Active drag of front crawl swimmers: estimation, measurement and analysis

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Candidate's Declaration

I, Pendar Hazrati, hereby declare that this thesis is my own work and does not, to the best of my knowledge, contain material from any other source unless due reference is made. The thesis was completed under the guidelines set out by The University's Faculty of Health Sciences for the degree of Doctorate of Philosophy and has not been submitted for a degree or diploma at any other academic institution.

I, Pendar Hazrati, hereby declare that I was the principal researcher of all work included in this thesis, including work published with multiple authors. A statement from the authors confirming the authorship and contribution of the PhD candidate to published work is at the beginning of each chapter.

Signed ______________________ Date: 29/03/2016

Abstract

Drag is the water resistance acting to oppose a swimmer while the swimmer propels the body forward. This drag force has been determined as a negative factor on the swimmer's performance. Hence, it is important for swimming coaches to know how much drag is produced by the swimmer during swimming and gliding and how this force can be reduced. Many researchers have attempted to measure drag force during swimming. The drag force may be measured or estimated in two conditions. The first is active drag, which occurs when the body is actively propelling itself forward. The second is passive drag, which occurs when the body is floating without any propelling movement. Active drag has been estimated by a number of research teams using different methods, but there was considerable variation between results found, although the reasons for this have not been exactly identified. One of the methods used to estimate active drag is the Assisted Towing Method (ATM) with fluctuating speed. This allows the swimmers to have a fluctuating speed that enables them to maintain normal stroke technique as much as possible while being towed. The aims of this thesis were to assess the reliability of the ATM method with fluctuating speed and, by using this method, investigate the validity of the estimation of active drag.

A review of previous methods was undertaken to understand how the resistive forces in swimming were measured and calculated (chapter 2). Each method has both strengths and weaknesses in the measurement of active drag. Comparisons between the outcomes of methods were conducted to evaluate their measurement based upon advantages and disadvantages. The aim of this section was to provide a better understanding of each method and to evaluate which of them measures or estimates active drag more accurately than the other.

The reliability of estimating active drag in swimming using the ATM with fluctuating speed was investigated in chapter 3. To assess the reliability, two statistical analyses were performed to examine Intra-class Correlation Coefficients (ICC) within-subject for each day, and the ICC was compared between two different days when the five active drag values were averaged. The ICCs within-subject were moderately reliable for day one (0.82) and day two (0.85); however, high reliability (ICC = 0.92) was obtained when averaged active drag values were used.

In chapter 4, mean active drag values were obtained from two methods (assisted and resisted methods) using consistent equipment to assess whether these two methods measured the same values for active drag. The result of this study showed there was no significant difference between the mean active drag values of the two methods ($p = 0.127$). This finding does not suggest that the two measures were actually the same, because of the small number of subjects. However, the individual results showed that some swimmers demonstrated large differences in the active drag obtained from the assisted and resisted methods. Three reasons for this were suggested: 1) unequal swimmer power output under two conditions, 2) the square relationship between the drag and speed, 3) uncertainty in measured variables (belt force, tow speed and free swim speed).

Active drag using the ATM method is calculated from a function of three measured variables: swim speed, tow speed and belt force, using two assumptions about the power output between trials and the quadratic relationship between drag force and swim speed. The accuracy of active drag estimated using the ATM method is dependent on the accuracy of these three variables and the two assumptions, and on the way they contribute to the overall estimation of active drag. In chapter 5, the uncertainty of each variable was computed and the contribution of each uncertainty into the active drag value was calculated. Results indicated that if power changes by 7.5% under the free and the tow swimming conditions, it leads to about 30% error in calculated drag. Consequently, if a swimmer cannot maintain constant power output under two swimming conditions, there would be substantial errors in the calculation of active drag. Also, the result showed that if the uncertainty of the speed exponent is assumed ± 0.4 in a range exponent of 1.8 to 2.6, this uncertainty would lead to about 5% error in active drag value. The contributions of the measured variables to active drag were approximately 6–7% error for the free swim speed, the tow speed and 2–3% error for the belt force.

Previous studies using the ATM method have presented an active drag profile of front crawl swimmers. This profile is calculated from the instantaneous values of three variables: free swim speed, tow speed and tow force. A dynamometer measured the tow force and it incorporated a velocity transducer to measure the tow speed. The shape of the free swim speed profile was assumed to be approximately similar to the shape of the towing speed profile, and the only difference between these two profiles was that the free swim speed profile moved 5% to 8% above or below the towing speed profiles for the assisted and the resisted methods respectively. Therefore, the aim of chapter 6 was to compare the free swim speed profile, which was obtained from a speed transducer, with the assisted tow and the resisted tow speed profiles, which were obtained from a dynamometer. Comparisons between intra-cyclic speed fluctuations and the stroke mechanics of free, assisted and resisted swimming were performed. The range of variation between maximum and minimum speeds within stroke, and the stroke rate, stroke length and stroke phases were assessed for these comparisons. The speed profiles of the three swimming conditions showed that swimmers had the greatest variation from the maximum to the minimum speeds within stroke in the free swimming condition compared to the other two swimming conditions. The two speed profiles of neither the assisted nor the resisted swimming closely resembled those of the free swimming speed profiles. It can be concluded that although the assisted and the resisted swimming have a fluctuating speed, these fluctuations are not as large as those that occur during free swimming. It is suggested that, to have a greater variation in speed within each stroke, the dynamometer be modified in some way that allows the swimmer to swim more closely to the free swimming condition.

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Dedication

This thesis is dedicated to my husband, Amir, who has served as my inspiration,

and to my beautiful little daughter, Nika – since she was born, my spiritual life has changed.

To Mum and Dad, who first encouraged me to go on this path,

thank you for the love and support you have always given me.

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Glossary of terms and abbreviations

A	*A*, The maximal cross sectional area of the considered body perpendicular to the direction of the considered hydrodynamic force.
AIS	Australian Institute of Sport
ATM method with a constant speed	Assisted Towing Method with a constant speed, a method that estimates active drag by pulling a swimmer using the dynamometer at a constant velocity. This method estimates active drag based upon the three assumptions of the VPM method.
ATM method with a fluctuating speed	Assisted Towing Method with a fluctuating speed, a method that estimates active drag by pulling a swimmer using the dynamometer while allowing the swimmer to have the fluctuating velocity. This method estimates active drag based upon the three assumptions of the VPM method.
$\mathbf{C_d}$	A drag coefficient, i.e. a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment. The drag coefficient, related to the swimmer's speed, shape, body position and inclination, and the flow condition on the swimmer's drag.
Entry and catch phase	The entry and catch begins when the arm enters the water and then stretches forward through elbow extension. The phase then continues with downward movement of the arm.
$\mathbf{e_P}$	Propelling efficiency, i.e. the ratio between of the power to overcome drag and the total mechanical power output.
$\mathbf{F_A}$	Active drag, which is the water resistance associated with dynamic swimming. The active drag is a consequence of the body actively propelling itself forward. The active drag is exerted by the water on the swimmer

F_B	The cable force, a force that tows the swimmer while swimming using a dynamometer.
Fp_d	Passive drag, which occurs when the body is floating without any propelling movement. The passive drag can occur in anybody position.
Fp_r	Propulsive force, which is a force exerted on the swimmer by the water.
F_r	Froude number, a dimensionless number defined as the ratio of the flow inertia to gravitational forces. The Froude number is based on the speed–length ratio.
F_r	Skin friction drag that drag occurs between the water layer and the skin of the swimmer during swimming.
F_W	Wave drag occurs essentially because the swimmer performs at the interface between two fluids, water and air.
FINA	Federation Internationale de Natation
MAD system	Measurement of Active Drag system, a system that measures the active drag through the propulsive forces measurement of the arms when a swimmer pushes against paddles fixed to a force transducer in the pool.
P_d	A power produced by the swimmer to overcome drag.
P_k	A power wasted in giving kinetic energy change to the water.
P_0	Total mechanical power output, i.e. the amount of power that is produced by the swimmer to overcome active drag, plus the amount of power wasted.

Pull phase	This phase occurs from the beginning of the hand's backward movement to the hand's arrival in the vertical plane to the shoulder relative to the swimmer.
Push phase	The push begins from the hand's position under the shoulder to its exit from the water.
Recovery phase	The recovery occurs when the hand exits the water and continues to the hand's following entry into the water.
S	Stroke, a stroke occurs when the swimmer performs a full stroke with the right arm and the left arm alternately while kicking.
SR	Stroke rate, the stroke frequency in strokes per minute
SL	Stroke length, the distance the body travels per stroke
$\mathbf{t_E}$	The time from the hand's entry into the water to the beginning of its backward movement.
$\mathbf{t_{PL}}$	The time from the beginning of the hand's backward movement to the hand's arrival in the plane vertical to the shoulder.
$\mathbf{t_{PS}}$	The time from the hand being in position under the shoulder to its exit from the water.
$\mathbf{t_R}$	The time from the hand's exit from the water to its following entry into the water.

VPM method Velocity Perturbation Method, a method that estimates active drag using the hydrodynamic body which is attached via a cable to a swimmer. The active drag estimates based upon the three assumptions;

- a constant mechanical power output in both conditions
- a constant average velocity during each trial
- a change of drag in proportion to speed squared.

CHAPTER 1

Introduction

1.1 Background

1.1.1 Resistive force

Competitive swimming starts with a dive and continues with swimming phases and turns. For both the swimmer and coach, the goal of competitive swimming is to finish the required distance in the shortest possible time. Swimmers spend approximately 8–9 seconds implementing starts and turns in 100 m front crawl but most of their competition is spent in the swimming phase (85%) (East, 1970). Hence, it is essential for the swimmers and the coaches to know which factors influence this phase and how they can improve those factors for achieving better performance. Researchers have resolved that to determine swimming performance, they must estimate the drag force and propulsive force to calculate total efficiency of the swimmers, as it is the fundamental aspect in swimming (Clarys, 1979; Di Prampero, Pendergast, Wilson, & Rennie, 1974; Zamparo, Gatta, Pendergast, & Capelli, 2009).

A swimmer's maximum speed is determined by two major forces. One of these is the propulsive force that a swimmer must produce to propel the body forward. The other is the drag force exerted by the water on the swimmer (Alcock and Mason, 2007). Drag can be defined as "a resistance of the water to the swimmer's movements through it" (Maglischo, 2003, pp. 6) and the drag force is applied in the direction opposite to the movement of an object. It is the force that swimmers have to overcome while attempting to maintain their movement through the water. Drag force may be measured or estimated for swimmers performing under two conditions, the first being active drag when the swimmer is propelling the body forward, and the second being passive drag when the swimmer is gliding in a streamline position while being towed (Kolmogorov & Duplishcheva, 1992).

Since 1970, a number of measurement techniques have been developed to assess and estimate active drag directly or indirectly. There has been controversy about the methods used to measure active drag because the researchers having reported significantly different values for active drag (Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Mason, et al., 2011; Toussaint, Ross, & Kolmogorov, 2004; Wang et al., 2007; Zamparo, Gatta, Pendergast, & Capelli, 2009).

1.1.2 Methods of active drag measurement

In the early 70's, researchers measured active drag based on extrapolation techniques that involved indirect calculations from changes in oxygen consumption due to the additional loads placed on the swimmer (Clarys & Jiskoot, 1974; Di Prampero, Pendergast, Wilson, & Rennie, 1974). They calculated a linear relationship between maximum oxygen consumption (VO_{2net}) and drag. This linear relationship was identified at a range of swim velocities. The relationship between maximum oxygen consumption and drag was calculated by the least-squares method for a linear regression.

The three most common methods of measuring active drag are the Measuring Active Drag (MAD) system (Hollander et al., 1986), the Velocity Perturbation Method (VPM) (Kolmogorov & Duplishcheva, 1992) and the Assisted Tow Method (ATM) (Alcock & Mason, 2007). The MAD system (Hollander et al., 1986) directly measures the propulsive force of the arms when a swimmer pushes against paddles fixed to a force transducer in the pool while performing the front crawl action (Figure 1.1). A small pull-buoy is situated between the swimmer's legs to prevent the use of the legs during the swimming action as well as to maintain the body in a horizontal position. The MAD system calculates active drag from the mean propulsive force on the principle that, at a constant swimming speed, the mean active drag is equal to the mean propulsive force (Schleihauf et al., 1983).

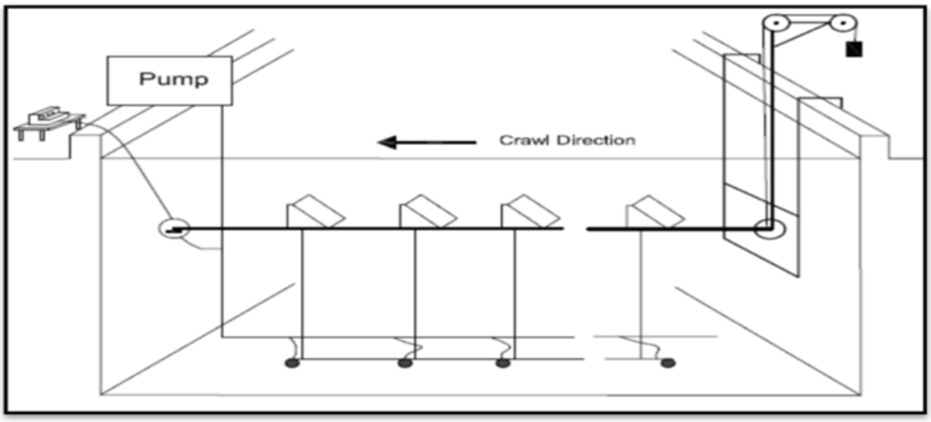

Figure 1.1 – MAD-system setup for drag collection: adapted from Hollander et al. (1986)

In contrast, the VPM method (Kolmogorov & Duplishcheva, 1992) uses a hydrodynamic body to estimate active drag (Figure 1.2). Firstly, the swimmers must swim without any attachments—freely—with their maximal effort and, secondly, the swimmers swim with their maximal effort while a hydrodynamic body is attached to the back of their waist to create a known additional resistance. The estimation of active drag in this method is based upon the assumption that the swimmer is able to generate a constant mechanical power output in both free and resisted swimming conditions as well as maintaining a constant mean speed during trials. Another assumption of this method in the estimation of active drag is that drag changes in proportion to speed squared. In both these conditions, the swimmer must swim with their maximal effort over the same distance.

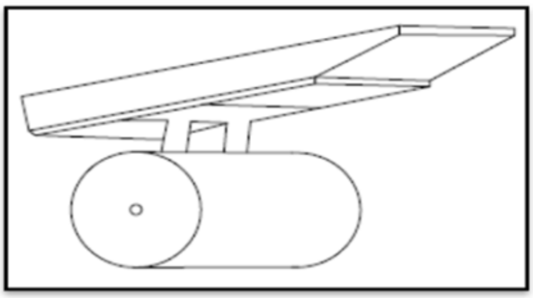

Figure 1.2 – Structure of the additional hydrodynamic body: adapted from Kolmogorov & Duplishcheva (1992)

The ATM method (Alcock & Mason, 2007) was developed based upon the three assumptions of the VPM method (Kolmogorov & Duplishcheva, 1992). In this method, active drag is estimated using a controller motor-driven cable at a constant tow speed (Figure 1.3). To achieve a constant speed, a maximum force setting (550 N) on the dynamometer was set. This is similar to the VPM method except that the swimmer is assisted rather than being resisted. A criticism of towing at a constant speed is that in free swimming the swimmer has intra-stroke speed fluctuations that are not replicated in normal swimming stroke mechanics during the process of being towed at constant speed. Therefore, Mason et al. (2011) advanced the ATM method by reducing the amount of tow force setting. The maximum tow force setting was reduced from 550 N to a force equivalent to the mean passive drag of each swimmer (in a range of 50 to 110 N), with the dynamometer still pulling the swimmer 5-8% faster than their free swimming speed. Therefore, this setting allowed intra-stroke speed fluctuations to occur. A motion controller was used by Mason et al. (2011) with the aim of achieving a fluctuating speed within stroke. To achieve this, the maximum possible force, considered equivalent to the mean passive drag of the swimmer, was set very low on the dynamometer to allow the motion controller to fluctuate tow speed. In the ATM method with the fluctuating speed (Mason et al., 2011), intra-stroke speed was constantly changing due to the various propulsive and recovery phases within a typical stroke, which therefore meant active drag was also changing.

Mason et al. (2011) illustrated an active drag profile that was calculated from the instantaneous values of three variables: free swim speed, tow speed and tow force. To determine the active drag during free swimming, Mason et al. (2011) assumed that the free swim speed profile is approximately similar to the towing speed profile, and the only difference between these two profiles was that the free-swim speed profile moved 5% to 8% below of the towing speed profile. Mason et al. (2011) has demonstrated that the ATM method with fluctuating speed can estimate active drag more accurately than previous studies using the ATM at a constant speed (Alcock & Mason, 2007; Formosa, Mason, & Burkett, 2011) because the swimmer can swim with their normal stroke mechanics.

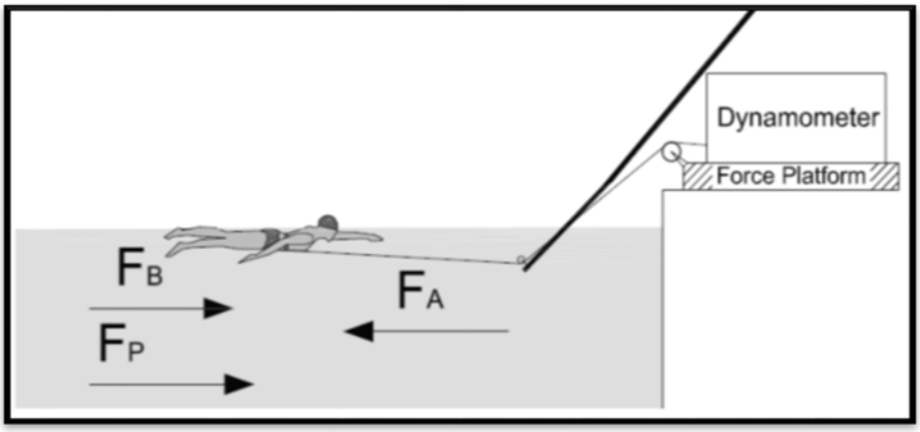

Figure 1.3 – Assisted Towing Method setup: this diagram illustrates the direction of towing as represented by the cable force (F_B), the direction of the propulsive force (F_P), the direction of active drag (F_A)

1.1.3 Limitations of methods in active drag measurement

Each of these methods has advantages and disadvantages in the measurement of active drag. The advantage of the MAD system is that it measures actual propulsive forces while a swimmer pushes against the paddles; however, the MAD system prevents the swimmer having natural stroke mechanics (Poizat, Ade, Seifert, Toussaint, & Gal-Petitfaux, 2010). The swimmer must match stroke length to the distance between the two paddles and contact with the fixed paddles prevents any movement of the hands in the water. In normal swimming, however, a swimmer's hands move in relation to the water. The advantage of both the VPM method and the ATM method is that they can estimate active drag for all four strokes. However, the disadvantage of these two methods is that calculations of active drag are based upon the assumption of equal power output between the free swimming and the towing conditions and if the swimmer cannot maintain the same power output, then the calculation of active drag would be incorrect. The other disadvantage of these two methods is that active drag is calculated only at the maximal swim speed of the swimmer.

Although there have been widespread investigations into the area of active drag in front crawl swimming (Clarys, 1979; Di Prampero et al., 1974; Formosa, Toussaint, Mason, & Burkett, 2012; Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Mason et al., 2011; Toussaint et al., 2004; Schleihauf et al., 1983; Wang, Wang, Yan, Li, & Shen, 2007), there has been controversy due to the varying values being reported. Differences within the literature are most likely to reflect the varying methodologies and protocols adopted by each researcher.

1.2 Significance of thesis

The studies within this thesis are provided to evaluate the estimation of active drag using the ATM method and contribute to the progression of science research and swimmers' performance. This is the first study to explore the accuracy of active drag estimation using the ATM method at the Australian Institute of Sport (AIS). It is hoped that this thesis will be able to provide a more accurate drag measurement by assessing the reliability and validity of the estimation of active drag using the ATM method with fluctuating speed. The results of these studies could provide new information to help swimming biomechanics generally, and especially those at the AIS, to improve the current ATM method. Ultimately, a swimmers performance will benefit if active drag during swimming is reduced.

1.3 Aims of the thesis

This thesis aims to investigate several areas relating to the reliability and validity to assess the accuracy of the estimation of active drag using the ATM method in the estimation of front crawl swimming, a method that swimmers attempted to maintain constant technique while being towed. Construct validity was used to investigate the validity of estimation of active drag. It also aims to increase the information available to swimmers and coaches by:

1) providing comprehensive information about reliability
2) evaluating the validity of the estimation of active drag using the ATM method during the naturally occurring fluctuating speed.

1.3.1 Objectives of the thesis

To achieve the aims of the thesis, the following objectives were developed:

1) evaluate whether the estimation of active drag using an assisted tow is reliable in producing repeatable values within a single day as well as over two separate days
2) compare estimated active drag values from resisted towing with those from assisted towing values to evaluate whether the two methods estimate the same values for active drag
3) determine uncertainties in estimation of active drag calculated from the ATM method and how they affect the active drag value
4) compare intra-cyclic speed fluctuations of the assisted and the resisted methods with those of the free swimming condition in an attempt to evaluate the accuracy of the assumption of similarity between the free swim speed profile and the towing speed while using the ATM method.

1.4 Delimitations

There were a number of delimitations for these studies:

- testing protocols were required to be completed at the technology pool of the Australian Institute of Sport in Canberra, Australia
- for at least one of the 100m, 200m or 400m distances in the front crawl, participants must have registered a personal best time equal to or greater than a FINA point score of 600 points during the last 12 months
- the swimmers had to be healthy and have no physical injury or illness which would mean they would not be able to complete the required tests

- the swimmers were required to hold their breath during the data collection of all four studies.

1.5 Outline of the thesis

Based upon the objectives of the thesis, the following outlines are presented in seven chapters.

Chapter 1: provides a brief background about the active drag measurement and the problems being addressed by this thesis, states the aims and objectives of this thesis and provides an outline of the thesis chapters

Chapter 2: provides a comprehensive review of previous methods that have been used to measure active drag and compares those methods

Chapter 3 – Study 1: demonstrates the reliability of estimating active drag in swimming using the assisted towing method (ATM) with fluctuating speed

Chapter 4 – Study 2: presents a comparative analysis of two types of active drag measurement in front crawl swimming

Chapter 5 – Study 3: shows how uncertainty affects estimation of active drag using the assisted towing method in front crawl swimming

Chapter 6 – Study 4: presents the effect of the assisted and the resisted swimming on intra-cyclic speed fluctuations and stroke mechanics and compares those with that of the free swimming in front crawl swimming

Chapter 7: summarises the results of chapters 3–6 and discusses both these results and the final conclusions of this thesis. Chapter 7 also provides future research directions in this area.

1.6 Journal publications

Chapter 3 is presented as: Hazrati, P., Sinclair, P. J., Ferdinands, R. E., & Mason, B. R. (2015). Reliability of estimating active drag in swimming using the assisted towing method (ATM) with fluctuating speed. *Journal of Sport Biomechanics*, Paper accepted for publication.

Chapter 5 is presented as: Hazrati, P., Sinclair, P. J., Ferdinands, R. E., Spratford, W., & Mason, B. R. (2015). Contribution of uncertainty in estimation of active drag using assisted towing method in front crawl swimming. *Journal of Sport Sciences*, Paper currently under review.

Chapter 6 is presented as: Hazrati, P., Sinclair, P. J., Ferdinands, R. E., Spratford, W., & Mason, B. R. (2016). Comparisons between intra-cyclic speed fluctuations and the stroke mechanics of free, assisted and resisted swimming. *Journal of Sport Biomechanics*, Paper currently under review.

1.7 Conference presentations

Hazrati, P., Mason, B., & Sinclair, P. J. (2013, July). Reliability of estimating active drag using the assisted towing method (ATM) with the fluctuating speed. Paper presented at the 31st ISBS, 252–255, Taiwan, Taipei.

Hazrati, P., Mason, B., & Sinclair, P. J. (2014, April). Development of a new resisted technique in active drag estimation. XII International Symposium on BMS, 136–141, Australian Institute of Sport, Australia, Canberra.

Hazrati, P., Mason, B., & Sinclair, P. J. (2014, July). Validity of estimating active drag using the both assisted and resisted techniques with fluctuating velocity. Paper presented at the 32nd ISBS, 105–108, USA, Johnson City.

Hazrati, P., Sinclair, P.J., Mason, B.R., & Spratford, W. (2015, Jun). Comparison between velocity profiles of the assisted towing method and free swim velocity. Paper presented at the 33rd ISBS, France, Poitiers.

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CHAPTER 2

Literature Review

2.1 Introduction

Successful competitive swimming performance depends upon a number of factors such as physical, technical and individual characteristics, and mental ability. Each of these components has a considerable effect on overall performance. For example, good technique allows the swimmer to achieve higher swim speed because a swimmer would be able to generate more propulsion and reduce drag force during throughout a stroke cycle. The propulsive force is produced by the combined motions of the arms and legs. On the other hand, some factors such as a hydrodynamic drag force have a negative effect upon swimming performance and the swimmer has to overcome this negative force for maintaining the propulsive force at the highest possible speed (Kjendlie & Stallman, 2008). Hence, good swimming performance is dependent on achieving the maximum propulsion force, while attempting to reduce the drag force (Formosa, Mason, & Burkett, 2010).

2.2 Front crawl technique

Front crawl is the fastest stroke and each stroke cycle includes an alternating arm action and continuous up and down movement of the legs. The propulsive forces generated in front crawl are mainly due to arm movements, more so than leg movements (Hollander, De Groot, Van Ingen Schenau, Kahman, & Toussaint, 1988). The stroke cycle is categorised into four distinct phases consisting of entry and catch, pull, push and recovery (Seifert, Chollet, & Bardy, 2004) (Figure 2.1). This categorised is only one of the ways to categorise the stroke cycle. The stroke cycle consists of the propulsion phase (pull and push) and non-propulsive phase (entry and catch, and recovery) (Seifret et al., 2004).

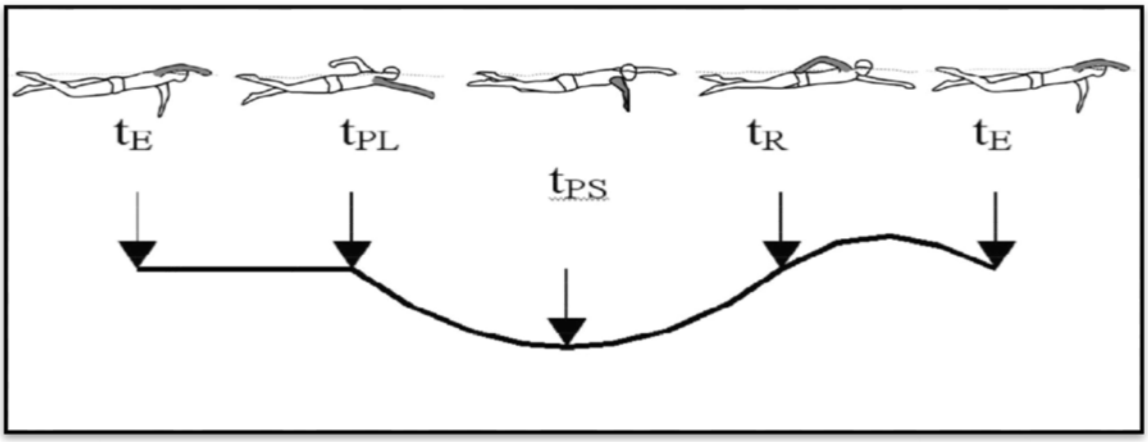

Figure 2.1 – Illustration of intra-stroke phases in front crawl swimming: t_E represents the time of hand's entry and catch phase, t_{PL} represents the time of pull phase, t_{PS} represents the time of push phase and t_R represents the time of recovery phase.

2.2.1 The entry and catch phase

The entry and catch begins when the arms enter the water and then stretch forward through elbow extension. The entry also occurs when a swimmer rotates the body downward on the side of the entering arm during the stretch. This phase then continues with the downward movement that is called the catch phase. At the end of the catch phase, the shoulder, elbow and hand are positioned on the same vertical plane.

The resultant speed of the swimmer decreases during the entry phase because both arms are in the non-propulsive phase—one arm is at the entry and catch phase and the other one is at the beginning of the recovery phase (Gourgulis et al., 2010). Hence, the duration of this phase increases as the swim speed decreases. By stretching the arm in the entry phase, the swimmer can reduce drag force (Holmer, 1979). During the downward movement, the hand speed is slightly increased because the catch position is achieved; a better position of the catch would enable the swimmer to produce more propulsive force and higher speed during the pull phase (Gourgulis et al., 2010).

2.2.2 The pull phase

The propulsive force is largely generated from downward and backward movements of the arm while keeping the elbow up during this phase. This phase occurs from the beginning of the hand's backward movement to the hand's arrival in the vertical plane to the shoulder. At the beginning of the phase, as the elbow flexes, hand speed moderately increases and, hence, propulsive force is produced (Barthels, 1979). The resistive force profile of Kolmogorov (2008) showed that the resistive force of the swimmer during this phase increased when the speed increased.

2.2.3 The push phase

The push begins from the hand's position under the shoulder to its exit from the water. In this phase, the hand starts to sweep outward from underneath the body, and then it continues with upward movement until the hand approaches the surface of the water. The push phase is the second part of the propulsive phase; hand speed increases rapidly and reaches the greatest possible amount of propulsive force (Barthels, 1979) and greatest amount of resistive force (Kolmogorov, 2008). In this phase, the swimmer starts to turn the head to breathe during upward movement and the breath then would be finished in the first part of the recovery phase. The head position during the breathing phase increases drag on the body of the swimmer (Payton, Bartlett, Baltzopoulos, & Coombs, 1999).

2.2.4 The recovery phase

The recovery starts when the arm exits the water and ends when the arm drops back into the water. This phase is a non-propulsive phase with the arm and hand not producing a large resistive force. Therefore, the length of the recovery should be minimised to enable the swimmer to reach the propulsive phase during pull and push (Seifert et al., 2004).

2.3 Mechanical power output in swimming

Correct front crawl technique throughout the phases is vital for power production. However, the relationships between the useful mechanical power output, the active drag, the hydrodynamic force coefficient, and the maximal swim speed are more important to achieve better swimming performance (Kolmogorov & Duplishcheva, 1992). The swimmer producing a power to overcome drag (P_d) and the power wasted in giving kinetic energy change to the water (P_k) are defined as the total mechanical power output (P_o) (Di Prampero, Pendergast, Wilson, & Rennie, 1974; Toussaint et al., 1988a):

$$P_o = P_d + P_k \quad (1)$$

Hence, the P_d at a swimming speed (v) and drag force (F_d) is given by:

$$P_d = F_d . v \quad (2)$$

And the P_k is given by:

$$P_k = \frac{1}{2} m(\Delta v)^2 f \quad (3)$$

where m is the mass of the pushed away water, $\Delta v$is the speed change and f is the stroke frequency. The ratio between the power to overcome drag to the total mechanical power output (Di Prampero et al., 1974; Toussaint et al., 1983; Toussaint et al., 1988a):

$$e_p = \frac{P_d}{P_0} \quad (4)$$

Based upon equation (4), the swimming performance is not only dependent on the mechanical power output (P_o), it also depends upon the propelling efficiency (e_p) of a swimmer (Toussaint et al., 1988a).

Total efficiency (e_m) is defined as the ratio between total power output and the rate of energy expenditure (Holmer, 1972). In this case, a higher total efficiency would be a consequence of an increase in the power output or a reduction in the overall energy expenditure of the swimmer. Therefore, it is necessary to reduce the drag forces so there will be less power output necessary to overcome them. Knowing how to reduce the drag forces requires understanding what they are and how they affect the swimmer's performance.

2.4 Resistive forces

A swimmer pushes against the water and at the same time, the water pushes back against the swimmer with an equal and opposite force (Newton's Third Law). Therefore, the propulsive force is a force exerted on the swimmer by the water. However, the water creates a resistance or a drag force in the opposite direction on the swimmer's body to decelerate the forward movement. Drag force has been defined as "a resistance of a fluid to the swimmer's body movements through it" (Maglischo, 2003, pp. 6). The speed, shape, size, frontal surface area of the swimmer and submerged body surface area all affect the magnitude of drag forces (Kjendlie & Stallman, 2008). Hence, it is important for the swimmer to minimise drag while attempting to maintain their movement through the water.

To minimise drag force, understanding how water flow influences the swimmer's body is essential. Physical features of the water such as density, viscosity and surface tension describe the nature of hydrodynamic resistance. The density of the water is the mass of the water per its unit volume (V), which depends on the temperature of the water. The water's density varies with temperature and it decreases with increasing the temperature. Viscosity of the water is a measure of the water resistance to deformation by either shear stress or tensile stress and causes the resistance to the water (Vogel, 1994). The temperature dependence of liquid viscosity and the viscosity of water decreases with increasing temperature. Surface tension is an effect of intermolecular attraction (Vogel, 1994).

There are three components of drag force that negatively impact a swimmer's movement in the water: pressure resistance (form drag), wave drag and skin friction drag (Toussaint et al., 1988b). Pressure or form drag is caused by the shape and position of the swimmer while swimming (Maglischo, 2003). Wave drag happens at the interface between two fluids: air and water. Wave drag may be reduced by performing some sections of the stroke completely under the water rather than on the surface (Vennell, Pease, & Wilson, 2006). Skin friction drag is a consequence of the surface area of a swimmer in contact with the surrounding water (a layer of molecules) and the smoothness of that surface (Vorontsov & Rumyantsev, 2000).

Drag force can be separated, based upon the swimmer's action, into active and passive drag. Active drag occurs when a swimmer is propelling forward and passive drag when a swimmer is gliding without active propulsion (Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997). During competitive freestyle swimming the swimmer encounters passive drag only during glide after the start and turns, but the swimmer encounters a lot more active drag force during swimming. There have been conflicting reports as to whether the active drag experienced during swimming is greater or less than passive drag during the streamline position. Clarys (1979), Di Pramperto et al. (1974) and Pendergast et al. (1977) reported that the active drag is 1.5 to 2 times higher than the passive drag. Their findings were in line with another study which used a pulley system to tow the swimmer 5% faster than their mean maximum swimming speed (Formosa, Mason, & Burkett, 2011) and reported the active drag is higher than the passive drag. That study's findings contradicted previous studies that used resisted methods (Kolmogorov and Duplishcheva, 1992; Kolmogorov et al., 1997; Shimonagata, Taguchi, Taba, & Aoyagi, 1998). For example, Shimonagata et al. (1998) found that the mean active drag was 76% of the mean passive drag. Differences in the findings are likely to result from the different methods used to estimate active drag. These differences in findings and methods will be discussed in more detail in this review's section on the comparison between different techniques of active drag measurement (section 6.2).

2.4.1 Pressure Drag

Pressure drag or form drag occurs when there is a difference in pressure between the front of and behind the swimmer's body and the water. Rumyantsev (1982) showed that the magnitude of the pressure drag (F = 93.5 N) was considerably greater than the wave drag and skin friction drag, F = 5 N and 0.05 N, respectively. According to the drag force equation, pressure drag has a square relationship with swim speed $F_A = \frac{1}{2} C_d . \rho . A . v^2$. With an increase or decrease in swim speed, the form drag is increased or decreased. The magnitude of form drag depends upon the shape (C_d) and the frontal cross-section area (A). Also, a larger frontal surface area of a swimmer produces more pressure drag. For example, a swimmer should keep their body in the streamline position and narrow to minimise turbulent flow for reducing drag force (Vorontsov & Rumyantsev, 2000) and because the horizontal body position produces less form drag. Hence, any change in the body position such as greater angles of hip, legs or trunk incline would increase form drag (Zamparo, Gatta, Pendergast, & Capelli, 2009). The effect of the larger frontal surface area has been shown by Toussaint et al. (1988b), in which study males had higher active drag values than females.

Breathing to the sides could also increase the magnitude of form drag by changing the surface area. The breathing is performed at the surface of the water and can generate greater form drag at the surface interface than the form drag generated when the head is submerged in the water (McMaster & Troup, 2001). Di Prampero et al. (1974) found that the breathing phase may increase the hydrodynamic drag of the body. It was also reported that efficiency of stroke mechanics might be impeded by the breathing frequency (Stager et al., 1989). Therefore, researchers suggest limiting the breathing rate to reduce the form drag during competitive swimming (Di Prampero et al., 1974; McMaster & Troup, 2001; Pendergast et al., 1977). However, restricting breathing patterns during a race may reduce the level of oxygen in the muscles and the physiological cost to the muscles is increased (Counsilman 1975; Town & Vanness, 1990). The accumulation of lactic acid in muscles is often related to a decrement in maximal force generation (Sahlin, 1992). Hence, most coaches suggest that researchers should identify the cost/benefit ratio in limitation of the breathing rate as one of the factors for achieving the highest performance in different distance events.

2.4.2 Wave Drag

Two different types of wave drag are produced during swimming competition: external waves that are created by other swimmers or wind (if the competition takes place in an outdoor pool), and internal waves that are created by the swimmer. Lane-line ropes minimise the effect of external waves (Stager & Tanner, 2005). Internal wave drag is generated when a swimmer moves on the surface of the water or near the surface (Toussaint, Van Stralen, & Stevens, 2002). Energy is supplied by the swimmer to produce these waves and the main wave is created in front of the body. According to the formula presented by Rumyantsev (1982), the force of the main wave is equal to:

$$F_w = \rho\left(\frac{A^3}{\lambda^2}\right)(v \sin\alpha)^3 \cos\alpha\, \Delta t \qquad (5)$$

where ρ is water density, A is amplitude of the wave, λ is the length of the wave, v is the wave speed (swimming), Δt is the time unit and α is the angle between the direction of general centre of mass movement and the front of the main wave. Hence, the force is proportional to the cube of the wave speed, while the form drag is proportional to the square of the speed. Therefore, contributions of the wave drag to the total drag become more important when a swimmer swims at maximum swim speed. The drag is dependent on the ratio of its speed to that of a water wave with a wave length equal to the swimmer's length, i.e. the Froude number (Vorontsov & Rumyantsev, 2000):

$$F_r = \frac{v}{\sqrt{gL}} \quad (6)$$

where v is the swimming speed, g is acceleration due to gravity and L is length of the swimmer. A swimmer with a length of 1.8 m and speed of 1.8 m/s had F_r= 0.42. When the arms were extended to total length (2.3 m), however, the Froude number decreased to F_r= 0.40 and, consequently, wave drag and total drag decreased (Van Manen & Van Oossanen, 1988). Also, the speed of a swimmer has a direct effect on the wave drag, and the contribution of wave drag to the total drag increases with greater speed of the swimmer (Vorontsov & Rumyantsev, 2000, Toussaint et al., 2002, Wilson & Trop, 2003). The contribution of wave drag to the total drag was estimated using the Measuring of Active Drag (MAD) system and results showed 10% and 21% at speeds 1.7 and 1.9 m/s respectively (Toussaint et al., 2002). Other research (Wilson & Trop, 2003) estimated the contribution of wave drag at different speeds and found higher speed (2.0 m/s) had the greatest contribution (35%), which was consistent with Toussaint et al. (2002).

2.4.3 Skin Friction Drag

Skin friction drag occurs between the water layer and the skin of the swimmer during swimming, known as the boundary layer. The shape, size and orientation of a swimmer's body, their hair, the tightness of their swimsuit and the type of swimsuit fabric have an effect on the skin friction drag by affecting the boundary layer (Vorontsov & Rumyantsev, 2000). For example, a swimmer with bigger body surface and size has a greater influence on the formation of eddies in the boundary layer. Therefore, an increment of turbulence in the boundary layer occurs with incremental skin friction drag (Maglischo, 2003). Swimming at the higher speed produces greater friction between the water and the swimmer. The friction drag may be estimated as (Vorontsove & Rumyantsev, 2000, chapter 9, pp.186):

$$F_r = \mu \left(\frac{dv}{dZ}\right) S_{fr} \quad (7)$$

where F_r is friction drag; μ is coefficient of dynamic viscosity; dv is difference between speed of water layers; dz is difference in thickness of boundary layers and S_{fr} is wetted body surface area.

In 2000, Speedo® introduced a new design of swimsuit to improve the performance of a swimmer with the aim being to create less skin friction drag. Some studies compared the new swimsuit (Fastskin^{TM}) with the conventional swimsuit to better understand the contribution of each component (Benjanuvatra et al., 2002; Toussaint et al., 2002). Comparison of the full-body and the whole leg swimsuits, and the normal swimsuit showed that stroke length increased and oxygen consumption was reduced by using the full-body suit and the whole legs (Chatard & Wilson, 2008). Reductions in drag (5% to 10%) by using Fastskin^{TM} were reported by recent researches (Benjanuvatra et al., 2002; Chatard & Wilson, 2008) and were in line with the result Speedo reported (4%) on their website. It is likely that reduction in drag would be due to the elastic fabric which does not allow water to be absorbed and creates a smooth surface to reduce the skin surface in contact with the water. However, another study reported no statistically significant drag reduction when swimmers were wearing the Fastskin^{TM} (Toussaint et al., 2002). The friction drag makes very little contribution (less than 5%) to the total drag (Rumyantsev, 1982) but it should not be ignored, because in competitive swimming, the difference between success and failure may be 0.01s. Hence, small reductions in total drag would be essential for coaches and swimmers.

2.4.4 Passive hydrodynamic resistance (Passive Drag)

During competitive freestyle swimming, passive drag occurs when a swimmer is in the prone and dorsal positions with the arms together, stretched tightly straight ahead from the shoulder during the glide (Clarys, 1979; Kolmogorov et al., 1997; Lyttle, Blanksby, Elliott, & Lloyd, 2000) or in the prone position with the arms extended from the sides of the body (during breaststroke start and turns). Several researchers have demonstrated that passive drag depends upon body position, head position such as under or above the water, anthropometric factors and the level of the swimmer (Chatard, Bourgoin, & Lacour, 1990a; Clarys, 1979; Di Prampero et al., 1974; Holmer, 1974; Klauck & Daniel, 1976).

Towing devices (motorised winches) have been used to measure passive drag at different velocities and depth. Some previous studies showed that passive drag increases while the towing speed increases (Clarys, 1979; Lyttle, Blanksby, Elliott, & Lloyd, 1998; Maiello, Sabatini, Demarie, Sardella, & Dal Monte, 1998; Zamparo et al., 2009). Maiello et al. (1998) compared two different depths (surface and 0.5 m below) with different velocities in the swimming flume and reported that the passive drag value at the surface of the water (62.4 ± 10.3 N) was higher than below the water (55.3 ± 6.4 N) at 1.76 m/s. This suggests that the passive drag decreases when the swimmer moves below the water. Another study compared the passive drag value at three different depths from the surface of the water (0.2 m, 0.4 m and 0.6 m) (Lyttle et al., 1998). That study found no significant difference between the passive drag values at 0.4 m and 0.6 m below the surface. However, significant difference was observed between 0.2 m and the other two depths. The result of previous studies (Lyttle et al., 1998; Maiello et al., 1998) suggests that passive drag decreases when the swimmers immerse more than 0.2 m below the surface of the water. Therefore, the explanation is that the contribution of wave drag increases when the swimmers move closer to the water surface or are at the surface.

High correlations between passive drag and height, weight and body surface area were indicated by Chatard et al. (1990a). The study of Chatard et al. (1990a) showed that passive drag can be considered as a significant indicator of performance in the gliding phase swimming. Kolmogorov and Duplishcheva (1992) measured passive drag at the free maximum swim speed in the gliding position by using a dynamometrical system and found that the amount of passive drag depended upon the individual's anthropometry (height and weight) in the streamline position. Vorontsove and Rumyantsev (2000) made a similar observation and also demonstrated that the value of passive drag was related to body position during the measurement, particularly the head position.

2.4.5 Active hydrodynamic resistance (Active Drag)

In swimmers, active drag is the resistive force on a swimmer actively swimming at the surface in a fluid (water), and depends on the viscous, pressure and wave effects of the fluid on the swimmer (Wilson & Trop, 2003). The active drag associated with the velocity fluctuations of the swimmerSeveral studies have calculated active drag directly from propulsive measurements (Di Prampero et al., 1974; Hollander et al., 1986) or indirectly from active drag estimation (Formosa, et al., 2011; Kolmogorov & Duplishcheva, 1992; Mason, Sacilotto, & Menzies, 2011; Wang, Wang, Yan, Li, & Shen, 2007). The value of active drag has been found to vary considerably between methods, although the reasons for this have not been exactly identified. In the next section, these methods are introduced with explanations how the researchers have calculated active drag and some of their findings are presented.

2.4.6 Active drag and swimming performance

In competitive swimming, two factors—active drag and propulsive forces—are commonly identified as being responsible for swim speed (Barbosa, Costa, Marques, Silva & Marinho, 2010; Benjanuvatra, Blanksby & Elliott, 2001; Chatard et al., 1990a). The ability of a swimmer to reduce the active drag encountered allows for propulsive forces to be efficiently applied, therefore producing faster swim speeds (D'Acquisto, Berry & Boggs, 2007; Marinho et al., 2010). Clarys (1979) confirmed that the changes in the body's shape and the movement of the body segments influenced the active drag. One study found no significant correlation between active drag and level of swimming performance in trained swimmers (Hollander, Toussaint, & de Groot, 1985). It was concluded that drag is not a determining factor of the maximal swimming speed (Hollander et al., 1985). However, some studies have found that there is a significant correlation between active drag and the performance of the swimmer (Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997; Toussaint & Beek, 1992). Kolmogorov et al. (1997) showed that elite swimmers were more able to reduce active drag than non-elite swimmers were able to.

