the body during the streamline phase of the turn and specific phases of the stroke such as hand entry or the catch. A DVD of the underwater video footage was created and sent to coaches along with feedback from staff at the camp.

Team Centre Website

At the P2 camp sessions were given for P2 Athletes & Coaches on how to use the valuable tool. This is how it works:

Paralympic Preparation Program Team Centre Website

By Sacha Fulton AIS Sports Based Scholar Australian Paralympic Swim team

The technology of the Internet is a common component of the everyday life. Swimming Australia in conjunction with the Australian Paralympic Committee, The Australian Institute of Sport and the University of the Sunshine Coast has developed a website called the APC, a Paralympic, Preparation Program swimmer and their coaches. This customised website enables swimmers and coaches residing all over Australia to "tag in" and access important information relating to SWO swimming in Australia. Swimmers and their coaches are allocated a username and password in order to access the site and ensure that their personal and training information remain confidential.

The website features eight different sections in a clean and simple format that is easy to follow for computer users of all levels. The Members Page is the home page of the website and offers a News Update and Newsletter section, Events Calendar, Articles on the Masters and Swim Series section where the current PPSU squad can be viewed, in the Details section a swimmer can change their password and word of their choice, and also allows them to directly access the database of all the APC in order to keep their personal data up to date. This section also allows the swimmer to update their race results. The Team Information, Publicis and Photos section allows swimmers to view important information and documentation relating to the Australian SWO program and view photos of swimmers in action.

A training diary in the form of an excel spreadsheet has been loaded into a calendar within the Log/Program section of the website for swimmers to log their training sessions on a daily basis. In order to make sure the data is accurate and complete, data should be recorded including times, heart rate and rate of perceived exertion (RPE), scores, and the equipment used. This information has been provided to the swimmers in the form of a Polar FS3 heart rate monitor, a mains copy of the Fing FS4 scale and laminated version of the online diary to document their training details and transfer them to the online diary at a later stage. The diary has been laminated in a matt finish so a led pencil can record the sessions regardless of contact with water. Within this section of the website is also a Coach Chat section where swimmers can quickly and easily communicate with their coach. Finally the Swimming Team Centre features a Forum section as well as a Contact Us section where swimmers can select a staff member of the Paralympic Team and directly email them with any questions, queries or comments.

The Swimming Team Centre has so far proven to be an invaluable tool for our own swimmers. Members of the team are regularly updated with important Paralympic swimming news and information. Detailed accounts of the swimming team's training sessions are documented weekly. Soon to be added to the website will be a Race Analysis Report section, where swimmers can download data analysis reports, including segment times and stroke parameters of their competitive performances over the weeks. A training report section will also be added to the website to give swimmers and coaches a break down of their training information per session and per week. It is envisaged that the Swimming Team Centre will greatly assist swimmers and coaches in their preparation for the 2008 Paralympic Games in Beijing, China.

For more information on the Paralympic Preparation Program – Swimming Australia email: Melanie Jenkins – Paralympic Program Coordinator melanie.jenkins@swimming.org.au Wendy Ross – Paralympic Program Development Officer – venyross@ mail.com.au
Appendix E: Paralympic Team Centre Website

Figure 1. Swimming team centre training diary webpage

Figure 2. Training diary template
Appendix F: ASCTA Journal Article (Fulton, 2006)

Kick & Pull Test Protocol for Swimmers with a Disability

by Sacha Fulton

THE DEVELOPMENT OF SPECIFIC POOL-BASED PHYSIOLOGICAL AND BIOMECHANICAL TESTS FOR SWIMMERS WITH A DISABILITY REMAINS LARGELY UNTouched IN COMPARISON TO ABLE BODIED SWIMMERS.

The underlying rationale is that physiological and biomechanical testing provides critical information for the sports scientist and coach regarding a swimmer's strengths and weaknesses.

A well-structured testing plan can assist the swimmer to plan individual conditioning programs, determine training loads, and monitor performance improvements. When a coach possesses a basic understanding of exercise physiology of swimming, they should be able to make better decisions concerning program design. Likewise, biomechanical testing provides information regarding a swimmer's mechanical strengths and weaknesses, for coaches to plan technique sessions and monitor improvements. Specific pool-based test protocols should lead to a better understanding of the physical capabilities and limitations of swimmers with disabilities, and consequently improve competitive performance. Kick and pull tests are one protocol implemented by the Paralympic Swimming Team to monitor improvements in training performance.