Previously, Kolmogorov and Duplishcheva (1992) had reported that better performance was shown by the swimmers who increased their swimming speed while simultaneously decreasing their active drag or showing only a small increase in their active drag. The increase in active drag could be due to higher propulsive forces that the swimmers were able to generate; these forces had correspondingly higher drag values as a result of the increase in the size of the muscles involved in the propulsive phase of swimming. The higher propulsive forces should lead to greater work generation during the propulsive phase and consequently to a longer distance per stroke (Toussaint & Beek, 1992). Hence, swimming with higher swim speed may depend on the ability of the swimmer to reduce drag through an efficient stroke technique, which will generate a higher speed and limit the power lost in wasted kinetic energy (Barbosa et al., 2008). Therefore, it would be beneficial for an individual swimmer to be able to reduce the drag through technique changes without affecting the propulsion.

2.5 Methods of drag force measurement

2.5.1 Interpolation methods

One of the interpolation methods was designed to investigate the relationship between the energy cost of swimming, the speed, the drag, and the mechanical efficiency of the swimmer (Di Prampero et al., 1974). The active drag estimated depended upon extrapolation and it was determined by adding or subtracting a known extra weight while towing at different swim velocities to provide assisted or resisted tow. The tow rope was located through a system pulley which maintained a force to operate horizontally along the direction of the swimmer's movement (Figure 2.2).

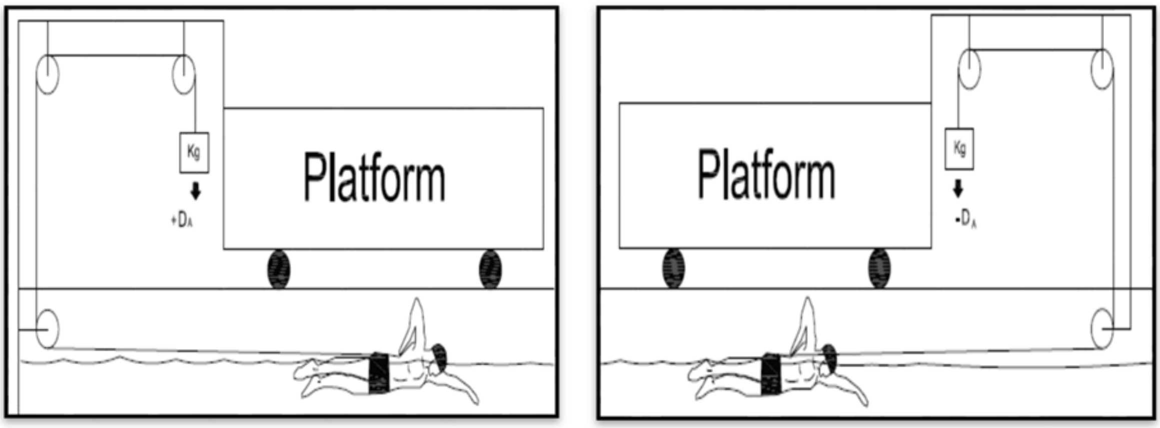

Figure 2.2 – Experimental set up of the interpolation method. The swimmer is connected to a known weight via a pulley system which is fixed to the platform: adapted from Di Prampero et al. (1974)

Oxygen consumption was also calculated during both swimming at constant speed and at resting time while the swimmer was lying stationary in the water: that is, with and without added drag, to understand how much energy a swimmer expends during each trial. The variation in oxygen consumption between swimming at a constant speed and at resting time was used as the basis for calculating, for each swimmer, the small extra force that had to be applied to keep that swimmer in a constant position. Hence, the extra force was measured and related to the swimmer's energy expenditure to calculate the drag as well as the swimmer's mechanical efficiency. A linear relationship between oxygen consumption ($VO2_{net}$) and drag (D_A) was identified at the constant velocities to use for calculation of drag. This linear regression relationship between oxygen consumption and drag was calculated by the least-squares method. The linear regression extrapolation of $VO2_{net}$ on drag to $VO_{net2} = 0$ indicated the force which was applied to the swimmer.

The other interpolation method was introduced by Clarys (1979). Active drag and passive drag were measured using a Dutch ship model basin test. The other equipment of this method consisted of a water tank 200 m long, an electrically driven towing carriage, a photoelectric cell system for the purpose of speed control, a telescopic towing device, force transducers and a galvanometer recording system for automatic recording of drag and speed data. In this method, external forces-positive force (positive force (towing force) and negative force (pushing force)) were applied on a carriage during towing of a swimmer. The change in external forces (positive or negative forces) as a function of imposed external forces was extrapolated. Therefore, external forces were measured by the telescope towing device (Figure 3) which was attached to the swimmer's waist and were amplified.

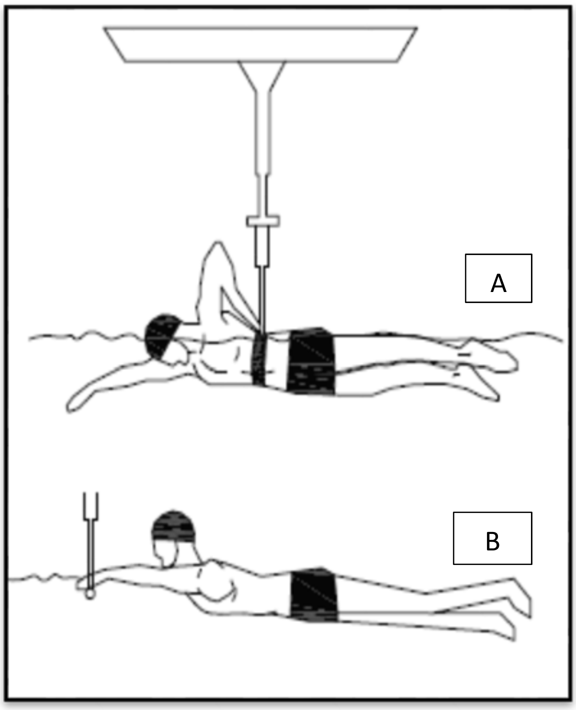

Figure 2.3 – (A) the active drag while swimming and (B) the passive tow: adapted from Clarys (1979).

The average force for each speed was derived from direct recording, then each average resistance was plotted as a function of its corresponding speed:

$$F_A = K.v^n \quad (8)$$

where *K* and n are predetermined constants and *v* is the speed of swimming. The main approach to drag force measurement using this method was to find the relationship between resistance and speed. Clarys (1979) considered that the positive force is a force developed by the towing carriage towing the body through the water and is called resistance force. On the other side, the negative force refers to a pushing force as the body pushes against the towing mechanism and is called propulsion force: this is the force produced by the swimmer to overcome water resistance. Clarys (1979) stated that at a constant mean speed, the mean propulsive force exerted by the swimmer will be equal and opposite to the active drag produced.

2.5.2 Measuring Active Drag (MAD)

The Measuring Active Drag (MAD) system was introduced by Hollander et al. (1986) to measure propulsive force and active drag force while swimming front crawl. The aims of this method were, firstly, to measure propulsive force and, secondly, to measure active drag from the measured propulsive force. To measure propulsive force, a tube of length 23 m was fixed under the water and about 15 paddles were attached on the tube. The tube had force transducers at one end of the pool wall to measure the force exerted by the swimmer on the tube (Figure 4). The MAD system measured the propulsive force of the arms when a swimmer pushed the paddles fixed to a force transducer in the pool. The active drag was measured by the propulsive force of the hands on the paddles. Also, to measure the propulsive force of the arm, a small pull-buoy was situated between the swimmer's legs to prevent use of the legs during swimming. Hence, it would be concluded that the measured hand propulsion forces equal the active drag. Another reason to use the small pull-buoy was to maintain the body in a horizontal position such as occurred during actual swimming.

The mean propulsive force was calculated by adding the force measurements of all paddles together over one lane at a constant speed. To obtain accurate constant speed, the force measurements of the first and last paddles were eliminated. The mean active drag of each lane was considered to be equal to the mean propulsive force of that lane at a constant swimming speed (Schleihauf et al., 1983).

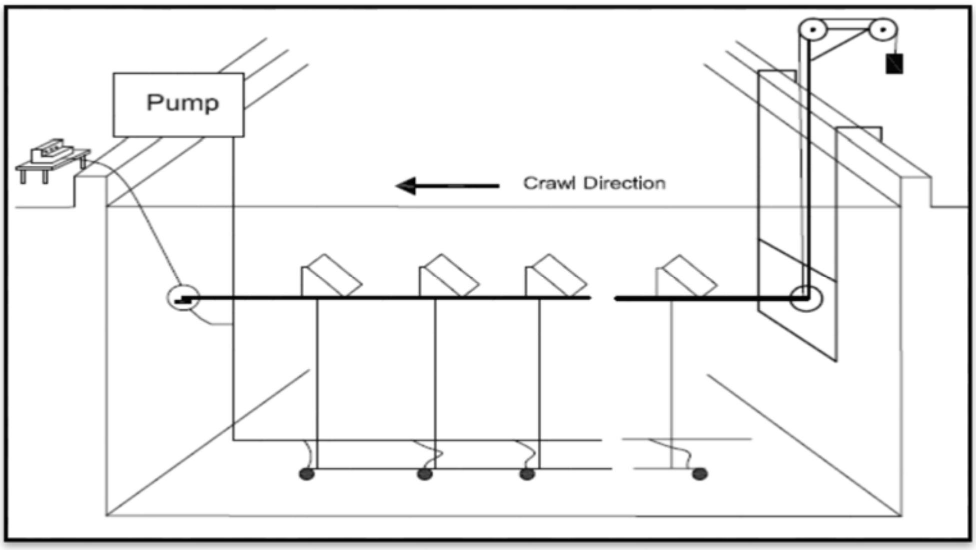

Figure 2.4 – Side view of the MAD system. The left end of the tube contains the force transducer and the right end is used for gauging: adapted from Hollander et al. (1986).

The swim speed was determined from the pad distance and sample frequency (except the first and last paddles). In this method, each test yielded ten data points of propulsive forces at ten different velocities and ranged from minimal to maximal swim speed. Ten speed active drags data were least-square fitted to the below function:

$$F_A = A \,.\, v^x \qquad (9)$$

where F_A represents total active drag, A is a constant which is incorporated with the density, coefficient of drag and frontal surface area, v is the mean swim speed and x is the parameter of the exponent of speed.

2.5.3 Velocity Perturbation Method (VPM)

The Velocity Perturbation Method (VPM) has been used to estimate active drag indirectly since 1992. The VPM method was introduced by Kolmogorov and Duplishcheva (1992) using an additional hydrodynamic body. The additional hydrodynamic body was attached to a swimmer's waist and produced a known extra drag on a swimmer (Figure 2.5). For estimation of active drag, the swimmer swam one trial without and one trial with the hydrodynamic body and all trials were performed in a 50 m swimming pool over 30 m (from the 15 m to 45 m points). First, the swimmer swam without the hydrodynamic body with maximum effort and the time was recorded for the 30 m. Then the hydrodynamic body was attached and the swimmer again swam, but with that hydrodynamic body, while swimming with maximum effort over the same distance.

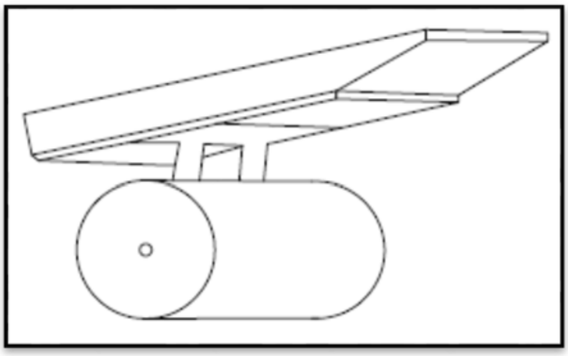

Figure 2.5 – Structure of the additional hydrodynamic body that was attached to the swimmer's waist via rope: adapted from Kolmogorov and Duplishcheva (1992).

The estimation of active drag was based upon three assumptions: first, a swimmer is able to deliver an equal mechanical power output (a power necessary to overcome drag) between the free swimming and the swimming with the hydrodynamic body; second, the mean speed for each stroke remained constant between strokes; however, the speed changes within a stroke. The third assumption was that the drag changes in proportion to the speed squared. The constant mean speed throughout a trial was assumed, but Kolmogorov and Duplishcheva (1992) mentioned that swimmers swim with varying speeds during the stroke cycle and, therefore, do not swim with constant speed. To find out the error induced by these variations in stroke, they performed computer simulations and reported an error of approximately 6–8% resulting from speed variations (Kolmogorov & Duplishcheva, 1992, pp.316). To reduce the effect of these variations (not more than 10%), different sizes of hydrodynamic body were built and based upon the performance level of a swimmer; one of those hydrodynamics was applied. Under the assumption of equal power output between both conditions:

$$P_1 = P_2 \qquad (11)$$

where P_1 is the power output during free swimming and P_2 is the power output during swimming with the hydrodynamic body. Therefore, active drag force in free swimming multiplied by speed is equal to active drag force with added resistance multiplied by speed:

$$F_1 \,.\, v_1 = F_2 \,.\, v_2 \qquad (12)$$

Also, according to Toussaint et al. (1988b), the active drags in free swimming (5) and in swimming with a hydrodynamic body (6) are:

$$F_1 = \frac{1}{2}\, C_d . \rho . A . v_1^2 \qquad (13)$$

$$F_2 = \frac{1}{2}\, C_d . \rho . A . v_2^2 + F_B \qquad (14)$$

where F_1 and F_2 are the active drag during free swimming and swimming with the hydrodynamic body, ρ is water density, A is the cross sectional area of the swimmer, C_d is the drag coefficient, F_B is the added drag due to the hydrodynamic body, and v_1 and v_2 are the swimmer's mean maximum speed for free swimming and swimming with the hydrodynamic body. They used the following equation to calculate active drag for the free swimming condition at the maximum speed:

$$F_d = \frac{F_B . v_2 . v_1^2}{v_1^3 - v_2^3} \qquad (15)$$

2.5.3.1 Drag Coefficient

The drag coefficient (C_d) is a dimensionless quantity that is used to quantify the resistance or the drag of an object in a fluid environment. According to the drag equation:

$$C_d = \frac{F}{\frac{1}{2}\rho A v^2} \qquad (16)$$

where C_d is the drag coefficient, F is the active drag, ρ is water density, A is the front surface area of the swimmer and v is the swimming speed. A lower drag coefficient indicates the object will have less hydrodynamic drag, based upon the shape and Reynold's number of the object.

Wang et al. (2007) suggested that there were the problems that could affect the estimation of active drag using the additional resisted force created by the hydrodynamic body (Kolmogorov & Duplishcheva, 1992). They mentioned that, firstly, the additional resisted force created by the hydrodynamic body cannot change easily and, secondly; the floating movements caused by the hydrodynamic body can influence the value of additional resistance. Therefore, Wang et al. (2007) designed a simple device (Figure 2.6) to estimate active drag using a gliding block that allowed changes in the amount of additional resistance. The aim of using this device was to minimise changes in the cable force that, in the method of Kolgomorov and Duplishcheva (1992), had resulted from changes in float height. This device was designed to allow the swimmers to have speed fluctuations within stroke. Active drag testing was performed in a 50 m swimming pool and two starting blocks were fixed each side of the pool and connected to each other with a 50 m length of steel wire. The bolts holding the wire to the blocks made it possible to adjust the stiffness of the wire to reduce its oscillations. This tightening was based on the swimming speed during each swimmer's stroke cycle. A force transducer was fixed between the gliding block and the swimmer's belt to measure the variation in the thread fluctuations (F_t) when the gliding block was moved by the swimmer (Figure 6.2). To estimate active drag, Wang et al. (2007) used the equations and the assumption of mechanical power output of Kolmogorov & Duplishcheva (1992). The results showed that the tension of the thread fluctuates and, as a result, the additional resistance in the swimming direction was variable, not a constant value as Kolmogorov and Duplishcheva (1992) had assumed.

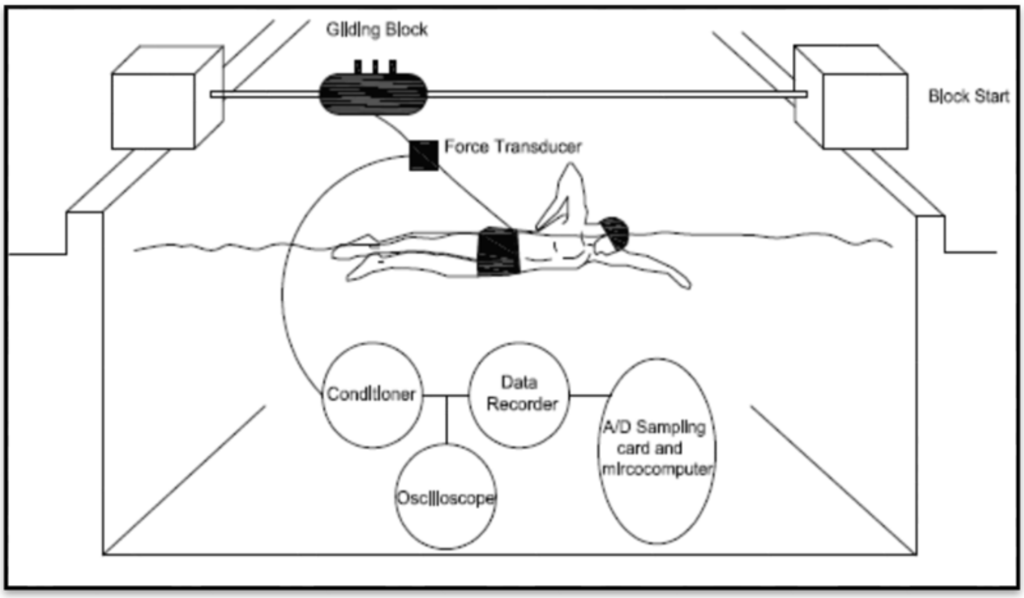

Figure 2.6 – Device for measuring active drag. A force transducer measures a variation in tension. A gliding block is attached to the steel wire and three bolts are on the gliding block: adapted from Wang et al. (2007).

2.5.4 Assisted Tow Method (ATM)

The Assisted Towing Method was developed by Alcock and Mason (2007). This method used similar assumptions to, and the equations of, the VPM method (Kolmogorov & Duplishcheva, 1992), except that the swimmer was assisted by a dynamometer at a constant swim speed rather than having a force resisting the swimmer. In this method, a swimmer was assisted by a motor-driven cable at a constant swim speed. Alcock and Mason (2007) increased mean tow speed to approximately 10% greater than the swimmer's mean speed during free swimming. It was assumed that a small increase in maximum speed would not affect stroke mechanics. The maximum force setting on the dynamometer was set at 550 N to maintain a constant speed of the swimmer. However, the actual force was continually adjusted by the motor controller to achieve the target speed (10% greater than the swimmer's mean speed).

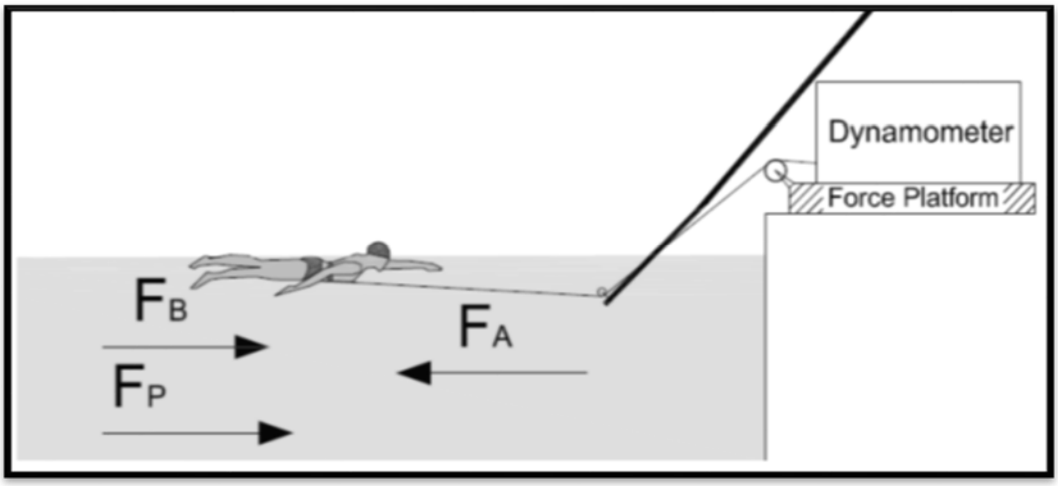

Figure 2.7 – Assisted Towing Method setup: this diagram illustrates the direction of towing as represented by the cable force (F_B), the direction of the propulsive force (F_P), the direction of active drag (F_A)

Wang et al. (2007) showed that the swimmer's speed is not constant throughout the stroke due to the intra-stroke fluctuations in speed. Mason et al. (2011) therefore further developed the ATM method (Figure 2.7). In this system, swimmers were allowed to maintain their normal stroke technique as much as possible, while being towed, by virtue of a lower force and greater speed fluctuations. The aim of this method was to tow swimmers approximately 5% faster than their mean maximum swim speed of free swimming while allowing the swimmers to have a fluctuating speed in the intra-stroke cycle. In order to achieve this, the maximum force setting on the dynamometer was reduced to the passive drag value of the swimmer and the dynamometer then adjusted the force during the trial to achieve a speed 5%–8% greater than the free swimming speed.

For estimation of active drag, the swimmer swam three free swimming trials and for each trial, the mean maximum speed of the swimmer was calculated over a 10 m distance. Then, swimmers were towed at the mean maximum free swim speed in the streamline position over a 10 m distance to determine the mean passive drag value of the swimmer. This mean value was used to set up the dynamometer. Finally, the swimmer was towed by the dynamometer with the setting of the low force and the setting of the speed.

2.6 Comparison between different methods of active drag measurement

Several previous studies have used one or more of the six mentioned methods over 40 years to measure active drag (Clarys, 1979; Di Prampero et al., 1974; Formosa et al., 2011; Hollander et al., 1986; Kolmogorov & Duplishcheva., 1992; Mason et al., 2011; Toussaint, Ross, & Kolmogorov, 2004; Wang et al., 2007; Zamparo et al., 2009), but there is no consensus on the best method. Some of the previous studies found similar active drag, while the other studies found that active drag values were considerably greater or lower than each other.

Previous studies that used the interpolation methods (Clarys, 1979; Di Prampero et al., 1974; Rennie, Pendergast, & Di Prampero, 1974) found similar active drag values to each other when the active drag was calculated based upon the assumption that propelling efficiency did not change between swimming conditions (the assisted and the resisted swimming). It is likely that propelling efficiency would not be constant, even at a constant speed, when external forces are applied, but this has not been investigated in human swimming. Investigation of propelling efficiency in fish swimming showed that efficiency is strongly dependent on power output (Bone, 1975) and it was reported that the power output was not constant. Hence, efficiency is unlikely to be constant in humans either. Also, Di Prampero et al. (1974) stated that all extra forces in swimming contributed to active drag; hence, it is likely that propelling efficiency would be changed as the power to overcome drag changed. In addition, Toussaint et al. (1983) explained that small changes in the value of the maximal oxygen consumption due to small deviations in propelling efficiency will be amplified by the interpolation methods. Consequently, it can be suggested that the interpolation methods overestimated active drag.

Previous studies that used the MAD system (Formosa, Toussaint, Mason, & Burkett, 2012; Hollander et al., 1986; Toussaint et al., 2004; Toussaint et al., 1990, Toussaint et al., 1988b; Van der Vaart et al., 1987) found similar active drag values to each other when the active drag was calculated based upon the assumption that the mean propulsive force would be equal to the mean active drag values when the swim speed is constant (Schleihauf et al., 1983). Hollander et al. (1986) found a mean propulsive force of 75.7 N at a mean speed of 1.66 m/s. This finding was in agreement with the propulsive force value of 72 N at a swim speed of 1.66 m/s of Schleihauf et al. (1983). Schleihauf et al. (1983) used a three-dimensional kinematic analysis method to calculate the propulsive force of hand and forearm. To calculate the propulsive of hand and forearm, the hand angle of pitch and the hand sweepback angle were determined using 8 markers were located on the swimmer's hand and forearm. These two results (Hollander et al., 1986; Schleihauf et al., 1983) were similar to the passive drag value (76 N at a swim speed of 1.66 m/s) of Clarys (1979). It might be suggested that the MAD system measured the active drag to be approximately similar to the passive drag, while the active drag calculated from the interpolation method was approximately 1.5 to 2 times greater than the passive drag (Clarys, 1979). This can be another indication that the interpolated method overestimates the calculation of active drag.

The MAD system measures the propulsive forces of each arm which are generated by the swimmer, but there are some criticisms of this measurement method. This system prevents the swimmer having natural stroke mechanics (Poizat, Ade, Seifert, Toussaint, & Gal-Petitfaux, 2010) and can be used only at a constant speed. The swimmer must match stroke length to the distance between the two paddles (Poizat et al., 2010). Also, there is no side-to-side hands movement and a swimmer has to push the paddles straight backwards. However, in reality, water exerts a force on the swimmer. While there has been criticism that the MAD system does not match the requirements for free swimming (Poizat et al., 2010), there has been other research supporting the use of the MAD system to analyse swimming (Clarys et al., 1986). This research used the EMG to record the muscular activity of arms during swimming with the MAD system and compared that with the muscular activity of arms in free swimming, as the swimmer had to adapt the movement of the arms during swimming with the MAD system. Clarys et al. (1986) showed that the swimmer did not employ different muscles when they had to adapt the arm movement in the MAD system. The other criticism of this method is that it only measures force when the hand is in contact with the fixed pad, not the entire time the hand is submerged. Another criticism of this method is of the swimmer swimming while holding a small pull-buoy between the legs. This method measures only the propulsive force of the arms; therefore, it ignores the contribution of kicking actions in propulsion. It has been shown that the contribution of the legs to propulsion when using the MAD system has been reported to increase mean power by up to 11.7% compared to using the hand only (Hollander et al., 1988). It can be suggested that this method is an effective way for direct measurement of the upper body forces under conditions of the MAD system; however, this measurement is not comparable with normal swimming. Consequently, it is likely that the MAD system would not measure the active drag of normal swimming.

Previous studies that used the resisted methods (Kolmogorov et al., 1997; Kolmogorov & Duplishcheva, 1992; Marinho et al., 2010; Toussaint et al., 2004; Wang et al., 2007) found similar active drag values to each other. The active drag values were compared with the passive drag values (Kolmogorov & Duplishcheva, 1992) and reported that the mean active drag was lower than the mean passive drag. The passive drag was measured using a dynamometer system (Kolmogorov & Duplishcheva, 1992). For example, Kolmogorov and Duplishcheva (1992) found the mean active drag value and the mean passive drag value obtained from the VPM method were 84.26 ± 37.3 N and 86.83 ± 10.9 N respectively at a mean maximum speed of 1.80 m/s. On the other hand, previous studies that used the assisted methods (Formosa et al., 2012; Formosa et al., 2011; Mason et al., 2011; Sacilotto, Mason, & Ball, 2012) found active drag values which were significantly higher than the passive drag values. For example, Formosa et al. (2011) found the active drag and the passive drag values obtained from the assisted method at a constant speed were 262.4 ± 33.4 N and 80.3 ± 4.0 N respectively at a mean maximum speed of 1.89 m/s. From comparison of the two studies, it is clear that both methods measured passive drag values that were similar to each other, but there is a significant difference between estimated active drag values. Because both the resisted methods and the assisted methods were developed based upon the same assumptions and equations, a question is why do the active drag values obtained from the resisted method differ from the active drag values obtained from the assisted method?

The advantage of both the resisted and the assisted methods over the MAD system is that swimmers are able to perform their arm and hand movements similarly to the normal technique. However, some previous studies reported that the technique of swimmers changed for both the resisted and assisted swimming and that these changes were less for the assisted swimming than the resisted swimming (Girold, Calmels, Maurin, Milhau, & Chatard, 2006; Williams, Sinclair, & Galloway, 2006). The result of the assisted tow swimming of Williams et al. (2006) showed that there was a significant increase in stroke rate and stroke length when compared to the stroke rate and the stroke length of free swimming. Changes in these two parameters would change swim speed, as it is the product of the stroke rate and the stroke length. It might be suggested that the power output produced by the swimmer increases by the swim speed being increased during the assisted tow swimming. Therefore, the power output between the two swimming conditions (free and towing) could be different to each other.

This review presented some of active drag methods and the advantage and the disadvantage of each method were mentioned. In the next part, some approaches of those methods are presented to give the reader a better view of their results (Figure 8). Comparison between some previous approaches (Figure 8) will not indicate which method has measured the active drag correctly because different swimmers with different performance levels, technique and anthropometric features participated in those studies, but it would be suggested that if, for example, the results of these active drag methods were too far from the other methods, it is more likely that those methods measured active drag incorrectly. For example, figure 8 shows that the results of the interpolation methods and the assisted method at a constant speed were considerably greater than the other results. Therefore, it can be suggested that these two methods (Interpolation and assisted towing method at a constant speed) are less likely to have calculated active drag correctly.

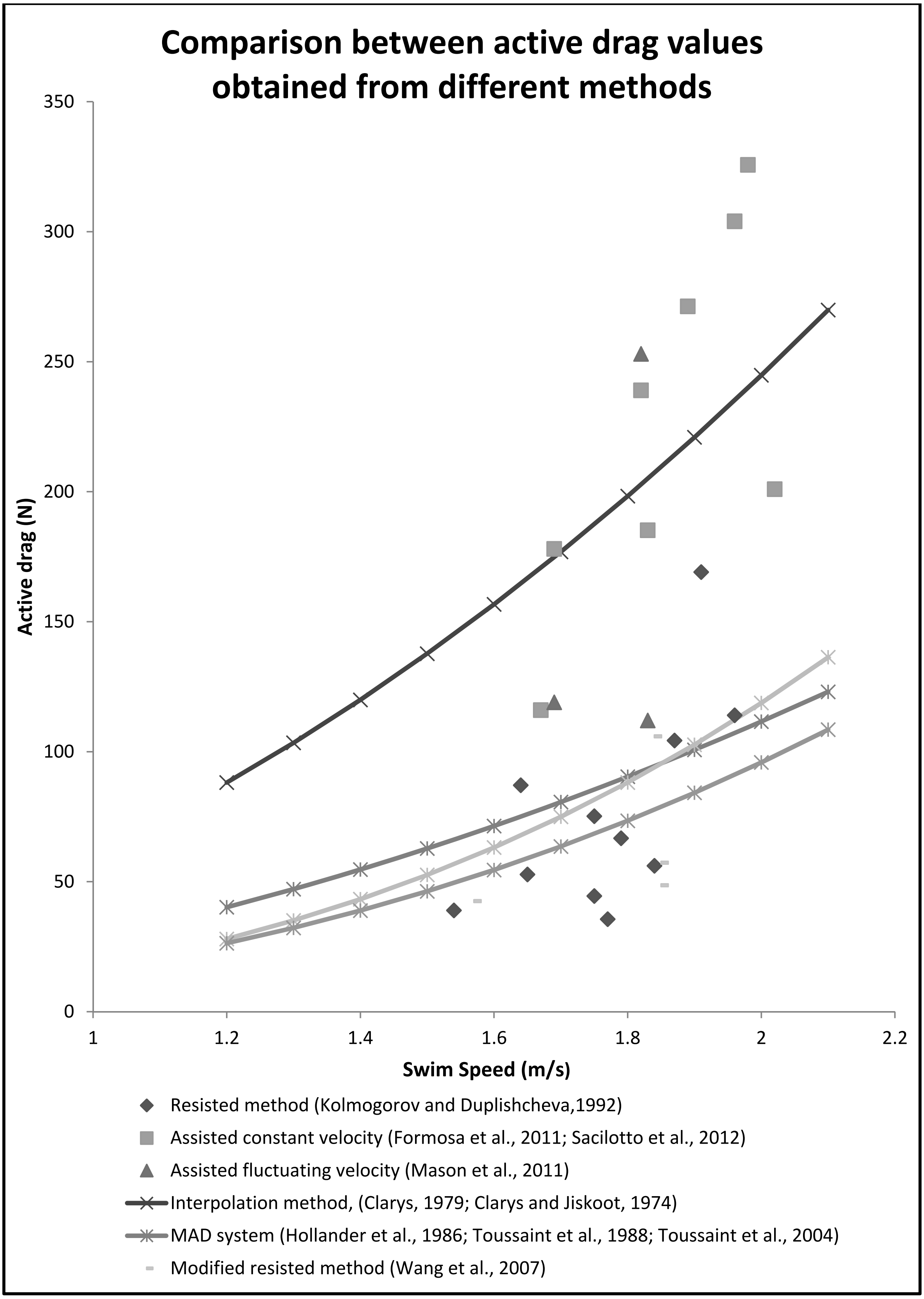

Figure 2.8 – Showing active drag measured by different methods.

Toussaint et al. (2004) compared the MAD system with the VPM method (resisted method) and found that the mean active drag obtained from the VPM method was approximately 20% lower than the mean active drag obtained from the MAD system. The mean active drag values obtained from the same swimmers using both methods were 53.2 N for the VPM method and 66.9 N for the MAD system at the mean maximal speed of 1.64 m/s. On the other hand, Formosa et al. (2012) compared the MAD system with the ATM method at a constant tow speed and found that the mean active drag obtained from the MAD system was approximately 55% lower than the mean active drag obtained from the ATM method at a constant speed. The mean active drag values obtained from the MAD system and the assisted method at a constant speed were 82.3 N and 148.3 N respectively at a mean maximum speed of 1.68 m/s.

Toussaint et al. (2004) explained that the main reason for the difference in active drag results is likely to be an unequal power output when swimming with and without added resistance during the VPM method. They estimated that there was a significant difference in power output between the free and the towing trials ($\Delta P = 13.2$ W). The mean power output of the free swimming trials was higher than the mean power output of the towing trials. Formosa et al. (2012) reported that the differences in the active drag values of their study may also be explained by violation of the equal power output assumption. Therefore, it could be suggested that the resisted methods underestimate active drag relative to the MAD system and the assisted methods overestimate active drag relative to the MAD system. Toussaint et al. (2004) also reported that differences between the active drag value obtained from the VPM and the active drag value obtained from the MAD system can also be related to the assumption of a square relationship between drag and swim speed. They found a 10% difference between active drags obtained from the VPM method and the MAD system at an exponent value of 2, while those active drag values obtained from both methods were the same when the exponent of speed was 2.34.

2.7 Conclusion

In the last forty years, research based upon five methods of measuring active drag has been conducted. These measurements are the interpolation method, the MAD system, the VPM method, the Modified Resisted method, and the ATM method at constant speed and with fluctuating speed. The interpolation method measures the active drag based on the ideas from the energetics approach in relation to mechanical power output. The MAD system is the only system to directly measure active drag and it has been shown that there are questions about the validity of measuring an action where the hands are fixed in the water. The VPM method and the ATM method measure active drag indirectly and are based upon the equal power output assumption. The advantage of the application of measurement is that swimmers are able to perform their arm and hand movements in a technique similar to the normal one, in particular when allowing normal speed fluctuations.

It is likely that the VPM method, the ATM method with the fluctuating speed, and the MAD system would be more appropriate than the other methods. However, the main concern with the direct methods has been shown to be the assumptions related to the active drag equation. Error in the assumptions associated with the equation can cause inaccuracy in the active drag result. This thesis can provide an assessment of the validity of assumptions made in the implementation of the ATM method with fluctuating speed.

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CHAPTER 3

Reliability of estimating active drag in swimming using the assisted towing method (ATM) with fluctuating speed

Statement from co-authors confirming the authorship contribution of the PhD candidate "As co-authors of the paper '**Reliability of estimating active drag in swimming using the assisted towing method (ATM) with fluctuating speed**' we confirm that Pendar Hazrati has made the following contributions:

- Conception and design of the research question
- Data collection
- Analysis and interpretation of findings
- Writing the paper and critical appraisal of its content
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3.1 Abstract

The reliability of active drag values was examined using a method that compared free swim speed with measurements taken by towing swimmers slightly faster than their maximum swim speed, while allowing their intra stroke speed fluctuations. Twelve national age and open level swimmers were tested on two alternate days (Day 1 and Day 2). All participants completed four maximum swim speed, three passive drag and five active drag trials on each of the days. The reliability was determined using within-subject intra-class correlation coefficients (ICC) within each day and between the days. The ICCs for Day 1 and Day 2 were 0.82 and 0.85 respectively, while the ICC of the mean active drag values between days was 0.93. The data showed that the assisted towing method (ATM) with fluctuating speed was only moderately reliable within a single test. However, this method was more reliable when using the mean value of active drag from both days (ICC = 0.93). This study identified that the ATM method with fluctuating speed had moderate reliability within-subject trials on values in a single day but high reliability for the mean active drag values across different days.

Keywords: Resistance, active drag, fluctuating speed, front crawl

3.2 Introduction

Swimmers push their arms backward and move their legs to produce a propulsion force that propels their bodies forward. However, resisting their efforts is a drag force exerted by movement through the water. Drag force on the swimmer's body through the water can be divided into active and passive drags. Active drag occurs when a swimmer propels the body forward and passive drag when a swimmer glides in a streamline position (Kolmogorov & Duplishcheva, 1992). The swimmer encounters passive drag only during the glide after the start and turns in front crawl swimming; however, the majority of drag force which the swimmer encounters during swimming competition is active drag.

Active drag is the water resistance acting to oppose the swimmer while propelling the body forward (Mason, Sacilotto, & Menzies, 2011). That means that elite swimmers must try to optimise propulsion force, while minimising the drag force (Formosa, Mason, & Burkett, 2010). Several studies have been undertaken to estimate active drag, but no consensus has been reached on their efficacy since each study tends to use different methodology (Formosa, Mason, & Burkett, 2011; Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Mason et al., 2011; Toussaint, Ross, & Kolmogorov, 2004; Wang, Wang, Yan, Li, & Shen, 2007). Nevertheless, three different techniques are commonly used to measure active drag: Measurement of Active Drag (MAD system) (Hollander et al., 1986), Velocity Perturbation Method (VPM) (Kolmogorov & Duplishcheva., 1992), and Assisted Towing Method (ATM) at constant (Alcock & Mason, 2007) or fluctuating speed (Mason et al., 2011).

The MAD system was designed to measure propelling forces directly (Hollander et al., 1986). The active drag was calculated by measuring the propulsive force applied to paddles fixed to a force transducer in the pool and assumed that mean drag and mean propulsive forces are equal when swimming at constant mean speed. The VPM method is based on the main assumption that a swimmer is able to generate a constant mechanical power output in both free swimming and swimming with hydrodynamic body conditions (Kolmogorov & Duplishcheva, 1992). This method is also based upon two other assumptions. The first is that swimmers maintain a constant mean speed throughout the trial. Speed will change within each stroke, however the mean speed between strokes should remain constant (Kolmogorov and Duplishcheva, 1992). The second is that drag changes in proportion to speed squared. The swimmers performed two trials; first time without any external attachment and second time with a hydrodynamic body attached to the back of the swimmer's waist. Then, the mean free swim speed and mean swim speed with the hydrodynamic body are compared to estimate the active drag at maximum swim speed during free swimming.

The ATM method was designed to estimate active drag at a constant swim speed (Alcock & Mason, 2007). In this method, a swimmer was assisted by a motor driven cable at a constant swim speed rather than resisting a swimmer. Active drag was estimated based upon three assumptions of the VPM technique (Kolmogorov & Duplishcheva, 1992). Mean active drag of freestyle was determined with increasing mean tow speed approximately to 10% greater than actual swimmer's speed and maximum force setting on the dynamometer was set up 550 N to maintain speed of the swimmer at a constant. However, the actual force was continually adjusted by the motor controller to achieve the target speed. It was assumed that a small increase in maximum speed would not affect stroke mechanics. However, in reality, a swimmer has intra stroke speed fluctuations in free swimming; therefore, by using the ATM method at a constant speed, the swimmer was not able to replicate the normal swimming stroke mechanics. Mason et al. (2011) presented speed graphs of both a constant tow speed and a fluctuating speed. There was greater variation between the maximum and the minimum speeds for the fluctuating speed trial than there was for the constant speed trial.

Subsequently, Mason et al. (2011) adapted the ATM method to reduce towing force and allowed swimmers to have a fluctuating speed that enabled them to maintain normal stroke technique as much as possible while being towed.

Equipment used to perform research always has measurement error and even the most valid and reliable tools have this as a problem. Therefore, when the observed value of a measurement includes measurement error, that value differs from the true value. Hence, it is essential for researchers to be confident about reliability and validity of their system before using it in measurement (Hopkins, 2000). The present study examines the reliability of the ATM method, with work ongoing in our laboratory to address the question of validity. Factors such as sample size, performer variability, multiple trials, and statistical design can affect the reliability of research, while contributing to the statistical power (Bates, Dufek, & Davis, 1992). Increased statistical power is important because it increases the likelihood of research being able to detect a significant difference between variables in a sample when there is a true difference between populations. A combination of sufficient sample size and number of trials can help to achieve a reasonable reliability in research. Several researchers have examined the number of participants necessary to provide stable data. Morrow and Jackson (1993) reported that a small sample size reliability study produces potentially unstable reliability estimates for a population. For example: a reliability estimate of 0.80 from a sample size of 15 would have a 0.95 Confidence Interval (CI) lower limit of 0.482 which suggests quite an unstable measurement in the sample. A sample of 30, however, would have a 0.95 CI lower limit of 0.608 that might be considered acceptable. Morrow and Jackson (1993) recommended that at least 30 participants are required to accurately measure the reliability of a measure.

A single trial has been suggested to be unreliable due to the potential inability of that trial being able to represent the generalised performance (Bates et al., 1992). The reliability of eight trials was compared with single trial and the result indicated that the reliability levels of eight trials ranged from 0.54 to 1.00, while reliabilities from a single trial were between 0.13 to 0.97 (Salo, Grimshaw, & Viitasalo, 1997). It can therefore be concluded that more than one trial is needed to provide an accurate quantitative result. A question arises, however, regarding the number of trials that are necessary to achieve high performance stability. Previous studies have concluded that the use of multiple trials influence the stability in the variation and represents a more accurate mean value of the variation (Connaboy, Coleman, Moir & Sanders, 2010; Dufek, Bates, & Davis, 1995; Morrow & Jackson, 1993). For example: Bates et al. (1992) reported that to obtain statistical power values greater than 90%, researchers need to have a minimum 10, 5 and 3 trials in conjunction with a sample size of 5, 10 and 20 respectively. However, performing multiple trials by a participant in one session may cause more fatigue; therefore, it would have a negative effect on performance. For example: swimmers in this study are required to exert the same power output during all trials while swimming with their maximum effort, so the number of trials must be considered.

The ATM method is a relatively new technique in the estimation of active drag. A few studies have previously examined the reliability of the ATM method at constant swim speed (Formosa et al., 2011; Sacilotto, Mason, & Ball, 2012). The finding of both studies revealed that the ATM method at a constant speed is highly reliable (ICCs = 0.96, Formosa et al., 2011; ICC = 0.91, Sacilotto et al., 2012). While the ATM method with fluctuating speed has been used since 2011, no research has examined the reliability of the current ATM method with this fluctuating speed. Therefore, it is important to examine the reliability of the current ATM method, which may differ from the previously reported ATM method using constant speed. The purpose of this study was therefore to determine the reliability of the ATM method when using a fluctuating speed tow. It was hypothesised that the ATM method that incorporates fluctuating speed in intra stroke would be highly reliable for both within a single day and across days.

3.3 Methods

3.3.1 Participants

Twelve highly trained swimmers (five males and seven females, age (mean ± standard deviation, 17.7 ± 2.9 years), who had participated in swimming competitions regularly in the 12 months prior to commencing the study volunteered to participate. Participants were international representatives (n=6) and state competitors (n=6) and had a best personal time for 100 m freestyle that was fast enough to earn at least 600 FINA points (Federation Internationale de Natation, 2013). Training sessions ranged between 6-11 times per week. Swimmers were in healthy physical and mental condition. Only one of the participants had participated in previous experiments with the passive and active drag towing system and none were familiar with the test conditions. Both the Human Research Ethics Committee of the Australian Institute of Sport (AIS) and the Human Review Ethics Committee of the University of Sydney approved the study. All participants were informed about the purpose and nature of study and provided written informed consent.

3.3.2 Testing protocol

The ATM method was implemented. Testing sessions were performed over a two-day period (alternate days) and swimmers were instructed in regard to testing protocols on Day 1. A 20 minute warm up as a normal race strategy was conducted immediately prior to each testing session. Participants were requested to perform front crawl and hold their breath for 10 metres during all trials (free swimming, passive drag and active drag trials). Swimmers performed at least one practice trial for each condition to become familiar with the nature of the experiment. The participants' maximum speed was examined during the practice trial to be sure that they were able to achieve their maximum speed in the first 15 m distance (before starting data collection). The participants were given five minutes rest between each trial to minimise the influence of fatigue on their performance.

Participants first completed four free swimming trials to determine their mean maximum swim speed. Secondly, three passive drag tests were completed at the mean maximum swim speed of the swimmers. This passive force was later used to estimate dynamometer force during the active drag trials. Finally, five active towing tests were performed at approximately 5%-8% greater than the swimmer's mean maximum swim speed. The choice of 5%-8% was a recommendation by a workshop involving many of the researchers working in this area (Mason et al., 2013). Increasing speed by less than 5% resulted in the cable becoming slack, with consequent errors in measuring swim speed. On the other hand, increasing by more than 8% could change the normal stroke mechanics of the swimmer (stroke length and stroke rate).

3.3.3 Free swimming trials

Swimmers were requested to swim with maximum effort over a 25 m distance. They started from the 25 m mark and mean swim speed was averaged from the footage captured between 15 m to 5 m from the wall using two 50 Hz cameras (Samsung model SCC-C43101P, Korea). The participants were required to approach their maximum speed in the first 10 m and to maintain that throughout data collection. Swim track software (a custom program from the AIS, Australia) was used to time the swimmer over the 10 m distance. The mean speed of all four trials was calculated to determine the swimmer's mean maximum swim speed.

3.3.4 Passive drag trials

Passive drag tests were performed at the participant's mean maximum swim speed. Prior to testing, the swimmers were instructed how to hold their body in the streamline position without any motion (shoulders fixed with the arms together and stretched tightly overhead, and with one hand placed over the other). Passive drag towing was performed with a plastic handle that attached to a cord through a high tensile strength cable (Spectra Blue cable, Diameter: 2mm, Canberra, Australia) linked to a dynamometer. Our measurements estimate that 20 m of cable would stretch approximately 1.4 cm when force varied between our typical minimum and maximum values of 20 N and 35 N respectively. The swimmer was towed from surface of the water and from 25 m mark out and passive drag value was averaged from 15 m to 5 m mark. A passive drag trial was accepted when the participant was able to maintain a streamline position just below the water surface and there was visible water flow passing over the head, back and feet (Formosa et al., 2010) (Figure 1).

Towing was conducted using a flux vector dynamometer (a controller motor with variable frequency UniDrive SP panel mount high performance AC drives 0.37 kW-132 kW, Control Technique Instruments, Sydney, Australia) mounted directly on a calibrated Kistler^{TM} force platform (Type: Z20916, Kistler Instruments, Winterthur, Switzerland). A dynamometer controller (SYPT pro demo version 2.5.2, Emerson Industrial Automation, Australia (EIAA)) applied enough force (up to maximum force 550 N) to maintain constant speed at the swimmer's mean maximum swim speed.

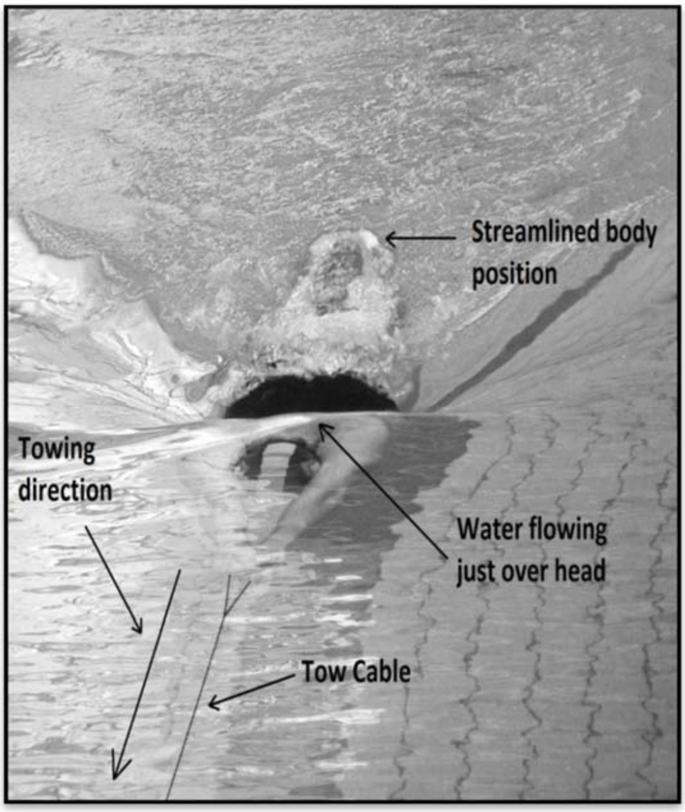

Figure 3.1 - Showing the towing direction of swimmer at the mean maximum swim speed (streamline position while towing).

3.3.5 Active towing trials

Active towing tests were completed at a speed approximately 5%-8% greater than each participant's mean maximum speed. During five trials, the swimmers were towed by the dynamometer via a belt (Eyeline, Australia) attached anterior to the waist and the force platform recorded the force profile that was generated by the swimmer during towing. The Spectra cable was passed through a pulley located 0.7 m below surface of the water (Figure 2). The range of angle between the surface of the water and the cable throughout the data collection was between 2° and 4°. The cable angle of the assisted swimming was ignored in the measurement of speed because the horizontal force was used to measure the cable force and the vertical component did not need to be measured; therefore, the horizontal speed was used.

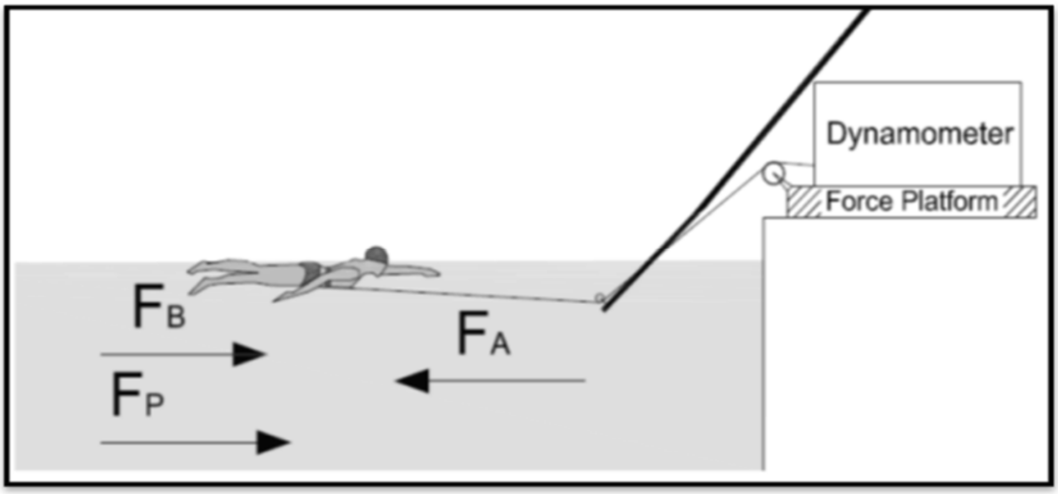

Figure 3.2 - Assisted towing method set up; this diagram illustrates the direction of towing as represented by the cable force (F_B), the direction of the propulsive force (F_P) and the direction of active drag (F_A).

The dynamometer force was set at a level high enough for force to reach the target mean speed, but low enough to allow the swimmer to have intra-stroke fluctuations. A force range from three quarter to half mean passive drag value of each swimmer was initially used and the speed setting on the dynamometer set at 120% of the swimmer's mean maximum speed (Mason et al., 2013). Prior to experimental testing, an initial trial was conducted with these settings and if the mean tow speed was not between the range of 5% to 8% greater than the mean maximum swim speed, then the dynamometer force was adjusted. Then, another trial was performed to test the new force setting for correct speed range.

3.3.6 Data collecting

The dynamometer and force platform were used to record the speed and the force signals from the swimmer during each trial. The tow speed was measured based upon the wheel angular speed of a wheel of the dynamometer. Data was sampled with a 12 bit analogue to digital card at 500 Hz. Then both outcomes of the tow force and the tow speed were smoothed with an 8 Hz low pass Butterworth filter. The swimmer swam from 30 m mark out and data recording of these signals commenced at the beginning of trial and mean tow speed and mean tow force calculated from first trigger signal for the full four strokes (beginning with right hand entry after 20 m mark) and finished after the second trigger signal. The trigger was also synchronised on a video timer to synchronise the video footages with the force data. Each trial was video recorded by using three genlocked cameras which captured at 50 Hz. Two cameras were located from the side on, pool deck underwater (Swim Pro analogue camera) and above water (Model 301 underwater video analogue camera, Applied Micro video, USA), mounted on a moveable trolley that travelled with the swimmer. Images were mixed with an Edirol video mixer (EDI-8V, USA). The third camera was located head-on (underwater) and captured at 50 Hz (JVC-Mini DV Camcorder GY-DV550, Japan).

3.3.7 Data processing

Both outcomes of the force platform and the tow speed were smoothed with an 8 Hz low pass Butterworth filter. A Residual Analysis (Winter, 2005) was used to confirm this choice of cut-off frequency. Active drag at the mean maximum swimmer's speed was computed using the difference between normal free swimming speed and the measured tow speed, as well as using the force profile needed to pull the swimmer at the increased speed. The following equations were used to estimate active drag. The equations were originally obtained from Kolmogorov and Duplishcheva (1992) and were modified for the ATM method by Alcock and Mason (2007). According to the VPM method:

$$F_{A1} = \frac{1}{2}\, C_d\, \rho A v_1^2 \qquad (1)$$

$$F_{A2} = \frac{1}{2}\, C_d\, \rho A v_2^2 \qquad (2)$$

where F_{A1} and F_{A2} are the active drag during free swimming and assisted towing; ρ is water density; A is the front surface area of the swimmer; C_d is the drag coefficient; and v_1 and v_2 are the swimmer's mean maximum speed for free swimming and towing.

Figure 3 shows the three force vectors while a swimmer is towed by the dynamometer,

$$F_{P2} = F_{A2} - F_B \qquad (3)$$

where F_B is the force needed to tow the swimmer at the increased speed as measured with the force plate.

It is assumed that a swimmer is able to produce the same power output (P) during free swimming and towing (Kolmogorov & Duplishcheva, 1992):

$$P_1 = P_2 \qquad (4)$$

$$F_{P1}.v_1 = F_{P2}.v_2 \qquad (5)$$

At a constant mean swimming speed, the mean propulsive force is equal in magnitude but opposite indirection to the mean active drag force (Kolmogorov & Duplishcheva, 1992). Substitution of $F_{P1}$and F_{P2} into equation (5), then gives:

$$F_{A1}.v_1 = (F_{A2} - F_B).v_2 \qquad (6)$$

Substitution of F_{A1} and F_{A2} into equation 6, then gives:

$$\left(\frac{1}{2}C_d\rho A v_1^2\right).v_1 = \left(\frac{1}{2}C_d\rho A v_2^2\right).v_2 - F_B.v_2 \qquad (7)$$

Rearranging the formula to find C_d:

$$C_d = \frac{F_B v_2}{\frac{1}{2}\rho A(v_2^3 - v_1^3)} \qquad (8)$$

Finally, Substituting C_d in equation (1) gives the active drag formula during free swimming:

$$F_{A1} = \frac{F_B \, v_2 \, v_1^2}{v_2^3 - v_1^3} \qquad (9)$$

3.3.8 Statistical analysis

Active drag was estimated over four full strokes from each swimming trial. All five trials collected were selected for statistical analysis. A one-way intra-class correlation coefficient (ICC) was employed to assess whether there was high reliability within participants on each single day. Additionally, the mean from five active drag values of each participant was calculated to use for the determination of ICC between days. According to Vincent (1999), an ICC value above 0.90 is considered high, between 0.80 and 0.90 moderate and, below 0.80 questionable. SPSS software (Version 19, IBM, Chicago, IL, USA) was used for statistical analyses and a statistical significance for the reliability coefficient was set at the 95% confidence level ($p<0.05$).

3.4 Results

Individual results for each participant in Day 1 and Day 2 are presented in Table 3.1. The data presented in Table 3.2 show that the ICCs for single trials within day one and two were 0.822 and 0.854, respectively, and the likely ranges were 0.658 to 0.935, and 0.711 to 0.948 at a 95% confidence interval, respectively. The ICC within Day 1 and Day 2 were moderately reliable in regard to Vincent (1999).

Table 3.1 – Summary of the Individual values of active drag (N) with fluctuating speed in Day 1 and Day 2

Participant	Gender	Mean max speed	Trial1	Trial2	Trial3	Trial4	Trial5	Mean ± SD
Day one								
1	F	1.58	102.1	106.3	73.6	84.3	72.9	87.8±15.6
2	F	1.61	87.8	84.4	87.1	114.4	93.8	93.5±12.1
3	F	1.65	59.5	67.3	71.5	69.3	65.1	66.5±4.6
4	F	1.60	86.1	83.3	88.4	104.4	68	86.0±12.9
5	F	1.58	111.3	115.6	109.9	126.1	113	115.1±6.5
6	F	1.53	70	74.5	68.5	73.7	79.1	73.1±4.1
7	F	1.62	135.8	128.5	143.9	131.1	134.8	134.8±5.8
8	M	1.87	112.4	109.2	118.6	82.1	98.9	104.2±14.3
9	M	1.93	125.1	148.8	158.6	152.1	190.8	155.0±23.6
10	M	1.78	123.9	123.7	160.9	132.2	156.4	139.4±17.9
11	M	1.87	138.5	108	158.3	185.4	140.2	146.0±28.4
12	M	1.87	157.2	164.7	158.5	163.3	145.1	157.7±7.7
Day two								
1	F	1.57	74.2	60.5	61.2	82.3	73.6	70.3±9.3
2	F	1.63	59.2	115	42.3	98.3	118	86.5±34.0
3	F	1.65	65	65.8	66.5	70.1	64	66.2±2.3
4	F	1.58	54.9	54.8	66.6	73.4	70.4	64.0±8.7
5	F	1.57	105	108.5	106.2	96.5	100.1	103.2±4.8
6	F	1.57	60.1	65.9	65.8	61.1	64.8	63.5±2.7
7	F	1.61	125.9	146.9	152.3	120.4	128	134.7±14.0
8	M	1.88	99	131.2	102.4	132.6	112.8	115.6±15.7
9	M	1.92	138.2	139.8	131.9	155.6	164.8	146.0±13.6
10	M	1.80	132.6	115.8	108.5	148.9	149.4	131.0±18.7
11	M	1.88	181	164.9	169.3	179	150.9	169.0±12.1
12	M	1.87	158.3	123	154.6	137.3	130.8	140.8±15.2

The ICC of mean values between both days was 0.926 and the likely range was 0.772 to 0.978 at a 95% confidence interval (Table 3.2). The ICC between Day 1 and Day 2 showed high reliability in regard to Vincent (1999).

Table 3.2 – Intra-class correlation coefficients

		ICC	**95% confidence interval**	
			Lower bound	**Upper bound**
Day 1	Single measures	0.822	0.658	0.935
Day 2	Single measures	0.854	0.711	0.948
Between Day 1 & Day 2	Single measured	0.926	0.772	0.978

3.5 Discussion and Implications

The purpose of this study was to examine the reliability when estimating active drag using the ATM with fluctuating speed tow. The result of this study indicated that using the ATM method with fluctuating speed is moderately reliable in regard to within-subject values on each day (ICCs = 0.82 and 0.85) and therefore do not support the first hypothesis that the ATM method is highly reliable within a single day. The mean active drag value of a few swimmers was 10–25% different over the two days. However, the result of the ICC indicated that this method is more reliable using the mean value of active drag from both days, when measurements were averaged from five trials on each day (ICC = 0.93). Therefore, the results of this study support the hypothesis that the ATM method with fluctuating speed is reliable between two different days.

The ICCs of each single day (Table 3.2) showed lower reliability to those reported by Formosa et al. (2011) and Sacilotto et al. (2012). The disparity between outputs of this study compared to previous studies is likely due to the number of trials and/or the statistical methodology. For example, Sacilotto et al. (2012) selected three trials from five trials for examining reliability and the first trial was selected from the median of all five trials and the two trials that were nearest in value to the original median. The other two values that were far from the median value were eliminated from the reliability calculation. It seems that the main reason to achieve high reliability in the study of Sacilotto et al. (2012) could therefore be ignoring those values which were far from the median value. Furthermore, Dufek et al. (1995) reported that for obtaining accurate reliability, researchers need to accomplish at least 5 trials in conjunction with a sample size of 10. These specifications were also supported by Connaboy et al. (2010). However, previous studies (Formosa et al., 2011; Sacilotto et al., 2012) recruited only seven and eight participants respectively.

Formosa et al. (2011) reported that the ICCs of five active drag trials were 0.96 to 1.00 for different days. Only four participants participated in their reliability research and, according to previous studies (Bates et al., 1992; Dufek et al., 1995; Hopkins, 2000), at least 10 to 15 participants are required in conjunction with five trials in order to reach an acceptable level of reliability. It would therefore appear that only four participants were not enough to confidently establish reliability of the measurement. To establish reliability of a measurement with only four participants, it is required to have at least seven trials (Bates et al., 1992). However, an increase in the number of trials in one day would introduce a systematic bias because fatigue would prevent participants from performing at the same power output. Many trials were examined during pilot tests and the results showed that the swimmers felt fatigue after four and five trials, as the outcome of the mean tow speed increased more than 9% of the mean free swim speed. Hence, to avoid fatigue on performance and also, to achieve acceptable level of reliability, repeating the testing protocol on a different day was used for the present study.

Higher reliability is obtained by averaging values rather than using a single value. For example, Hunter, Marshall and McNair (2004) employed 28 participants to perform three trials for a reliability calculation and compared the ICC results between one trial and the mean of three trials. They observed that by taking the mean of three trials, the reliability was improved when compared with the reliability of single trial. Therefore, the recommendation of Hunter et al. (2004) was used in the present study to achieve a higher reliability while comparing the ICC between two different days in this study. The results indicated that by using the mean active drag value of all five trials from both days (0.93) was higher than single Day 1 (0.82) and Day 2 (0.85).

A small sample size reliability study can potentially produce unstable reliability estimates for a population. Particularly in the lower limit, a lower limit CI estimate of 0.70 from a sample size of 10 has a 95% CI lower limit of 0.199, which suggests quite unstable measurements in the sample (Morrow & Jackson, 1993). They recommended that at least 30 participants are required to accurately measure the reliability of a measure. However, this number of participants with a high swim performance level was not feasible in this study. Because equal power output in both free swimming and towing conditions was required, only a high ranking swimmer would be able to generate the same power and complete the whole testing protocol. Connaboy et al. (2010) have previously observed that 15 participants s in conjunction with five trials are enough for obtaining reliable measurement. Balancing previous suggestions to achieve reliability (Bates et al., 1992; Connaboy et al., 2010; Dufek et al., 1995) with the limited number of skilled participants, the present study enlisted a sample of 12.

In this study, it was observed that the males had higher active drag values than the females (Table 3.1) which was supported by previous research (Kolmogorov & Duplishcheva, 1992; Sacilotto et al., 2012; Wang et al., 2007). Lower active drag values could be due to the smaller body size of females and a lower drag coefficient (Kolmogorov & Duplishcheva, 1992), or a higher body composition which enable females to improve buoyancy (Pendergast, Di Prampero, Craig, Wilson & Rennie, 1977) and/or a lower swim speed. The active drag is more dependent upon swimmer's technique (Kolmogorov & Duplishcheva, 1992), therefore, greater active drag value in a female could likely be caused by swimming technique. In some cases, however, female swimmers with a lower mean maximum swim speed had greater active drag values than men with the higher mean maximum swim speed. For example: Mason et al. (2011) reported that the female swimmer had the active drag of 128 N at 1.61 m/s while, the active drag of the male was 124 N at 1.82 m/s.

The active drag values from the present study were in accordance with the finding of a previous study which utilised the AIS assisted technique with fluctuating speed (Mason et al., 2011), but these values were considerably lower than the results of others which used the AIS assisted technique at a constant speed (Formosa et al., 2010; Formosa et al., 2011; Sacilotto et al., 2012). The difference in the active drag values between those studies and this study would be related to the dynamometer force (up to 550 N) which was used to maintain constant speed during a trial. It could indeed be expected that towing with a constant speed changes stroke mechanics (stroke rate and stroke length) and the swimmer therefore would not replicate the stroke mechanics that occur in normal swimming. It is more likely that the mechanical power output would not be the same in both conditions: free swimming and swimming while towing, however, it was assumed that mechanical power output is constant (Kolmogorov & Duplishcheva, 1992). On the other side, the results of this study were significantly higher than the results previously obtained using resisted techniques (Kolmogorov & Duplishcheva, 1992; Wang et al., 2007).

Past approaches to calculating active drag have achieved varying results. It would be expected that the studies which based their technique on the assumptions of the VPM method (Kolmogorov & Duplishcheva, 1992) would obtain a similar result, despite using resisted or assisted techniques. These differences could be explained by a violation of the underlying assumptions. Therefore it is necessary to consider the validity of these assumptions. The present paper, however, has examined only the reliability of the ATM method with fluctuating speed. Further research is ongoing in our laboratory to consider the validity of these results.

3.6 Conclusion

The generation of high quality research is dependent on the reliability and validity of measurement. Demonstration of intra-reliability for a new instrument or method prior to undertaking extensive research is essential. Therefore, the aim of this study was to assess the reliability of the current ATM approach using a fluctuating speed tow for the estimation of active drag in order to prepare the system for use in future fluctuating speed investigations. The results of this study identified that the ATM method with fluctuating speed is moderately reliable within-subject in a single day. The mean active drag value of a few swimmers had 10-25% different between two days, however; high reliability has been found for the mean active drag values across different days.

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CHAPTER 4

A comparative analysis of two types of active drag measurement in front crawl swimming

Statement from co-authors confirming the authorship contribution of the PhD candidate "As co-authors of the paper '**A comparative analysis of two types of active drag measurement in front crawl swimming**', we confirm that Pendar Hazrati has made the following contributions:

- Conception and design of the research question
- Data collection
- Analysis and interpretation of findings
- Writing the paper and critical appraisal of its content

Signature:…………… P. Sinclair …………. Date:............... 29/03/16...........

Peter J Sinclair

Signature:……… Bruce R Mason ………. Date:........ 29 Mar 16..........

Bruce R Mason

Signature:……… Rene' Ferdinands ……… Date:....... 29/03/16.................

Rene E Ferdinands

Signature:…………… …………. Date:........... 29/03/16.............

Wayne Spratford

4.1 Abstract

Two different methods of estimating active drag were used to compute active drag based upon assumptions of the Velocity Perturbation Method. One of the methods estimates the active drag by decreasing the swimmer's speed and the other one estimates it by increasing the speed. Previous studies using those two methods reported that active drag values were either less than or greater than passive drag respectively. This study employed those methods using consistent equipment to determine whether these two methods measure active drag the same. Ten elite male swimmers performed two free swimming trials, two passive trials and two active drag trials in each of the two methods. The results of a one-way ANOVA with repeated measures indicated there was no significant difference between the mean active drag values obtained from the assisted (105.3±24.7 N) and resisted method (90.7±17.1 N) (p = 0.127). There were, however, large differences between the mean active drag values calculated by the two methods for some participants. If the two methods did elicit different power outputs, then the calculated drags would be different.

Keywords: swimming, resistance, active drags, fluctuating speed, front crawl

4.2 Introduction

Drag can be defined as "a resistance of the water to the swimmer's movements through it" (Maglischo 2003, 6). Drag force on the swimmer's body through the water may be classified into active and passive drag. Active drag occurs when a swimmer propels the body forward using arm stroking and leg kicking and passive drag occurs when a swimmer glides without action in the water (Kolmogorov & Duplishcheva, 1992). In competitive swimming the swimmer encounters passive drag only during the glide after the start and the turns; however, most of the drag force produced during swimming competition is active drag. Active drag is exerted by the surrounding water on the swimmer. Therefore, if the water exerts less resistance on the swimmer's body, then less energy will be required for the swimmer to overcome this force. For this reason, it is important that both swimmers and coaches understand how much active drag is produced during the swimming and how the swimmer can reduce that. Hence, determination of drag force is an important consideration in swimming performance.

A number of methods have been developed to calculate passive drag and active drag directly and indirectly (Clarys, 1979; Formosa, Mason, & Burkett, 2011; Kolmogorov & Duplishcheva, 1992; Mason, Sacilotto, & Menzies, 2011, Wang, Wang, Yan, Li, & Shen, 2007). The value of active drag has been found to vary considerably with the method of estimation, although the reasons for this have yet to be established. By finding an accurate active drag measurement, sport scientists and coaches can help their swimmers to achieve better performance.

Hollander et al. (1986) developed a system to directly measure the propulsive force of the arms when a swimmer pushed the paddles fixed to a force transducer in the pool while performing the front crawl action. The aim of this device was to measure active drag from these measurements of propulsive force. The Measurement of Active Drag (MAD) system calculated active drag from the mean propulsive force as it was assumed that at a constant swimming speed, the mean active drag is equal to the mean propulsive force (Schleihauf, Gray, & DeRose, 1983). The MAD system measures actual forces while a swimmer pushes on the paddles, but it prevents the swimmer having natural stroke mechanics (Poizat, Ade, Seifert, Toussaint, & Gal-Petitfaux, 2010). In this case, the swimmer must match stroke length to the distance between the two paddles. Another problem with the MAD system is that the swimmer has contact with the fixed paddles. However, in normal swimming, a swimmer's hands move in relation to the water. The other criticism of this system is that a small pull-buoy was situated between the swimmer's legs to prevent use of the legs during swimming and to maintain the body in a horizontal position.

Kolmogorov and Duplishchea (1992) estimated mean active drag using the Velocity Perturbation Method (VPM) at the swimmer's maximal swim speed. In this method, the swimmer is required to swim first with a hydrodynamic body attached to the back of the swimmer's waist, producing a known additional resistance, and secondly to swim without any resistance. The VPM method estimated mean active drag based upon the main assumption that a swimmer is able to generate a constant mechanical power output under both conditions of free swimming and swimming with added resistance. This method is also based upon two other assumptions. The first is that swimmers maintain a constant mean speed throughout the trial. Speed will change within each stroke, but the mean speed between strokes should remain constant (Kolmogorov & Duplishcheva, 1992). The other additional assumption is that the drag changes in proportion to the speed squared.

Mason et al. (2011) developed a pulley system (Assisted Towing Method) using a dynamometer to determine active drag. This method used the same assumptions and equations of the VPM method (Kolmogorov & Duplishcheva, 1992). In this method, the swimmers were towed 5% faster than the mean maximum swim speed by an additional force which was set up on the dynamometer. The ATM method (Mason et al., 2011) aimed to allow swimmers to have a fluctuating speed in order to maintain their normal stroke technique while being towed. Reducing the amount of tow force and increasing the tow speed setting on the dynamometer allowed intra-stroke speed fluctuations to occur. Therefore, a motion controller was used by Mason et al. (2011) with the aim of achieving a fluctuating speed within stroke. To achieve this, the maximum possible force, considered equivalent to the mean passive drag of the swimmer, was set very low on the dynamometer to allow the motion controller to fluctuate tow speed.

Toussaint, Ross and Kolmogorov (2004) assessed the difference between the active drag values measured with the MAD system and those estimated by the VPM method. The mean value of the VPM method (53.2 N) was lower than the mean value of the MAD system (66.9 N) at the same mean maximal speed. To further understand this, Formosa, Toussaint, Mason and Burkett (2012) compared the mean active drag values of the ATM method at a constant speed tow with those values of the MAD system. The mean calculated using the MAD system (82.3 N) was significantly lower than those values of the ATM constant speed tow method (148.3 N) at the swimmer's same mean maximum speed. According to the previous studies (Formosa et al., 2012; Toussaint et al., 2004), it can be suggested that the VPM method reduces the measure of active drag, whereas the ATM method increases this calculation.

Given the disparity among previous results, the present study utilised both the assisted towing method and the resisted method using the same equipment and protocol to compare active drag values obtained from the two methods. The findings of this study might provide appropriate information for the sport researchers to improve the active drag measurement. Therefore, the purpose of this study was to explore whether the assisted and the resisted methods produce the same active drag value if the same equipment is used. The null hypothesis of the study was that active drag values obtained from the assisted method would be the same as those values obtained from the resisted method. However, if the results were to differ between the two methods, this could be due to: 1) the assumptions of equal power output, 2) the assumption that the drag changes in proportion to the speed squared of the VPM method (Kolmogorov & Duplishcheva, 1992) and 3) uncertainty in measurement of the measured variables (belt force, tow speed and swim speed).

4.3 Methods

4.3.1 Participants

Ten national and international male swimmers, who had participated in swimming competitions regularly in the 12 months prior to commencing the study, volunteered to participate. In Table 4.1, the mean and standard deviation values of their age, height, weight, best FINA (Federation Internationale de Natation, 2013) points in long course (50 m pool) and the type of event in which they participated are presented. Height was measured using a wall mounted stadiometer (model 222, Scales Galore, New York, USA) and the participants were asked to stand with their back to the height rule, with the back of the head, back, buttocks, calves and heels touching the upright, and the feet together. Body mass was measured with a digital scale while the participants were wearing swimsuits. All participants were informed of the purpose and nature of the study and provided written informed consent. Both the Human Research Ethics Committee of the Australian Institute of Sport (AIS) and the Human Ethics Review Committee of the University of Sydney approved the study.

Table 4.1 – Anthropometrics variables, the FINA point and the type of event of individual swimmers

Participant	Age	Height (cm)	Body mass (kg)	FINA point	Type of event
1	22	170	68.8	910	Sprinter (50-100)
2	21	177	75.4	855	Sprinter (50-100)
3	16	176	77.2	750	Mid-distance (200)
4	19	173	70.7	795	Mid-distance (200)
5	20	182	75.0	814	Sprinter (50-100)
6	26	197	92.5	922	Sprinter (50-100)
7	22	197	89.5	915	Sprinter (50-100)
8	23	190	83.0	848	Sprinter (50-100)
9	18	188	87.3	810	Mid-distance (200)
10	20	197	88.6	820	Mid-distance (200)
Total (M ±SD)	20.6 ± 2.8	184 ± 10.5	80.8 ± 8.4	844 ± 57	

4.3.2 Testing Protocol

A 20-minute warm-up as a normal race strategy was conducted immediately prior to the testing session. Swimmers performed at least one practice trial for each condition to become familiar with the nature of the experiment. The participants' maximum speed was examined during the practice trial to be sure that they were able to achieve their maximum speed in first 15 m distance (before starting data collection). Participates were given five minutes rest between each trial to minimise the influence of fatigue on their performance. Participants were requested to hold their breath for 20 metres during all trials (free swimming, passive drag and active drag trials). The testing protocol included two free swimming trials, two passive drag tests, two active towing tests using the resisted method and two active tow tests using the assisted towing method.

4.3.3 Free swimming trials and apparatus

Swimmers were asked to swim with maximum effort over a 40 m distance. They started from the 40 m mark out from the wall for eight full strokes and their mean swim speed was assessed between the footage captured the 25 m to 5 m marks (Mason et al., 2013) using a series of PAL cameras (Samsung model SCC-C43101P, Korea). The participants were required to approach their maximum speed in first 15 m and maintained that throughout data collection. The analogue video cameras recorded images at 50 Hz were located directly perpendicular to and across the pool at the 5 m, 7.5 m, 10 m, 15 m, 20 m and 25 m marks and approximately 3 m above the surface of the pool. Swim tracking software (Tor, Peace, Knight, & Ball, 2015) was developed by the Aquatic, Training, Testing and Research Unit (ATTRU) at the AIS, using analogue video cameras to control the display of the video field for calculating mean swim speed. Images displayed both the image from the camera and the time in seconds. The time intervals were recorded as the centre of the swimmer's head passed through specific points (Tor et al., 2015). The mean speed of two trials was calculated for determination of the participant's mean maximum swim speed.

4.3.4 Passive drag trial

Passive drag tests were performed at the participant's mean maximum swim speed. Prior to testing, the swimmers were instructed how to hold their body in the streamline position. Passive drag towing was performed with a plastic handle that was attached to a cord through a synthetic fibre of high-tensile strength cable (Spectra Blue cable, Diameter: 3mm, Racepec, Canberra, Australia) linked to a dynamometer. The swimmer was towed on the surface of the water and from the 35 m mark out, with passive drag averaged from the 25 m to the 5 m mark.

4.3.5 Active towing trials (assisted and resisted methods)

Active tow tests were completed over a 40 m distance and data of tow speed and tow force collected for eight full strokes. Based upon a random selection, half of the participants performed the first two trials using the resisted method and then two trials using the assisted towing method. For the other half, the trials were completed using first the assisted towing trials, then the resisted trials.

To perform resisted trials, the cable was passed through a pulley, which was located 1.25 m above the surface of the water (Figure 4.1) to be high enough for preventing kicking to the cable by the participants. The swimmers started from wall without push off the wall and stayed in a floating position and they approach their maximum speed in first 10 m and remain their maximum speed up to the end of data collection. The data collection was started at the 10 m mark and finished around the 30 m mark. The angle made between the resistance force (cable) and the line of travel at the 10 m mark was 7 degrees. This angle was decreased to 2 degrees when the swimmers were around the 30 m mark. The cable angles of the resisted swimming were ignored in the measurement of speed. Because, the horizontal force was considered to measure the cable force and the vertical component didn't need to measure, therefore, the horizontal speed was considered. An additional resistance force was applied by the dynamometer to the opposite direction of the swimmer's movement. This resistance force reduced their mean maximum speed to approximately 5%–8% less than each participant's mean maximum speed of free swimming (Hazrati, Mason, Sinclair, & Sacilotto, 2014). The force level was set between 4 and 10 N, as pilot tests with a force less than 4 N showed that the swimmers did not encounter actual resistance force to reduce their mean maximum speed. On the other hand, adding a force higher than 10 N caused the swimmers to reduce their mean maximum speed more than 8%.

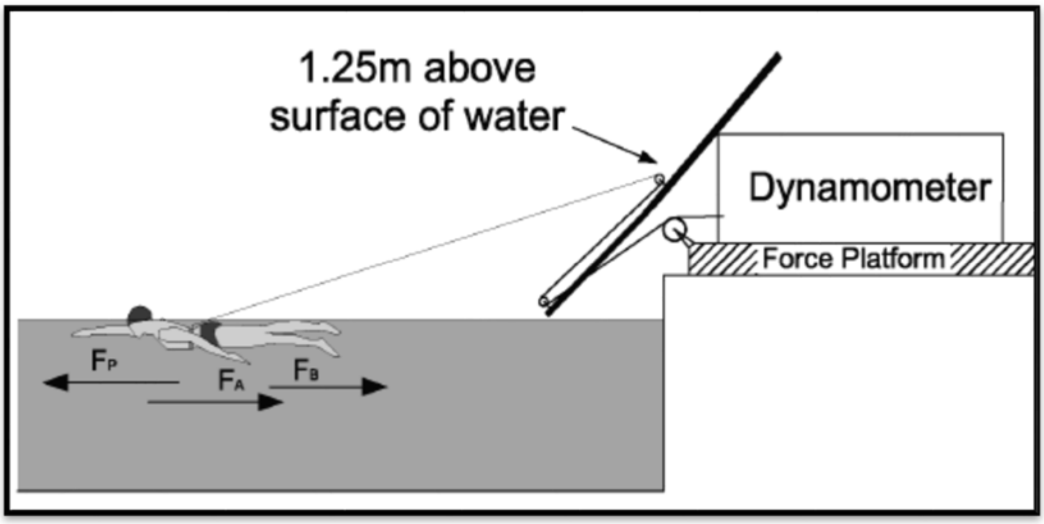

Figure 4.1 – Resisted method setup: this diagram illustrates the direction of towing as represented by the cable force (F_B), the direction of the propulsive force (F_P), the direction of active drag (F_A) and the cable was attached to the swimmer posterior to the waist and the location of the cable (1.25 m above the surface of water).

To perform assisted towing trials, the cable was passed through the pulley, which was located 0.7 m below the surface of the water (Figure 4.2 to be low enough for preventing the participants' hand from hitting the cable. The data collection was started at the 40 m mark and finished around the 10 m mark. The angle made between the resistance force and the line of travel at the 30 m mark was 1.25 degrees. This angle was increased to 4 degrees when the swimmers were around the 10 m mark. The cable angles of the assisted swimming were ignored in the measurement of speed. Because, the horizontal force was considered to measure the cable force and the vertical component didn't need to measure, therefore, the horizontal speed was considered. An additional force was applied in the same direction of the swimmer's movement. Applying this additional force caused the swimmers to increase their mean maximum speed by approximately 5%–8% more than their mean maximum speed during the free swimming.

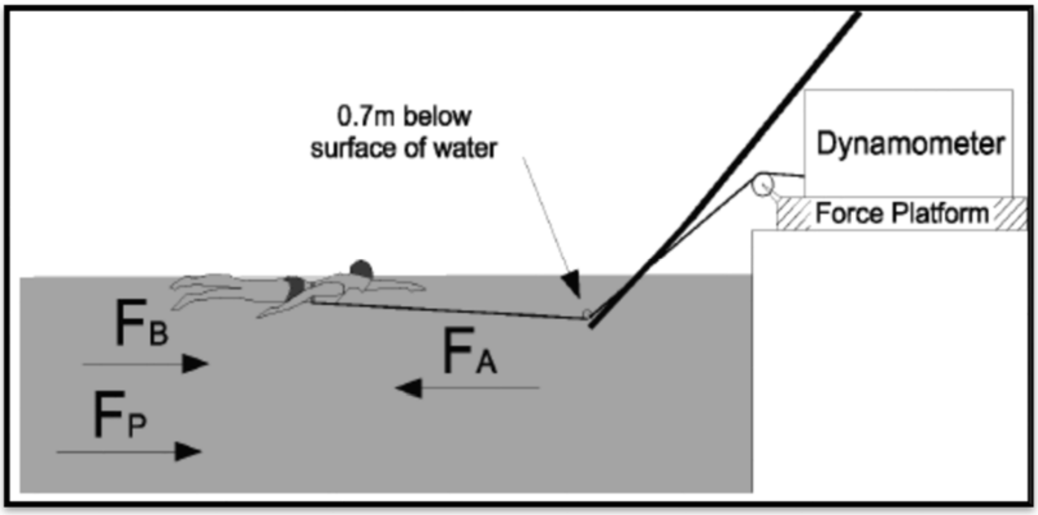

Figure 4.2 – Assisted towing method setup: this diagram illustrates the direction of towing as represented by the cable force (F_B), the direction of the propulsive force (F_P), the direction of active drag (F_A) and the cable was attached to the swimmer anterior to the waist and the location of the cable (0.7 m below the surface of the water).

Increasing or decreasing speed by less than 5% resulted in the cable becoming slack, with consequent errors in measuring swim speed. On the other hand, increasing or decreasing speed by more than 8% would be more likely to change the normal stroke mechanics of the swimmer (stroke length and stroke rate) (Mason et al., 2013). Therefore, initial trials were conducted for both the assisted and the resisted methods separately and, if the mean tow speed of each method was not in the range of 5% to 8%, then the dynamometer tow force was adjusted.

4.3.6 Materials and apparatus for completing passive and active drag trials

Towing was conducted using a flux vector dynamometer (a controller motor, Emerson Industrial Automation, Sydney, Australia), which measured the instantaneous speed of the swimmer during each trial. The Dynamometer was mounted directly on a calibrated Kistler^{TM} force platform (Type: Z20916, Kistler Instruments, Winterthur, Switzerland). The Kistler^{TM} force platform measured the instantaneous forces generated by the swimmer's body during towing. The Eyeline belt was attached anterior to the waist for the assisted trials and posterior to the waist for the resisted trials. A high-tensile strength cable (Spectra Blue cable, Diameter: 3mm, Canberra, Australia) was linked from one end to the belt, which was attached to the swimmer. The other end of the cable was attached to the dynamometer.

4.3.7 Data processing

Data was sampled with a 12 bit analogue to digital card at 500 Hz. Then both outcomes of the tow force and the tow speed were smoothed with an 8 Hz low pass Butterworth filter. A Residual Analysis (Winter, 2005) was used to confirm this choice of cut-off frequency. Active drag for both the methods was computed using the difference between normal free swim speed and the measured tow speed, as well as the force needed to decrease or increase the speed of the swimmer. The following equation was used to estimate active drag (Kolmogorov & Duplishcheva, 1992):

$$F_{A1} = \frac{F_B\, v_2\, v_1^2}{v_1^3 - v_2^3} \qquad (1)$$

where F_{A1} is the active drag during free swimming, F_B is the force needed to slow or increase the speed of the swimmer to the desired speed, and v_1 and v_2 are the swimmer's mean maximum speed for free swimming and swimming with an additional force respectively. Belt force (F_B) would be positive or negative based upon the direction of the swimmer while swimming (Figures 4.1 & 4.2). The following equation was used to calculate the estimated power output of free swimming:

$$P_1 = F_{A1} * v_1 \quad (2)$$

where P_1 is the power output during free swimming.

4.3.8 Statistical Analysis

The mean active drag value of each trial was calculated from the mean belt force, tow speed and free swim speed of that trial. Then the mean active drag values were calculated from the two assisted trials and two resisted trials. To test for significant differences in the active drag values calculated from the assisted and the resisted methods and the passive drag values, a one-way ANOVA with repeated measures was carried out, using the SPSS software (Version 19, IBM, Chicago, IL, USA). Statistical significance was set at the 95% confidence level.

4.4 Results

The mean active drags for the assisted and resisted methods were 105.8 ± 26.1 N and 88.5 ± 15.3 N respectively and the mean passive drag was 94.8 ± 11.9 N (Table 2). Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated (p = 0.127). Correlation between the two methods was 0.32 and this gave an effect size of 0.58. Results from the one-way ANOVA with repeated measures with a Greenhouse-Geisser correction showed that there were no significant differences between these three drag measurements (p = 0.171).

Table 4.2 – Mean value and half of range of assisted, resisted and passive drags (N), and the estimated power output of the free swimming during the assisted ($Power_A$) and the resisted ($Power_R$) (Wt) of individual swimmers

Participant	Assisted Active drag (N)	Resisted Active drag (N)	Passive drag (N)	$Power_A$ (Wt)	$Power_R$ (Wt)
1	92.9 ± 3.7	83.5 ± 5.9	91.0 ± 1.1	184.9 ± 7.3	166.1 ± 11.8
2	91.5 ± 1.8	124.9 ± 4.5	93.5 ± 2.6	167.4 ± 3.7	227.7 ± 8.4
3	106.5 ± 3.1	81.6 ± 6.1	103.8 ± 4.1	185.3 ± 5.5	142.1 ± 10.5
4	77.5 ± 3.2	100.5 ± 8.2	76.0 ± 4.6	136.5 ± 5.7	176.9 ± 14.4
5	92.5 ± 3.9	86.8 ± 0.6	94.0 ± 1.8	165.7= ± 7.0	156.4 ± 1.1
6	115.3 ±0.2	95.8 ± 5.4	109.7 ± 2.9	220.3 ± 0.4	183.0 ± 10.3
7	159.0 ± 6.7	74.8 ± 5.2	108.2 ± 1.7	305.3 ± 13.0	143.6 ± 10.0
8	94.7 ± 5.8	61.7 ± 9.0	103.6 ± 4.5	169.4 ± 10.4	110.4 ± 16.1
9	86.5 ± 2.8	96.7 ± 3.1	76.2 ± 1.3	157.4 ± 5.0	176.0 ± 5.7
10	142.6 ± 4.2	86.3 ± 2.9	92.3 ± 3.1	268.0 ± 8.0	162.3 ± 5.5
Total	**105.8 ± 26.1**	**88.5 ± 15.3**	**94.8 ± 11.9**	**196.1 ± 53.2**	**163.3 ± 28.2**

Note: Using an ANOVA with repeated measures with a Greenhouse-Geisser correction (p = 0.171). There were no statistically significant differences between any of the three methods for measuring drag.

The mean values, the standard deviations of the maximum speed of the free swimming, the assisted and the resisted swimming, and the mean values of the belt force of the assisted and the resisted methods are presented in Table 4.3.

Table 4.3 - Mean value and half of range of free, assisted and resisted swim speeds (m/s) and belt force (N) of individual swimmers

Participant	Mean Free swim speed (m/s)	Mean assisted swim speed (m/s)	Mean resisted swim speed (m/s)	Mean Tow force assisted (N)	Mean Tow force resisted (N)
1	1.99 ± 0.02	2.09 ± 0.01	1.86 ± 0.01	14.61 ± 0.1	-15.80 ± 0.6
2	1.83 ± 0.01	1.92 ± 0.02	1.74 ± 0.00	12.60 ± 2.6	-17.35 ± 0.5
3	1.74 ± 0.03	1.83 ± 0.01	1.63 ± 0.00	16.65 ± 0.2	-14.48 ± 1.0
4	1.76 ± 0.00	1.86 ± 0.01	1.66 ± 0.01	12.78 ± 0.1	-16.58 ± 0.2
5	1.80 ± 0.01	1.92 ± 0.01	1.68 ± 0.00	22.80 ± 0.8	-16.74 ± 0.6
6	1.91 ± 0.01	2.04 ± 0.00	1.80 ± 0.01	24.15 ± 0.2	-15.99 ± 0.9
7	1.92 ± 0.00	2.02 ± 0.01	1.78 ± 0.01	24.14 ± 1.0	-15.78 ± 0.5
8	1.79 ± 0.01	1.92 ± 0.01	1.65 ± 0.01	20.12 ± 0.1	-14.43 ± 1.2
9	1.82 ± 0.01	2.18 ± 0.01	1.73 ± 0.01	20.76 ± 2.1	-17.11 ± 0.3
10	1.88 ± 0.02	2.00 ± 0.01	1.76 ± 0.01	27.03 ± 0.5	-15.38 ± 0.0

4.5 Discussion

The purpose of the present study was to explore whether the assisted and the resisted methods produce the same active drag value while using the same equipment. The result of this study indicated that the active drag values obtained from the assisted method were not significantly different to those of the resisted method (p = 0.171). The finding of this present study was not consistent with findings reported by the previous literature. Some previous studies have found that active drag was one to two times greater than passive drag (Clarys, 1979; Formosa et al., 2011; Mason, Formosa, & Raleigh, 2009; Mason et al., 2011), while some others have reported that active drag was lower than passive drag (Kolmogorov & Duplishcheva, 1992; Shimonagata, Taguchi, Taba, & Aoyagi, 1998). The next paragraph discusses why the result of the present study was different to that of the previous studies.