To establish test protocols for swimmers with a disability, it is important to standardize the classification system sanctioned by the International Swimming Federation, Federation Internationale de Natation Amateur (FINA) and the International Paralympic Committee (IPC).

The classification system in Paralympic swimming combines the physical characteristics of classes S1 - S13 and classes S1 - S13 of the visually impaired. The Prefa S denotes the class for freestyle, backstroke and butterfly. The Prefa SW denotes the class for freestyle and backstroke. The class system ranges from swimmers with the most severe disabilities (S1, S2) and multiple disabilities (S10, S8, S9) to those with the most physical ability or minimal disability (S1, S2, S3, S4).

At IPC-sanctioned events, distances S1 - S13 (see the following distances): Freestyle (50, 100, 200, 400m), Backstroke (50, 100m, 50, S10, S11, S12, S13), Breaststroke (50, S1, S2, S3, S4, S5, S6, S7, S8, S9), Butterfly (50, 77, 60m, S10, S11, S12, S13), and Individual Medley (50, S10, S11, S12, S13, 200m).

The 100m kick and pull tests are used routinely for Australian Paralympic Preparation Program (APP) swimmers. The tests are designed to identify strengths and weaknesses in the upper and lower body propulsive movements for swimmers with disabilities. The tests determine the relative contribution of kicking and pulling to swimming velocity by exclusion of the arm or leg contribution to the effort. Research has shown that the pull component of the arm stroke in swimming has a high propulsive force; in contrast, the flutter kick used in freestyle serves primarily to stabilize the body against the forces exerted on the water by the arm movements.

At a high swimming velocity there is an increase in hydrodynamic lift that assists the legs and reduces drag. Additionally, an increase in kicking also elevates the legs and reduces the drag forces produced. When the propulsive force of the lower limbs is diminished the legs tend to sink. Drag force is increased, leading to a greater oxygen cost and a reduced efficiency in propulsion. 

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YOUTH DEVELOPMENT

Swimming efficiency. Swimming speed is optimised when the propulsive force is greater than the drag force. Identification and reduction of resistive forces that act on a swimmer's body will reduce the amount of propulsive force needed to maintain any given speed. Swimming efficiency is dependent on a combination of swimming space, the stroke used and the skill of the swimmer. In competitive swimming, maximum efficiency is not necessarily a goal; however, optimal efficiency for maximum effectiveness is essential. The effectiveness of the swimming performance is measured by the speed with which a distance is covered. Understanding the contributions of the upper and lower body to full body swimming provides useful information to maximise propulsion, reduce drag forces and improve velocity and performance.

The 100m kick and pull test protocols for swimmers with a disability are completed on a regular basis at Australian Institute of Sport (AIS) and State-based training camps. A strict protocol is followed to ensure reliability and validity of the tests. The tests are completed for freestyle and backstroke and the swimmer's form stroke and commenced from a push start. Time is recorded manually for each 100m maximum effort. Swimmers perform their own standardised pre-race warm-up prior to each test. The kick and pull test protocols for Freestyle and Backstroke are performed on the same day with 15-20mins rest between tests. Each test uses a kickboard with neither hand allowed to move off the board during the test, while the pull test uses a pull decent and less rubber band around the ankles with no paddles. Measurements recorded during the test include 50m and 100m time, and stroke count and stroke rate in the pull test.

Typical times for the 100m kick and pull test protocols vary greatly depending on the nature of the swimmer's disability, whether the swimmer is upper or lower limb affected, and the class in which the swimmer competes. For example, two swimmers with cerebral palsy will have very different kick and pull times if one swimmer competes in class 5 and one in class 10. Below are typical kick and pull freestyle test times for Australia's top swimmers including their disability class and sex. The swimmer's current personal best 100m freestyle race time has also been included for comparison.