The active drag values from the present study, measured using the assisted towing method with resistive force (Table 2.4), were considerably lower than in previous studies that used the ATM method at a constant speed (Formosa et al., 2011; Mason et al., 2009; Mason et al., 2011; Sacilotto, Mason, & Ball, 2012). These differences could be due to the magnitude of the belt forces applied during the towing of each swimmer of the present study (Table 3.4). The previous studies, conducted by Formosa et al. (2011) and Mason et al. (2009) utilised a force up to 550 N to maintain constant speed during a trial. Applying a large force would prevent the swimmer from having in-stroke speed fluctuations and thus would likely change the swimmer's stroke mechanics, making it potentially more likely that the swimmer's power output was not constant between trials and therefore leading to incorrect measures of active drag. Comparisons between the results of the resisted method of the present study (Table 2.4) and the resisted method of Kolmogorov and Duplishcheva (1992), however, showed similarity between the mean active drag values. This similarity could be explained by the lower resisted forces which were used in the present study and by Kolmogorov and Duplishcheva (1992).

The assisted and the resisted methods estimated the active drag values the same (p = 0.171) in the present study and this finding was in contrast to the previous studies (Formosa et al., 2012; Toussaint et al., 2004). This finding could be due to the small sample size (n = 10). The sample size has a direct relationship with the power of a test. It affects the achievement of a statistically significant difference in the experimental test. The power analysis of the sample size of 10 for the present study was 0.32 and this means that there was only a 32% chance to have a statistically significant difference between the active drag values of the two methods. It is obvious to the researchers of the present study that if more participants were employed, the researchers would be more confident about the result. However, a sample size more than n = 10 was not feasible for the present study.

Another reason for the disparity between the result of this study and previous studies (Formosa et al., 2012; Toussaint et al., 2004) could be due to the number of trials (n = 2): that is, two trials are less likely to be representative of the true performance capability than would be a greater number of trials. Performing multiple trials of the free, the assisted and the resisted swimming would cause swimmers to feel fatigued; therefore, the swimmer would not be able to deliver the same power output under both conditions. The feeling of fatigue was reported by some of the swimmers during the testing protocol. To eliminate the effect of swimmer fatigue on the measurement, high level swimmers with enough capacity were required to perform all testing protocols at the same power. Hence, based upon the small sample size, it would be difficult to be conclusive that the two measures were actually the same.

Comparison between individual results indicated that some swimmers had a large difference between the active drag obtained from the assisted and resisted methods (Table 4.2). A few of them had higher active drag values for the resisted method than the assisted method, for example, participants 2, 4 and 9. On the other hand, a few of them had higher active drag values for the assisted method than the resisted method, for example, participants 3, 7, 8 and 10. Toussaint et al. (2004) explained that the main reason for the difference in active drag results is likely to be an unequal power output when swimming with and without added resistance during the VPM method. The differences in the individual results of the present study may be explained by the same reason. However, the results of participants 1 and 5 in the estimated power output (Table 4.2) showed that there was less power output difference for them between the two swimming conditions (resisted and assisted) than for the other participants. It might therefore be concluded that, depending upon the swimmer, active drag values from both methods can be the same if the swimmer produces the same power outputs during the assisted and the resisted methods.

More than one variable is involved in the estimation of active drag, i.e. belt force, swim speed and tow speed. Therefore, a large difference between active drag values of the two methods for the present study could be related also to each of these variables, not only to unequal power output. For example, participant 7 had the highest active drag value (159.0 ± 9.6 N) for the assisted method when compared with the other participants, but he had the lowest active drag value (74.8 ± 7.5 N) for the resisted method compared with the other participants. The possibility of obtaining different active drag values could be related to uncertainty in measurement of the measured variables (belt force, tow speed and swim speed). Therefore, the next chapter focuses on the uncertainty of these variables to understand how they would affect the value of active drag.

Another possibility for obtaining incorrect active drag values can be related to the assumption of a square relationship between drag and swim speed. Toussaint et al. (2004) found that the active drag values calculated from the MAD system and the VPM had about 10% difference when the exponent of swim speed was equal 2 (v^2). Active drag values for both the MAD system and the VPM method were the same, however, when the exponent of the swim speed was equal 2.34 ($v^{2.34}$). The present study could not examine this assumption. It is suggested that the uncertainty of the speed exponent equal 2 be calculated, as well as how that uncertainty is contributed to in the estimation of active drag.

4.6 Conclusion

Active drag values obtained from the assisted towing method were compared with the resisted method's active drag values and there was statistically no significant difference between the mean values observed. Because of the relatively small number of participants available, it was difficult to be conclusive that the two measures were actually the same. Also, the result of the correlation (0.32) between the active drag values calculated from the two methods indicated that only 10% of the variability in the measures from one method could be explained by the variability of the measures in the other.

A large difference between active drag values was found for some of the swimmers. This could be due to the two assumptions of the VPM method or uncertainties of measured variables (belt force, swim speed and tow speed) in measurement of the ATM method. Nevertheless, the question whether the assisted and the resisted methods calculate the same active drag value when using the same equipment, is not finally answered by the present study, so still needs to be investigated further before any final conclusion can be drawn.

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CHAPTER 5

Contribution of uncertainty in estimation of active drag using assisted towing method in front crawl swimming

Statement from co-authors confirming the authorship contribution of the PhD candidate "As co-authors of the paper '**Contribution of uncertainty in estimation of active drag using assisted towing method in front crawl swimming**', we confirm that Pendar Hazrati has made the following contributions:

- Conception and design of the research question
- Data collection
- Analysis and interpretation of findings
- Writing the paper and critical appraisal of its content
- Corresponding author for communication with journals

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Wayne Spratford

5.1 Abstract

Active drag force in swimming can be calculated from a function of three variables: swim speed, tow speed, belt force and two assumptions: power output, and the exponent of speed. Accuracy of the drag force value is dependent on the accuracy of each variable, and how each contributes to active drag estimation. For evaluating the uncertainty of active drag estimation, twelve national age and open level swimmers were employed to complete testing protocols on two alternate days. All participants completed four maximum swim speed, and five active drag trials on each of the days. To calculate the uncertainty of active drag, active drag was considered as a function of each variable. Results showed that there are some errors in the measurement of active drag using the ATM method. Contribution of the uncertainties for the free and the tow swim velocities and the belt force into active drag values were approximately 6–7% error, and 2–3 % error respectively. The contribution of unequal power output showed that if power changed 7.5% between conditions, there would be about 30% error in calculated drag. Consequently, if a swimmer cannot maintain constant power output between conditions, there would be substantial errors in the calculation of active drag.

Keywords: Uncertainty, methodology, active drag estimation, front crawl swimming

5.2 Introduction

Active drag has been estimated using different equipment and equations (Formosa, Toussaint, Mason, & Burkett, 2012; Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992; Mason, Sacilotto, & Menzies, 2011). One of the main methods was developed by Hollander et al. (1986) and is known as the Measurement of Active Drag (MAD) system. This method measures the forces of the arms while the swimmer performs pushing actions against fixed paddles (Hollander et al., 1986). The aim of this method is to measure propulsive force so that active drag can be measured from the propulsive force measurements at a different swim speed. The MAD system calculates active drag from the mean propulsive force, as it is assumed that at a constant swimming speed, the mean active drag is equal to the mean propulsive force (Schleihauf, Gray, & De Rose, 1983). The subsequent speed -active drag data were least-square fitted to the below function:

$$F_P = F_A = Av^n \quad (1)$$

where F_P is the propulsive force at mean speed, F_A is the drag at mean speed, A and n are parameters of the power function and v is mean swim speed.

The Velocity Perturbation Method (VPM, Kolmogorov & Duplishcheva, 1992), estimates active drag using a hydrodynamic body (resisted force) attached to the swimmer. In this method, the maximal speed of the swimmer towing a hydrodynamic body is compared with the maximal free swimming speed. Estimation of active drag depends on three assumptions: first, that a swimmer can deliver an equal mechanical power output during either free swimming or swimming with the hydrodynamic body; second, that the drag changes in proportion to the speed squared; and third, that the swimmer can maintain a constant mean speed throughout the trial. The latter assumption is still valid if the speed changes within each stroke as long as the mean speed between strokes remains constant (Kolmogorov & Duplishcheva, 1992). The active drag in the VPM method is calculated from the following equation:

$$F_A = \frac{F_B\, v_2\, v_1^2}{v_1^3 - v_2^3} \quad (2)$$

where F_A is the active drag, F_B is additional resistance force, v_1 is the swimmer's mean maximum speed during free swimming and v_2 is the swimmer's mean maximum speed during tow swimming. The Assisted Towing Method (ATM) at a constant tow speed (Formosa et al., 2012) and the ATM at a fluctuating speed (Mason et al., 2011) estimated active drag based upon the assumptions and equations of the VPM method (Kolmogorov & Duplishcheva, 1992). The ATM method under both conditions is similar to the VPM method except that the swimmer is assisted by a dynamometer at a constant swim speed rather than having a force resisting the swimmer.

Toussaint, Roose and Kolmogorov (2004) compared the MAD system with the VPM method and found that the mean active drag obtained from the VPM method was approximately 20% lower than the mean active drag obtained from the MAD system ($p = 0.029$). In contrast, Formosa et al. (2012) compared the MAD system with the ATM method at a constant tow speed and found that the mean active drag obtained from the MAD system was approximately 55% lower than the mean active drag obtained from the ATM method at a constant speed ($p = 0.002$). These two studies (Formosa et al., 2012; Toussaint et al., 2004) suggest that the VPM technique underestimates active drag relative to the MAD system and the ATM method overestimates active drag relative to the MAD system. Toussaint et al. (2004) explained that the main reason for the difference in active drag results is likely to be a result of violation of the equal power output assumption of the VPM method.

As previous studies (Formosa et al., 2012; Toussaint et al., 2004) utilised different equipment and protocols, the study reported in chapter 4 of this thesis was conducted to compare both the ATM method and the resisted method using the same equipment and protocols. That study of chapter 4 showed that there was no significant difference between the mean active drag values of the ATM and the resisted methods (p = 0.171). However, on an individual basis, the methods yielded large differences in active drag for some swimmers. Further, it was explained that a number of different factors could have led to this difference: unequal power output assumptions, uncertainty in the calculation of belt force, tow speed and swim speed, and the assumption of the square relationship between drag and swim speed.

All measurements of scientific quantities are subject to some error in their measurement. Error in a calculation means that the calculated value differs from the true value. This error contributes to the uncertainty of the result (Taylor, 1982). Therefore, uncertainty is the quantification of the doubt about the measurement result. Uncertainty calculation gives researchers an idea of the precision and accuracy of their measurement (Bevington & Robinson, 1992). Hence, it is necessary to estimate the extent of inaccuracy and how much that would affect the measurement. Also, more uncertainty in a test can exist if the measurement is repeated several times, as different values would be obtained. If the mean of values is calculated, the uncertainty of each trial can affect the amount of uncertainty in the mean value (Bevington & Robinson, 1992) Active drag force using the ATM method is calculated from a function of three different variables and two assumptions. These variables are belt force, tow speed and free swim speed and the assumptions are power output and, the exponent of drag force as a function of free swim speed and tow speed (v^x). Hence, it is important to know how much confidence we can place in any decision based on those variables used. The purpose of this study, therefore, is to quantify how much uncertainty in the active drag value may be produced by each component variable using the ATM method with the fluctuating speed.

5.3 Methods

5.3.1 Participants

Twelve elite swimmers (five males and seven females, age (mean ± standard deviation), 17.7 ± 2.9 years), who had participated in swimming competitions regularly in the 12 months prior to commencing the study volunteered to participate. Participants were international representatives (n=6) and state competitors (n=6) and had a best personal time for 100 m freestyle that was fast enough to earn at least 600 FINA points (Federation Internationale de Natation, 2013). Only one of the participants had participated in previous experiments with the passive and active drag towing system and none were familiar with the test conditions. Both the Human Research Ethics Committee of the Australian Institute of Sport (AIS) and the Human Review Ethics Committee of the University of Sydney approved the study. All participants were informed about the purpose and nature of study and provided written informed consent.

5.3.2 Free swimming trials

Testing sessions were performed on two separate days and swimmers were instructed about testing protocols on Day 1. The whole tests were repeated on Day 2. Before starting the testing session, a 20-minute warm up as a normal race strategy was conducted. Swimmers performed at least one practice trial for each condition to become familiar with the nature of the experiment. The participants' maximum speed was examined during the practice trial to be sure that they were able to achieve their maximum speed in first 15 m distance (before starting data collection). Then swimmers were asked to perform four free swimming trials and were required to hold their breath for 25 m. Swimmers were given five minutes rest between each trial to minimise the influence of fatigue on their performance. The trial started from the 30 m mark out from the wall and swimmers were required to swim with their maximum effort. The mean swim speed was averaged from the 15 m to the 5 m marks. The participants were required to approach their maximum speed in first 15 m and maintained that throughout data collection. The mean speed of four trials was calculated to determine each participant's mean maximum swim speed.

5.3.3 Material and apparatus for completing free swimming trials

A series of PAL cameras (Samsung model SCC-C43101P, Korea) was used to record the free swimming trials. The analogue video cameras recorded images at 50 Hz and were located along the interior surface of the pool building wall at the 5 m, 7.5 m, 10 m, 15 m, 20 m and 25 m marks, directly perpendicular to and approximately 3 m above the surface of the pool. Swim tracking software was developed by the Aquatic Training Testing Research Unit at the AIS, using analogue video cameras to control the display of the video field for calculating the mean swim speed (Tor, Peace, Knight, & Ball, 2015). Images displayed both the image from the camera as well as the time in seconds. The time intervals were recorded as the centre of the swimmer's head passed through specific points (Tor et al., 2015).

5.3.4 Active towing trials

Swimmers performed five active towing trials with their maximum effort over a 25 m interval while being towed. Before starting active drag trials, swimmers performed practice trials to become familiar with the nature of the experiment. The swimmer swam from the 30 m mark out and data recording of these signals commenced at the trial's beginning. Mean tow speed and mean drag force were calculated from the right hand entry after the 20 m mark and finished when the four full strokes were completed.

The swimmers were towed between 5% and 8% faster than their mean maximum speed while swimming. In order to achieve this range, a force and a tow speed on the dynamometer were required to be set for the towing. To choose the force for each swimmer, we measured the passive drag of each swimmer and it was used as an indicator. Three-quarters to half of the mean passive drag value of each swimmer was initially used and set up on the dynamometer. Also, the tow speed was chosen to be 120% faster than the swimmer's mean maximum speed of free swimming. Increasing speed by less than 5% resulted in the cable becoming slack, with consequent errors in measuring swim speed. On the other hand, increasing by more than 8% would be more likely to change the normal stroke mechanics of the swimmer (stroke length and stroke rate) (Mason et al., 2013). Prior to experimental testing, an initial trial was conducted with these settings and if the mean tow speed was not in the range of 5% to 8% greater than the mean maximum swim speed, then the dynamometer force was adjusted.

5.3.5 Materials and apparatus for completing active towing trials

Towing was conducted using a flux vector dynamometer (a controller motor, Emerson Industrial Automation, Sydney, Australia), which measured the instantaneous speed of the swimmer during each trial. The dynamometer was mounted directly on a calibrated Kistler™ force platform (Type: Z20916, Kistler Instruments, Winterthur, Switzerland). The Kistler™ force platform measured the instantaneous forces generated by the swimmer's body during towing. The Eyeline belt was attached anterior to the waist and the dynamometer recorded the speed profile of the swimmer during towing. A high-tensile strength cable (Spectra Blue cable, Diameter: 3mm, Canberra, Australia) was linked from one end to the belt, which was attached to the swimmers. The other end of the cable was attached to the dynamometer. The cable was passed through a pulley located 0.7 m below the surface of the water for the assisted trials.

5.3.6 Data processing

Data was sampled with a 12 bit analogue to digital card at 500 Hz. Then both outcomes of the tow force and the tow speed were smoothed with an 8 Hz low pass Butterworth filter. Outcomes of tow speed and belt force were smoothed with an 8 Hz low pass Butterworth filter. A Residual Analysis was used to confirm this choice of cut-off frequency (Winter, 2005). Active drag was estimated from the equation (2).

5.3.7 Propagation of uncertainty calculation

To obtain accuracy of active drag value from the assisted towing method, it was considered that unequal power output could exist between the two conditions, therefore giving:

$$P_1 = P_2 + \Delta P \quad (3)$$

where P_1 is the power output of free swimming, P_2 is the power output of tow swimming and ΔP is the different power output of those two conditions:

$$F_{P1}.v_1 = F_{P2}.v_2 + \Delta P \quad (4)$$

Finally, equation (2) was modified to include the different power variable (ΔP) from equation (4). Also, the exponent 2 was replaced by a variable x in equation (2) as an exponent of speed:

$$F_A = \frac{(\Delta_P - F_B\, v_2)v_1^x}{v_1^{x+1} - v_2^{x+1}} \quad (5)$$

Taylor (1982, p.65) explains that, to calculate the uncertainty of one variable, it is necessary to calculate the derivative of that function with respect to the variable and then to multiply by the uncertainty of that variable. Therefore, first, the derivatives of the active drag equation (4) with respect to each variable were derived by using Mathematica software 9.0 (Wolfram Research):

$$dF_A/d\,v1 = \frac{-(\Delta P - FBv2)(v1^4 + 2v1v2^3)}{(v1^3 - v2^3)^2} \quad (6)$$

$$dF_A/d\,v2 = \frac{-v1^2\left(-3\Delta P v2^2 + FB\left(v1^3 + 2v2^3\right)\right)}{(v1^3 - v2^3)^2} \quad (7)$$

$$dF_A/d\,FB = \frac{v1^2 v2}{-v1^3 + v2^3} \quad (8)$$

$$dF_A/d\,\Delta P = \frac{v1^2}{v1^3 - v2^3} \quad (9)$$

$$dF_A/dx = \frac{v_1^x v_2^{1+x}(F_B v_2)(log[v_1] - log[v_2])}{\left(v_1^{1+x} - v_2^{1+x}\right)^2} \quad (10)$$

Second, each derivative (6) to (10) was multiplied by the uncertainty of each variable respectively:

$$\delta_{V1} = \left|dF_A/d\,v1\right| * \delta_{\overline{v_1}} \quad (11)$$

$$\delta_{V2} = \left|dF_A/d\,v2\right| * \delta_{\overline{v_2}} \quad (12)$$

$$\delta_{F_B} = \left|dF_A/d\,FB\right| * \delta_{\overline{FB}} \quad (13)$$

$$\delta_{\Delta P} = \left|dF_A/d\,\Delta P\right| * \delta_{\overline{\Delta p}} \quad (14)$$

$$\delta_x = \left|dF_A/dx\right| * \delta_{\overline{x}} \quad (15)$$

where δ_{v1} is the contribution of uncertainty of mean free swim speed in active drag value, $\delta_{\overline{v}_1}$ is the uncertainty of free swim speed, δ_{v2} is the contribution of uncertainty of towing speed in active drag value, $\delta_{\overline{v}_2}$ is the uncertainty of the tow speed, δ_{FB} is the contribution of uncertainty of belt force in active drag value, $\delta_{\overline{FB}}$ is the uncertainty of belt force, $\delta_{\Delta P}$ is the contribution of uncertainty of differences between the power outputs of free swimming and tow swimming in active drag value, $\delta_{\overline{\Delta P}}$ is the uncertainty of the ΔP, δ_x is the contribution of uncertainty of the exponent of speed in active drag value, and $\delta_{\overline{x}}$ is the uncertainty of the V^x.

To calculate the uncertainty of the measured variables, the standard error of the mean (Taylor, 1982) was used. Taylor (1982, p. 102) explains that if a variable is measured N times, then the best value of that variable is the mean of N measurements and random component of uncertainty is calculated by the standard deviation of that mean divided by the square root of the number of measurements:

$$\delta_{(\overline{z})} = SD_{\bar{z}}/\sqrt{N} \qquad (16)$$

where $\delta_{(\overline{z})}$ is the uncertainty of the mean, $SD_{\bar{z}}$ is the standard deviation of the measured values, and N is the number of measurements. The mean value and standard deviation (mean ± SD) of free swim speed were calculated from four free swimming trials, while the belt force and tow speed were calculated from five active drag trials.

To estimate the uncertainty of ΔP, it was assumed that there could be a potential change in power of 7.5% between both free swimming and towing conditions (Toussaint et al., 2004). Therefore, to calculate the uncertainty of ΔP, 7.5% change in power was multiplied by the mean power of free swimming.

$$\delta_{\overline{\Delta p}} = 7.5\% * P_{F_A} \qquad (17)$$

where $\delta_{\Delta p}$ is the uncertainty of delta power and P_{FA} is the mean active drag multiplied by the mean free swim speed.

An exponential range of 1.8 to 2.6 was used to be consistent with the study of Toussaint et al. (2004). To calculate the uncertainty of the speed exponent, it was considered that the uncertainty is half of the range (± 0.4).

To calculate the total contribution of uncertainty of all variables into the active drag value, the formula of Taylor (1982, p.75) was used**;** If x,…,z are measured with independent and random uncertainties δx,…,δz and are used to compute q(x,…,z) then the uncertainty in q. In this case, the total random uncertainty was calculated from the random uncertainty of independent variables according to the following formula:

$$\delta_F = \sqrt{\left(\frac{dF}{dv_1}\,\delta v_1\right)^2 + \left(\frac{dF}{dv_2}\,\delta v_2\right)^2 + \left(\frac{dF}{dF_B}\,\delta F_B\right)^2 + \left(\frac{dF}{d\Delta P}\,\delta \Delta P\right)^2 + \left(\frac{dF}{dx}\,\delta x\right)^2} \quad (18)$$

where δ_F is the total contribution of all uncertainties in the calculation of active drag.

5.4 Results

The mean active drag values of Day 1 and Day 2 were 112.9 ± 34.5 N and 102.2 ± 36.6 N respectively. Table 5.1 shows the mean value of measured variables (free swim speed and towing speed, belt force) and also the mean active drag for each participant.

Table 5.1 – Summary of the individual means value of measured variables for Day 1 and 2

Participant	Mean max speed ± SD (m/s)	Mean max tow speed ± SD (m/s)	Mean belt force ± SD (N)	Mean active drag (N)
Day One				
1	1.58 ± 0.02	1.71 ± 0.01	21.09 ± 3.1	89.0
2	1.61 ± 0.02	1.71 ± 0.01	16.82 ± 0.3	94.8
3	1.66 ± 0.01	1.79 ± 0.01	17.24 ± 0.7	69.2
4	1.60 ± 0.03	1.74 ± 0.01	22.68 ± 2.9	84.2
5	1.57 ± 0.01	1.66 ± 0.01	18.78 ± 1.2	109.3
6	1.53 ± 0.01	1.62 ± 0.01	13.31 ± 0.8	75.2
7	1.62 ± 0.01	1.70 ± 0.00	21.90 ± 1.4	133.9
8	1.87 ± 0.01	2.03 ± 0.02	26.29 ± 0.9	103.4
9	1.93 ± 0.02	2.07 ± 0.02	32.22 ± 1.6	155.5
10	1.78 ± 0.01	1.92 ± 0.02	31.68 ± 0.6	140.5
11	1.87 ± 0.02	2.01 ± 0.03	31.41 ± 2.6	137.4
12	1.88 ± 0.01	2.01 ± 0.01	35.10 ± 1.6	164.8
Day Two				
1	1.57 ± 0.01	1.65 ± 0.01	11.12 ± 0.3	67.6
2	1.63 ± 0.01	1.70 ± 0.02	10.37 ± 1.9	79.8
3	1.65 ± 0.02	1.76 ± 0.01	13.40 ± 0.8	68.0
4	1.58 ± 0.02	1.70 ± 0.02	14.39 ± 0.9	64.0
5	1.57 ± 0.01	1.68 ± 0.00	19.42 ± 0.5	92.3
6	1.57 ± 0.01	1.68 ± 0.01	13.50 ± 0.8	63.6
7	1.61 ± 0.02	1.70 ± 0.01	24.33 ± 2.5	135.0
8	1.88 ± 0.01	1.99 ± 0.01	19.35 ± 1.0	117.0
9	1.92 ± 0.01	2.09 ± 0.02	37.74 ± 3.3	145.7
10	1.80 ± 0.01	1.95 ± 0.03	30.52 ± 3.3	110.4
11	1.88 ± 0.02	1.99 ± 0.01	28.68 ± 0.4	161.2
12	1.86 ± 0.02	2.01 ± 0.02	32.72 ± 1.0	132.6

Table 5.2 shows the mean value of each variable, the uncertainty, and the contribution of each variable into active drag value separately for Day 1 and Day 2. The results indicated that some uncertainties were involved in all variables (Table 5.2). The results of the contribution of ΔP uncertainty into active drag value showed that there was considerably greater contribution than by the other variables, if it is assumed that there was a potential change in

power of 7.5% between conditions (Table 5.2). Also, the results showed that the belt force had the lowest contribution into active drag when compared with the contributions of free swim speed and towing speed into active drag values.

Table 5.2 – The uncertainties calculation of active drag variables and the contribution of each variable into active drag value

Variable	**Mean ± SD**		**Uncertainty ± SD**		**Contribution to active drag uncertainty ± SD (N)**	
	Day 1	**Day 2**	**Day 1**	**Day 2**	**Day 1**	**Day 2**
v_1 (m/s)	1.73 ± 0.15	1.73 ± 0.15	0.0065 ± 0.003	0.0065 ± 0.003	6.2 ± 2.8	5.8 ± 3.6
v_2 (m/s)	1.85 ± 0.17	1.85 ± 0.17	0.0068 ± 0.004	0.0065 ± 0.003	6.2 ± 4.2	5.1 ± 2.4
BF (N)	25.0 ± 7.4	22.07 ± 9.5	0.72 ± 0.42	0.54 ± 0.5	2.8 ± 1.7	1.8 ± 0.8
ΔP (W)	0	0	14.9 ± 5.6	13.6 ± 5.9	36.2 ± 12	34.3 ± 14
x	2.2	2.2	0.29	0.29	7.2 ± 2.1	6.6 ± 2.3
Total					38 ± 13.4	35.8 ± 14.9

Note 1: v_1 = Free swim speed; v_2 = Towing speed; BF = Belt force; ΔP = Difference between power outputs of free swimming and tow swimming; x= Exponent of speed.

Note 2: Mean and standard deviation of X value are assumed with uncertainties estimated from the study of Toussaint et al. (2004).

Note 3: The mean and uncertainty values for v_1 and v_2 were measured in m/s and the mean and uncertainty values for BF and active drag were measured in Newtons.

5.5 Discussion

The purpose of this study was to investigate how much uncertainty in the active drag value may have been produced by each component variable when estimating active drag using the ATM with fluctuating speed tow. To investigate the uncertainty, the following independent variables were considered: free swim speed, towing speed, belt force, and equal power output between both conditions and drag changes as a function of the exponent of speed. All variables showed they had uncertainty in their measures (Table 5.2). Therefore, those uncertainties affect the active drag value (Table 5.2). The contribution of the uncertainty of power output into the active drag value was greater than that of the other variables.

A previous study (Toussaint et al., 2004) found that the mean active drag value calculated from the MAD system was significantly greater than from the VPM method. However, that study could not find any pattern by looking at the individual's active drag results. Some swimmers had a greater active drag value for the MAD system than the VPM method, but some swimmers had the opposite result, while others had similar active drag results. Similar observations in chapter 4 of this thesis were obtained when the ATM method was compared with a resisted method. The findings of a previous study (Toussaint et al., 2004) and chapter 4 of this thesis were explained by the violation of the equal power output assumption. The result of the uncertainty of ΔP in the present study is a way to explain how much uncertainty is created by an unequal power between conditions in previous findings (Toussaint et al., 2004).

The result of the present study suggests that if the swimmer cannot deliver the same power output under the two conditions, this inequality has an effect on the calculated active drag value. The finding of the present study can be supported by the finding of previous studies (Williams, Sinclair, & Galloway, 2006; Sacilotto, 2014) that compared the relationship between stroke length and stroke rate during assisted swimming with those measured during normal swimming. The results of the assisted tow swimming of and Sacilotto (2014) and Williams et al. (2006) showed that there were significant increases in stroke rate and stroke length when compared to those of free swimming. Williams et al. (2006) concluded that the increases in stroke length were likely to be related to the hand slipping through the water, rather than to the hand shortening or lengthening the stroke-cycle. Sacilotto (2014) suggested the swimmers may have let the ATM method pull them along rather than doing free swimming. As the swimmers increased the stroke rate during towing (ATM method), it is likely that they attempted to produce the same propulsive force as they produced during the free swimming. Therefore, they must have increased their backward hand/arm speeds (relative to their body) to compensate for the faster body speed through the water. Hence, it is likely that the swimmers produced different power outputs under between conditions and this inequality would affect the calculation of active drag.

5.5.1 Uncertainty analysis of the violation of the equal power output assumption

The result of the current study showed that if there is a 7.5% difference between the power outputs of free swimming and tow swimming, there should have been 32 N and 33 N errors in active drag for Day 1 and Day 2 respectively. There was similarity between the current study's result and that of a previous study (Toussaint et al., 2004) reporting that a 15% difference between power outputs leads to a 30% error in drag value. Therefore, if the swimmer does not have the capability of delivering a constant power output, then the calculation of active drag will not be accurate. The accuracy of this calculation depends on the ability of swimmers to maintain their level of motivation.

5.5.2 Uncertainty analysis of the measured variables: free speed, tow speed and belt force

The result of the present study showed that the measured variables had the lower amount of uncertainties in their measurements. Also, the contributions of these uncertainties into the active drag value were about 6–7 % for both the free swim and the towing speeds and about 2–3 % for the belt force. The contributions of the measured speeds were significantly less than the contribution of different power outputs under two conditions.

5.5.3 Uncertainty analysis of the exponent of speed assumption

To calculate the uncertainty of the swim speed exponent, the exponential range of 1.8 to 2.6 was considered. Table 5.2 shows that within this range, the contribution of the V^X into the values of active drag for Day 1 and Day 2 were 7.2 ± 2.1 N and 6.6 ± 2.3 N, respectively. Toussaint et al. (2004) reported that the active drag values calculated from the MAD system and the VPM had about 10% difference when the exponent of swim speed was equal 2. However, Toussaint et al. (2004) reported that active drag values for both the MAD system and the VPM method were the same, when the exponent of the swim speed was equal 2.34. The results of the present study showed that an exponent of swim speed in the range of 1.8 to 2.6 leads to 5% error in active drag, which is less than the previous studies (Toussaint et al., 2004). The difference between the results of this study and the previous study could be due to different models having been used for the calculation. The present study considered that the uncertainty of the swim speed exponent is half of the range of 1.8 to 2.6, while the previous study used a simulated model to calculate the relative difference in drag value between the MAD system and the VPM method; this relative difference was dependent on the value of the exponent of the power.

5.6 Conclusion

The findings of this study show that there are some errors in the measurement of active drag using the ATM method. The measured variables (swim speed, tow speed and belt force) had the smallest amount of uncertainties. The contributions of those uncertainties into active drag values were approximately 6–7% error for the free and tow swim velocities and 2–3 % error for the belt force, while, if a power were to change 7.5% between conditions, it would lead to about 30% error in calculated drag. This issue can be solved if a swimmer produces the same power output under the conditions of free swim and assisted towing. Another finding of this study was that the uncertainty in a range exponent of 1.8 to 2.6 would lead to about 5% error in active drag value. Despite some uncertainties in the active drag measurement using the ATM method, future work needs to concentrate on how the researchers can make the power output between conditions more consistent. The uncertainty estimates used in this chapter are only for the random uncertainties in the measurements.

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CHAPTER 6

Comparisons between intra-cyclic speed fluctuations and the stroke parameters of free, assisted and resisted front crawl swimming

Statement from co-authors confirming the authorship contribution of the PhD candidate "As co-authors of the paper '**Comparisons between intra-cyclic speed fluctuations and the stroke mechanics of free, assisted and resisted front crawl swimming**', we confirm that Pendar Hazrati has made the following contributions:

- Conception and design of the research question
- Data collection
- Analysis and interpretation of findings
- Writing the paper and critical appraisal of its content
- Corresponding author for communication with journals

Signature:………… …………… Date:.......... 29/03/16...............

Peter J Sinclair

Signature:………… .. …… Date:.... 29 Mar 16 ..

Bruce R Mason

Signature:…… ………… Date:............ 29/03/16.............

Rene E Ferdinands

Signature:………… … …… Date:............ 29/03/16............

Wayne Spratford

6.1 Abstract

The Assisted Towing Method has been used to provide the active drag time profile of swimmers at the Australian Institute of Sport. This profile is based upon the instantaneous value of three variables: free swimming speed, towing speed and belt force. The free swim speed profile is assumed to be similar to the towing speed profile. This study investigated whether speed profiles of towed swimming are identical to free swim speed profiles. Within-stroke ranges of maximum–minimum speeds, stroke rate and length, as well as the duration of stroke phases, was evaluated comparing these three swim speed profiles. Eight male elite swimmers performed two free swims using a speed transducer and two assisted and two resisted swims using a dynamometer. The difference between maximum and minimum speeds was approximately 36%, 25.3% and 12.7% for the free, assisted and resisted swimming respectively. The swimmers' stroke rates did not change with swimming conditions. However, stroke length increased and decreased during assisted and resisted swimming respectively. Results of within-stroke phases revealed that assisted and resisted towing resulted in entry/catch and push phases significantly different to the free-swim condition. It can be concluded that the assisted and resisted swims' speed profiles were dissimilar to the free swimming's speed profile.

Keywords: Intra-stroke speed fluctuations, free swimming, assisted, resisted, front crawl

6.2 Introduction

Competitive swimming performances depend upon anthropometric features (Grimston and Hay, 1986), swim speed (Arellano, Brown, Cappaert, & Nelson, 1994), arm coordination (Chollet, Chalies, & Chatard, 2000), propulsive forces (Schleihauf, Gray, & De Rose, 1983) and passive and active drag (Kolmogorov and Duplishcheva, 1992). The swimmer propels the body by pushing against the water to overcome the negative force of drag. Therefore, if the swimmer encounters less active drag, less energy will be required to overcome this negative force. Also, the ability of a swimmer to reduce active drag will allow propulsive forces to be applied efficiently; therefore, the swimmer will produce a faster swim speed. For this reason, it is important that both swimmers and coaches understand how active drag changes during the swimming stroke.

Previous studies have determined that active drag has a relationship with swim speed, and that it changes with increasing and decreasing speed irrespective of the swimmer's level of skill (Mason, Formosa, & Toussaint, 2010; Toussaint et al., 1988). Research has emphasised the relationship that exists between swim speed, stroke mechanics, arm coordination, and the amplitude of speed fluctuation (maximum and minimum instantaneous speed during a stroke cycle) (Chollet et al., 2000; Seifert, Chollet, & Bardy, 2004b).

Several methods have been developed to measure active drag. One of these, the Assisted Towing Method (ATM), has been used as a feedback tool for coaches to identify strengths and weaknesses within a swimmer's stroke cycle. It provided video synchronised active drag time profiles of a swimmer's performance (Mason, Sacilotto, & Menzies, 2011). This profile was calculated from the instantaneous values of three variables: free swim speed, tow speed and tow force. The ATM method was based on the assumption that a free swim speed profile approximates that of a towing speed that is consistently reduced by 5–8%. However, no study has examined the relationship between the free swim speed and the towing speed to assess whether a similarity exists as proposed by the previous study (Mason et al., 2011).

Researchers have investigated the effect of resisted and assisted swimming on two stroke parameters (stroke rate and stroke length) and compared the results of the stroke rate and stroke length of the two types of training with the stroke rate and stroke length of free swimming to determine how specific training interventions influenced the swimmer's performance (Maglischo, Magischo, Zier, & Santos, 1985; Sacilotto, 2014; Williams, Sinclair, & Galloway, 2006). Results have indicated that there were significant decreases in the stroke rate (SR) and stroke length (SL) of resisted swimming (Maglischo et al., 1985; Williams et al., 2006). In comparison, there were significant increases in the SR and the SL of assisted swimming (Sacilotto, 2014; Williams et al., 2006). Both stroke rate and stroke length need to be controlled because these two parameters change arm coordination (Chollet et al., 2000). Seifert et al. (2004b) stated that the changes in arm coordination can be identified by the ratio of the stroke rate to stroke length.

Due to these changes in the stroke mechanics, several studies have investigated stroke phases (entry and catch phase, pull phase, push phase and recovery phase) and how the duration of those phases changed when speed increased (Chollet et al., 2000; Seifert et al., 2004a, 2004b). Results showed that as swim speed increased, the time of entry/catch and the recovery phases decreased, while the time of propulsive phases increased. These changes caused a lag of time or an overlap time between the propulsive phases of the two arms (Chollet et al., 2000).

Based upon the previous findings (Chollet et al., 2000; Maglischo et al., 1985; Seifert et al., 2004a, 2004b; Williams et al., 2006), it can be said that changes in the swim speed affect the stroke mechanics and the stroke phases. Therefore, the free swim speed profile and the towing speed profile may differ slightly from each other. Hence, it is necessary to examine the similarity between these three speed profiles before sport scientists can provide feedback to coaches when using the ATM method. Therefore, the aims of this study were to investigate whether the towing speed profiles of the assisted and resisted methods are similar to the free swim speed profile by comparing the following three aspects: the range of variation of speed in intra-stroke, the SR and the SL, and the stroke phases. A null hypothesis of the study was that there would not be a significant statistical difference between the free swim speed profile and the towing speed profiles of the assisted and resisted methods.

6.3 Methods

6.3.1 Participants

The participants were eight male elite swimmers (mean ± standard deviation: age = 22.8 ± 2.1 years) who had participated voluntarily in this study. The participants had a best personal time for 100 m freestyle that was in a range of 690 ± 35 points of Federation Internationale de Natation (FINA, 2014). Swimmers were in healthy physical and mental condition. Both the Human Research Ethics Committee of the Australian Institute of Sport (AIS) and the Human Review Ethics Committee of the University of Sydney approved the study. All participants were informed about the purpose and nature of the study and provided written informed consent.

6.3.2 Data collection for free swimming trials

Tests were performed on one day. Before starting the testing session, a 20-minute warm up was conducted. Swimmers performed at least one practice trial for each condition to become familiar with the nature of the experiment. The swimmers were requested to swim two free swimming trials with maximum effort over 25 m and they required to start from the wall. During the 25 m distance, the swimmers were required to hold their breath. Each swimmer was given five minutes rest between each trial to reduce the influence of fatigue on their performance. Swimmers started from the wall without push off it, and the data were recorded between the 10 m and 20 m marks, with the mean swim speed being averaged from the first right arm entry after the 10 m mark until four full strokes had been completed.

6.3.3 Material and apparatus for measuring free swimming speed

Free swim speed was measured based upon the instantaneous displacement of the hip. A wheel was connected to an encoder (Contactless Angle Sensor, Meggitt, Spain) to measure displacement (Figure 6.1). The wheel and the encoder were connected to a motor (110 W, 23.5 V dc, RS Brushed DC Motor, Northants, UK). This motor was required to generate a small amount of force. This force maintained a tension on a non-stretch cable (polyethylene, Berkley Fireline Company, USA) and prevented oscillations in the cable. This cable was connected to a belt (Eyeline, Australia) and this belt was worn around the swimmer's waist. The cable passed through the pulley located 2.1 m above the surface of the water and was wound up on the wheel. The angle between the line of swimming (the surface of the water) and the cable was considered in the measurement of speed. To measure the angle, the cosine rule was used to calculate the horizontal distance of the swimmer, as the distance travelled cable was calculated from the encoder, and the height of pulley (2.1 m above the water) was known. Then the horizontal distance was calculated that had been travelled by the swimmer. Finally, the horizontal distance was divided by the time. These calculations were conducted in a computer program designed by the researcher and her AIS supervisor.

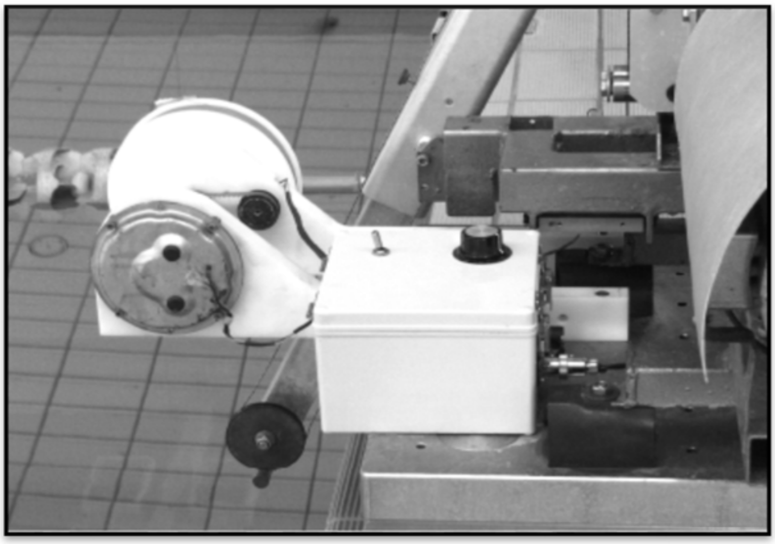

Figure 6.1 – The velocity transducer device set up for operation.

6.3.4 Data collection for assisted swimming trials

The ATM method (Figure 6.2) was used for performing assisted swimming trials. Swimmers were towed using a dynamometer at approximately 5%–8% greater speed than each participant's mean maximum speed, which had been obtained from the free swim trials. Increasing speed by less than 5% resulted in the cable becoming slack, with consequent errors in measuring swim speed. On the other hand, increasing by more than 8% could change the normal stroke mechanics of the swimmer (Mason et al., 2013). Swimmers performed two assisted swimming trials over a 25 m interval and the swimmers were required to swim with their maximum effort. Four complete stroke cycles were captured. Data collection was started 20 m out from the wall for the assisted trials and finished when four full strokes had been completed.

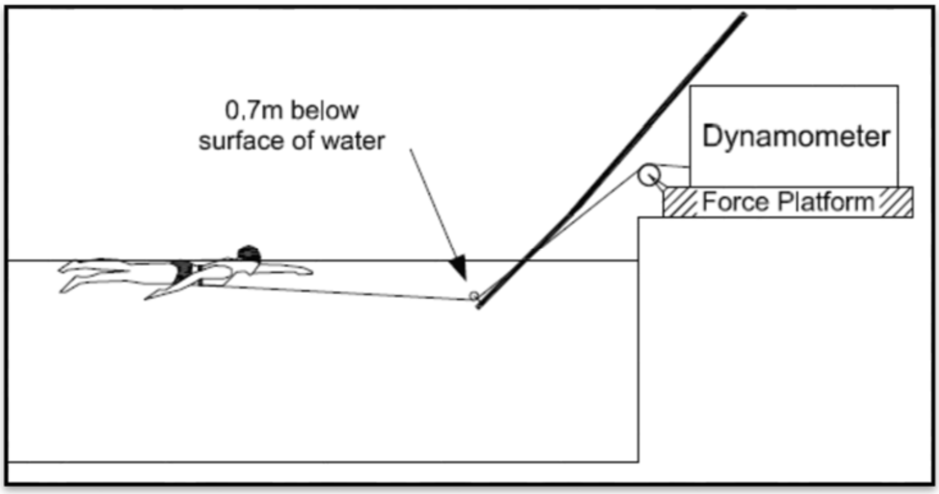

Figure 6.2 – Illustration of the swimmer's direction and the location of the cable (0.7 m below the surface of the water) during assisted swimming trials

6.3.5 Data collection for resisted swimming trials

The resisted method (Figure 6.3) was used to perform resisted swimming trials. Swimmers swam against a resistance force applied by the dynamometer in the opposite direction to their movement. This resistance force decelerated their forward movement approximately 5%–8%

less than each participant's mean maximum speed which had been obtained from the free swimming trials. Swimmers performed two resisted swimming trials over a 25 m interval and the swimmers were required to swim with their maximum effort. The swimmers started from the wall and data capturing was started with the right arm entry at the 10 m mark and finished when four full strokes had been completed.

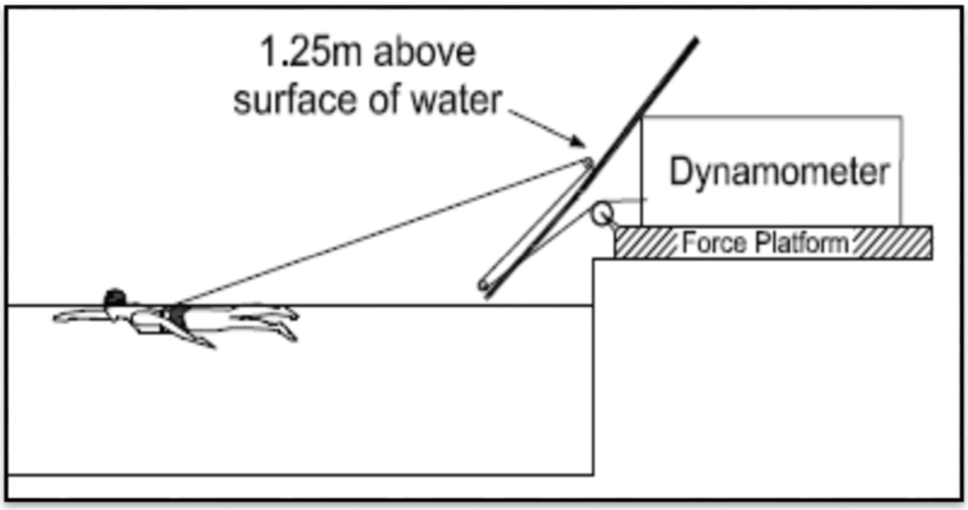

Figure 6.3 – Illustration of the swimmer's direction and the location of the cable (1.25 m above the surface of the water) during resisted swimming trials

6.3.6 Materials and apparatus for measuring assisted and resisted towing speeds

The assisted and resisted swim speed was measured using a dynamometer (a controller motor, Emerson Industrial Automation, Sydney, Australia) (Figure 6.4). It was mounted directly on a calibrated Kistler™ force platform (Type: Z20916, Kistler Instruments, Winterthur, Switzerland). The measurement was based upon the wheel angular speed of the dynamometer.

The Eyeline belt was attached to the waist of each swimmer. This belt was attached to a high-tensile strength cable (Spectra Blue cable, Diameter: 3mm, Canberra, Australia) and this cable was wound up on the wheel of the dynamometer. This cable was passed through a pulley located 0.7 m below the surface of the water for the assisted trials (Figure 6.2). The range of angle between the surface of the water and the cable throughout the data collection was between 2° and 4°. During the resisted swimming, the cable was passed through a pulley located 1.25 m above the surface of the water (Figure 6.3). The range of angle between the surface of the water and the cable throughout the data collection was between 7° and 3.6°. The cable angles of both the assisted and the resisted swimming were ignored in the measurement of speed. This was because the horizontal force was used to measure the cable force in the measurement of active drag and the vertical force did not need to be measured. Therefore, the horizontal speed was used.

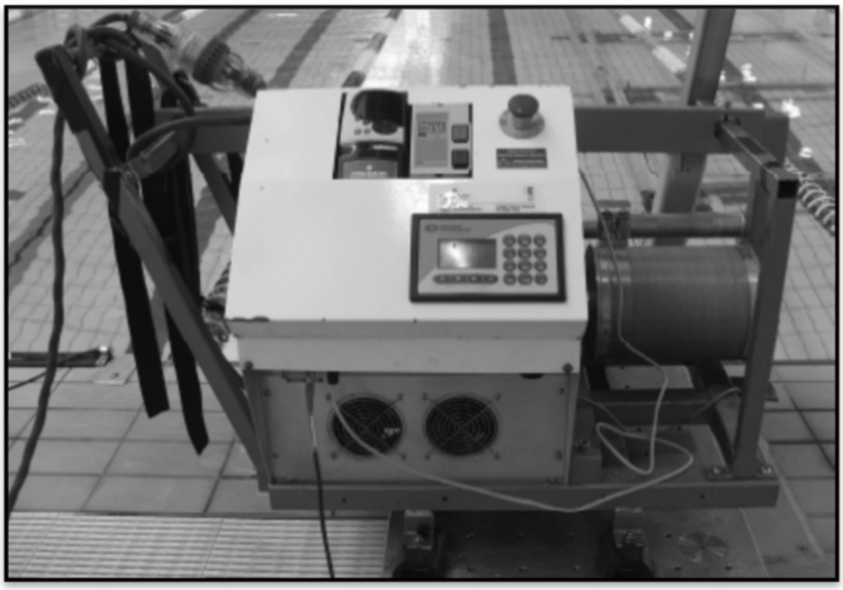

Figure 6.4 – Illustration of the motorised towing device that measured the instantaneous speed of the swimmers during the assisted and the resisted swimming

6.3.7 Data processing and video system

Speed data were collected for each condition and were recorded in motion analysis software (Contemplas GmbH Templo Motion Analysis, version 6.2.274, Germany). These data were processed using an export/import function in a Contemplas player linked to an AIS customised analysis program. Data was sampled with a 12 bit analogue to a digital card at

500 Hz. Then both outcomes of the free swim speed and the tow speed were smoothed with an 8 Hz low pass Butterworth filter. A Residual Analysis (Winter, 2005) was used to confirm this choice of cut-off frequency.

Two genlocked cameras were used to capture swimming trials at 50 Hz and both of them were mounted on a moveable trolley, which was located on the side of the pool. One of the cameras was placed in the water below the trolley (Swim Pro analogue camera) and the other one above water level (Model 301 underwater video analogue camera, Applied Micro, USA) and both cameras were under and above water in the sagittal plane. The sagittal plane camera images were mixed with a video mixer (EDI-8V) and a video recording was conducted on a moveable trolley. A digital time-code was applied to both camera inputs to visualise the time spent for each phase. A trigger was also used to synchronise the images with the speed data for identifying different phases of a stroke.

6.3.8 Data analysis

6.3.8.1 Range of maximum to minimum speed

Maximum speed (V_{max}) and minimum speed (V_{min}) (m/s) were obtained from the speed profile of all three swimming conditions (free swimming trials, and assisted and resisted swimming trials). The calculation of the difference between the maximum and the minimum speeds normalised for the mean stroke cycle speed was used to determine the range of speeds within stroke ($([V_{max} - V_{min}])/V_{mean}$) (Psycharakis, Naemi, Connaboy, McCabe, & Sanders, 2010). All eight single-stroke cycles were used for calculating the mean range of speeds. The range of speeds was presented as a percentage of the mean speed.

6.3.8.2 Stroke rate and stroke length

The two cameras located on the side, together with the time-code, enabled the quantification of SR and SL. The SR was obtained from the following equation (60s / [time of four full strokes/four]). The SL was obtained: (speed (m/s) × SR) / 60s (Seifert et al., 2004b).

6.3.8.3 Stroke phases

Each right arm stroke as recorded on the video camera was broken down into four phases (Chollet et al., 2000):

- Phase 1: Entry and catch. The time from the hand's entry into the water to the beginning of its backward movement
- Phase 2: Pull. The time from the beginning of the hand's backward movement to the hand's arrival in the plane vertical to the shoulder
- Phase 3: Push. The time from the hand's position under the shoulder to its exit from the water, and
- Phase 4: Recovery. The time from the hand's exit from the water to its following entry into the water.

To obtain the duration of each phase, one of two trials of each swimming condition which showed a constant pattern between strokes was chosen. Each right arm stroke was time normalised to 100%. The four right arm strokes were used to calculate the mean percentage time spent on each phase.

6.3.9 Statistical analysis

To test for significant differences in each variable (the percentage range of V_{max} and V_{min}, mean speed, stroke rate and stroke length), a one-way ANOVA with repeated measures was used to compare the free, the assisted and the resisted swimming condition separately for each variable. To test for significant differences in the percentage time (dependent variable) of each stroke phase (independent variable) and the three swim conditions (independent variable), it was initially required to determine if any interaction existed between the two independent variables. A two-way ANOVA with repeated measures was used to assess whether time varied between the stroke phases and conditions. Secondly, if a significant difference existed between the interactions, a one-way ANOVA with repeated measures was used to compare the mean percentage duration of each phase for the three swimming conditions. SPSS software was used to perform both the two-way and one-way ANOVA (Version 19, IBM, Chicago, IL, USA). Statistical significance was set at the 95% confidence level.

6.4 Results

6.4.1 Mean swim speed and range of maximum to minimum speed

The mean value and the standard deviation of swim speed for each swimming condition were obtained and presented in Table 6.1. There were significant differences between the swim speeds and the swimming conditions (free, assisted and resisted swimming) ($p < 0.001$). The resistive protocol slowed speed by 0.16 m/s (8.5%) compared to free swimming speed, while the assistive protocol increased speed by 0.8 m/s (4.2%).

Mean range of V_{max} and V_{min} within strokes, standard deviation and the percentage of that range for each condition are presented in Table 6.1. Significant differences were found between the percentage of V_{max} and V_{min} of the free, the assisted and the resisted swimming ($p < 0.001$). More variation in the V_{max} and V_{min} was observed in the free swimming condition than the assisted and the resisted swimming conditions (Table 6.1).

Table 6.1 – Mean and standard deviation of the mean swim speed and the range of maximum (V_{Max}) to minimum speeds (V_{Min}) and the percentage range of them for three conditions

Variable	**Swim Speed Mean ± SD (m/s)**	**Range of V_{Max} to V_{Min} within stroke Mean ± SD (m/s)**	**Percentage range V_{Max} to V_{Min} within stroke Mean ± SD**
Resisted Swimming	1.73 ± 0.09	0.21 ± 0.04	12.7 ± 1.47
Free swimming	1.89 ± 0.09	0.68 ± 0.25	35.9 ± 5.26
Assisted swimming	1.97 ± 0.09	0.50 ± 0.08	25.3 ± 4.09

Note: there were significant differences between the mean swim speed and the range of maximum to minimum speeds within stroke with a Greenhouse-Geisser correction ($p = 0.000$).

6.4.2 Stroke rate and stroke length

The mean value and standard deviation of two variables (SR and SL) for each swimming condition were obtained and presented in Table 6.2. No significant differences were found between the SR of the free swimming (52.52 ± 3.71 stroke/min), the assisted swimming (52.05 ± 2.92 stroke/min), and the resisted swimming (51.08 ± 3.68 stroke/min) ($p = 0.071$). However, there was a significant difference between the SL of the free swimming condition compared with the SL of the assisted and resisted swimming conditions ($p < 0.001$). The SL of the assisted swimming had the greatest length compared with the other two conditions.

Table 6.2 – Mean and standard deviation and significant values of stroke rate (SR) and stroke length (SL)

Variable	SR (stroke/min) Mean ± SD	SL (m/stroke) Mean ± SD
Resisted swimming	51.08 ± 3.68	1.47 ± 0.18
Free swimming	52.52 ± 3.71	*1.63 ± 0.17
Assisted swimming	52.05 ± 2.92	1.71 ± 0.15

* = significant main within-subject effect from swim condition with a Greenhouse-Geisser correction.

6.4.3 Stroke phases

The mean percentage time and standard deviation of each phase are presented in Table 6.3. The result of two-way ANOVA with repeated measures showed that the times varied significantly between phases ($p < 0.001$), and that the recovery phase had a greater percentage of time than the other phases. However, the percentage time was not found to be significantly different between swim conditions ($p = 0.618$). Also, there was a significant interaction between phase and swim condition ($p = 0.001$).

The result of one-way ANOVA with repeated measures showed that there were significant differences between the percentage times of the entry and catch phases of the free swimming and of the assisted and resisted swimming conditions ($p = 0.001$). The duration of the entry and catch phases for the assisted swimming was longer than the free and the resisted swimming respectively. Also, significant differences were found between the percentage times of the push phase for the free, the assisted and the resisted swimming ($p < 0.001$). The duration of the push phase was longer for the resisted swimming than for the other two swimming conditions. However, there were no significant differences between the percentage times of the pull phase ($p = 0.376$) and the recovery phase ($p = 0.248$) of these three conditions.

Table 6.3 – Mean and standard deviation (Mean ± SD) of the time spent on each phase, shown as a percentage of a single right hand stroke

	Entry and Catch	**Pull**	**Push**	**Recovery**
Resisted swimming	*22.99 ± 4.75	19.93 ± 2.63	*21.86 ± 1.50	35.22 ± 2.68
Free swimming	25.34 ± 5.16	19.90 ± 2.77	20.74 ± 2.28	34.02 ± 2.79
Assisted swimming	31.63 ± 6.92	18.90 ± 2.83	16.82 ± 2.72	32.65 ± 4.30

* = significant difference between free, assisted and resisted swimming with a Greenhouse-Geisser correction.

6.5 Discussion and implications

6.5.1 Mean swim speed and range of maximum to minimum speeds within stroke

The purpose of this study was to compare the intra-stroke speed fluctuation of the towing speed profiles during the assisted and the resisted swimming with the free swimming speed profile. The results of the present study indicated that the free swim trials had greater variations from V_{max} to V_{min} within stroke (36 %) than did the assisted (25 %) and resisted swimming (13 %). It may be explained that less speed variation for the assisted and the resisted trials could be related to the action of the dynamometer. The dynamometer acts in one direction only for each condition. The dynamometer automatically attempts to adjust the force output to prevent the speed of the swimmer falling outside the target speed range and to maintain it near the target speed. Figure 6.5 shows that the maximum values for free and assisted conditions were quite similar. This is because the force applied by the dynamometer in the assisted trial was increased only when the instantaneous speed of the swimmer decreased below the target speed, thus preventing a large drop in speed. Therefore, the dynamometer would not decrease the cable force if the instantaneous speed of the swimmer increases above the target speed. While in the resisted trial, the dynamometer was increased force when the speed of the swimmer increased above the target speed to prevent the swimmer from swimming too fast.

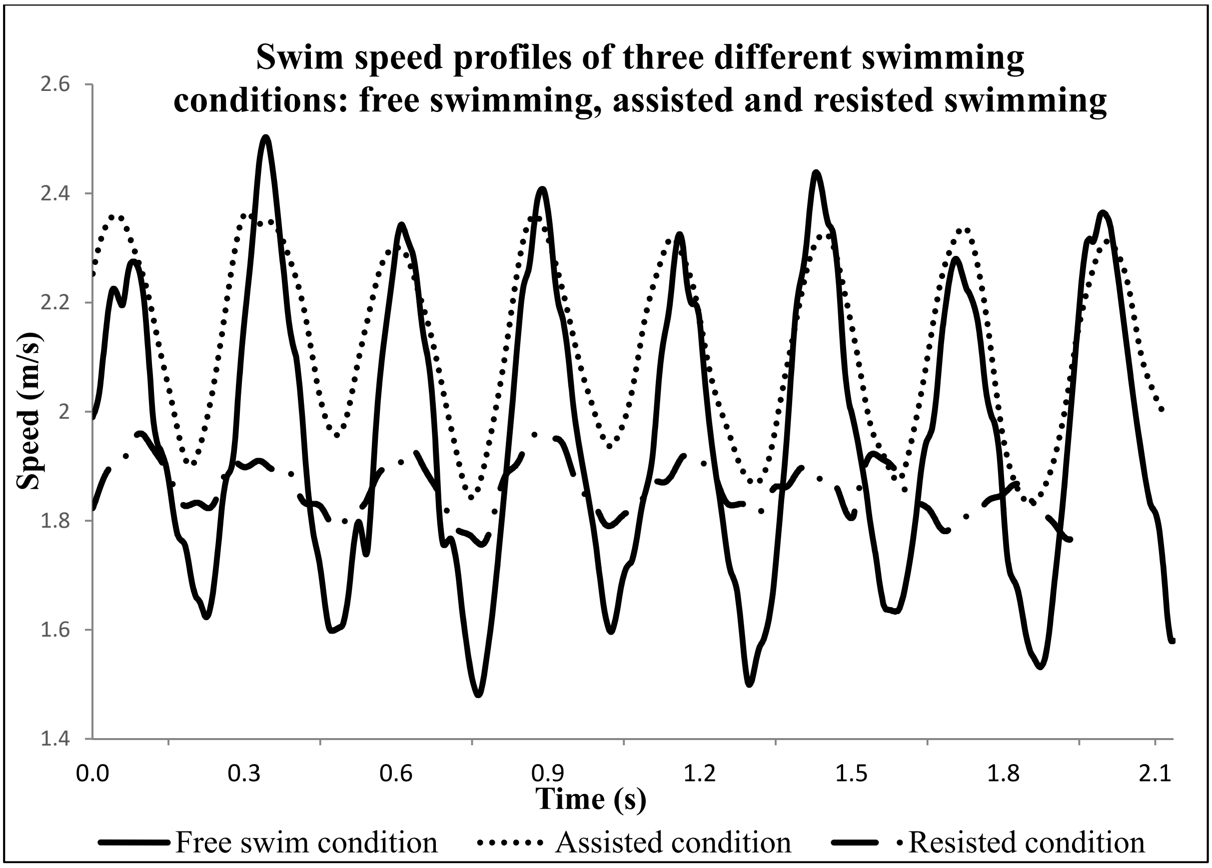

Figure 6.5 – Free swim speed, and the assisted and resisted speed profiles of one of the swimmers

The results of the present study in regard to the free swimming condition showed that the mean range of V_{max} to V_{min} within stroke was approximately 36% at the mean speed of 1.89 ± 0.09 m/s. This percentage variation was less than the other front crawl studies that used a similar device (Alberty, Sidney, Hout-Marchand, Hespel, & Pelayo, 2005; Craig and Pendergast, 1979). Alberty et al. (2005) found that the mean of this range was approximately 45% at the mean speed of 1.31 ± 0.1 m/s. This range was mirrored by Craig and Pendergast (1979) who obtained a mean speed of 1.61 m/s. It is possible that the differences observed between the results of these studies and the current study are due to the higher swim speeds and higher skill levels of the swimmers who participated in this study (1.89 ± 0.09 m/s). Another possible explanation is that the different results were due to differences in the stroke rate and the index of coordination.

In contrast, the results of the present study in the mean range for the free swimming condition (36%) were higher than in another study, which measured speed data from the displacement of the centre of the mass using the three-dimensional video (3D method) (Psycharakis et al., 2010). Those researchers found the mean of this range was approximately 22% at the mean speed of 1.42 ± 0.2 m/s. The difference between the range of speeds of the present study and that study (Psycharakis et al., 2010) is likely due to the displacement of the mass instead of the displacement of the hip. The centre of mass method would be expected to have less variation because of the mutual movement of the arms.

The result of the present study showed that the range of V_{max} to V_{min} within stroke for the resisted swimming (13%) was considerably less than in a previous study, which measured these ranges for a resisted swimming condition (85%) (Gourgoulis et al., 2013). In that study, a bowl was pulled by an elastic tube to provide a passive resistance force and the bowl was tethered to a belt around the waist of the swimmer. Three different sizes of bowl were used to make three different amounts of additional resistance (low, moderate and high). The differing results of the present study and the Gourgolis study could be due to the amount of resistance forces and the pattern of force application that were attached to the swimmer during the resisted swimming. In the present study, the resistance force was applied using the active dynamometer and the force slowed the mean maximum speed of the swimmers only up to 8.5%, while the study of Gourgoulis et al. (2013) showed that the resistance force decreased the mean speed of the swimmers between 26% and 49%. It is likely that this range of reduction in speed would not allow the swimmers to maintain their normal stroke mechanics (Kolmogorov & Duplishcheva., 1992; Mason et al., 2013).

6.5.2 Stroke rate and stroke length

The SR of the swimmers did not change with swim conditions ($p = 0.071$); this finding was not consistent with the findings of previous studies (Girold et al., 2006; Williams et al., 2006). They reported that the SR increased during the assisted swimming and the SR decreased during the resisted swimming. This can be related to the amount of decreasing or increasing of the swim speed during the towing. Williams et al. (2006) reduced the mean speed of the swimmers by 17% and increased the mean speed by 16%, compared to respective values of 8.5% and 4.2% for the present study.

The swimmers increased SL during the assisted swimming and decreased during resisted swimming in the present study. These results were consistent with previous studies (Sacilotto, 2014; Williams et al., 2006). Williams et al. (2006) reported that the range of movement of the hand during either the assisting or resisting condition did not change. Therefore, Williams et al. (2006) indicated that the changes observed in SL were probably due to the amount of slip experienced by the hand through the water and not a shortening or lengthening of the arm stroke. In the present study, the stroke rate remained the same between the free and towing conditions; therefore, it is obvious that the stroke length must have increased to increase the swim speed in the assisted towing trials. In the resisted swimming trials, on the other hand, the cable pulled the swimmer back and therefore reduced the stroke length.

6.5.3 Stroke phases

The swimmers performed the longest duration for the entry and catch phase during the assisted swimming (Table 6.2), and performed this phase in the shortest duration during the resisted swimming ($p = 0.001$). It is assumed that the swimmers stayed steady during this phase in assisted towing in an attempt to maintain their arm coordination due to being pulled faster than the mean maximum speed. The swimming conditions did not affect the duration of the recovery phase ($p = 0.248$).

The swimming conditions also did not change the time of the pull phases ($p = 0.376$); however, a significantly longer push phase for the resisted swimming was observed in comparison to the free swimming and the assisted swimming ($p < 0.001$). This finding was consistent with the finding of Gourgoulis et al. (2013), who reported that the swimmers spent a longer time during the push phase of the resisted swimming compared with the free swimming. Having more time during the push phase for the resisted swimming could be due to the amount of additional force that was applied to reduce the swimmer's speed; they then attempted to produce more propulsive force to overcome that additional force. On the other hand, less time during the assisted swimming might suggest that the swimmers did not push as hard as they did during the free swimming and let the pulley system pull them along. Therefore, the resistance against the swimmer's hand was less during the assisted swimming. These findings might suggest that the swimmers swam with different power outputs during the towed swimming. It should be noted, however, that there were no propulsive forces calculated in this study.

Some previous studies compared stroke phases over different ranges of distances and velocities (Chollet et al., 2000; Seifert et al., 2004b). They established that the swimmers reduced the duration of the entry and catch phase when they swam with higher speed over a shorter distance. The differing results of the present study and previous studies could be due to the test conditions. The swimmers in the previous studies increased their swim speed by themselves, while, in the present study, the dynamometer towed the swimmers faster than their maximum speed.

The changes in the entry and the catch phase, and in the push phase during the assisted and the resisted swimming could be due to the action of the dynamometer; this action is likely to change the coordination between the two arms. According to the arm coordination of Collet et al. (2000), the increased entry and catch phase and the decreased push phase in the assisted swimming can cause a lag time between propulsive phases of the two arms. On the other hand, the decreased entry and catch phase and the increased push phase in the resisted swimming can cause an overlap in the propulsive phase of both arms. These changes in the arm coordination could affect the instantaneous speed of the swimmer during the towing trials.

6.6 Conclusion

The findings of this study show that the swimmers had greater variations from the V_{max} to V_{min} within stroke (36%) for the free swimming compared to those of the assisted and resisted swimming conditions (25.3% and 12.7%, respectively). The longest SL was observed in the assisted swimming condition and the shortest for the resisted swimming condition, while the SR did not change between swim conditions. The assisted swimming increased the duration of the entry and catch phase (32.38%) and the resisted swimming condition also increased the duration of the push phase (20.86%).

In conclusion, the towing speed profiles did not closely resemble that of the free swimming speed profiles. The assumption of a consistent speed pattern between the free and assisted swimming of the ATM method has not been demonstrated. Therefore, further study should be undertaken to apply a constant belt force to investigate whether this consistency in the belt force can allow greater speed variations during intra-cycle.

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CHAPTER 7

Discussion and Conclusion

7.1 Introduction

The movement of swimmers through the water is retarded due to drag force created by the viscosity of the water and turbulence created by the swimmers around themselves. Three drag forces impacting negatively on a swimmer during swimming are pressure resistance (form drag), wave drag and skin friction drag (Toussaint et al., 1988b). The swimmer has to overcome this resistive force by maintaining propulsive force at the highest possible speed (Formosa, Mason, & Burkett, 2011). A considerable part of the energy expenditure in swimming is consumed in overcoming drag force (Di Prampero, Pendergast, Wilson, & Rennie, 1974). Hence, reducing drag force will enable the swimmer to expend less energy and to achieve higher total efficiency (Toussaint et al., 1988a). Researchers have attempted to measure this force using different methods (Di Prampero et al., 1974; Formosa et al., 2011; Hollander et al., 1986; Kolmogorov and Duplishcheva, 1992; Mason, Sacilotto, & Menzies, 2011). These methods have enabled coaches to learn how changes in the swimmer's technique can reduce drag; however, no consensus has been reached on their efficacy.

One of the most recent methods of estimating active drag is the Assisted Towing Method (ATM) (Mason et al., 2011), developed at the Australian Institute of Sport (AIS) to estimate active drag and assess performance of front crawl swimmers. A main role of the AIS is that of assisting Australian athletes to achieve success in the sporting world. The AIS biomechanics team is working to enhance swimming performance in different areas. The ATM method has been used as a feedback tool while synchronising active drag time profiles with the video for coaches and swimmers to identify strengths and weaknesses within the stroke cycle of a swimmer's performance and allows objective assessment of the stroke mechanics (Mason et al., 2011). This can give a chance to coaches and swimmers to change the swimmer's technique based upon objective quantifiable feedback. However, the accuracy of active drag value obtained from the ATM method with fluctuating speed must be assessed.

In order to provide this assessment four studies were carried out. The first study described the reliability of estimating active drag in swimming using the assisted towing method (ATM) with fluctuating speed. The findings of this study were presented in chapter 3. Previous researches (Formosa et al., 2012; Toussaint et al., 2004) compared the MAD system with the ATM method and the VPM method respectively: it was suggested that the ATM method overestimates active drag relative to the MAD system and that the VPM technique underestimates active drag relative to the MAD system. Given the disparity between those two previous researches, this second study (chapter 4) was conducted to compare the active drag values obtained from the two assisted and the resisted methods. This second study was implemented to confirm that the different results were obtained by previous researches due to the swimmer assisting or resisting, rather than to the different equipment used. The findings of this study were reported in chapter 4.

The third study calculated the contributions of all variables involved in the estimation of active drag and how those contributions would affect the overall uncertainty in the estimation of active drag. This study was completed using the assisted towing method in front crawl swimming. Its results were presented in chapter 5. The fourth study compared the intra-cyclic speed fluctuations of the free swimming with those of the assisted and the resisted methods and the findings were presented in chapter 6.

7.2 Specific objectives

The following objectives outlined in Chapter 1 were met:

Objective 1: evaluate whether the estimation of active drag using an assisted tow is reliable in producing repeatable values within a single day as well as over two days

Based on the finding of chapter 3, the active drag values obtained using the ATM method with fluctuating speed were moderately reliable in regard to the intra-class correlation coefficient (ICC) within-subject on each day (Day 1, 0.82 and Day 2, 0.85). This method was highly reliable when using the mean active drag values of five trials from both days (ICC = 0.93). The findings of chapter 3 suggested that a highly reliable method requires that multiple trials be measured, the mean of those trials be calculated and, finally, the mean value should be used for calculation of active drag.

Objective 2: compare estimated active drag values from resisted towing with those from assisted towing values to evaluate whether the two methods estimate the active drag value the same as each other

As the finding of chapter 4 showed, there was no significant difference between the mean active drag values obtained from the resisted and assisted methods (p = 0.171). However, for some swimmers, there were large differences between the mean active drag values calculated by the two methods. These large differences could be due to the violation of the assumptions. On the other hand, the individual results of a few swimmers showed less difference between the active drag values obtained from the two methods. It might be suggested that they produced approximately the same power output under all swimming conditions. If the assumptions were not violated by some swimmers, but were by others, this could account for the variability of results between individuals.

Objective 3: determine uncertainties in estimation of active drag calculated from the ATM method and how they affect the active drag value

The results of chapter 5 revealed that if a swimmer had a changed power output of 7.5% between conditions, this change would lead to an error of 30% in the estimation of active drag. The result of the uncertainty of the speed exponent, if it was assumed to be ± 0.4 in a range exponent of 1.8 to 2.6, was that this uncertainty would lead to about 5% error in active drag value. The contribution of those uncertainties to active drag values were approximately 6–7% error for the free and tow swim velocities and 2–3 % error for the belt force. The constant power output assumption contributed large uncertainty to active drag measurement. This finding potentially explains the large difference in individual results of the chapter 4. It is probable that it is not easy for a swimmer to produce the same power output in a tow swim as in a free swim. This issue could be solved if the power output of a swimmer could be estimated during the free swimming and the tow swimming conditions.

Objective 4: compare intra-cyclic speed fluctuations of the assisted and the resisted methods with that of the free swimming condition in an attempt to evaluate the accuracy of the assumption of similarity between the free swim speed profile and the towing speed while using the ATM method

According to the findings of chapter 6, the swimmers had greater variations from the maximum to minimum velocities within stroke for the free swimming compared to those of the assisted and resisted swimming conditions. The stroke length of the swimmers increased and decreased during the assisted and resisted swimming respectively. Results of within-stroke phases in chapter 6 revealed that the assisted and the resisted towing resulted in entry/catch and push phases that were significantly different to the free swim condition. These results could suggest that power output across the entire stroke was not likely to be constant; the swimmers produced different power during the towing trials compared with the power they produced during the free swimming.

7.2.1 Estimation of active drag

The studies for this thesis examined the validity of assumptions that have been made in previous studies in the estimation of active drag using the ATM method with the fluctuating speed. The ATM method with fluctuating speed (chapter 3) can be more reliable if the mean of multiple trials are calculated. The result of chapter 5 demonstrated that the large overall uncertainty of 43% came from the contribution of individual measurements in the estimation of active drag. A large proportion of this uncertainty was created by uncertainty in the equal power assumption; if the power output of a swimmer changed 7.5% between the free swimming and the tow swimming, it would lead to 30% error in calculated active drag. The finding of chapter 3 indicates that swimmers can produce consistent performances in tow swimming trials, but their power outputs in tow swimming compared with free swimming conditions are not equal (chapter 5). It can therefore be suggested that the swimmers generally produced less power during towed swimming than during free swimming.

The finding of chapter 4 showed the two methods did not measure the same active drag values. Chapter 4 also shows that large differences in the individual results for the swimmers were observed. The disparity between these two findings of chapter 4 could be due to the number of trials (n = 2): that is, two trials are less likely to be representative of the true performance capability than would be a greater number of trials. However, an increase in the number of trials in one day would introduce fatigue to the swimmers' performances because fatigue would prevent them from performing their trials at the same power output.

Less variation in intra-cycle speed fluctuations, demonstrated in chapter 6 could support the idea of less power output by the swimmers during the assisted trial. The minimum speed of the swimmers could not drop too far from the target speed because of an external force. This external force would help the swimmers to maintain their power at the lower speed while they were applying minimum sufficient force by themselves. Therefore, the swimmers were attempting to generate only sufficient force to reach the maximum speed. Furthermore, the swimmers were not applying sufficient force to maintain power at the higher speed, and therefore changed their coordination pattern. For example, shortening the push phase and increasing the entry/catch phase could suggest the swimmers perform the arm coordination in a form of catch-up because of a lag time in the propulsive phase of both arms. The shortening of the push phase (chapter 6) could be due to the consequence of slippage of the hand in the water. It might be suggested that they let themselves be pulled by the dynamometer rather than swimming. The result of the differing value of stroke length between the three conditions in chapter 6 might support the idea that the swimmers changed the power output between the swimming conditions. However, high intra-cyclic speed variation observed in the free swimming could suggest that more power was needed to be generated by the swimmer to reach the maximum speed in each cycle.

The swimmers increased the duration of the push phase during the resisted swimming compared with that of the free swimming (chapter 6). In relation to the decrease of the mean swim speed in the resisted swimming, the hand speed of the swimmers should be slowed down during this phase and thus did not generate sufficient force, so less power output would be produced in this phase. The longer time during the push phase for the resisted swimming than for the free swimming was accompanied by a slowing hand speed, so a shorter stroke length occurred (chapter 6). Indeed, a decrease in the stroke length is related to a decrease in the hand speed during the propulsive of the stroke cycle. Lift force may also be generated by pushing water backwards using intermediate angles of pitch (Costill, Maglischo, & Richardson, 1992). Drag and lift both contribute to the net force produced by the hand. Therefore, they could generate greater lift force to contribute in the greater propulsive force and greater power output would then be produced. It cannot be concluded from either of the two possible explanations just given what causes the different power outputs. The important observation here is that the power outputs under different conditions should not be equal. Measurement of power would not be possible during the current testing protocol. It is suggested that the testing protocol is implemented in a flume to measure the mechanical power output by measuring oxygen consumption and swimming efficiency during both the free swimming and tow swimming. Further research should be undertaken to estimate the power output of the swimmer during free and tow swimming.

Chapter 5's finding indicated that there were large uncertainties in the estimation of active drag in regard to the different power outputs throughout the trial. However, the result of the stroke phases study (chapter 6) might specify which phase could have caused this difference in power output. The results of chapter 6 might suggest that the power outputs were different and were most likely related to the duration of the entry/catch and push phases. However, the duration of the pull and the recovery phases were the same in all three swimming conditions, but this does not necessary mean that power output was the same during these two phases. Overall, these results could suggest that power output across the whole stroke could not be constant. It might be suggested that if the duration of the push phase of the assisted and the resisted swimming conditions were to be the same as the duration of the push phase of the free swimming, then the issue of unequal power output under the two conditions might be resolved. Hence, the findings of chapters 5 and 6 would explain the large difference in individual results of chapter 4 and it would then be more reasonable to accept that the two assisted and the resisted methods should calculate active drag differently from each other.

7.3 Limitations

The limitations affecting these studies included:

- consistent participant motivation throughout trials to produce maximum effort could not be guaranteed
- the number of trials, as a participant performing multiple trials in one session would increase either the chance of having a more appropriate mean value and/or affect accuracy of the reliability of a measurement, but would increase the swimmer's performance fatigue, while, to estimate active drag accurately, swimmers had to exert the same power output during all trials while swimming with their maximum effort
- the number of participants, as performing multiple trials of the free, the assisted and the resisted swimming in one day would cause swimmers to feel fatigued; therefore, the swimmer would not be able to deliver the same power output under both conditions. To eliminate the effect of swimmer fatigue on the measurement, high level swimmers with enough capacity were required to perform all testing protocols at the same power
- the lack of familiarity of swimmers with the experimental protocols, as performing the testing protocol regularly could enable the swimmer to be more consistent between swimming conditions for producing equal power output.

7.4 Implications of this thesis

The aims of this thesis were to assess the reliability of the ATM method with the fluctuating speed and, by using this method, to investigate the validity of the estimation of active drag. The results of this thesis have implications for swimming biomechanics and the AIS.

The results of this thesis can assist swimming biomechanics generally and especially those at the AIS in improving the current ATM method. AIS biomechanics researchers using this method want to ensure correct feedback to help swimmers improve their performance. Further, for swimmers and coaches, accurate drag time profiles synchronised to video footage would be ideal for identifying strengths and weaknesses: this is because the assumption of equal power output for each of the swimming conditions was shown to be the critical factor in estimating active drag using the ATM method with fluctuating velocities. In addition, the results of this thesis show that it is probably not easy for a swimmer to produce the same power output in non-free swim conditions as in a free swim condition; therefore, there can be substantial errors in the estimation of active drag. To avoid this issue in the estimation of active drag, it can be recommended that the testing protocol be performed in a flume and mechanical power output estimated by measuring oxygen consumption and swimming efficiency during both the free swimming and the tethered swimming.

7.5 Conclusions

The mean active drag estimated using the ATM method with the fluctuating speed in this thesis indicated that this method is highly reliable when drag is calculated from the mean value of a number of trials, rather than being calculated from single measurements. This suggests that the mean value should be used for calculation of active drag. The comparison between the active drag values obtained from the assisted and the resisted methods of this thesis showed that there was no significant difference between the mean active drag values obtained from these two methods. However, because of the small number of participants for this thesis, this finding could not conclude that the same active drag values were measured by the two methods. Also, another reason that it could not conclude that these two methods measure active drag the same because of small number of participants for this thesis However, having a greater number of participants who had a high level ranking was not feasible for this thesis, as its requirement was that the swimmers generate the same power output in both swimming conditions; this might be possible for a high ranking swimmer or to be fit enough to recover completely after the rest time.

Calculations of the uncertainties in the estimation of active drag confirmed that the same active drag values cannot be measured by the two assisted and resisted methods. Two possibilities were suggested: firstly, unequal power output between the free and the towing conditions and secondly, the square relationship between the active drag and the swim speed. Unequal power output not only affected the active drag value but made the greatest contribution in the estimation of active drag. The other variables also had some uncertainties (6% to 7%) in the estimation of active drag, but those uncertainties were less than the uncertainty of the unequal power output (30%).

In this thesis, there were greater variations obtained from maximum to minimum velocities within the free swimming stroke, with changes in the duration of the entry/catch phase, than were obtained in the push phase during the assisted and resisted swimming. These results suggest that there was a different power output between the free and the tow swimming conditions.

7.6 Directions for Future research

The following further researches are suggested to improve the estimation of active drag:

The findings of chapter 3 showed that the ATM method is highly reliable when using the mean of active drag values. The findings of chapter 3 showed that the swimmers were able to swim consistently in all the towing trials. However, it is clear, based upon the findings of chapter 5, which if power output changed by 7.5% between the two swimming conditions, there would be a 30% uncertainty in the estimation of active drag using the ATM method. Therefore, given that high reliability was obtained, a major requirement to achieve a more accurate method would be to provide a system which enables swimmers to produce more consistent power outputs between conditions. The current equipment is specifically designed to achieve a target speed and reduce the range of speeds present. **Further research** should be undertaken to apply a constant belt force to investigate whether such consistency in the belt force can cause the power output to remain constant throughout the trial.

The result of chapter 4 indicated that there was no significant difference between the mean active drag values obtained from the resisted and assisted methods. Because of the small number of participants, this is not to suggest that the two measures were actually the same. The 10 participants provided the power analysis of 0.32 and this indicates that there is a 32% chance that the active drag values obtained from the assisted method from the total population of swimmers were actually larger than the active drag values obtained from the resisted method. **Further study** should be conducted to recruit more participants (at least 20) and examine whether the finding of chapter 4 was related to the sample size or was due to the uncertainty in the estimation of active drag.

The result of chapter 4 indicated a large difference for some swimmers between the active drag values of the ATM method and the resisted method. This can probably be explained by the swimmers changing power output during the ATM method and the resisted method. As the estimation of active drag was based upon the assumption of equal power output, **further study** is recommended for researchers to estimate the power output during each trial, so as to be confident that the swimmer is able to maintain constant power output under all trial conditions.

The result of chapter 6 showed that the free swim speed profile had the greatest magnitude from maximum to minimum points in a single stroke compared with the other two methods. It can be concluded that the ATM method has a fluctuating speed. However, these fluctuations are not as large as those that occur during free swimming. Therefore, **further study** should be undertaken to apply a constant belt force to investigate whether this consistency in the belt force can allow greater speed variations during intra-cycle.

The duration of the push phase of the free swimming was different to the duration of the push phase of the assisted and resisted swimming conditions. These differences could be a reason there were different power outputs in the different swimming conditions. **Further study** should be undertaken to modify the combination of belt force and towing speed for creating equal duration of the push phase in different swimming conditions.

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CHAPTER 8

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Appendix

Testing protocols of the four studies

Testing protocol of Study 1

The testing protocol for Study 1 was based upon the testing protocol of the ATM method with fluctuating speed (Mason, Sacilotto, & Menzies, 2011). The testing protocol started with providing information about the testing protocol to the swimmers. Then the swimmers performed a 20-minute warm up as a normal race strategy.

Differences between testing protocols of Studies 1 and 2

Table 1 shows the differences between the testing protocols of Study 1 and Study 2. The testing protocol for Study 2 (number of trials, distance and number of full strokes) was changed because of the recommendations of scientists expert in the active drag area who participated in the 2013 AIS workshop (see chapters 3, 4, 5 and 6). This workshop was held after I had completed my first study, so the protocol of my Study 2 could not be the same as my Study 1.

Table 1: Numbers of trials and distance that travelled by the swimmer in testing protocols of Study 1 and Study 2

	Number of trials			Distance in a trial		
	Free swimming	Passive towing	Active tow swimming	Free swimming	Passive towing	Active tow swimming
Study 1	4	3	5	10	10	Four full strokes (approximately 10m)
Study 2	2	2	2	20	20	Eight full strokes (approximately 20m)

Reasons for the testing protocol change:

1) The number of trials was reduced from four to two trials, as too many trials may have caused some swimmer fatigue, possibly resulting in unreliable results

2) The distance was increased to minimise error measurement, as 20m represents a more realistic race distance (Mason et al. 2013)
3) The number of passive drag trials was reduced from three to two trials to be consistent with the free swimming trials and the active tow trials of the assisted and the resisted methods of Study 2.

Testing protocol of Study 3

After the results of Study 2, it was necessary to examine the contribution of uncertainty to the active drag value. To conduct this study, a few trials were needed, from which I did not collect new data, as I had enough data from Study 1. Therefore, the results of Study 1 were used for examining the uncertainty in the estimation of active drag.

Difference between testing protocols of Studies 1, 2 and 4

Table 2 shows the difference between the testing protocols of Studies 1, 2 and 4. The difference between these testing protocols is the starting point of the swimmer in the free swimming trials. In Study 4, the swimmer had to start from the wall because the velocity transducer was mounted on the Kistler force platform and the cable was attached to the swimmer posterior to the waist. A small amount of force was applied to maintain tension on the cable to prevent oscillations in the cable. The swimmer could not start away from the wall because the tension on the cable would not have been enough to tow the swimmer. Therefore, the cable would have become became slack. However, the small amount of tension on the cable was enough when the swimmer started from the wall.

Table 2: Starting point of the swimmer in the testing protocols of Study 1, 2 and 4

	Start point		
	Free swimming	Assisted method	Resisted method
Study 1	out from wall	out from wall	N/A
Study 2	out from wall	out from wall	wall
Study 4	wall	out from wall	wall

Setting up the dynamometer for the assisted method

It was necessary to insert two values (tow speed and tow force) into the Universal AC Drive SP of the dynamometer to perform the active towing trials. To insert a value for tow speed in the Unidrive of the dynamometer, 120% of the mean maximum swim speed calculated from the four free swimming trials was used. To insert a value for tow force in the Universal AC Drive SP of the dynamometer, the force range from three-quarters to half of the mean passive drag value was used.

The speed setting is the target value that the controller aims for, not the actual value achieved, while the force setting is the maximum force able to be applied if the speed is below the target. A combination of the tow speed setting that is higher than that actually desired (120% of the mean maximum swim speed), together with a tow force setting that is too low to achieve the controller's target speed (ranging from three-quarters to half of the mean passive drag value) increased the mean speed of the swimmers to the range of only 5% to 8%.

Setting up the dynamometer for the resisted method

Two values (tow speed and tow force) had to be inserted into the Unidrive SP of the dynamometer to perform the active towing trials. To insert a value for tow speed in the Unidrive of the dynamometer, 90% of the mean maximum swim speed calculated from the two free swimming trials was used. To insert a value for the tow force in the Unidrive of the dynamometer, a force range between 4 and 10 N was used, as pilot tests showed that with a force less than 4 N, the swimmers did not encounter actual resistance force to reduce their mean maximum speed. On the other hand, adding a force higher than 10 caused the swimmers to reduce their mean maximum speed more than 8%.

A combination of the tow speed setting (90% of the mean maximum swim speed) and the tow force setting (the range between 4 N and 10 N) decreased the mean speed of the swimmers only in the range of 5% to 8%.

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RELIABILITY OF ESTIMATING ACTIVE DRAG USING THE ASSISTED TOWING METHOD (ATM) WITH FLUCTUATING VELOCITY

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The aim of this study was to examine the reliability of active drag values obtained using a method that compared free swim velocity with measurements taken by towing swimmers slightly faster than their maximum swim speed, while allowing for intra stroke velocity fluctuations. Using nine national level swimmers on two alternate days, reliability was determined using within-subject intra-class correlation coefficients (ICC) within each day and between the days. The ICCs for days one and two were 0.80 and 0.84 respectively, while the comparison of mean active drag values between days was 0.92. Results found that the ATM method with fluctuating velocity to be only moderately reliable within a single test. Taking average values improved this reliability, even when measured over different days. Further investigation is suggested to improve the current method.

KEYWORDS: Swimming, Resistance, Active drag, fluctuating velocity, Front Crawl

INTRODUCTION: For both swimmer and coach alike, the goal of competitive swimming is to finish the required distance in the shortest possible time. The majority of race time is spent in free swimming, requiring the swimmer to propel the body by pushing against the water to overcome the negative force of drag. Active drag is the water resistance acting to oppose the swimmer while propelling the body forward (Mason et al. 2011). Several methods have been developed to assess active drag directly or indirectly; however there is no consensus on the best method. Two major methods for measuring active drag have been developed by Holander et al. (1986) (the measurement of active drag [MAD]) and Kolmogorov (1992) (Velocity Perturbation Method [VPM]).
The MAD system (Hollander et al. 1986) determined active drag by measuring the propulsive force applied to paddles fixed to a force transducer in the pool whilst the swimmer performing the front crawl action. A small pull-buoy w assituated betwee nthe swimm er'sleg sto prevent using the legs during swimming while maintaining the body in a horizontal position. The VPM method (Kolmogorov & Duplishchea 1992) estimated active drag using a resisted method to compare free swimming velocity with velocity of swimmer while a hydrodynamic body attached by acabl et oth eswimm er'swaist. The measurement of activ edrag w asbased upon two assumptions; first, the swimmer was able to generate a constant mechanical power output in both conditions, and second, the swimmer maintained a constant average velocity during each trial.
Alcock and Mason (2007) assessed active drag by using the Assisted Tow Method (ATM) at the Australian Institute of Sport (AIS). The method was similar to the assumptions of the VPM method except that the swimmer was assisted by a motor driven cable at a constant mean swim velocity rather than having a force resisting the swimmer. A criticism of the method developed by Alcock and Mason (2007) was that in free swimming, there are intra-stroke velocity fluctuations, which are not present when towed at a constant velocity. Recent research (Mason et al. 2011) allowed the swimmer to have a fluctuating velocity which enable them to maintain their normal stroke technique whilst being towed, making it much more like free swimming than the constant velocity tow condition. The purpose of the present research was to examine the reliability of using a fluctuating velocity tow when estimating active drag and, also help the researchers to find a reliable testing protocol for a resisted method in the future.