<table>
<thead>
<tr>
<th>DISABILITY</th>
<th>CLASS</th>
<th>SEX</th>
<th>PULL HOR</th>
<th>KICK HOR</th>
<th>100M FREESTYLE PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Amputee</td>
<td>S20</td>
<td>Male</td>
<td>1:12.11</td>
<td>1:26.44</td>
<td>58.69</td>
</tr>
<tr>
<td>Arm Amputee</td>
<td>S6</td>
<td>Male</td>
<td>1:09.50</td>
<td>1:19.58</td>
<td>56.71</td>
</tr>
<tr>
<td>Leg Amputee</td>
<td>S6</td>
<td>Male</td>
<td>1:05.00</td>
<td>1:17.57</td>
<td>50.02</td>
</tr>
<tr>
<td>Control Palsy</td>
<td>S6</td>
<td>Female</td>
<td>1:24.60</td>
<td>1:35.84</td>
<td>1:08.61</td>
</tr>
<tr>
<td>Short Stature</td>
<td>S6</td>
<td>Female</td>
<td>1:16.90</td>
<td>1:26.00</td>
<td>1:08.85</td>
</tr>
</tbody>
</table>

Table 1: Current kick and pull freestyle test times for Australia's top swimmers with a disability.

Future development of the 100m kick and pull test protocols is necessary to ensure reliability, validity and consistency with scientific work as a National testing protocol. Additional measures including stroke length, kick rate, heart rate and blood oxygen uptake may be used to enable specific kicks and pull tests for swimmers with cerebral palsy (CP) and upper and lower limb amputees (ULA). The Australian Paralympic swimming team is primarily comprised of swimmers between the ages of 8-10. For this reason, the kick and pull tests have been tailored specifically towards the 100m distance as this is the most common distance raced by these swimmers at IPC-sanctioned events. Swimming Australia is currently developing the weaker class of S1-5 in the Paralympic Preparation Program to increase Australia's chances of medals at future IPC-sanctioned events. For this reason, we are in the process of refining the current kick and pull protocols to include a 50m protocol for swimmers in these classes. We also are considering establishing a new set of standards for swimmers with a disability for the 100m kick and pull tests. These times may need to be class or disability specific in order to provide accurate information for individuals. Coaches should be able to administer the kick and pull tests and compare the performance times with other swimmers.
Appendix G: Race Analysis Report

Figure 3. A race analysis report generated at competitions by sport scientists; used by coaches to guide training programs.
Appendix H: Inertial Sensor Algorithm Development

Introduction
Inertial sensor devices are commonly used to assess sport-specific movements patterns through acceleration and angular velocity and swimming studies have been at the forefront of this research (Ichikawa et al., 2003; Ohgi & Ichikawa, 2003; Ohgi et al., 2003). Chapter 3 of this thesis presented a detailed evaluation of a tri-axial accelerometer (MiniTraqua™) and associated software (Logan) to quantify kick count and kick rate in freestyle swimming. The chapter specifically described the external dimensions and internal electronic configuration of the MiniTraqua™ and the development of the kick detection algorithm. More importantly the chapter addressed the validity and reliability of the algorithm to detect the up and down beat of individual kicks from the gyroscope trace of the sensor. Subsequent experimental studies in this thesis (Chapters 4 and 5) addressed specific kick-related research questions using the MiniTraqua™ application. The purpose of this appendix is to evaluate the development pathway of the algorithm that was created to detect kicking characteristics in swimming.

Firmware and Hardware
There were some minor firmware problems encountered with one batch of the MiniTraqua™ inertial sensors where the gyroscope trace failed during calibration or there was no data collected during trials. On these occasions new inertial sensors were issued with no further problems. The hardware problems encountered during testing related to the external packaging and water proofing capabilities. When trialling was undertaken without additional waterproofing, water damage to the internal electronics resulted (Figure 4). Additional waterproofing was trialled extensively and a combined approach, using a clear plastic balloon and zip lock pouch was eventually adopted (Figure 5). Other limitations of the external packaging included difficulties with repair and servicing to the internal electronics, and degradation of materials associated with constant use in a chlorine-rich environment. These problems were not resolved during the course of this research and pave the way for continued development of the technology.
Calibration