METHOD: Nine national age and open level swimmers (5 males and 4 females, 17.7±2.9 years) participated in this study. Participants were required to complete all tests on two alternate days starting with a 20 minutes warm-up. Participants performed at least one practice trial to become familiar with the nature of the experiment and were given 5 minutes rest between each trial to eliminate the influence of fatigue on their performance. Firstly, each participant completed four maximum free swim velocity trials over a 10 m interval, starting from 25m out and the velocity measured over the interval 15 m to 5 m out from the wall using two 50 Hz cameras. Th e mea n velocity w as used to determine the swimmer‘s free swim velocity. Secondly, three passive drag tests were compl eted at the swimm er's free swim velocity. Finally, participants were then requested to swim five trials with maximum effort whilst a belt was attached around participaw 'ntsaist connected to the dynamometer mounted directly on a calibrated Kistl™er for ceplatform)Kistler Instrument sType Z20916) (Figure 1). Four complete stroke cycles were captured for the analysis of the active drag trials. The cable pulled the swimmers at approximately 5% higher than their free swim velocity with a maximum force level set low enough to allow intra-stroke velocity fluctuations to occur (Mason et al. 2011). The maximum force level was set between 25 to 50% of passive drag force and adjusted if assisted swim velocity was more than 10% faster than free swim velocity.

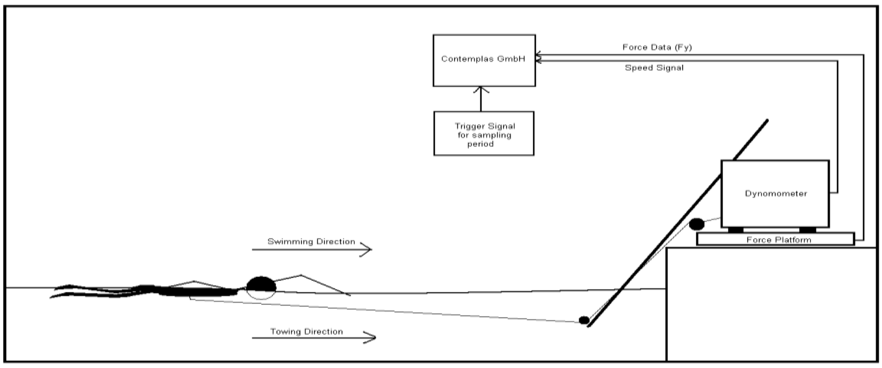

Figure 7: Assisted Towing Method set up (Sacilotto et al. 2012)

Active drag was calculated from the assisted towing formula of Alcock and Mason (2007) a revised version of the equation derived by (Kolmogorov & Duplishcheva 1992). Consequently, the formula for estimating active drag was:

$$F_d = \frac{F_t . V_2 . V_1^2}{V_2^3 - V_1^3}$$

Where F_t is the force required to pull the swimmer at the increased velocity, as measured with the force platform, V_1 i s the swimmer's free swim maximum mean velocity, and V_2 is the increased tow velocity taken from the dynamometer.

All five trials collected were selected for statistical analysis. A one-way intra-class correlation coefficient (ICC) was used to test with-in subject reliability on days one and two. The average from five active drag values of each subject was calculated to use for the determination of ICC between days. SPSS software (Windows version 19) was used for statistical analyses and a statistical significance for the reliability coefficient was set at the 95% confidence level ($p<0.05$).

RESULTS: The reliability of active drag values of both days and also a comparison between mean values were calculated for each subject (Table 1). For repeated trials within days one and two, ICCs were 0.80 and 0.84 respectively, with 95% confidence intervals ranging between 0.59 to 0.94 for day one and 0.66 to 0.95 for day two. Between days, the ICC of average values was 0.92, with 95% confidence interval between 0.71 and 0.98.

Table 1
Individual values of active drag (N) with fluctuating velocity in day 1 and 2

Participan	Gender	Mean max velocity	Trial1	Trial2	Trial3	Trial4	Trial5	Mean ± SD
Day one								
1	F	1.58	102.1	106.3	73.6	84.3	72.9	88±16
2	F	1.61	87.8	84.4	87.1	114.4	93.8	93±12
3	F	1.65	59.5	67.3	71.5	69.3	65.1	66±5
4	F	1.60	86.1	83.3	88.4	104.4	68	86±13
5	M	1.87	112.4	109.2	118.6	82.1	98.9	104±14
6	M	1.93	125.1	148.8	158.6	152.1	190.8	155±24
7	M	1.78	123.9	123.7	160.9	132.2	156.4	139±18
8	M	1.87	138.5	108	158.3	185.4	140.2	146±28
9	M	1.87	157.2	164.7	158.5	163.3	145.1	157±8
Day two								
1	F	1.57	74.2	60.5	61.2	82.3	73.6	70±9
2	F	1.63	59.2	115	42.3	98.3	118	86±34
3	F	1.65	65	65.8	66.5	70.1	64	66±2
4	F	1.58	54.9	54.8	66.6	73.4	70.4	64±9
5	M	1.88	99	131.2	102.4	132.6	112.8	115±16
6	M	1.92	138.2	139.8	131.9	155.6	164.8	146±14
7	M	1.80	132.6	115.8	108.5	148.9	149.4	131±19
8	M	1.88	181	164.9	169.3	179	150.9	169±12
9	M	1.87	158.3	123	154.6	137.3	130.8	140±15

DISCUSSION: Prior to the current investigation, no research had described the reliability of the current ATM method for estimation of active drag with fluctuating velocity. The result of this study indicated that using the ATM method with fluctuating velocity is moderately reliable in regards to within-subject values on each day (ICCs = 0.80 and 0.84). This method is more reliable, however, when using the average value of active drag from both days (ICC = 0.92). Therefore, using the average active drag value of five trials in the current testing protocol will produce a more reliable result.

As expected, the males in this research had higher active drag values than the females (Kolmogorov & Duplishcheva 1992; Xin-Feng et al. 2007). Mason et al. (2011) utilised the current ATM method with fluctuating velocity and revealed similar values for their males (112 and 124 N at maximum velocity of 1.83 and 1.82 m/s respectively for two subjects) compared to the current research. However, the mean values of the female subjects from Mason et al. (2011) (for example, two subjects had 128 and 119 N at maximum velocity of 1.61 and 1.69 m/s respectively) were considerably higher than present research. The difference in active drag values between studies may possibly be explained by a difference in age, size and/or technique of the swimmers.

The active drag values collected in the current research and by Mason et al. (2011) were significantly higher than the results previously reported by Hollander et al. (1986), Kolmogorov et al. (1992) and Xin-Feng et al. (2007). For example, Xin-Feng reported that the active drag value and additional drag (F_t) of one of the male was 57.25±3.04 and 13.96 N at a mean maximum velocity of 1.85 m/s while in the present research, the mean active drag value and mean additional drag (F_t) of subject 9 at day 2 were 140.8±15 and 32.75 N at a mean maximum velocity of 1.86 m/s. The higher value of active drag in the present study was probably the consequence of a higher tow force (F_t). Another reason for a difference active drag value may be the result of the Xin-Feng et al. (2007) being resisted whereas the present study used an assisted method to assess active drag. This is an important area of future investigation.

ICC values from the current research (0.80 and 0.84) were significantly lower than previous studies 0.99 and 0.91 respectively reported by Formosa et al. 2010 and Sacilotto et al. 2012. Sacilotto et al. 2012 analysed reliability from three of five active drag trials using a different statistical calculation (Hopkins, 2011). The difference in the reliability result could be due to differences in the testing protocol, the standard of swimmer, and/or the statistical calculation. Dufek et al. (1995) reported that to achieve better reliability, it is necessary to maximise the number of trial s per subject. The swimmers' fatigue, howev,er shoul d al so be considered when increasing the number of the trials. Connaboy et al. (2010) examined fifteen subjects to find the optimum number of trails and concluded that five trials per session, with five minutes r est betwee n ea ch trial, provide s a suitabl e mea sure of reliability. Connaboy' s rese arch di d not investigate the number of swimmers required to reach a sound value for reliability. Morrow et al. (1993), however, recommended that at least 30 subjects are required to achieve reliable measurements. Considering the difficulty in finding 30 subjects with the high swim performance level required for these measures, it is proposed to follow the suggestion of Connaboy et al. (2010) for a sample size of 15.

CONCLUSION: The result of this study identified that ATM method with fluctuating velocity is moderately reliable within-subject in a single day, while high reliability has been found for the average active drag values across different days. The positive result for the average value of active drag obtained between days persuades the researches to increasing the sample size to progress this study. Future investigation should be performed to assess the validity of this method compared to other measurement techniques.

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Development of a new resisted technique in Active Drag estimation

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This investigation aimed to develop a new technique for the estimation of active drag in front crawl swimming at the swimmer's maximum swim speed, while allowing for intra stroke velocity fluctuation. This new resisted technique was developed using similar assumptions to that of the Velocity Perturbation Method (VPM) of Kolmogorov & Duplishcheva (1992). The investigation included twelve national and international male swimmers who were asked to perform two maximum effort free swim trials, two passive and two active drag trials. The data required for the calculation of active drag were maximum swim speed, which was derived from the free swim trials, and a force set between 4 to 10 N and which was dependent upon the mean value of passive drag. Mean active drag ranged from 68 to 123.2 N in front crawl. The mean active drag values found in this investigation were in agreement with those previously reported by Kolmogorov & Duplishcheva (1992) and Wang et al. (2007). These three techniques using resisted swimming (VPM, Wang et al and the current study) provided similar values for mean active drag to one another.

Keywords: Biomechanics, swimming, resistance, active drag, front crawl

INTRODUCTION

Drag force on the swimmer's body through the water can be divided into active and passive drags. Active drag occurs when a swimmer propel themselves forward and passive drag when a swimmer glides in a streamline position (Kolmogorov and Duplishcheva, 1992). The swimmer encounters passive drag only during the glide after start and turns; however, the majority of drag force which the swimmer encounters during swimming competition is active drag. Passive drag has been investigated by several researchers (Clarys, 1979; Kolmogorov and Duplishcheva, 1992; Shimonagata et al., 1998). A number of measurement techniques have been developed to assess and estimate active drag directly or indirectly, however, there has been controversy as the techniques used often reported varying values (Clarys and Jiskoot, 1974; Clarys, 1979; Formosa et al., 2011; Kolmogorov and Duplishcheva, 1992; Kolmogorov et al., 1997; Mason et al., 2011; Toussaint et al., 2004; Wang et al., 2007; Zamparo et al., 2009).

Hollander et al. (1986) designed a measurement of active drag (MAD) system which is the only system that measures propelling forces directly. The MAD system measured active drag by measuring the propulsive force applied to paddles fixed to a force transducer in the pool whilst swimmers performed the front crawl action. Kolmogorov and Duplishchea (1992) estimated active drag using the Velocity Perturbation Method (VPM) at maximal swim velocity; once with a hydrodynamic body attached that produces an additional known resistance, and once without the added resistance. The measurement of active drag was based upon two assumptions; the swimmer was able to generate a constant mechanical power output in both conditions, and the swimmer maintained a constant average velocity during each trial.

Toussaint et al. (2004) assessed the difference between the active drag values measured with the MAD system (Hollander et al., 1986) and the active drag values estimated by the VPM technique (Kolmogorov and Duplishcheva, 1992). They reported that the main reason for the difference in active drag results was an unequal power output when swimming with and without added resistance during the VPM method. Wang et al. (2007) designed a new device to estimate active drag by using a gliding block to provide an adjustable drag which was attached to the swimmer by a force transducer. They calculated active drag based upon the equal power output assumption of Kolmogorov and Duplishcheva (1992) (with and without a small additional drag).

Mason et al (2011) determined the value of active drag at maximal swim velocity by towing a swimmer at 5% higher than mean maximum velocity. The Assisted Towing Method (ATM) was designed to allow swimmers to have a fluctuating velocity which enabled them to maintain their normal stroke technique whilst being towed. The measurement of active drag was based upon the same assumptions as the VPM technique (equal power output in the free swimming and when being assisted with the tow).

The purpose of the present research was to implement a new technique to estimate active drag using an electrically braked resisted force rather than an assisted tow, whilst fluctuations in intra-stroke velocity were still allowed. This technique is similar to the methods of Kolmogorov & Duplishcheva (1992) and Wang et al. (2007), but enabled more precise control of the braking force and subsequent resisted swim velocity.

METHOD

Twelve national and international male swimmers (mean ± standard deviation: age= 20.5 years; height= 1.85 cm; weight= 79.5 kg, FINA point rank of over 750) participated in this research. Swimmers were required to complete all tests in one day starting with a 20 minutes warm-up. Swimmers performed at least one practice trial to become familiar with the nature of the experiment and were given 5 minutes rest between each trial to eliminate the influence of fatigue on their performance.

Firstly, each swimmer completed two maximum free swim velocity trials over a 25 m interval, starting from 35 m out, and the velocity measured over the interval 25 m to 5 m out from the wall using two 50 Hz cameras. Velocity was averaged from the two trials to determine the swimmer's maximal free swim velocity. Secondly, two passive drag trials were completed at the swimmer's free swim velocity. The passive drag trial was acceptable when the subject was able to maintain a streamline position just below the water surface and there was visible water flow passing over the head, back and feet (Formosa et al, 2010). Finally, the swimmers were then required to swim two trials with maximum effort with a belt attached around the swimmers' waist and connected to a dynamometer mounted directly on a calibrated Kistler™ force platform (Kistler Instruments Type Z20916). Active drag trials were performed using an electrically braked cable to achieve a velocity 5% to 8% less than mean maximum swim velocity over a 25 m interval with velocity averaged over six full strokes. The force level was set between 4 to 10 N and adjusted if the resisted swim velocity was more than 8% less than free swim velocity.

The dynamometer and force platform were instrumented to capture the velocity and the force generated by the swimmer during each trial. Collecting the data was started by pressing a trigger signal at the beginning of six full strokes (beginning with right hand entry) and finished with another the trigger signal after the six full strokes were completed to allowed for digital data smooth. Data was sampled using a 12 bit analogue to digital board, with a sampling rate of 500 Hz. Prior to experimental testing, a range of cut- off frequency was examined to determine the most appropriate cut off frequency. Examining Active drag profiles demonstrated that an 8 Hz Butterworth low-pass digital filtered was most appropriate.

Active drag at the maximal mean swim velocity was computed using the difference between normal free swimming velocity and the measured resisted velocity, together with the force needed to slow the swimmer to the desired velocity range. The following equations were used to estimate active drag and were originally introduced by Kolmogorov and Duplishcheva (1992):

$$F_{A1} = \frac{1}{2} C_d \rho A V_1^2 \qquad (1)$$

$$F_{A2} = \frac{1}{2} C_d \rho A V_2^2 \qquad (2)$$

where F_{A1} is the active drag during free swimming, F_{A2} is the active drag resisted towing, ρ is water density, A is the front surface area of the swimmer, C_d is the drag coefficient, $V_1$is the swimmer's maximum mean swim velocity for free swimming, and V_2 is the decreased resisted velocity.

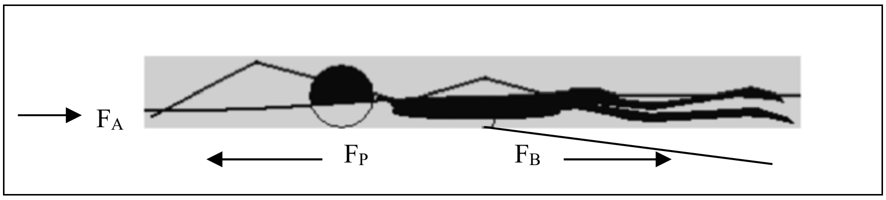

Figure 2: Propulsive (F_P), Active drag (F_A) and Belt force (F_B) vectors in Resisted Method

As figure 2 shows the three forces vectors while a swimmer is resisted by the dynamometer,

$$F_{P2} = F_{A2} + F_B$$

where F_{P2} is the propulsive force during resisted swimming, F_{A2} is the active drag force resisted towing and F_B is the force needed to slow the swimmer to the desired velocity.

Based on the equal power assumption in both the free swimming and the resisted tow swimming conditions:

$$P_1 = P_2$$

where P_1 is the power output during free swimming and P_2 is the power output during resisted towing.

And therefore,

$$F_{P1}.V_1 = F_{P2}.V_2$$

At a constant swimming velocity, the mean propulsive force is equal in magnitude but opposite indirection to the mean active drag force (Toussaint et al. 1983). Therefore, substitution of $F_{P1}$and F_{P2}, then gives:

$$F_{A1}.V_1 = (F_{A2} + F_B).V_2$$

Substitution of F_{A1} and F_{A2} then gives:

$$\left(\frac{1}{2} C_d \rho A V_1^2\right).V_1 = \left(\frac{1}{2} C_d \rho A V_2^2\right).V_2 + \mathrm{F_B}.\mathrm{V_2}$$

Rearranging the above formula to find C_d:

$$C_d = \frac{F_B V_2}{\frac{1}{2} \rho A \left(V_1^3 - V_2^3\right)}$$

Finally, Substituting C_d in equation 1 and gives the active drag formula:

$$F_{A1} = \frac{F_B V_2 V_1^2}{V_1^3 - V_2^3}$$

Data was collected using motion analysis software (Contemplas GmbH) and then processed using an export/import function in Contemplas linked to an AIS customized analysis program. The average from two active drag resisted trials and two passive drag trials of each subject was calculated. A Paired t-test was used to perform on the mean active drag and mean passive drag values. SPSS software (Windows version 19) was used for statistical analyses and a statistical significance set at the 95% confidence level ($p<0.05$).

RESULT

Fluctuating velocity resisted active drag parameters were computed for each of the swimmers. Mean value ± standard deviation (SD) of the active drag was calculated for each swimmer. Table 1 presents the active drag value of trials 1 and 2 and also, the mean value of active drag and passive drag for each swimmer at the maximal swim velocity.

Table 1

Individual active drag values and the mean values at the mean maximal swim velocity

Participant	Mean max velocity	Mean Passive drag	Active drag Trial1	Active drag Trial2	Mean Active drag ± SD
1	1.99	91.0	89.5	77.6	83.5 ± 8.4
2	1.83	93.5	119.8	129	124.4 ± 6.5
3	1.74	104.5	76.0	88.1	82.1 ± 8.6
4	1.76	75.5	109.0	92.7	100.9 ± 11.5
5	1.80	94.0	86.2	87.4	86.8 ± 0.8
6	1.91	109.7	101.3	90.6	96.0 ± 7.6
7	1.92	108.2	80.4	70.0	75.2 ± 7.4
8	1.79	103.6	53.0	71.0	62.0 ± 12.7
9	1.82	76.2	107.4	101.1	104.3 ± 4.5
10	1.88	92.3	89.7	95.6	92.7 ± 4.2
11	1.80	96.0	86.8	99.8	93.3 ± 9.2
12	1.77	80.20	79.3	60.3	69.8 ± 13.4
Mean	1.83	93.7±11.73	89.8	88.6	89.2 ± 16.7

The average of active drag and the average of passive drag were 89.2 ± 16.7 N and 93.7 N respectively. The paired t-test revealed statistically no significant differences between the active drag and the passive drag values ($p=0.05$).

DISCUSSION

The primary aim of this research was to develop a new resisted technique in active drag estimation using an electrically braked resisted force. The result of this study indicated that there was no statistically significant difference between the active and passive drag measures. The small, non-significant, reduction in active drag compared to passive drag was similar to the result reported by Kolmogorov and Duplishcheva (1992), who did not perform any statistical test of the difference. Also another study found that no significant correlation ($r=0.24$) between the mean active drag value and the mean passive drag value (Shimonagata et al., 1998)and also, they reported that the mean active drag (64.85 ± 16.53 N) was 76% of the mean passive drag (85.24 ± 21.36 N).

The results of the present research are in conflict with prior findings reported by Formosa et al. (2011) and Mason et al. (2010). In those studies, the mean active drag values were considerably higher than the passive drag values (for example, Formosa et al, 2011: active drag 262.4 ± 33.4 N and passive drag 80.3 ± 4.0 N). While a higher maximal swim velocity produces more active drag, the difference in average velocity between the two studies is not enough to explain the difference in calculated drag. It can be explained that active drag may not change proportionally to velocity squared, and therefore an increase in towing velocity rather than a decrease in resisted velocity could possibility affect calculated drag. The difference between active drag calculated by assisted and resisted techniques could alternately be explained by the swimmers' ability to produce constant power under all conditions. If power was increased during resisted swimming and decreased during assisted swimming (or vice versa) then, that could be an alternate reason for the difference between the assisted and resisted techniques.

The mean active drag results of this research were similar to those previously reported by Kolmogorov & Duplishcheva (1992) and Wang et al. (2007). For example, Kolmogorov & Duplishcheva (1992) reported that the active drag value of a male was 104 N at a maximum velocity of 1.80 m/s and also, Wang et al. (2007) reported that the active drag value of a male was 105 ± 5.63 N at a maximum velocity of 1.83 m/s. In the present study, the mean active drag value of subject 9 was 104.3 ± 4.5 at a mean maximum velocity of 1.82 m/s. In contrast, the active drag values found in the ATM technique at constant velocity (Formosa et al. 2011; Sacilotto et al. 2012) and the ATM technique with fluctuating velocity (Mason et al. 2011; Hazrati et al. 2013) were significantly higher than those for the studies using resistive forces. The reason for these differences in active drag values is likely to be a consequence of using an assisted tow method, rather than a resisted method. While, the active drag values obtained from the ATM technique with the fluctuating velocity were much lower than those obtained from the constant velocity technique (for example, Hazrati et al, 2013: the mean active drag of male swimmers 140.2 ± 19.8 N at 1.87 m/s and Formosa et al, 2011: the mean active drag 262.4 ± 33.4 N at 1.92 m/s), they were still higher than all the studies that used resisted tow techniques. The present study, which used the same equipment as the four ATM studies, produced similar results to the previous two resisted techniques reported by Kolmogorov & Duplishcheva (1992) and Wang et al. (2007). It therefore seems likely that the higher drag values of the ATM technique (Formosa et al. 2011; Mason et al. 2011; Sacilotto et al. 2012; Hazrati et al. 2013) are caused by differences between assisted and resisted tow techniques, rather than a result of the methods used to control the amount of tether force.

CONCLUSION

The three resisted techniques (Kolmogorov & Duplishcheva (1992), Wang et al. (2007) and the current research) which estimated active drag during free swimming through the use of known resistive forces provided similar values to each other. In contrast, drag values calculated using the velocity-assisted techniques Mason et al. (2011), Formosa et al. (2011) Sacilotto et al. (2012) and Hazrati et al. (2013) provided substantially larger values. Further research should be undertaken to determine why this relationship exists between the resisted and assisted testing conditions.

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VALIDITY OF ESTIMATING ACTIVE DRAG USING THE BOTH ASSISTED AND RESISTED TECHNIQUES WITH FLUCTUATING VELOCITY

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The main purpose of this study was to examine the validity of assisted and resisted techniques which are used for active drag estimation. Ten national and international male sprint swimmers performed two maximum effort free swims, two passive trials and two active drag trials in each technique. The computation of active drag for both techniques was based upon assumptions of the Velocity Perturbation Method (VPM) of Kolmogorov and Duplishcheva (1992). Results of a one-way ANOVA with repeated measures indicated there was no statistical significance between the active drag values obtained from the assisted and resisted techniques (p=0.05). There was however variation between active drag values. This is likely due to different power outputs that were applied during the test conditions and also, active drag varies as a function velocity squared.

KEYWORDS: Swimming, Resistance, Active drag, fluctuating velocity, Front Crawl

INTRODUCTION: In competitive swimming, it is important that an elite swimmer applies more propulsion and less drag force to achieve a better result. Water resistance or drag force is defined as “the rate of removal of momentum from a moving fluid by an immersed body” (Vogel, 1994, pp.81). Determination of drag force is an important issue assisting in swimming performance. A number of measurement techniques have been developed to assess and estimate active drag directly or indirectly, however, there has been controversy as the techniques used often reported varying values (Clarys, 1979; Kolmogorov and Duplishcheva, 1992; Toussaint et al., 2004; Mason et al., 2011).

Hollander et al. (1986) designed a measurement of active drag (MAD) system which is the only system that measures propelling forces directly. The MAD system calculated active drag by measuring the propulsive force applied to paddles fixed to a force transducer in the pool and assumed that mean drag and mean propulsive forces are equal when swimming at constant velocity. Kolmogorov and Duplishcheva (1992) estimated active drag using the Velocity Perturbation Method (VPM) at maximal swim velocity; once with a hydrodynamic body attached that produces an additional known resistance, and once without the added resistance. The measurement of active drag was based upon assumptions; the swimmer was able to generate a constant mechanical power output in both conditions, the swimmer maintained a constant average velocity during each trial, and that drag was assumed to change in proportion to velocity squared.

Mason et al. (2011) determined the value of active drag at maximal swim velocity by towing a swimmer 5% greater than the mean maximum swim velocity. The Assisted Tow Method (ATM) was designed to allow swimmers to have a fluctuating velocity which enabled them to maintain their normal stroke technique whilst being towed. Hazrati et al. (2014) developed a new system to estimate active drag by using an electrically braked resisted force which resulted at 5% to 8% lowering than average swim velocity, while allowing for intra-stroke velocity fluctuations. The measurement of active drag was based upon the same assumptions as the VPM technique (equal power output in the free swimming and the towing).

Toussaint et al. (2004) assessed the difference between the active drag values measured with the MAD system (Hollander et al., 1986) and the active drag values estimated by the VPM technique (Kolmogorov and Duplishcheva, 1992). They reported that the main reason for the difference in active drag results was likely to have been an unequal power output when swimming with and without added resistance during the VPM method. The purpose of the present research was to examine the validity of the active drag estimation using the both the assisted and resisted techniques and, also to help researchers find a valid testing protocol for estimating the active drag in the future.

METHOD: Ten national and international male swimmers (mean ± standard deviation SD: age= 20.5 years; height= 183 cm; weight= 70.5 kg, FINA point rank of over 750) participated in this research. Swimmers were required to complete all tests in one day starting with a 20 minute warm-up. Swimmers performed at least one practice trial to become familiar with the nature of the experiment and were given 5 minutes rest between each trial to eliminate the influence of fatigue on their performance. Firstly, each swimmer completed two maximum free swim velocity trials over a 20 m interval, starting from 35 m out and the velocity measured over the interval from 25 m to 5 m out from the wall using two 50 Hz cameras. The velocity was averaged to determine the swimmer's maximal free swim velocity. Secondly, two passive drag trials were completed at the swimmer's free swim velocity. Finally, swimmers were then requested to swim four trials with maximum effort whilst a belt was attached around swimmers' waist connected to a dynamometer mounted directly on a calibrated Kistler™ force platform (Kistler Instruments Type Z20916) (Figure 1 and 2). Eight complete stroke cycles were captured for the assisted trials and six complete stroke cycles for the resisted trials. Dynamometer force was adjusted to achieve a velocity of between 5-8% faster and slower than maximum mean swim velocity for the assisted and resisted trials respectively. Subjects were randomised so that half performed the assisted trials before the resisted while the other half reversed this order.

Figure 1: Set up for the Resisted technique

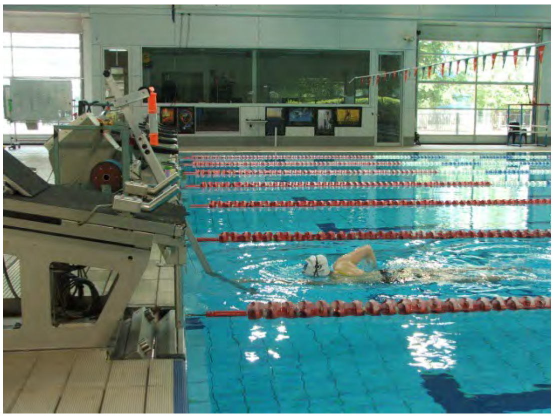

Figure 2: Set up for the Assisted technique

Active drag was calculated from the free swim and towed trials using the formula of Kolmogorov & Duplishcheva (1992):

$$F_d = \frac{F_B V_2 V_1^2}{V_1^3 - V_2^3}$$

Where F_B is the force needed to increase or decrease the swimmer to the desired velocity as measured with the force platform, V_1 is the swimmer's free swim maximum mean velocity, and V_2 is the velocity during the towing trials.

Data was collected using motion analysis software (Contemplas GmbH) and then processed using an export/import function in Contemplas linked to an AIS customized analysis program. The average from two active drag assisted trials and two active drag resisted trials of each subject was calculated to use for the determination of the validity of the techniques. A one-way ANOVA with repeated measures was used to test validity of the technique. SPSS software (Windows version 19) was used for statistical analyses and a statistical significance set at the 95% confidence level ($p<0.05$).

RESULTS: Fluctuating velocity assisted and resisted active drag parameters were computed for each of the swimmers. Mean value (Mean) ± standard deviation (SD) of the passive drag and the assisted and resisted active drag were calculated for each swimmer. Table 1 presents the average active drag value of the assisted and the resisted trials and also, the mean value of passive drag for each swimmer at the maximal swim velocity.

Table 1
The mean values of Assisted, Resisted and Passive drags at the mean maximal swim velocity

Participant	Mean max velocity	Mean Assisted Active drag ± SD	Mean Resisted Active drag ± SD	Mean Passive drag
1	1.80	92.0±5.5	86.8±0.8	94.0±2.51
2	1.91	115.3±0.3	96.0±7.6	109.7±3.6
3	1.92	153.3±1.5	75.2±7.4	108.2±2.3
4	1.79	94.7±8.3	62.0±12.7	103.6±6.3
5	1.82	87.1±3.9	104.3±4.3	76.2±1.8
6	1.88	142.6±6.0	92.7±4.2	92.3±4.3
7	1.99	92.9±5.1	83.5±8.4	91.0±1.5
8	1.83	91.5±2.5	124.4±6.5	93.5±3.6
9	1.74	106.9±4.4	82.1±8.6	103.8±5.8
10	1.76	77.6±4.5	100.9±11.5	76.0±6.5
Mean	1.83	105.3±24.7	90.7±17.1	94.8±12

The average active drags for the assisted and the resisted techniques were 105.3±24.7 N and 90.7±17.1 N respectively and also, the averaged passive drag was 94.8 N. One-way general liner model (ANOVA) revealed no significant differences between the active drag calculated by the assisted and resisted techniques and the passive drag value (p=0.05).

DISCUSSION: In the majority of swimmers, the values of active drag obtained from the assisted technique were higher than the passive drag values; however, the values of active drag calculated from the resisted technique were lower than the passive drag values. Previous resisted techniques have reported that the active drag values were lower than the passive drag values (Kolmogorov and Duplishcheva, 1992; Shimonagata et al., 1998) which were similar to the result of resisted technique of the present study. Although another study by Clarys (1979), estimating active drag from the forces required to change the velocity of swimmer in a flume at constant velocity and reported that their active drag measurement were higher than passive drag. This result is similar to the result of assisted technique of the present study. It seems likely that the contradictions between results are caused by using different techniques.

The results of this study indicate that there was no significant difference between the active drag calculated by the assisted and resisted techniques. This lack of significant difference should be interpreted as being the result of high variability between the active drag values obtained from both techniques (e.g. swimmers 3, 6 and 8) rather than indicating consistency between the two methods. A major component of the difference in active drag values can be explained by the difference in power output between the free swimming trial and the assisted and resisted towing trials. Another study compared the active drag values obtained from the MAD system with the VPM technique (Toussaint et al., 2004). The MAD system calculated the active drag (66.9 N) higher than the VPM technique (53.9 N) at a maximum swim velocity of 1.64 m/s. The result of current study was consistent with Toussaint et al. (2004).

A difference in values between techniques for individual subjects can be explained by the swimmers producing different external power output during each technique. For example: swimmer number 3 had the higher value in the assisted trials, while the swimmer number 8 had the higher value in the resisted trials. Therefore, it seems that the swimmer number 3 produced more power during the assisted trials while, the swimmer number 8 produced more power during the resisted trials. If power was increased during resisted swimming and decreased during assisted swimming (or vice versa), then, that could be another possibility for the difference between the assisted and resisted techniques.

Another issue affecting active drag values from the assisted and resisted techniques could be the assumption that drag is proportional to velocity squared. Toussaint et al. (2004) reported that drag values at different velocities were dependent on the value of the exponent of the power, and found a 20% difference between active drags calculated using the VPM technique and the MAD system at an exponent value of 2.34. Another study utilising the MAD system to examine the effect of the different exponent on the active drag value observed errors of 15% when velocity was raised to a power within the range of 1.9 to 2.8 (Toussaint et al. 1988).

CONCLUSION: The results of this study indicate that there was no significant difference between the active drag values obtained from the assisted and resisted techniques. There was high variability between the two methods in respective of the swimmers having a high or low drag value. The reasons for the high variability between both techniques could be due to unequal power that was produced by each swimmer during towing and free swimming trials, and drag is proportional to velocity squared. Further study should be undertaken to improve testing protocols to achieve much closer values from the both techniques.

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COMPARISON BETWEEN VELOCITY PROFILES OF THE ASSISTED TOWING METHOD AND FREE SWIM VELOCITY

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Active drag is computed based upon three variables: free swimming velocity, towing velocity and belt force. Mason et al. (2011) assumed that the shape of towing velocity profile was similar to the shape of free swim velocity profile. The aim of this study was to compare these two velocities profiles. Four national male swimmers performed two free swim trials using a velocity transducer and two assisted towing trials using the dynamometer. Relative maximum to minimum velocity of the mean value for free swimming trials and the towing trials was approximately 19% and 13% respectively. The different phases of the right arm stroke for both velocity profiles were compared and the result showed significant differences between all phases except the downsweep phase. It can be concluded that using the assisted towing method may change stroke mechanics.

KEYWORDS: Intra stroke velocity, velocity transducer, towing velocity, front crawl

INTRODUCTION: Active drag is the water resistance acting to oppose the swimmer while propelling the body forward (Mason et al., 2011). Therefore, elite swimmers must try to optimise propulsion force, while minimising the drag force. A number of measurement techniques have been developed to assess active drag directly (Clarys, 1979; Hollander et al., 1986) or estimate indirectly (Kolmogorov & Duplishcheva, 1992; Mason et al., 2011), however, there has been controversy, as the techniques used have often reported varying values.

Indirect techniques were designed to estimate active drag based upon three assumptions; the swimmer was able to generate a constant mechanical power output in both conditions (free swimming and swimming with additional drag force), the swimmer maintained a constant mean average velocity during each trial, and that drag was assumed to change in proportion to velocity squared (Kolmogorov & Duplishcheva, 1992; Mason et al., 2011). Mason et al. (2011) determined the value of active drag by towing a swimmer at 5% greater than the mean maximum swim velocity. This Assisted Tow Method (ATM) was designed to allow swimmers to have the natural fluctuations that occur and enabled them to maintain their normal stroke technique whilst being towed.

The advantage of the ATM method with the fluctuating velocity is that it allows the active drag and the towing velocity to be displayed graphically and plotted against time instead of providing only a single mean values (Kolmogorov & Duplishcheva, 1992). To determine the active drag during free swimming, Mason et al. (2011) assumed that the free swim velocity profile is approximately similar to the towing velocity profile, if the mean towing velocity only reduces 5% to 8%. However, no research has examined the relationship between the free swim velocity and the towing velocity, whether a similarity exists as proposed by previous research (Mason et al., 2011). The purpose of this research was to compare the towing velocity profile with the free swimming velocity profile.

METHOD: Four national level male swimmers (FINA point rank of over 700) participated in this research. Participants were required to complete all tests in one day starting with a 20 minute warm-up before performing at least one practice trial. Swimmers were then given 5 minutes rest between each trial to eliminate the influence of fatigue on their performance.

Each participant completed two free swim trials at maximum effort. To determine intra stroke velocity fluctuations, a velocity transducer device, developed and constructed at the Australian Institute of Sport was used, similar to the cable speed meter devised by Vilas-Boas et al. (2010). A belt was attached to the back of the swimmers' waist and a non-stretch cable attached to the belt by a reel. A small amount of force maintained a tension on the cable and prevented oscillations on the cable. Swimmers started from the wall and the velocity profile was recorded between the 7.5 m and 20 m locations down the pool. A trigger

was used to synchronise the video footage with the velocity data for identifying different phases of a stroke. Two side-on cameras were located on the pool deck to capture underwater video (Swim pro analogue camera) and above water video (Model 301 underwater video analogue camera, Applied Micro video, USA). Both cameras were mounted on a moveable trolley that travelled along beside the swimmer. Images were mixed with an Edirol video mixer (EDI-8V).
Participants were then requested to swim two trials at maximum effort whilst attached to a dynamometer mounted directly on a calibrated Kistler™ force platform (Kistler Instruments Type Z20916) via a belt around the swimmers' waist (Figure 1). Four complete stroke cycles were captured starting from 20 m out from the wall to capture active drag trials. The cable pulled the swimmers at approximately 5% to 8% higher than their free swim velocity with a maximum force level set low enough to allow intra-stroke velocity fluctuations to occur (Mason et al., 2011). The maximum force level was set between 25% to 50% of passive drag force and adjusted if assisted swim velocity was not between the range of 5% to 8% more than free swim velocity.

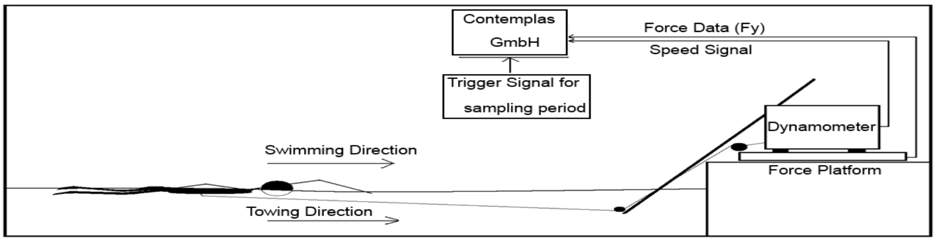

Figure 1: Assisted Towing Method set up

To analyse the velocity distribution within stroke cycle, five stroking phases were used as described by Maglischo (2003) including: entry and stretch, downsweep to catch, insweep, upsweep and recovery phase. The average of each phase of right arm was obtained from two right arm strokes. A Paired t-test was used to compare each phase of free swim velocity and each phase of towing velocity. SPSS software (Windows version 19) was used for statistical analyses and a statistical significance set at the 95% confidence level ($p<0.05$).

RESULTS AND DISCUSSION: The purpose of this study was to obtain the towing velocity profile from the ATM method. The velocity profiles obtained from the ATM method was compared with the free swimming velocity profiles obtained from the velocity transducer. Both the free swim velocity profile and the towing velocity profile of one of the subjects are presented in figure 2. Observation of the profiles indicated that the free swim velocity profile obtained from the velocity transducer was not identical to the tow velocity profile obtained using the dynamometer.
As expected, the mean tow velocity of swimmers was 5% to 8% greater (2.05±0.04 m/s) than that of the mean free swim velocity (1.92±0.02 m/s); however, there was greater variation between the maximum and the minimum velocities in each stroke for the free swim trial. Regardless of the swimmer's level, the relative maximum to minimum velocity of the free swim trials were approximately 19% of the mean free swim velocity and for the assisted towing trials were approximately 13% of the mean tow velocity. The dynamometer prevented the velocity of the swimmer from decreasing during the non-propulsive phase as much as in the free swimming (Figure 3). The dynamometer applies enough force to maintain velocity of the swimmer near to the target average velocity as set up on the dynamometer. Therefore, during the towing, if the instantaneous velocity of the swimmer decreases (recovery and hand entry phases) below the target average velocity, the dynamometer force automatically increases to prevent the velocity of swimmer dropping too far below the target velocity. On the other hand, if the instantaneous velocity of the swimmer increases above the target velocity then the dynamometer reduces the dynamometer force. Therefore, the swimmers did not swim too fast (Figure 2) and are able to maintain their normal stroke mechanics.
The result of this study in regards to the relative maximum to minimum velocity in free swimming was in line with Craig and Pendergast (1979) (20%) but not with Psycharisk et al.

(2010) (11%). The large differences between the results of previous studies are due to the different methodologies. Craig and Pendergast (1979) measured velocity of the hip using a speed cable. However, Psycharisk et al. (2010) measured velocity of the centre of mass calculated from film. The centre of mass method would be expected to have less variation because of the mutual movement of the arms.

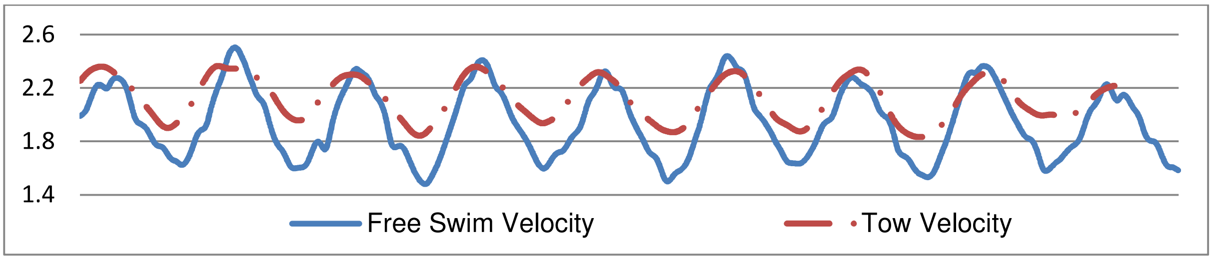

Figure 2: Free swim velocity profile from the velocity transducer and the tow velocity profile using the dynamometer of subject 1

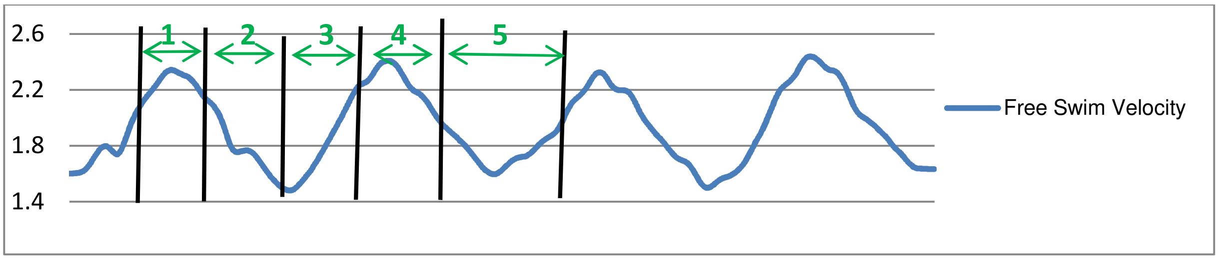

Figure 3: Free swim velocity profile for subject 1. 1=right hand entry and stretch, 2=right hand downsweep and catch, 3=right hand insweep, 4=right hand upsweep, 5=right hand recovery (Maglischo, 2003)

Mason et al. (2011) compared the velocity and active drag profiles obtained from the ATM method at a constant velocity with the velocity and active drag profiles obtained from the ATM method with fluctuating velocity. It was reported that the constant towing velocity profile had less variation from minimum to maximum velocities in the stroke, than the fluctuating towing velocity profile. Also, the constant towing velocity had a smoother shape than the fluctuating towing velocity. However, the result of this study indicated that the towing velocity graphs obtained from the dynamometer had a smoother shape than the free swim velocity graphs obtained from the velocity transducer (Figure 2). According to the results of Mason et al. (2011) and this study, it can be concluded that although the ATM method has a fluctuating velocity, these fluctuations are not as large as those that occur during free swimming.

Table 1
The time spent on each phase, as a percentage of a single right hand stroke (mean ± s)

	E&SP	DS&CP	ISP	USP	RP	Propulsive	Non-propulsive
Free swim	17.0±3.2*	16.7±2.9	13.2±1.9*	16.6±1.5*	36.5±2.7*	46.5±5.6	53.5±5.6
Tow Trial	23.8±5.7	16.7±1.5	11.8±2.4	15.3±2.1	33.7±1.5	43.8±6.4	57.5±6.0

E & S = Entry and Stretch Phase; DS & C P = Downsweep and Catch Phase; ISP = Insweep Phase; UPP = Upsweep Phase; RP = Recovery Phase; * = statistically different between free swim velocity and towing velocity at p<0.05 level

Table 1 presents the mean percentage value ± SD of the time spent by the subjects for each phase. Statistically significant differences were found between the insweep phases (p=0.031), the upsweep phases (p=0.039) and the recovery phases (p=0.037) of the free swimming velocity versus the towing velocity. The subjects spent shorter time during these three phases for the towing trials than the free swimming trials. It is suggested that the swimmers encountered a smaller amount of resistive force by the water while towing, therefore increasing the swimming velocity and spending a shorter time during the insweep, upsweep and recovery phases.

Another significant difference was found between the entry and stretch phases of the towing trials versus the free swimming trials (p=0.046). The subjects spent a longer time during the entry and stretch phase in the towing trials than in the free swimming trials. It is likely that by spending more time during the entry and stretch phase while towing, the subjects attempted to maintain their arm coordination, as the other arm spent more time during the recovery phase. On the other hand, no significant differences were observed for the downsweep and catch phase between two trials (p=0.99). In summary, although significant differences were found for all phases except the downsweep, no significant differences were observed between the propulsive phases (p=0.19) and non-propulsive phase of the free swimming trials versus the towing trials (p=0.12). Therefore, it can be concluded that towing faster than their mean maximum velocity may change stroke mechanics.