Every MiniTraqua™ inertial sensor used in testing was calibrated prior to data collection using a cradle with USB interface and a real-time connection to Logan (Figure 6). Manual orientation ensured that each axes of acceleration (X, Y, and Z) was equal to +1g and -1g. The X axis was calibrated for forwards (+1g) and backwards (-1g) movements, the Y axis calibrated for left and right or medial (+1g) and lateral (-1g) movements, and the Z axis calibrated for up (+1g) and down (-1g) movements (Figure 7). Gyroscope calibration involved rocking the MiniTraqua™ through the roll axis from horizontal to vertical to calibrate for 90° of movement.
Location

Unlike land-based sports, there are only certain locations on a swimmer’s body where monitoring devices can be attached without causing major interference while swimming. In pilot trials, placement of the inertial sensors on the anterior or lateral sides of swimmer’s lower limb segments proved uncomfortable or interfered with the streamlined position. Posterior placement on the lower limbs provided a clear gyroscope signal and did not inhibit kicking movements (Figure 8).
Algorithm Evolution

Numerous versions of the inertial sensor operating system, Logan, were created as the kick detection algorithm was modified and a version created that accounted for the majority of kicks during freestyle kicking movements. Some problems with the initial program included slow kicks which had a double trough and were detected as two separate kicks by the program. A modified algorithm ensured that once a trough was detected, Logan did not detect another trough until the next time the gyroscope trace crossed zero deg/sec. The modified algorithm addressed problems of swimmers taking small flutter movements between kicks and Logan subsequently missing detection (Figure 9). Closer analysis revealed that these leg movements were not intentional kicks, yet merely interruptions in the normal kick pattern, usually occurring when the swimmer broke their stroke to take a breath.

With subsequent iterations, the algorithm was improved to account for the majority of kicks (Figures 10 and 11). Modifications made to the original algorithm included:

- Changing the width of the “sliding window”
- Changing the filter of the gyroscope signal from 3 Hz to 4 Hz for greater kick detection accuracy
- Changing the angular velocity restriction between troughs from > 250 deg/sec to 300 deg/sec.
Figure 9. Small flutter movements between kicks on a gyroscope trace. Red lines indicate poor reliability of the algorithm to detect kicks.

Figure 10. A gyroscope trace from a regular freestyle kicking trial. Red lines indicate a reliable algorithm for kick detection.
Figure 11. The gyroscope trace of a 100 m freestyle time trial in a 25 m pool. The start and finish are indicated by green circles; blue circles indicate turns.

**Conclusion**

The inertial sensor technology and associated software used in this study is sufficiently valid and reliable for quantifying kick count and kick rate in freestyle swimming. The technology can be used by coaches and researchers interested in quantifying kick patterns in swimming to guide training regimes and for biomechanical and performance enhancement applications. In a single timed effort coaches and researches can expect almost perfect agreement between the sensor and video analysis for detecting kick count in freestyle swimming. Refinements to the current system are needed to fully automate the kick detection process, reduce associated measurement error and increase reproducibility when reporting small changes in kicking patterns.
Abstracts

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Measuring the kick in freestyle swimming

To compete and be successful on the world stage, swimmers need to enhance their technique for sports performance. Swimming performance is quantified by the international benchmarks of velocity, stroke length, and stroke rate. There is no current measurement for kick. The purpose of this research was to measure the parameters of kicking in freestyle swimming, in particular kick rate and kick count. Data were collected on 15 swimmers from the Australian 2006 IPC World Championship Swimming Team during national training camps held within Australia, and will continue at the World Championships held in South Africa. The data collection involved custom built accelerometers, which have evolved from the CRC in Microtechnology. The software for the accelerometers has been developed at the Australian Institute of Sport. During each testing session, swimmers were asked to complete two 100m maximal effort time trials performing freestyle swimming and freestyle kicking. The accelerometer devices were attached to each calf of the swimmer and timing of the 25m segments were recorded. The data logger for each accelerometer identified kick patterns for each trial, which was then analysed to provide kick count and kick rate for each segment. The results of this study objectively present for the first time the parameters of kick in elite swimmers. This information will aid future understanding of the most effective swimming race strategy, which will also be reflected in the swimming volume and intensity during training.
Appendix J: Chapter 7 Photographs

Figure 12. Dynometer and force platform system.

Figure 13. Maximal kicking condition.

Figure 14. Prone streamline condition.