CONCLUSION: This study measured the velocity profile of free swimming using the velocity transducer to evaluate whether the dynamometer measures a similar towing velocity to that of the free swim velocity. The result of this study indicated that the free swim velocity profiles had greater variations from the maximum to the minimum points during intra stroke (19% of the mean free swim velocity) than the towing velocity profiles (13% of the mean towing velocity). Also, the shape of towing velocity is smoother than the free swim velocity. Therefore, the result of this study showed that the towing velocity profile does not closely resemble that of the free swimming velocity profile. The assumption of a consistent velocity pattern between free and assisted swimming has not been demonstrated, therefore, further methods to obtain velocity fluctuations during the ATM towing should be considered.

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Australian Institute of Sport

MINUTE

TO:	Pendar Hazrati	CC:
FROM:	Ms Helene Rushby	
SUBJECT:	Approval from AIS Ethics Committee	DATE: 19th October 2012

On the 9th of October 2012, the AIS Ethics Committee gave consideration to your submission titled "Reliability of estimating active drag using the Assisted Towing Method with fluctuating velocity:" The Committee saw no ethical reason why your project should not proceed.

The approval number for this project: 20121004

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design,
Any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577

Sincerely
Helene Rushby
Secretary, AIS EC

THE UNIVERSITY OF SYDNEY

RESEARCH INTEGRITY
Human Research Ethics Committee
Web: http://sydney.edu.au/research_support/ethics/human/
Email: ro.humanethics@sydney.edu.au
Address for all correspondence:
Level 6, Jane Foss Russell Building - G02
The University of Sydney
NSW 2006 AUSTRALIA

GD/KR

15 November 2012

Dr Peter Sinclair
Discipline of Exercise and Sports Science
Faculty of Health Science
The University of Sydney
Email: peter.sinclair@sydney.edu.au

Dear Dr Sinclair

Title: Reliability of estimating active drag using the Assisted Towing Method with fluctuating velocity

Protocol No. 15488

PhD Student: Mrs Pendar Hazratiashtiani

The Executive of the Human Research Ethics Committee (HREC) has reviewed your study to include the PhD student – Mrs Pendar Hazratiashtiani and acknowledges your right to proceed under the authority of Australian Institute of Sport Ethics Committee.

The Human Research Ethics Committee advises that you consult with The University of Sydney **Audit and Risk Management Office** (http://sydney.edu.au/audit_risk/) to ensure that University of Sydney staff/students and premises are adequately covered for the purpose of conducting this research project.

Any modifications to the study must be approved by Australian Institute of Sport Ethics Committee. A copy of the approved modification, approved progress report and any new approved documents must be provided to The University of Sydney HREC for our records.

Please do not hesitate to contact Research Integrity (Human Ethics) should you require further information or clarification.

Yours Sincerely

Glen Davis
E

Professor Glen Davis
Chair
Human Research Ethics Committee

cc Mrs Pendar Hazratiashtiani [Email: Pendar.hazratiashtiani@ausport.gov.au]
Dr Rene Ferdinands [Email: Edouard.ferdinands@sydney.edu.au]
Dr Bruce Mason [Email: Bruce.Mason@ausport.gov.au]

Australian Institute of Sport

MINUTE

TO:	Ms Pendar Hazrati	CC:	
FROM:	Ms Helene Rushby		
SUBJECT:	Approval from AIS Ethics Committee	DATE: 17th December 2012	

On the 11th of December 2012, the AIS Ethics Committee gave consideration to your submission titled "**Establish a method to estimate active drag using resistance that incorporates a fluctuating velocity**". The Committee saw no ethical reason why your project should not proceed.

The approval number for this project: 20121204

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design,
Any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577

Sincerely
Helene Rushby
Secretary, AIS EC

Research Integrity
Human Research Ethics Committee

Wednesday, 13 February 2013

Dr Peter Sinclair
Exercise Health and Performance; Faculty of Health Sciences
Email: P.Sinclair@usyd.edu.au

Dear Peter

Title: Establish a method to estimate active drag using resistance that incorporates a fluctuating velocity

Project No: 2013/066

PhD Student: Pendar Hazrati

The Executive of the Human Research Ethics Committee (HREC) has reviewed your study to include the PhD student **Pendar Hazrati** and acknowledges your right to proceed under the authority of AIS Ethics Committee.

The Human Research Ethics Committee advises that you consult with The University of Sydney **Audit and Risk Management Office** (http://sydney.edu.au/audit_risk/) to ensure that University of Sydney staff/students and premises are adequately covered for the purpose of conducting this research project.

Any modifications to the study must be approved by the AIS Ethics Committee. A copy of the approved modification, approved progress report and any new approved documents must be uploaded onto IRMA.

Please do not hesitate to contact Research Integrity (Human Ethics) should you require further information or clarification.

Yours sincerely

Glen Davis
E

Professor Glen Davis
Chair
Human Research Ethics Committee

Research Integrity
Research Portfolio
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ABN 15 211 513 464
CRICOS 00026A

Australian Institute of Sport

MINUTE

TO:	Ms Pendar Hazrati	CC:	
FROM:	Ms Helene Rushby		
SUBJECT:	Approval from AIS Ethics Committee	DATE:	14th April 2014

On the 8th April 2014, the AIS Ethics Committee gave consideration to the minor variation in your submission titled "***The effect of breathing o0n active drag while swimming".*** The Committee saw no ethical reason why your project should not proceed.

The approval number for this project remains as: 20130403

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design,
Any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

Please note the approval for this submission expires on the 30th June 2016 after which time an extension will need to be sought.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577

Sincerely

Heléne Rushby
Secretary, AIS EC

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Participant Information Sheet

The aim of this research is to estimate active drag by using the Assisted Tow Method at the Aquatic Testing, Training and Research Unit of the AIS. Drag is a resistance force exerted by the surrounding water on the swimmer. Such resistive forces affect forward movement of the swimmer. This project is involved in exploring effective resistive forces on the swimmer's performance.

The project is being completed as one part of a PhD in the Biomechanics of Exercise degree that I am undertaking in the discipline of Exercise and Sport Science, Faculty of Health Sciences at University of Sydney. When it is completed, the thesis will be made available as a published document at the University of Sydney and AIS. Also, some of the results gathered in the course of this project may take other published forms such as journal articles or references books.

In this research, participants will be requested to complete four free swimming trials to measure their maximum swim velocity. Then, three passive drag trials will be completed where swimmers are towed by a cable at their mean maximum swim velocity which acquired from their free swimming trials as the tow speed. Participants will perform free swimming and passive trials over a 10 meter interval and starting from 25 meter mark. During passive drag trials, swimmer holds onto a plastic handle attached to a cord and the body will be in streamline position (shoulders fix with the arms together and stretch tightly overhead, and with one hand place over the other). Finally, five active drag trials will be completed at approximately 5% greater than maximum swim velocity. Active drag tests will be performed using a motor to tow participants via a cable attached to a belt while swimming over a 10 meter interval and staring from 25 meter mark. During free swimming, passive drag and active drag trials, participants will be requested to hold their breathing for 20 meters. A 20 minute race warm up and one familiarisation trial before each phase of testing will be given. Three high speed cameras will be used and placed on the side of pool deck and under the water to film each trial and software will be used to analysis the data captured. This entire protocol will be repeated on two separate days and each session will be run for one hour.

The research and data collection will be conducted in the AIS, Canberra. The risks involved in this study will be minimal. Participants will perform the same testing protocols already in use to estimate active drag at AIS. Also, I will give a feedback to your coaches and they will be able to give you feedback. Your data and reports will be provided confidentially to you and your coach.

Participants are invited to participate in this research only if they have time and inclination to do so, and only so much as their time and willingness permit. I intend to implement the testing protocols with participants at AIS at times convenient to them. I will seek participants by asking via email, on the telephone, or face to face communication from their coaches. I will obtain written informed consent from you if you agree to participate in this research. Participants are free to

withdraw from participation any time they wish and no reason for withdrawal need to be given. If a participant withdraws for any reason at all, the data they have provided to the point of withdrawal will be destroyed.

The identification of all participants through all stages of this research will be coded and de-identified. Published results will not contain identifiable data. All data, including video footages, analysis data, results and reports will be treated confidentially and stored securely.

Further to above, the participants are free to raise any query regarding the research projects by contacting me or my supervisors, Dr. Bruce Mason and Dr. Peter Sinclair.

Mrs. Pendar Hazratiashtiani
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Pendar.hazratiashtiani@ausport.gov.au

Dr. Bruce Mason
Head of Aquatics Testing Training and Research Unit
Australian Institute of Sport
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Bruce.Mason@ausport.gov.au

Dr. Peter Sinclair
Senior Lecturer in Exercise and Sport Science
Discipline of Exercise and Sport Science
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East Street, Lidcombe C42-Cumberland Campus
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0293519724
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Please, note that the ethical aspects of this research will be approved by the AIS Ethics Committee and the University of Sydney Human Research Ethics Committee. If you have any concerns or complaints about how this research has been conducted, please contact:

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Tel: +61262141577
Email: helene.rushby@ausport.gov.au

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Participant Information Sheet

The aim of this research is to estimate active drag by using both an Assisted and Resisted Method at the Aquatic Testing, Training and Research Unit of the AIS. Drag is a resistance force exerted by the surrounding water on the swimmer. Such resistive forces affect forward movement of the swimmer. This project is involved in exploring resistive forces on the swimmer's performance.

The project is being completed as one part of a PhD in the Biomechanics of Exercise degree that I am undertaking in the discipline of Exercise and Sport Science, Faculty of Health Sciences at the University of Sydney. When it is completed, the thesis will be made available as a published document at the University of Sydney and AIS. Also, some of the results gathered in the course of this project may take other published forms such as journal articles or in references books.

In this research, participants will be requested to complete two maximum effort free swimming trials to measure their maximum mean swim velocity. Then, two passive drag trials will be completed, where swimmers are towed by a cable using their maximum mean swim velocity, acquired from their free swimming trials. Participants will perform free swimming and passive trials over a 20 meter interval and starting from 25 meter mark. During the passive drag trials, the swimmers holds onto a plastic handle attached to a cord and while their body will be retained in streamline position (shoulders fixed with the arms together and stretched tightly overhead, and with one hand placed over the other). Finally, Participants will then be requested to swim four trials with maximum effort whilst attach to a cable. Randomly, half of participants will be requested to perform the first two trials using Assisted Method at approximately 5% higher than their maximum mean swim velocity. Then next two trials using Resisted Method will be completed at approximately 5% less than their maximum mean swim velocity. For the other half, the trials will be completed vice versa. Active drag tests (Assisted trials) will be performed using a dynamometer to tow participants via a cable attached to a belt while swimming over a 20 meter interval and staring from 25 meter mark. Active drag tests (Resisted trials) will be started from wall and finished at 25 meter mark. During free swimming, passive drag and active drag trials, participants will be requested to hold their breathing for 20 meters. A 20 minute race warm up and one familiarisation trial before each phase of testing will be given. Three high speed cameras will be used and placed on the side of pool deck and under the water to film each trial. Software will be used to analysis the data captured. This entire protocol will be completed in a single testing session and session will be run for 45 minutes.

The research and data collection will be conducted at the AIS, in Canberra. The risks involved in this study will be minimal. Participants will perform the same testing protocols already in use to estimate active drag at AIS. I will give a feedback to your coaches and they will be able to give you feedback. Your data and reports will be provided confidentially to you and your coach.

Participants are invited to participate in this research only if they have time and inclination to do so, and only so much as their time and willingness permit. I intend to implement the testing

protocols with participants at the AIS at times convenient to them. I will seek participants by asking via email, on the telephone, or face to face communication with their coaches. I will obtain written informed consent from you if you agree to participate in this research. Participants will be free to withdraw from participation at any time they wish, with no reason being required for withdrawal. If a participant withdraws for any reason at all, the data they have provided to the point of withdrawal will be destroyed.

The identification of all participants through all stages of this research will be coded and de-identified. Published results will not contain identifiable data. All data, including video footages, analysis data, results and reports will be treated confidentially and stored securely.

Further to above, the participants are free to raise any query regarding the research projects by contacting me or my supervisors, Dr. Bruce Mason and Dr. Peter Sinclair.

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Participant Information Sheet

The aim of this research is to determine the velocity profile of swimmer during free swim and compare with the tow velocity profiles of the assisted and resisted techniques at the Aquatic Testing, Training and Research Unit of the AIS. This project is involved in exploring resistive forces on the swimmer's performance during free swimming.

The project is being completed as one part of a PhD in the Biomechanics of Exercise degree that I am undertaking in the discipline of Exercise and Sport Science, Faculty of Health Sciences at the University of Sydney. When it is completed, the thesis will be made available as a published document at the University of Sydney and AIS. Also, some of the results gathered in the course of this project may take other published forms such as journal articles or in references books.

In this research, participants will be requested to complete two maximum effort free swimming trials to measure their maximum mean swim velocity (with breathing). A nylon cable will be attached to a belt around swimmer's waist and the other end connected to a velocity transducer which will be mounted at the end of the pool during free swim to measure instantaneous velocity in stroke. Then, two passive drag trials will be completed, where swimmers are towed by a cable using their maximum mean swim velocity, acquired from their free swimming trials. Participants will perform free swimming and passive trials over a 20 meter interval starting from the 30 meter mark. During the passive drag trials, the swimmers holds onto a plastic handle attached to a cord while their body will be retained in streamline position (shoulders fixed with the arms together and stretched tightly overhead, and with one hand placed over the other). Finally, Participants will then be requested to swim four trials with maximum effort whilst attach to a cable. Randomly, half of participants will be requested to perform the first two trials using Assisted Method (with breathing) at approximately 5% higher than their maximum mean swim velocity. Following this, next two trials using Resisted Method (with breathing) will be completed at approximately 5% less than their maximum mean swim velocity. For the other half of the subjects, the trials will be completed in reverse order. Active drag tests (Assisted trials) will be performed using a dynamometer to tow participants via a cable attached to a belt while swimming over a 20 meter interval and staring from 25 meter mark for eight full strokes. Active drag tests (Resisted trials) will be started from the wall and count eight full strokes from 7.5 meter and finished approximately at the 25 meter mark. During passive drag trials, participants will be requested to hold their breathing for 20 meters. A 20 minute race warm up and one familiarisation trial before each phase of testing will be given. Three high speed cameras will be used and placed on the side of pool deck and under the water to film each trial. Software will be used to analysis the data captured. This entire protocol will be completed in a single testing session and session will be run for 45 minutes.

The research and data collection will be conducted at the AIS, in Canberra. The risks involved in this study will be minimal. Participants will perform the same testing protocols already in use to estimate active drag at AIS. I will give a feedback to your coaches and they will be able to give you feedback. Your data and reports will be provided confidentially to you and your coach.

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Active Drag Swimming Research
'INFORMED CONSENT' FORM (Adult)

Project Title: Reliability of estimating active drag using the Assisted Towing Method with fluctuating velocity

Principal Researchers:

Mrs. Pendar Hazratiashtiani	Australian Institute of Sport/University of Sydney
Mr. Bruce Mason	Australian Institute of Sport
Mr. Peter Sinclair	University of Sydney

This is to certify that I,………………………..hereby agree to participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Pendar Hazratiashtiani. The investigation and my part in the investigation have been defined and fully explained to me by Pendar Hazratiashtiani and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.
- I understand that I am free to withdraw my data from analysis without disadvantage to myself.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- I understand that video footage of my swimming will be captured as part of the research procedure. It will be kept in a computer accessible only by password and stored securely at the Australian Institute of Sport.
- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.
- I am participating in this project of my own free will and I have not been coerced in any way to participate.

Signature of Subject: ________________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ______________________________ Date: ___/___/___

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Active Drag Swimming Research
'INFORMED CONSENT' FORM (Minor)

Project Title: Reliability of estimating active drag using the Assisted Towing Method with fluctuating velocity

Principal Researchers:

Mrs. Pendar Hazratiashtiani	Australian Institute of Sport/University of Sydney
Mr. Bruce Mason	Australian Institute of Sport
Mr. Peter Sinclair	University of Sydney

This is to certify that I,………………..hereby agree to give permission to have my child participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Pendar Hazratiashtiani.

The investigation and my child's part in the investigation have been defined and fully explained to me by Pendar Hazratiashtiani and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions my child or myself may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that my child is free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that my child is free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage.
- I understand that my child is free to withdraw his/her data from analysis without disadvantage.
- I understand that any data or answers to questions will remain confidential with regard to my child's identity.
- I understand that video footage of my child swimming will be captured as part of the research procedure. It will be kept in a computer accessible only by password and stored securely at the Australian Institute of Sport.
- I certify to the best of my knowledge and belief, my child has no physical or mental illness or weakness that would increase the risk to my child of participating in this investigation.
- My child is participating in this project of his/her own free will and my child has not been coerced in any way to participate.

Signature of Participant: ________________________________ Date: ___/___/___
Signature of Parent or
Guardian of minor: (under 18 years) _______________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ______________________________ Date: ___/___/___

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Active Drag Swimming Research
'INFORMED CONSENT' FORM (Minor)

Project Title: Establish a method to estimate active drag using resistance that incorporates a fluctuating velocity

Principal Researchers:

Mrs. Pendar Hazrati	Australian Institute of Sport/University of Sydney
Mr. Bruce Mason	Australian Institute of Sport
Mr. Peter Sinclair	University of Sydney

This is to certify that I,………………..hereby agree to give permission to have my child participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Pendar Hazrati.
The investigation and my child's part in the investigation have been defined and fully explained to me by Pendar Hazrati and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

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- I understand that any data or answers to questions will remain confidential with regard to my child's identity.
- I understand that video footage of my child swimming will be captured as part of the research procedure. It will be kept in a computer accessible only by password and stored securely at the Australian Institute of Sport.
- I certify to the best of my knowledge and belief, my child has no physical or mental illness or weakness that would increase the risk to my child of participating in this investigation.
- My child is participating in this project of his/her own free will and my child has not been coerced in any way to participate.

Signature of Participant: ________________________________ Date: ___/___/___
Signature of Parent or
Guardian of minor: (under 18 years) ______________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ______________________________ Date: ___/___/___

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Active Drag Swimming Research
'INFORMED CONSENT' FORM (Adult)

Project Title: Establish a method to estimate active drag using resistance that incorporates a fluctuating velocity

Principal Researchers:

Mrs. Pendar Hazrati	Australian Institute of Sport/University of Sydney
Mr. Bruce Mason	Australian Institute of Sport
Mr. Peter Sinclair	University of Sydney

This is to certify that I,………………………..hereby agree to participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Pendar Hazrati. The investigation and my part in the investigation have been defined and fully explained to me by Pendar Hazrati and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

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- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.
- I understand that I am free to withdraw my data from analysis without disadvantage to myself.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- I understand that video footage of my swimming will be captured as part of the research procedure. It will be kept in a computer accessible only by password and stored securely at the Australian Institute of Sport.
- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.
- I am participating in this project of my own free will and I have not been coerced in any way to participate.

Signature of Subject: ________________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ______________________________ Date: ___/___/___

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Active Drag Swimming Research
'INFORMED CONSENT' FORM (Minor)

Project Title: A comparison between the towing velocity profiles obtained from Assisted and Resisted techniques with the velocity profile during free swimming

Principal Researchers:

Mrs. Pendar Hazrati	Australian Institute of Sport/University of Sydney
Mr. Bruce Mason	Australian Institute of Sport
Mr. Peter Sinclair	University of Sydney

This is to certify that I,………………..hereby agree to give permission to have my child participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Pendar Hazrati.
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- I understand that video footage of my child swimming will be captured as part of the research procedure. It will be kept in a computer accessible only by password and stored securely at the Australian Institute of Sport.
- I certify to the best of my knowledge and belief, my child has no physical or mental illness or weakness that would increase the risk to my child of participating in this investigation.
- My child is participating in this project of his/her own free will and my child has not been coerced in any way to participate.

Signature of Participant: ________________________________ Date: ___/___/___
Signature of Parent or
Guardian of minor: (under 18 years) ______________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ______________________________ Date: ___/___/___

AUSTRALIAN INSTITUTE OF SPORT

Leverrier Crescent Bruce ACT 2617
PO Box 176 Belconnen ACT 2616
ABN 67 374 695 240

Tel 61 2 6214 1111
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www.ausport.gov.au

Active Drag Swimming Research
'INFORMED CONSENT' FORM (Adult)

Project Title: A comparison between the towing velocity profiles obtained from Assisted and Resisted techniques with the velocity profile during free swimming

Principal Researchers:

Mrs. Pendar Hazrati	Australian Institute of Sport/University of Sydney
Mr. Bruce Mason	Australian Institute of Sport
Mr. Peter Sinclair	University of Sydney

This is to certify that I,………………………..hereby agree to participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Pendar Hazrati. The investigation and my part in the investigation have been defined and fully explained to me by Pendar Hazrati and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.
- I understand that I am free to withdraw my data from analysis without disadvantage to myself.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- I understand that video footage of my swimming will be captured as part of the research procedure. It will be kept in a computer accessible only by password and stored securely at the Australian Institute of Sport.
- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.
- I am participating in this project of my own free will and I have not been coerced in any way to participate.

Signature of Subject: ________________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ______________________________ Date: ___/___/___

KISTLER
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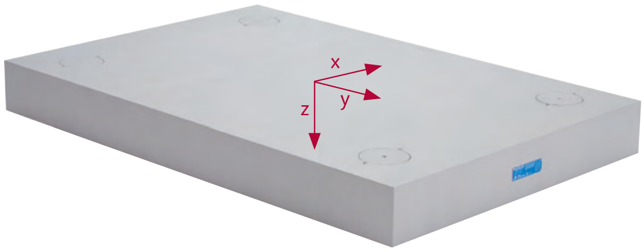
Multicomponent Force Plate

Type 9287C...

Large – for Dynamic Applications in Biomechanics, F_z –10 ... 20 kN

Multicomponent force plate with wide range for measuring ground reaction forces, moments and the center of pressure in biomechanics.

- Extremely wide measuring range
- Excellent measuring accuracy
- High natural frequency
- Versatile
- Threshold F_z <250 mN
- Large dimensions



Description

The multicomponent force plate Type 9287C... consists of a 900x600 mm aluminum sandwich top plate of advanced, lightweight construction and four built-in piezoelectric 3-component force sensors. Thus it is extremely rigid overall, and allows measurements over a very wide useful frequency range.

Thanks to the special properties of the piezoelectric sensors, the force plate is highly sensitive and can simultaneously measure very dynamic phenomena involved in a wide range of applications.

Application

This force plate is designed specifically for use in basic research and sport. Its large size, wide measuring range and high rigidity allow it to be employed for a very wide spectrum of measuring tasks and application sectors. Despite the very generous measuring range of –10 ... 20 kN, it offers excellent accuracy and linearity and even under a large preload allows precise measurement of minute forces. In all these situations the force plate can be mounted in any position without affecting the measurement result in any way.

The Type 9287CA has an built-in charge amplifier compatible with all of the common motion analysis systems.

9287C_000-712e-02.14

Technical Data

Dimensions		mm	900x600x100
Measuring range	F_x, F_y	kN	–10 ... 10
	F_z	kN	–10 ... 20
Overload	F_x, F_y	kN	–13/13
	F_z	kN	–10/25
Linearity		%FSO	<±0,2
Hysteresis		%FSO	<0,3
Crosstalk	F_x <–> F_y	%	<±1,5
	F_x, F_y –> F_z	%	<±1,5
	F_z –> F_x, F_y	%	<±0,5 [1]
Rigidity	x-axis ($a_y = 0$)	N/µm	≈150
	y-axis ($a_x = 0$)	N/µm	≈200
	z-axis ($a_x = a_y = 0$)	N/µm	≈30
Natural frequency	f_n (x, y)	Hz	≈750
	f_n (z)	Hz	≈520
Operating temperature range		°C	0 ... 60
Weight		kg	25
Degree of protection	EN 60529:1992		IP65

Force Plate without Charge Amplifier, Type 9287C

Calibrated range	F_x, F_y	kN	0 ... 10
	F_z	kN	0 ... 20
Calibrated partial range	F_x, F_y	kN	0 ... 1
	F_z	kN	0 ... 2
Threshold	F_x, F_y, F_z	mN	<50
Sensitivity	F_x, F_y	pC/N	–7,5 [2]
	F_z	pC/N	–3,8 [2]

[1] inside sensor rectangle
[2] nominal value

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Force Plate with Built-in 8 Channel Charge Amplifier, Type 9287CA

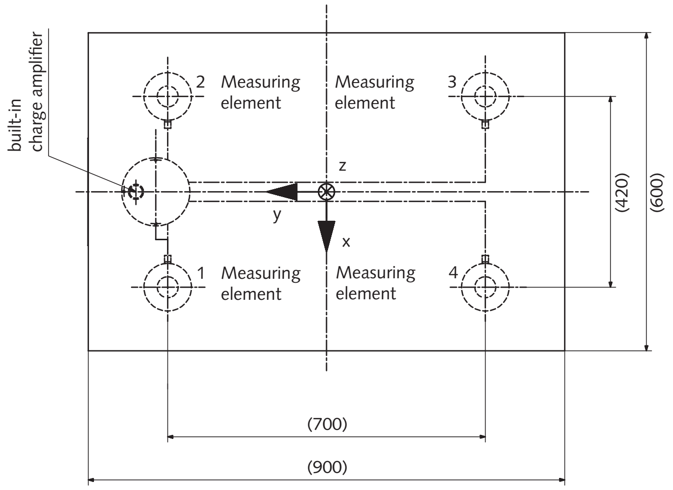
Calibrated range	F_x, F_y	kN	0 ... 5
	F_z	kN	0 ... 20
Calibrated partial range	F_x, F_y	kN	0 ... 1,25
	F_z	kN	0 ... 5
Sensitivity range 1	F_x, F_y	mV/N	≈40 [2)]
	F_z	mV/N	≈18 [2)]
Sensitivity range 4	F_x, F_y	mV/N	≈2,0 [2)]
	F_z	mV/N	≈0,9 [2)]
Ratio ranges 1:2:3:4			1 : 5 : 10 : 20 [3)]
Threshold		mN	<250 [4)]
Drift		mN/s	<±10
Supply voltage		VDC	10 ... 30
Supply current		mA	≈45

Output voltage	V	0 ... ±5
Output current	mA	–2 ... 2
Control inputs (optocoupler)	V	5 ... 45
	mA	0,4 ... 4,4

[2)] nominal value
[3)] ±0,5 % accuracy
[4)] only range 1

Conforms to the CE safety standards (73/23/EG) for electrical equipment and systems:
EN 60601-1:2005, EN 61010-1:2001
and the EMC standards (89/336/EG):
EN 60601-1:2005 (EN 55022 Class B), EN 61000-6-3:2004 (EN 55022 Class B), EN 61000-6-4:2001 (EN 55011 Class B), EN 60601-1:2005, EN 61000-6-1:2001, EN 61000-6-2:2005

Dimensions



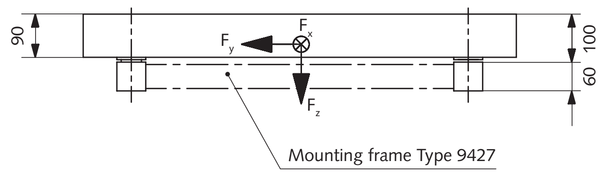


Fig. 1: Dimensions of the large multicomponent force plate Type 9287CA

9287C_000-712e-02.14

BioWare®

BioWare software is the engine behind the force plate system. It collects data from the force plates, converts the trials into useful information and plots the results. The force plates and charge amplifiers are fully remote controlled by BioWare thus making the system extremely flexible and easy-to-use.

Parameters of Gait

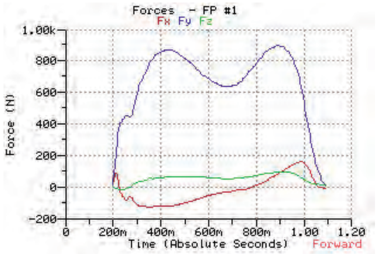


Fig. 2: Ground reaction forces (GRF)

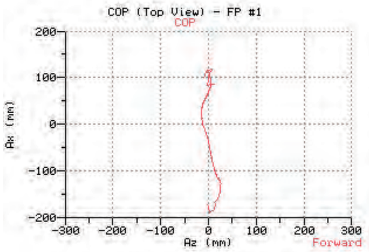


Fig. 3: Center of pressure (COP)

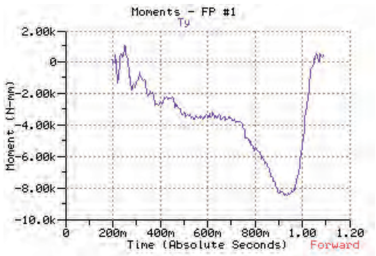


Fig. 4: Frictional torque T_z

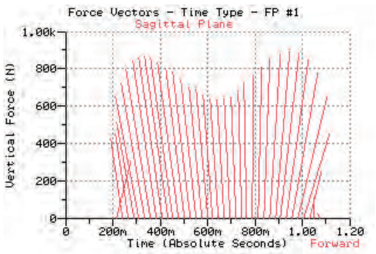


Fig. 5: Force vector

BioWare provides several performance specific evaluations.

Parameters of Countermovement Jump CMJ

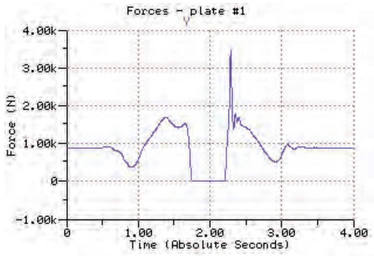


Fig. 6: Jump force

Fig. 7: Power

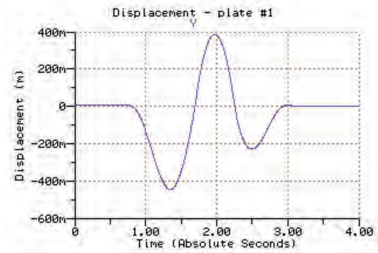


Fig. 8: Jump height (COM)

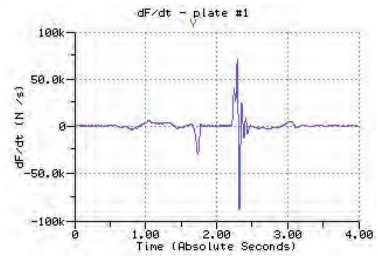


Fig. 9: Force gradient (Explosivity)

Other functions

- Coefficient of friction (COF)
- Frequency analysis, statistics, digital filters
- Full Windows® functionality

Other parameters

- Acceleration, velocity and displacement of the center of mass (COM)
- Work, energy, impulse
- Statistics, digital filters

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Typical Measuring Chains

	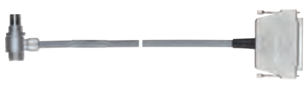		
Force plate with charge amplifier Type 9287CA	Connection cable Type 1759A...	DAQ system (USB 2.0) Type 5691A1	Laptop (provided by user) with BioWare

Fig. 10: Configuration of a typical measuring chain

			Ch 1 = F_x 1+2 Ch 5 = F_z 1 Ch 2 = F_x 3+4 Ch 6 = F_z 2 Ch 3 = F_y 1+4 Ch 7 = F_z 3 Ch 4 = F_y 2+3 Ch 8 = F_z 4
Force plate with charge amplifier Type 9287CA	Connection cable Type 1757A...	External Control Unit (8xBNC neg.) Type 5233A2	DAQ system provided by user (8 analog channels)

Fig. 11: Configuration of a typical measuring chain

Included Accessories	**Type/Art. No.**
For Type 9287C...	
• 1 Shim set	7.050.011
• 4 Eye bolts M6 with washers	6.170.007 6.220.040
• 4 Hexagon socket head cap screws M12x25	6.120.106
• 1 Hexagon socket wrench	1391
• 1 Voltage equalizing cable	5.590.175
• 4 Installation handles	7.511.437

Optional Accessories	**Type/Art. No.**
For Type 9287CA with built-in charge amplifier	
• 16ch DAQ-System for BioWare (USB 2.0)	5691A1
• Connection cable for 5691A, angle plug	1759A...
• 64ch DAQ-System for BioWare (USB 2.0)	5695B1
• Connection cable for 5695B, angle plug	1700A105A...
• External Control Unit (BNC out)	5233A2
• Connection cable for Type 5233A...	1757A...
• DAQ system BioWare (PCI-Bus)	2812A...

For Type 9287C with charge output	
• External charge amplifier	9865E...
• Connection cable, angle plug	1686A...
• DAQ system BioWare (PCI-Bus)	2812A...

Mounting frame for Type 9287C...	
• Standard mounting frame	9427
• Other mounting frames for multiple installations	on request

Ordering Key

Type 9287C ☐

Large Multicomponent Force Plate	
with charge output	–
with built-in charge amplifier	A

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BioWare® is a registered trade mark of Kistler Holding AG

EMERSON
Industrial Automation

Unidrive SP

Universal AC Drive Solutions Platform

0.37kW to 1.9MW
200V / 400V / 575V / 690V

CONTROL TECHNIQUES
www.controltechniques.com

The ultimate intelligent AC drive

Performance and flexibility allows you to do something new, creating opportunities to innovate, find better ways to control your application, increase speeds, improve processes and reduce the footprint of your system. Unidrive SP, Control Techniques' high-performance intelligent drive family allows you to achieve this. The ultimate AC drive.

One range, any power

Unidrive SP is a complete drive automation range that covers the power spectrum from 0.37kW to 1.9MW. All drives share the same flexible control interface regardless of the power rating. Drives are packaged in three formats: Panel Mount, Free Standing and Modular.

Panel Mount – Standard drive modules 0.37kW to 132kW

Unidrive SP panel mount drives are standard AC input, AC output modules for installation within a control panel. The modules are easy to install and commission and can be applied in a wide range of applications.

Unidrive SP size 0 is the latest member of the panel mount range. It reduces the drive size by 60% for motors from 0.37kW to 1.5kW. This model has the same parameter set, universal motor control and user interface as the rest of the Unidrive SP range.

Free Standing – Ready to run 90kW to 675kW

Unidrive SP Free Standing offers a fully engineered drive that is supplied within a standard sized cabinet. Free Standing can be ordered with input power equipment to facilitate immediate connection to the power supply and motor.

Unidrive SP Modular – Power system flexibility 45kW to 1.9MW

Unidrive SP Modular offers maximum power system design flexibility. Drive modules can be connected together in a variety of ways to create common DC bus systems, active input systems for returning excess energy to the power supply and parallel drives for high power motors. All drive modules are compact for easy handling.

N1652

2 YEAR Worldwide Warranty

E171230

EMERSON
Industrial Automation

Unidrive SP features

Smartcard for parameter, PLC and motion program storage

Drive identification marker rail

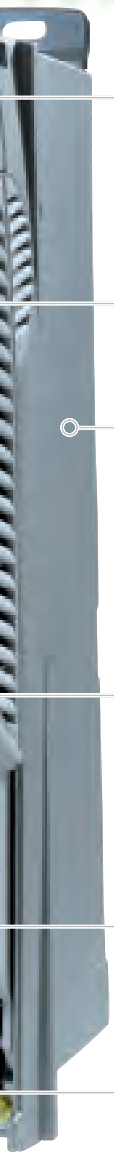
Optional Keypad, available as high brightness LED or multi-language LCD with plain text

Modbus communications port for PC programming and device interfacing

Terminal cover*

Sturdy cable management system providing an earthing point for shielded control and power cables

* Features and their locations vary on some drive sizes



Terminal cover for DC bus, low voltage power supply and onboard EMC filter

Power on / Drive status LED

Aluminium heatsink: drive can be mounted on a flat surface, or through panel mounted so that the heat is dissipated outside the enclosure*

3 universal option module slots for communications, I/O, additional feedback devices and automation/motion controllers*

Pluggable control connections with removable terminals

Power connections with removable terminals*

Universal encoder port supporting Incremental, SinCos, SSI, EnDAT and HIPERFACE encoder types

Panel Mount - Page 20

High performance AC & servo drive for standard power applications

Free Standing - Page 18

Fully engineered AC drive cabinet for higher power standard applications

Modular - Page 19

Modular high power performance AC drive for higher power custom applications

Voltage (V)	Power		
	Panel Mount	Free Standing	Modular
200 - 240 1Ph	0.37 - 1.5 kW	-	-
200 - 240 3Ph	0.37 - 45 kW	-	45 - 950 kW
380 - 480 3Ph	0.37 - 132 kW	90 - 675 kW	90 - 1900 kW
500 - 575 3Ph	2 - 150 HP	125 - 700 HP	125 - 1750 HP
500 - 690 3Ph	15 - 132 kW	90 - 660 kW	90 - 1800 kW

Any motor, any encoder

Unidrive SP provides high-performance motor control for induction motors, asynchronous servo and synchronous servo motors. The control mode is simply selected using the drive keypad.

- **Servo** – Precision, dynamic control supporting a wide range of rotary and linear motors
- **Closed Loop Vector** – Ultimate precision control of induction motors offering full motor torque at zero speed
- **RFC Mode (Rotor Flux Control)** – Superior dynamic performance and stability without a feedback device
- **Open Loop Vector** – Good open loop motor performance with minimum configuration
- **Open loop V/f Control** – A simple control algorithm that is ideal for parallel motors
- **Regenerative** – Active front end control mode for harmonic elimination and regeneration

Unidrive SP includes the hardware required to connect to virtually any feedback encoder type, allowing the designer to select the most appropriate technology for the application:

- **Incremental** - Offers a good balance of cost and performance
- **SinCos** - Provides increased position resolution for precision and low speed applications
- **SSI** - Provides absolute position feedback
- **EnDat & HIPERFACE** - These encoders transfer position data using a high speed communications network, often combined with SinCos technology

EtherCAT

Add the extra features you need

Click-in option modules allow you to customise the drive to suit your needs. Over 25 different options are available including Fieldbus, Ethernet, I/O, extra feedback devices and automation controllers.

Intelligently driven

Unidrive SP allows the drive system designer to embed automation and motion control within the drive.
This eliminates communication delays that reduce performance while CTNet, a high performance drive-to-drive network, links the different parts of the system.

Reliability and innovation

Unidrive SP is designed using a well proven development process that prioritises innovation and reliability. This process has resulted in Control Techniques having a market leading reputation for both product performance and quality.

Global Support

Control Techniques' 53 Drive Centres located in 31 countries , backed up by a further 37 carefully selected and fully trained international distributors, ensure that service, support and expertise are just around the corner, all around the world. Our engineers are passionate about drives and are able to offer the level of service that you need, from advice on an application problem to providing a complete drive solution design.

Unidrive SP functional safety

Control Techniques' drive based safety features provide an intelligent, programmable approach to meet modern functional safety standards. Machines can intelligently interact with people, increasing human protection and safety while enhancing the machine productivity.

Safety as standard

Unidrive SP's Safe Torque Off (STO) is a functional safety feature which complies with EN/IEC 61800-5-2 SIL 3 and is built in to the drive as standard. When the Safe Torque Off function is active, the drive output is disabled with a high degree of integrity.

- Certified by BGIA and TUV
- Allows the drive to become part of the machine safety system
- Reduces user cost in machine safety controller designs that must comply with EN/IEC 62061 up to SIL 3, EN ISO 13849-1 up to PL e, EN 954-1 category 3 and EN 81-1 for elevators
- Eliminates one or more power contactors
- Eliminates feedback checking arrangement
- Drive can be powered continuously

Safe Torque Off can form part of an EN 954-1 Category 4 system by adding control circuitry. Contact your local Drive Centre or Distributor.

For more information please refer to the Control Techniques Safe Torque Off Guide.
Also available for download from www.controltechniques.com/guides

Unidrive SP electrical and mechanical integration

Unidrive SP enables system designers to reduce costs. Standard features such as integrated EMC filters, through panel mounting and backup power supply inputs reduce cabinet size and eliminate external components.

Back-up power supply inputs for continuous operation

24VDC input - control
24VDC supply allows the control circuits of Unidrive SP to remain active when the AC supply is removed. This enables Fieldbus modules, application modules and encoders to continue to operate.

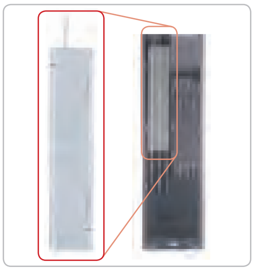
48-96VDC input - power
Allows the drive power output to control the motor, often used for emergency back-up situations such as for moving elevators to an exit during a power supply failure.

Easy compliance with global EMC standards

Unidrive SP features a built-in filter allowing the drive to comply with EN 61800-3. The filter can be easily removed if required such as when sensitive earth leakage protection is installed. External EMC Filters are available for compliance with EN 6100-6-4.

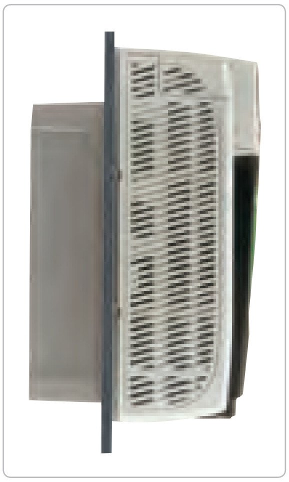
Integrated brake resistors

Unidrive SP frame sizes 0 to 2 feature an optional heatsink mounted brake resistor. This arrangement simplifies installation, requires no additional space and is self fusing with additional overload protection offered by the drive.

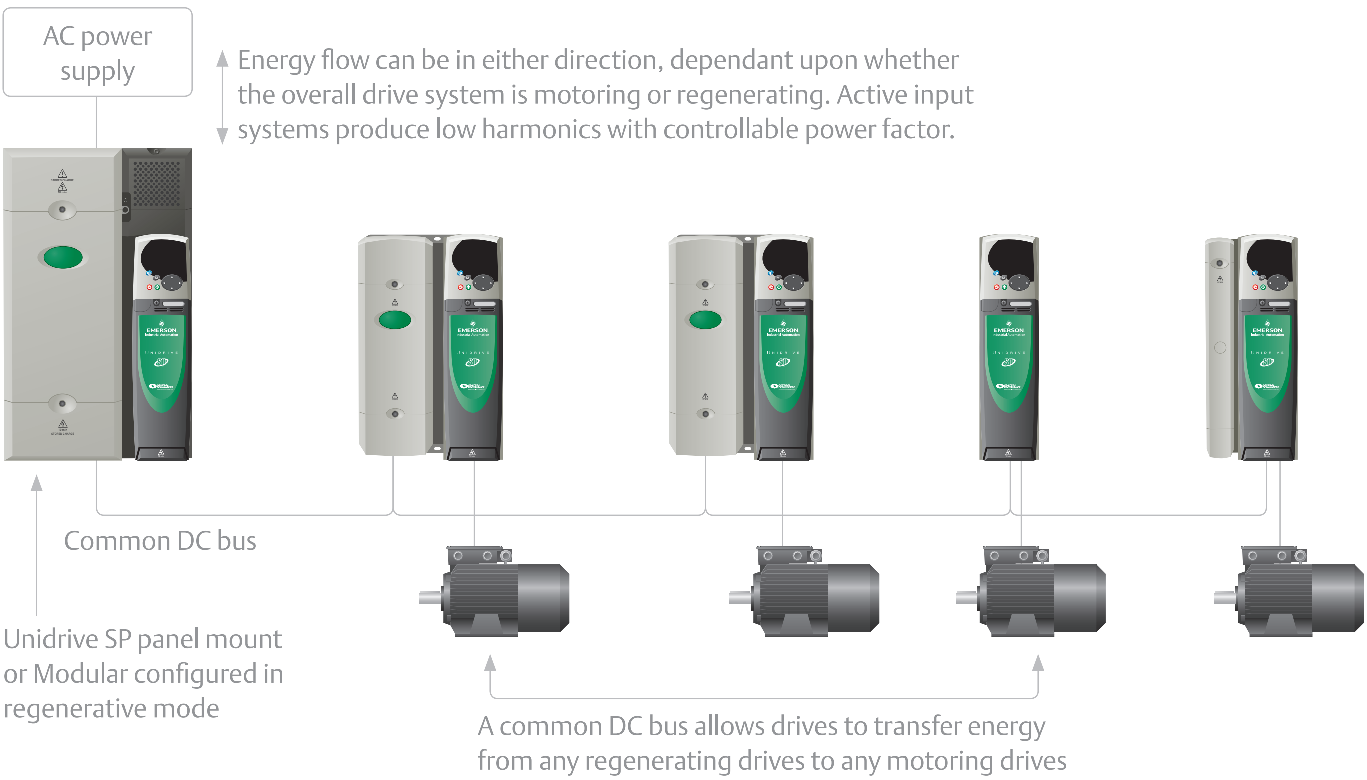


More compact drive systems

Unidrive SP panel mount sizes 1 – 6 and Unidrive SP Modular drives can be through panel-mounted to allow heat to be dissipated externally. This reduces the temperature rise inside the control panel. An IP54 mounting kit is included as standard and IP54 versions of the heatsink fan are available as an option. This mounting method allows smaller cabinet dimensions and reduces the need for ventilation.



Unidrive SP active input solution for improved energy efficiency



Energy saving and harmonic reduction

In most applications variable speed drives reduce energy consumption by matching the motor speed to the required load.

In applications where there is a significant amount of stored mechanical energy, the drive must be able to dissipate the energy to control the motor speed. This presents a further opportunity to reduce energy consumption by returning the excess energy to a shared DC bus or to the AC supply.

DC bus and active input systems can be configured using either Unidrive SP Modular or panel mount drives. DC bus systems reduce running costs by circulating energy between braking and motoring drives. Active input systems return excess braking energy to the mains supply. Benefits include:

- Energy saving
- Sinusoidal input current (low harmonic content)
- Unity or controllable input power factor

Unidrive SP set-up, configuration and monitoring

Unidrive SP is quick and easy to set-up. The drives may be configured using a removable keypad, Smartcard or the supplied commissioning software that guides the user through the configuration process.

User interface options

Unidrive SP benefits from a number of keypad choices to meet your application needs.

Keypad Options	Details
No Keypad	The drive is supplied as standard with no keypad. This is ideal for high volume applications or where you wish to prevent access to drive settings
SM – Keypad	Hot pluggable, high-brightness LED display
SM – Keypad Plus	Multi-lingual, hot pluggable, backlit LCD display. The display can be customised to provide application specific text
SP0 – Keypad	Hot Pluggable LED for the ultra compact Size 0

SM-Keypad

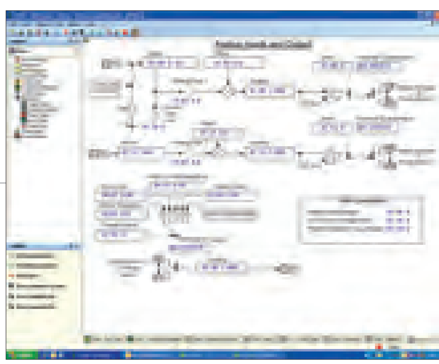
SM-Keypad Plus

SP0-Keypad

Software and Smartcard tools for rapid commissioning

Control Techniques software suite makes it easier to access the drive's full feature set. It allows you to optimize the drive tuning, back-up the configuration and set-up a communications network. The software tools can connect using Ethernet, Serial, USB or Control Techniques drive-to-drive network, CTNet.

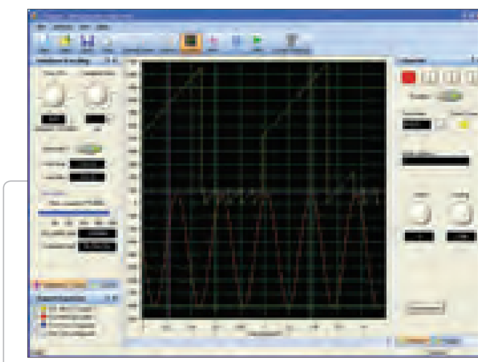
CTSoft



CTSoft is a drive configuration tool for commissioning, optimising and monitoring Control Techniques drives. It allows you to:

- Use the configuration wizards to commission your drive
- Read, save and load drive configuration settings
- Manage the drive's Smartcard data
- Visualise and modify the configuration with live animated diagrams

CTScope



CTScope is a full featured software oscilloscope for viewing and analysing changing values within the drive. The time base can be set to give high speed capture for tuning or for longer term trends. The user interface is based on a traditional oscilloscope, making it familiar and friendly to all engineers across the globe.

Try it, download the full version of CTSoft and CTScope software from www.controltechniques.com

FREE Software

CTOPCServer

CTOPCServer is an OPC compliant server which allows PCs to communicate with Control Techniques drives. The server supports communication using Ethernet, CTNet, RS485 and USB. OPC is a standard interface on SCADA packages and is widely supported within Microsoft® products. The server is supplied free of charge and may be downloaded from www.controltechniques.com.

Try it, download the full version of CTOPCServer from www.controltechniques.com

FREE Software

Smartcard

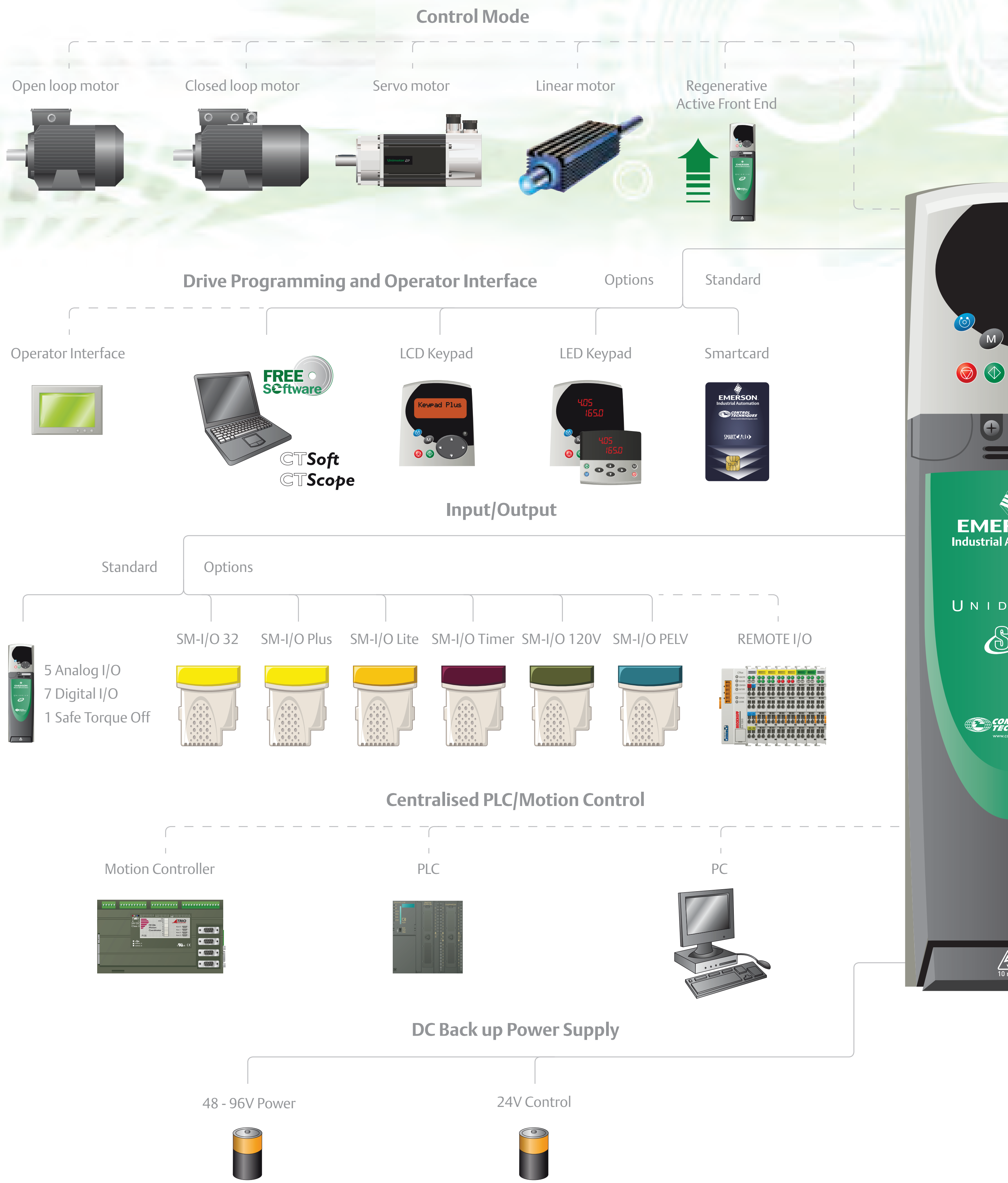
The Smartcard is a memory device that is supplied with every Unidrive SP, it can be used to back-up parameter sets and PLC programs and copy them from one drive to another.

- Parameter and program storage
- Simplify drive maintenance and commissioning
- Quick set-up for sequential build of machines
- Machine upgrades can be stored on a Smartcard and sent to the customer for installation

Easy performance tuning

Autotune features accessible through CTSoft or the keypad help you to get the best performance by measuring the motor and machine attributes and automatically optimising control parameters.

Unidrive SP - Unparalleled integration flexibility



Applications with PLC or Motion functionality

Standard

Onboard PLC
Easy to use onboard ladder logic PLC at zero cost, ideal for simple applications requiring extra drive functionality

Options

SM-Applications Lite V2
Powerful automation controller using a dedicated microprocessor giving full drive parameter access

SM-Applications Plus
Powerful automation controller with drive to drive networking and full motion capability

SM-EZMotion
Motion made easy with intuitive step-by-step configuration

SM-Register
High speed motion and registration control

Communications

Standard

- Modbus RTU

Options

- SM-EtherCAT
- SM-LON
- SM-Profibus DP
- SM-Interbus
- SM-CAN
- SM-DeviceNet
- SM-Ethernet
- SM-CANopen
- SM-SERCOS
- SM-PROFINET

Feedback

Standard

Incremental
SinCos high resolution
SSI Absolute
EnDat & HIPERFACE
Communications

Options

SM-Universal Encoder Plus
Accepts or replicates all standard feedback types, Input and output

SM-Encoder Plus
Incremental input

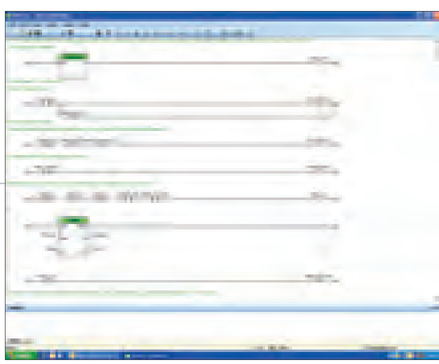
SM-Resolver
Resolver input
Incremental output

SM-Encoder Output Plus
Incremental Encoder Output, Input and output

Unidrive SP drive intelligence and system integration

Intelligent drives offer more compact, higher-performance and lower cost solutions in machinery automation applications. Over the past 20 years Control Techniques has pioneered the embedding of programmable automation, motion and communications features within drives.

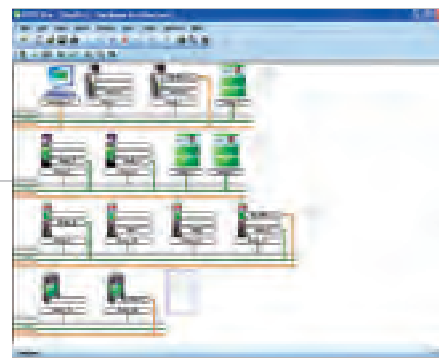
SyPTLite and onboard automation



Unidrive SP has an inbuilt programmable controller. It is configured using SyPTLite, an easy-to-use ladder logic program editor, suitable for replacing relay logic or a micro PLC for simple drive control applications.

The software is supplied free of charge. For evaluation, download the full version from www.syptlite.com.

SyPTPro automation development environment



SyPTPro is a full featured automation development environment that can be used for developing tailored solutions for single or multiple drive applications. The programming environment fully supports three industry standard languages: Function Block, Ladder and Structured Text. Motion control is configured using the new PLCopen motion language, supporting multiple axes.

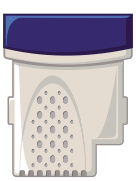
CTNet, a high-speed, deterministic drive-to-drive network links the drives, SCADA and I/O together to form an intelligent networked system, with SyPTPro managing both the programming and communications.

For evaluation, download a demonstration version from www.controltechniques.com.

High performance automation

All of Control Techniques automation option modules contain a high performance microprocessor, leaving the drive's own processor to give you the best possible motor performance.

SM-EZ Motion

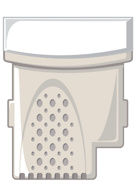


The SM-EZ Motion option module and PowerTools Pro software provides a user friendly environment for motion programming. The EZ-Motion approach is ideal for applications that are low volume and low engineering time.

- Simple drag & drop programming allows you to create programs "out of the box" without having to write a single line of code
- Programming completed in 5-steps, the software guides you through drive configuration, I/O configurations and programming steps
- Intuitive Windows environment with simple data entry

The module has four digital inputs and two digital outputs for high-speed I/O operations.

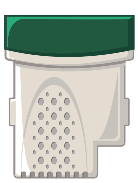
SM-Applications Lite V2



The SM-Applications Lite V2 module is designed to provide programmable control for standalone drive applications or when the drive is connected to a centralised controller via I/O or Fieldbus. SM-Applications Lite V2 may be programmed using ladder logic with SyPTLite or can make use of the full automation and motion capabilities contained within SyPTPro.

- Easy Powerful Configuration – SM-Applications Lite V2 can be used to tackle automation problems from simple start/stop sequencing with a single drive to more complex machine and motion control applications
- Real Time Control –The SM-Applications Lite V2 module gives you real-time access to all of the drives parameters plus access to data from I/O and other drives. The module uses a high speed multi-tasking operating system with task update times as low as 250µs. Tasks are synchronised to the drive's own control loops to give you the best possible performance for drive control and motion.

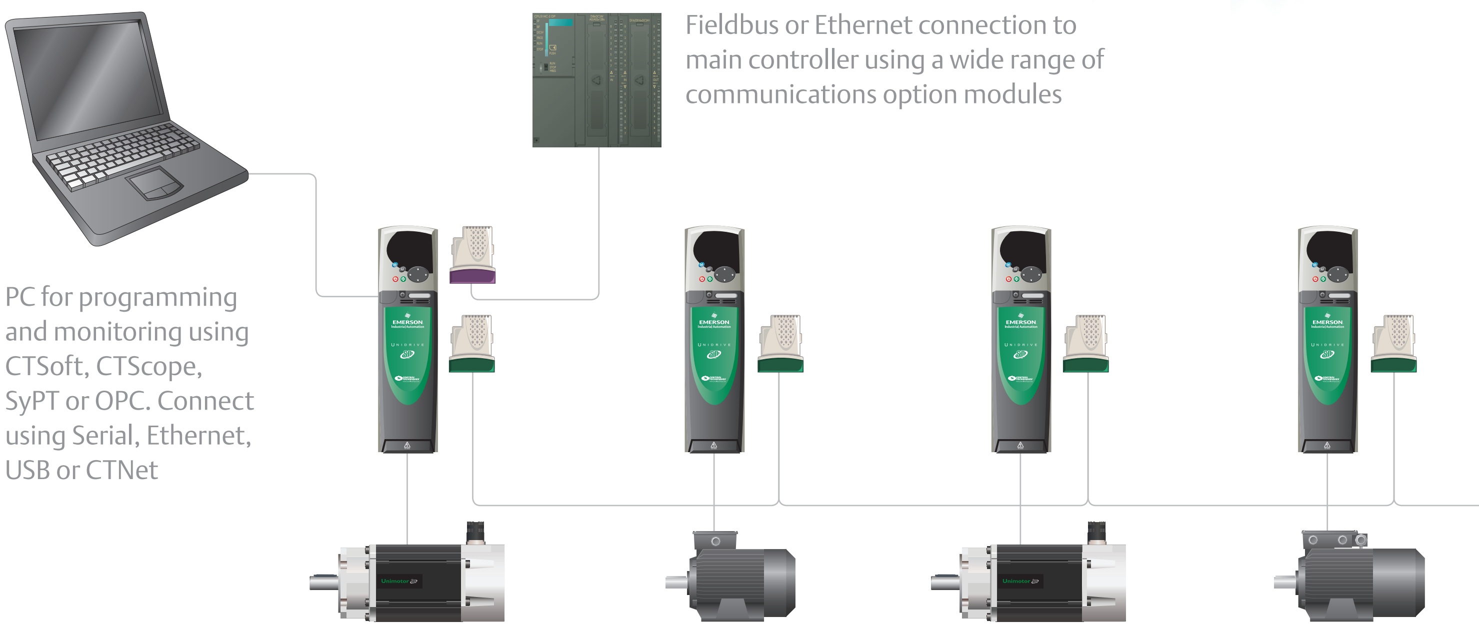
SM-Applications Plus



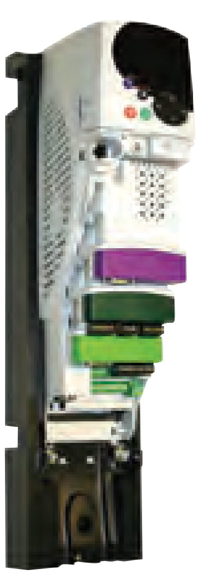
SM-Applications Plus offers all of the features of the SM-Applications Lite V2 module but with additional communications and high speed I/O. SM-Applications Plus is programmed using SyPTPro system programming tool.

- Inputs/Outputs – The module has two digital inputs and two digital outputs for high-speed I/O operations such as position capture and actuator firing
- High speed serial port - The module features a serial communications port supporting standard protocols such as Modbus for connection to external devices such as operator interface panels
- Drive-to-drive communications - SM-Applications Plus option modules include a high speed drive-to-drive network called CTNet, this network is optimised for intelligent drive systems offering flexible peer to peer communications. The bus has the capability to connect to remote I/O, operator panels, Mentor DC drives and PCs using an OPC server

Unidrive SP machine communications flexibility



SP Control Platform

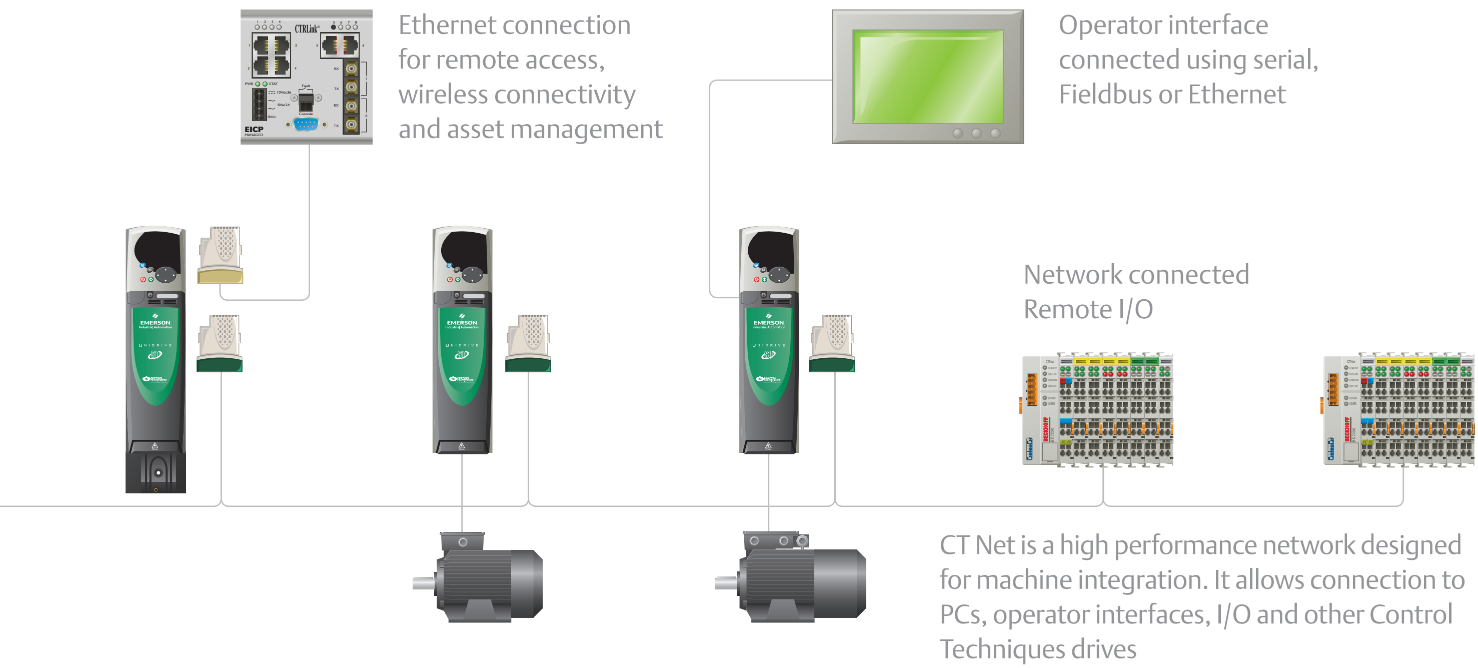


Experience has shown that the unique control flexibility of the Unidrive SP has led to many applications where it is being used solely for its option modules, with no motor connected. Examples include:

- Application as a protocol converter between a supervisory control system using one protocol and a drive system using another.
- Addition of an extra Unidrive SP to a system to accommodate additional option modules. Additional position feedback devices can also be added to a system in this way.

The SP Control Platform provides all the same functions as a Unidrive SP thus expanding the control flexibility without the ability to run a motor, eliminating a redundant power stage.

The SP Control Platform requires a 24Vdc power supply with a 3A, 50Vdc fuse.



Fieldbus communications

Option modules for all common Industrial Ethernet, Fieldbus networks such as Ethernet/IP and Profibus and Servo networks such as SERCOS and EtherCAT are available. We continually develop new modules as new technologies emerge.

Easy gateway

SM-Applications and CTNet allow machine designers to design an easy gateway into which customers are able to interface using their preferred Fieldbus or Ethernet interface. This solution improves the machine performance, simplifies the problem of being able to meet customer specifications for different Fieldbus communications and helps to protect your intellectual property.

	Onboard PLC	SM-Applications Lite V2	SM-Applications Plus
Intellectual property protection	✔	✔	✔
SyPTLite Programming	✔	✔	
SyPTPro Programming		✔	✔
Multi-tasking environment		✔	✔
Motion control capabilities		✔	✔
CTNet drive-to-drive network			✔
Serial port			✔
High Speed I/O			✔

EMERSON
Industrial Automation

Unidrive SP Free Standing 90kW – 675kW

Higher power performance AC drive

The Unidrive SP Free Standing drive range offers the same advanced feature set as the panel mount drives but in a convenient pre-engineered package.

The drive cabinets can be factory configured so that they are delivered ready to be connected directly to your supply, this eliminates the need for drive panel building saving you time and money whilst also allowing you to focus on your application.

The drive cabinets offer industry leading power / size ratios and are ordered using simple order codes.

Applications

The Unidrive SP Free Standing drives are suitable for higher power applications in both commercial and industrial installations. Typical applications include:

- Energy saving with higher power fans and pumps
- Metal production and processing
- Conveying and handling of bulk materials
- Pulp and paper processing
- Marine applications

Benefits

The Unidrive SP Free Standing drives enjoy the same advantages as our Panel Mounting drives with the following additional benefits:

- Standard AC in / AC out pre-engineered cabinet solution reduces design time, lowers project risk and allows you to focus on getting the application engineering right
- Simple order codes allow you to specify a factory fitted power input scheme for your Free Standing drive. This means your drive is delivered ready to be connected reducing your engineering effort and installation time.
- Matching empty cabinets and popular accessories are available to allow you to integrate your own power input scheme or control equipment alongside the drive
- Industry standard form factor and colour allow the cabinets to integrate with new and existing cabinets
- Available with and without braking transistors to optimise costs for your application
- IP21 and optional IP23 enclosures available
- Compact cabinet reduces the space requirement, especially important in retrofit applications: 350kW = 400mm wide & 675kW = 800mm wide

For more information please refer to the Unidrive SP Free Standing brochure. Also available for download from www.controltechniques.com

Unidrive SP Modular 45kW – 1.9MW

Modular high power performance AC drive

The Unidrive SP Modular Drives Range offers the same advanced feature set as the panel mount drives but with additional power system flexibility. Drive modules may be arranged to provide a common DC bus system with or without an active input (regenerative, 4 quadrant operation). Very high current motors may be controlled using a multi-drive modular arrangement.

Applications

The Unidrive SPM drives are suitable for applications in both commercial and industrial applications where power scheme flexibility and regenerative energy saving provides an operational advantage. Typical applications include:

- Automotive testing such as car, engine and gearbox dynamometers
- Web control and winding
- Conveying and processing of bulk materials
- Pulp and paper processing
- Marine applications
- Energy saving with high power fans and pumps
- Metal production and processing
- Large cranes
- Renewable energy systems such as photovoltaics

Benefits

Unidrive SP Modular drives enjoy the same advantages as the Panel Mounting drives but with the additional benefits of power system flexibility:

- Higher power motors are controlled using Unidrive SPM modules connected in parallel. This is an economic and compact solution that simplifies installation and improves serviceability
- Reduce running costs using a DC bus system to recycle energy between simultaneously braking and motoring drives such as in a winder / unwinder configuration
- Eliminate harmonics using an active front end
- Minimise harmonics with 12, 18 and 24 pulse operation to allow you to meet and exceed stringent supply regulations
- Modular approach can provide system redundancy, for example if a drive module was non operational in a multi-module installation it may still be possible to operate the application with the remaining modules
- Ultra compact modules allow high power systems to be constructed in non standard enclosures e.g. it is possible to implement a drive system of between 45kW to 1900kW in an enclosure no taller than 1m
- Operation with global power supplies 200V, 400V, 575V and 690V

Modular building blocks

The Unidrive SPM range comprises key modules that can be combined elegantly to achieve your design criteria with maximum economy.

SPMA	AC IN / AC OUT Drive Module
SPMD	DC IN / AC OUT Drive Module
SPMC	AC IN / DC OUT Rectifier
SM Control Master	Master control module for use with SPMA/D
SM Control Slave	Slave control module for use with SPMA/D
SPM Power Selector	Automatic selection/de-selection of drive modules

For more information and more configuration examples please refer to the Unidrive SPM brochure. Also available for download from www.controltechniques.com

Unidrive SP panel mounted 0.37kW – 132kW 200V 1ph / 200V 3ph / 400V / 575V / 690V

High performance AC & servo drive

Unidrive SP Panel Mount is a high performance drive module for system integration and stand alone applications.

Applications

Due to the inherent performance and flexibility of Unidrive SP, potential areas for its application are limitless, the drives' intelligence and dynamic response allow it to be applied in the most demanding applications.

Typical applications include:

- High speed machines
- Crane and hoist
- Lift and elevator controls
- Pulp and paper machines
- Metal production and processing
- Materials handling systems
- Marine applications
- Printing
- Textile machines
- Converting
- Energy saving with fans and pumps
- Plastics and rubber extrusion machines

Benefits

- Onboard programmable intelligence and generous connectivity allows the removal of external programmable logic controllers and motion controllers, reducing costs and the cabinet size. Unidrive SP features 5 analogue I/O and 7 digital I/O as standard
- Drive option module slots future proof your investment, it also means you only fit the functionality you need, reducing costs and removing complexity. Unidrive SP Sizes 1 to 6 benefit from three option slots with the ultra compact Size 0 featuring two slots
- Available option modules include advanced automation controllers, world-standard fieldbus connectivity options and a comprehensive range of digital and analogue I/O interfaces and feedback devices
- Optional Internal Brake Resistors for Unidrive SP Sizes 0, 1 and 2 reduce your space requirement
- The built in EMC filter is suitable for most applications and can be easily removed where required. Optional external footprint EMC Filters are available where more rigourous standards must be met
- Safe Torque Off, as standard, reduces system costs in machine safety designs
- IP54 through panel mount capability allows convenient heat dissipation and reduces cabinet size
- Operation with global power supplies 200V, 400V, 575V and 690V

Unidrive SP panel mount ratings and specifications

200-240VAC +/- 10% Single Phase (kW@220V) (HP@230V)

		Normal Duty			Heavy Duty		
Frame Size	Modules	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)
0	SP0201	-	-	-	2.2	0.37	0.5
	SP0202	-	-	-	3.1	0.55	0.75
	SP0203	-	-	-	4	0.75	1
	SP0204	-	-	-	5.7	1.1	1.5
	SP0205	-	-	-	7.5	1.5	2

200-240VAC +/- 10% (kW@220V) (HP@230V)

		Normal Duty			Heavy Duty		
Frame Size	Modules	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)
0	SP0201	-	-	-	2.2	0.37	0.5
	SP0202	-	-	-	3.1	0.55	0.75
	SP0203	-	-	-	4	0.75	1
	SP0204	-	-	-	5.7	1.1	1.5
	SP0205	-	-	-	7.5	1.5	2
1	SP1201	5.2	1.1	1.5	4.3	0.75	1
	SP1202	6.8	1.5	2	5.8	1.1	1.5
	SP1203	9.6	2.2	3	7.5	1.5	2
	SP1204	11	3	3	10.6	2.2	3
2	SP2201	15.5	4	5	12.6	3	3
	SP2202	22	5.5	7.5	17	4	5
	SP2203	28	7.5	10	25	5.5	7.5
3	SP3201	42	11	15	31	7.5	10
	SP3202	54	15	20	42	11	15
4	SP4201	68	18.5	25	56	15	20
	SP4202	80	22	30	68	18.5	25
	SP4203	104	30	40	80	22	30
5	SP5201	130	37	50	105	30	40
	SP5202	154	45	60	130	37	50

380-480VAC +/- 10% (kW@400V) (HP@460V)

		Normal Duty			Heavy Duty		
Frame Size	Modules	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)
0	SP0401	-	-	-	1.3	0.37	0.5
	SP0402	-	-	-	1.7	0.55	0.75
	SP0403	-	-	-	2.1	0.75	1
	SP0404	-	-	-	3	1.1	1.5
	SP0405	-	-	-	4.2	1.5	2
1	SP1401	2.8	1.1	1.5	2.1	0.75	1
	SP1402	3.8	1.5	2	3	1.1	1.5
	SP1403	5	2.2	3	4.2	1.5	3
	SP1404	6.9	3	5	5.8	2.2	3
	SP1405	8.8	4	5	7.6	3	5
	SP1406	11	5.5	7.5	9.5	4	5
2	SP2401	15.3	7.5	10	13	5.5	7.5
	SP2402	21	11	15	16.5	7.5	10
	SP2403	29	15	20	25	11	20
	SP2404	29	15	20	29	15	20
3	SP3401	35	18.5	25	32	15	25
	SP3402	43	22	30	40	18.5	30
	SP3403	56	30	40	46	22	40
4	SP4401	68	37	50	60	30	50
	SP4402	83	45	60	74	37	60
	SP4403	104	55	75	96	45	75
5	SP5401	138	75	100	124	55	100
	SP5402	168	90	125	156	75	125
6	SP6401	205	110	150	180	90	150
	SP6402	236	132	200	210	110	150

500-575VAC +/- 10% (kW@575V) (HP@575V)

Frame Size	Modules	Normal Duty			Heavy Duty		
		Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)
3	SP3501	5.4	3	3	4.1	2.2	2
	SP3502	6.1	4	5	5.4	3	3
	SP3503	8.4	5.5	7.5	6.1	4	5
	SP3504	11	7.5	10	9.5	5.5	7.5
	SP3505	16	11	15	12	7.5	10
	SP3506	22	15	20	18	11	15
	SP3507	27	18.5	25	22	15	20
4	SP4603*	36	22	30	27	18.5	25
	SP4604*	43	30	40	36	22	30
	SP4605*	52	37	50	43	30	40
	SP4606*	62	45	60	52	37	50
5	SP5601*	84	55	75	63	45	60
	SP5602*	99	75	100	85	55	75
6	SP6601*	125	90	125	100	75	100
	SP6602*	144	110	150	125	90	125

500-690VAC +/- 10% (kW@690V) (HP@690V)

Frame Size	Modules	Normal Duty			Heavy Duty		
		Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)	Max Cont Current (A)	Typical Motor Output Power (kW)	(HP)
4	SP4601	22	18.5	25	19	15	20
	SP4602	27	22	30	22	18.5	25
	SP4603	36	30	40	27	22	30
	SP4604	43	37	50	36	30	40
	SP4605	52	45	60	43	37	50
	SP4606	62	55	75	52	45	60
5	SP5601	84	75	100	63	55	75
	SP5602	99	90	125	85	75	100
6	SP6601	125	110	150	100	90	125
	SP6602	144	132	175	125	110	150

Notes: Select model on actual motor full load current. *The same model can be used on a 575V or a 690V supply, and has two different output ratings. For example: At Normal Duty, SP4603 is suitable for a 22kW output motor on a 575V supply and a 30kW output motor on a 690V supply. Can be used on IT supplies - all voltages, Grounded delta supplies - all voltages except 690V

Normal Duty Suitable for most applications, current overload of 110% for 165 seconds is available. Where motor rated current is less than the drive rated continuous current, higher overloads are achieved.

Heavy Duty Suitable for demanding applications, current overload of 175% for 40 seconds is available for frame size 0 - 5 in closed loop, 150% for 60 seconds in open loop. For frame size 6 current overload of 150% for 60 seconds is available in closed loop and 129% for 97 seconds in open loop. Where the motor rated current is less than the drive rated continuous current higher overloads (200% or greater) are achieved.

Environmental safety and electrical conformance

- IP20/Nema 1 rating, IP54 (NEMA 12) through panel mount
- Ambient temperature -15 to +40°C, 50°C with derating
- Humidity 95% maximum (non condensing) at 40°C
- Altitude: 0 to 3000m, derate 1% per 100m between 1000m and 3000m
- Vibration: Tested in accordance with IEC 60068-2-34
- Mechanical Shock Tested in accordance with IEC 60068-2-27
- Storage temperature -40°C to 50°C
- Electromagnetic Immunity complies with EN 61800-3 and EN 61000-6-2
- With onboard EMC filter, complies with EN 61800-3 (2nd environment)
- EN 61000-6-3 and EN 61000-6-4 with optional footprint EMC filter
- IEC 61000-3-4 Supply conditions
- IEC 60146-1-1 Supply conditions
- IEC 61800-5-1 (Power Drive Systems)
- IEC 61131-2 I/O
- EN 60529 Ingress protection
- EN 50178 / IEC 62103 Electrical safety
- Safe Torque Off (formally secure disable), independently assessed by BGIA to IEC 61800-5-2 SIL 3
- EN 81-1 assessed by TÜV
- EN 61000-6-2, EN 61000-6-4 EMC, UL508C, UL840

Dimensions and Options

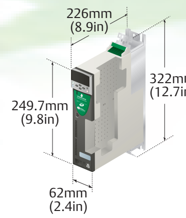
For Unidrive SP Free Standing and Unidrive SP Modular drive dimensions and ratings please refer to the relevant brochures.

SP Control Platform

Weight:
1.5kg (3.3lbs)

SP0

Weight:
2.1kg (4.6lbs)



SP1

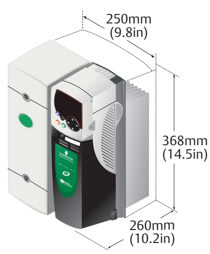
Weight: 5kg (11lbs)
SP1405 / SP1406:
5.8kg (13lbs)

SP2

Weight:
7kg (15.5lbs)

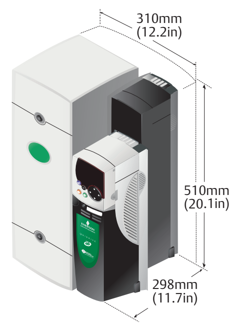
SP3

Weight:
15kg (33lbs)



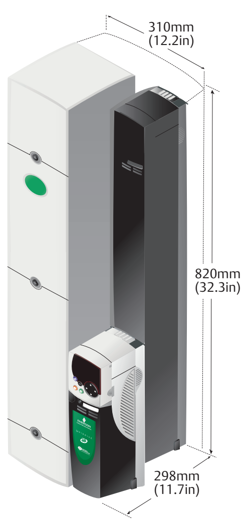
SP4

Weight:
30kg (66lbs)



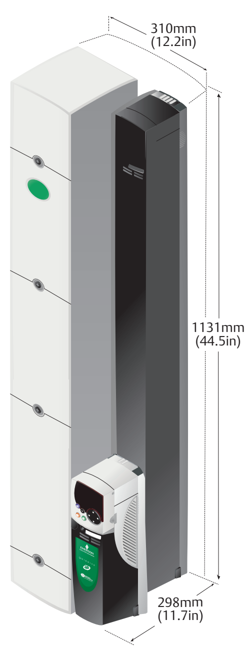
SP5

Weight:
55kg (121lbs)



SP6

Weight:
75kg
(165.3lbs)



Options

Interfaces

Order Code	Details
SP Control Platform	Control platform without power stage
SM – Keypad	Low cost, hot pluggable, LED display
SM – Keypad Plus	Multi-lingual, hot pluggable, backlit LCD display. The display can be customised to provide application specific text.
SP0 – Keypad	Hot Pluggable LED for the compact Size 0

Braking Resistors

Braking Resistor	Order Code
SP0 Braking Resistor	1299-0001
SP1 Braking Resistor	1220-2756-01
SP2 Braking Resistor	1220-2758-01

EMC Filters

Unidrive SP built-in EMC filter complies with EN 61800-3, External EMC Filters are required for compliance with EN 61000-6-4.

Drive	Order Code	Drive	Order Code
SP0201 to SP0205 (1ph)	4200-6000	SP2401 to SP2404	4200-6210
SP0201 to SP0205	4200-6001	SP3401 to SP3403	4200-6305
SP0401 to SP0405	4200-6002	SP4401 to SP4403	4200-6406
SP1201 to SP1202	4200-6118	SP4601 to SP4606	4200-6408
SP1203 to SP1204	4200-6119	SP5401 to SP5402	4200-6503
SP2201 to SP2203	4200-6210	SP3501 to SP3507	4200-6309
SP3201 to SP3202	4200-6307	SP5601 to SP5602	4200-6504
SP4201 to SP4203	4200-6406	SP6401 to SP6402	4200-6603
SP1401 to SP1404	4200-6118	SP6601 to SP6602	4200-6604
SP1405 to SP1406	4200-6119		

DRIVING THE WORLD...

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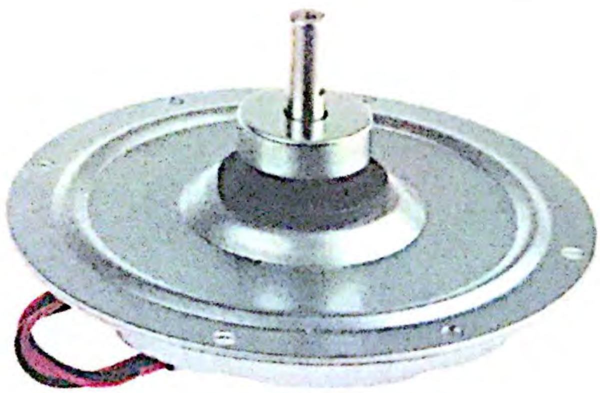
RS Brushed DC Motor, 110 W, 23.5 V dc, 35 Ncm, 3000 rpm, 9.995mm Shaft Diameter

RS Stock No. 225-9579
Manufacturer RS

$275.87
Price (ex. GST) Each

Qty 1
$275.87

In stock for delivery next working day



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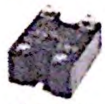
Technical data sheets

- RoHS Certificate of Compliance
- Linecard - RS Brand A&C Products
- GPM12 - Data Sheet
- Statement of conformity

Essential accessories



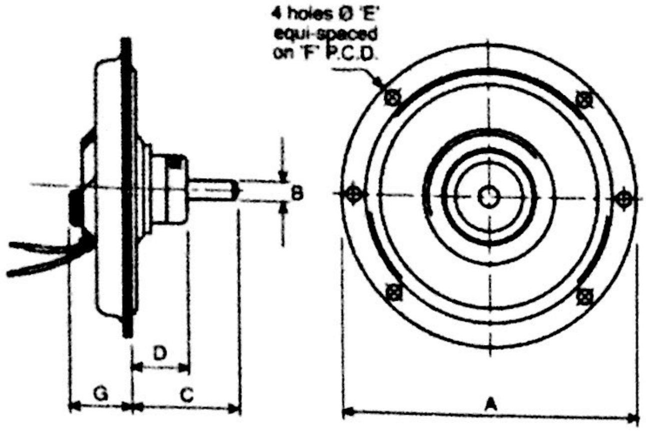
Voltage DC Motor Controller, 6 → 24 V dc, 40 A, Panel Mount
$116.55
Quick View

Product Details

Low Profile dc Motors

- Powerful, low profile motors offer many benefits when compared to a conventional permanent magnet dc motor
- Low profile construction requires less space than a conventional motor
- Long motor life even when operated at full rating
- High power to weight ratio
- Very smooth running at slow speeds
- Fast acceleration from rest under full load conditions
- Low inductance
- Low brush sparking
- Low r.f.i. emissions
- Available in two magnet materials:
- M Style uses ferrite magnet material
- N Style uses rare earth magnet material
- N Style provides up to 2 1/2 times power, three times higher torque, from the same size motor compared with M type

RS, Professionally Approved Products, gives you professional quality parts across all product categories. Our range has been testified by engineers as giving comparable quality to that of the leading brands without paying a premium price.



Low Profile DC Motors

Add product to Compare

Specifications

To find a similar product, based on selected attributes, click the green button

Current Rating	7.6 A
DC Motor Type	Brushed
Dimensions	152 Dia. x 60 mm
Length	60mm
Maximum Output Torque	35 Ncm
Output Speed	3000 rpm
Power Rating	110 W
Shaft Diameter	9.995mm
Supply Voltage	23.5 V dc

Customer reviews

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Similar Products

Alternative for RS Brushed DC Motor, 110 W, 23.5 V dc, 35 Ncm, 3000 rpm, 9.995mm Shaft Diameter

RS Brushed DC Motor, 200 W, 37.5 V dc, 64 Ncm, 3000 rpm, 9.995mm Shaft Diameter

$496.31

Compare All Alternatives

Related Products

Aluminium Timing Belt Pulley, 10mm Belt Width x 5mm Pitch, 28 Tooth, Maximum Bore Dia. 18mm

RS Steel 12 Teeth Spur Gear, 12mm Pitch Diam. , 14mm Hub Diam. , 6mm Bore Diam.

RS Universal Joint

$40.67

RS Barrel Gear Coupling Hub, 16mm

$17.86

(ENCODER)

Orange Pot α — Contactless Angle Sensor

⟨ RoHS Compliance ⟩

CP-45H

■ FEATURES

- Contactless rotary sensor, Combination of a magnet, Hall Effect Sensing Element and Custom IC
- Excellent absolute linearity
- Superb temperature characteristic
- Wide angle
- Long useful life

Electrical Specifications

Electrical Angle	360°
Output Range	5~95%Vin
Absolute Linearity	±0.4%FS(Ind.Linearity:±0.2%FS)
Input Voltage	DC 5±0.5V
Load Resistance	1MΩMIN.
Supply Current	30mA MAX.
Resolution	0.1°MAX. (400rpm MAX.)
Hysteresis	±0.5°(±0.14%FS=360°)
Temp. Characteristics −40℃~100℃ (Reference Temp. 25℃)	±0.3%FS (≒±1.08°) FS=360°

Mechanical Specifications

Mechanical Angle	360° Endless
Torque	1.8mN·m MAX.
Weight	Approx. 80g
Shaft radial load	6N MAX.
Shaft thrust load	2N MAX.

Enviromental Specifications

Life Cycles	50M Cycle MIN.
Vibration	200m/s² 5~500Hz(6min) 3axis 2hours
Shock	1,000m/s² 11ms 6axis 3times
EMS(IEC 61000-4-2)	10V/m, 80M~1GHz
Operating Temp.	-40~100℃
Storage Temp.	-40~100℃
ESD(Case~Each Terminal)	±8kV (IEC 61000-4-2)
ESD(Each Terminal)	±8kV (IEC 61000-4-2)
IP Level	IP40

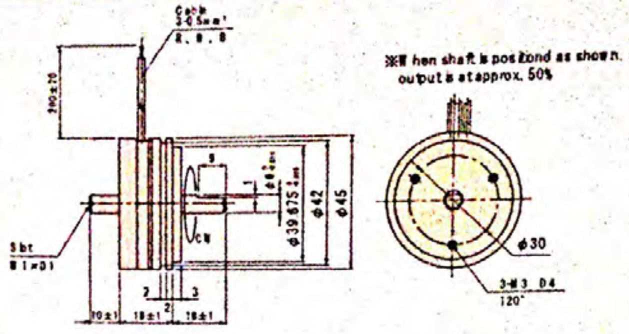
OPTIONS

- Electrical angle: 300°,200°
- Drip-proof: IP65

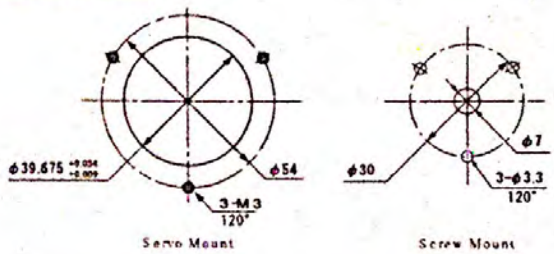
HANDLING INSTRUCTION

- In applying input power, voltage Vin must rise to 4.5V within 0.2 seconds, otherwise, output shall be disabled(Vout=0V)
- This product may be influenced from external magnetic field of apparatus which generates a magnetic field.
- Use this sensor in the place where is protected from ESD.

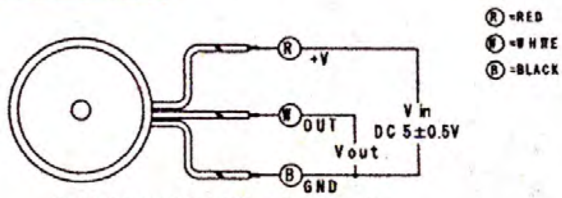
■ DIMENSION (mm)



■ MOUNTING

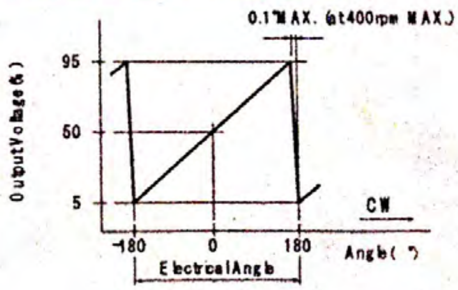


■ SCHEMATIC



Red, White and Black indicate harness colors

■ OUTPUT CHARACTERISTICS



■MOUNTING HARDWARE

Cleats : 3pcs