PASSIVE AND ACTIVE DRAG OF PARALYMPIC SWIMMERS

By

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ABSTRACT

The aim of this thesis was to contribute to the development of an objective, evidence-based international classification system for para-swimmers by quantifying the effect of physical impairment on passive and active drag. The thesis comprises five studies. Study 1 identified a significant relationship between normalised passive drag and the para-swimmers' International Paralympic Committee (IPC) Class, but an inconsistent difference in normalised passive drag between adjacent classes. High within-class variability in passive drag indicates that the current classification system does not always differentiate clearly between swimming groups. Study 2 found that anthropometric features of para-swimmers, such as height and body mass, differed significantly between IPC Classes, whereas Shoulder Width, Chest Depth, Shoulder Girth and Torso Girth did not. A weak correlation existed between para-swimmers' anthropometry and their passive drag, which indicates that other factors, such as impairment type, may be more important predictors of passive drag than anthropometry. Study 3 revealed that certain impairments, such as double-leg amputation above knee level, may predispose a para-swimmer to a relatively high passive drag which disadvantages them in competition. Study 4 compared two methods of estimating active drag during front crawl swimming: the Naval Architecture Based Approach (NABA) and the Active Towing Method (ATM). The means were not statistically different. Using a sensitivity analysis, the NABA was identified as the more reliable method of assessing active drag. Study 5 found that active and passive drag of elite para-swimmers are highly correlated but no relationship existed between active drag and International Paralympic Committee S Class (IPC S Class), indicating that factors other than impairment level may be more important in determining active drag. The relationships discovered between drag, IPC Class, anthropometry and impairments will contribute to the development of the future IPC Classification system.

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RESEARCH OUTPUTS FROM THE THESIS

At the time of the submission, the following research outputs have arisen from the thesis:

Articles published in peer-reviewed journals:

Oh, Y. T., Burkett, B., Osborough, C., Formosa, D., & Payton, C. (2013). London 2012 Paralympic swimming: passive drag and the classification system. *British Journal of Sports Medicine*, *47*(13), 838-843.

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CHAPTER ONE

INTRODUCTION

This chapter begins with a short historical overview of Para-swimming by describing how it started and how it developed into a highly competitive international sport. It then provides a brief explanation of the current IPC Swimming Classification system followed by a description of the factors that affect swimming performance. The chapter concludes with the aim, objectives and structure of the thesis.

1.1 AN INTRODUCTION TO DISABILITY SPORTS

It is widely acknowledged that Dr Ludwig Guttmann is the founder of the Paralympic movement. Commissioned by the British Government, he opened the National Spinal Injuries Unit at the Ministry of Pensions Hospital, Stoke Mandeville, Aylesbury in September 1943. The main role of this unit was to take care of the suffering soldiers and civilians who had spinal cord injuries sustained during the Second World War. Dr Guttmann recognised the psychological and physiological value of sport as a part of the rehabilitation program for paraplegic patients, so sport was actively developed and promoted at the hospital. From these beginnings as a rehabilitation program, disability sport has gradually developed into a recreational activity and then transformed into competitive sport (McCann, 1996).

With the pioneering work of Dr Guttmann, the first Stoke Mandeville Games, a competition for athletes with spinal-cord related injuries, were held in 1948. At this initial stage these Games were annually based. Even though these Games were a milestone for the world's second largest multi-sports event, the Paralympic Games, they began life merely as an archery demonstration between two paraplegic teams (Ministry of Pensions Hospital at Stoke Mandeville versus the Star and Garter Home for Injured War Veterans at Richmond in Surrey). Sixteen athletes competed in the Games. In 1952 the International Stoke Mandeville Games Federation (ISMGF) was founded and the Games were successfully expanded into an international sporting event with the participation of the Netherlands. The Stoke Mandeville Games of 1953 included swimming as one of its six major events (Archery, Javelin, Netball, Snooker, Swimming, Table Tennis); swimming has been included ever since. From 1948 to 1959 the Games were hosted annually in Stoke Mandeville even though by 1959 there were twenty-one participating countries. The first International Stoke Mandeville Games were held in Rome, Italy in 1960 and are considered to be the first Paralympic Games (the term 'Paralympic' was introduced later). One hundred and thirty-eight athletes from seventeen countries competed in eight major events (Archery, Athletics, Basketball, Dartchery, Fencing, Snooker, Swimming and Table tennis). Since then the International Stoke Mandeville Games have been held every four years with this name last being used at the 1972 Heidelberg Games (See Table 1.1.). This was the last time that the Games were restricted to athletes with spinal-cord injuries.

In 1961 the need to offer opportunities to other disability groups was agreed and the International Sports Organisation for the Disabled (ISOD) was established. They created the rules and classifications for a wide range of sports for athletes with cerebral palsy, amputations, visual impairments and '*les autres*' (the others). Under the leadership of Dr Guttmann (ISOD President from 1968 to 1979) ISOD joined with the ISMGF to organise the 1976 Olympics for the Physically Disabled in Toronto, Canada. Athletes with spinal cord injuries, amputations, and visually impairments participated. Athletes with cerebral palsy first appeared at the 1980 Olympics for the Disabled in Arnhem, the Netherlands and the '*les autres*' group participation began in 1984 at the New York International Games for the Disabled and Stoke Mandeville World Wheelchair Games (Brittain, 2012). The term '*Paralympic*' was first used at 1988 Seoul Paralympics and on 22nd September of the following year the International Paralympic Committee (IPC) was founded as the global governing body of the Paralympic movement. Immediately following the 1992 Barcelona Paralympic Games (3-14 Sept) in which amputees, blind & visually impaired, cerebral palsied, spinal code injuries and les autres groups participated, there was another Paralympic Games in Madrid (15-22 Sept) which was held for athletes with Intellectual Disability. Since then, athletes with intellectual disability participated in the 1996 Atlanta and 2000 Sydney Paralympic Games. However, following the 'Basketball Controversy' of the Spanish basketball team, athletes with intellectual disability were excluded from the 2004 Athens and 2008 Beijing Paralympic Games. They returned to Paralympic competition in London 2012. Table 1.1 shows former names of Paralympic Games.

Table 1.1 Former names of the Paralympic Games

Host City	Year	Names
Stoke Manderville	1948-1959	Stoke Manderville (annual) Games
Rome	1960	Internal Stoke Manderville Games (considered the 1st Paralympic Games)
Tokyo	1964	Internal Stoke Manderville Games
Tel Aviv	1968	Internal Stoke Manderville Games
Heidelberg	1972	Internal Stoke Manderville Games
Toronto	1976	Olympics for the Physically Disabled
Arnhem	1980	Olympics for the Disabled
New York	1984	International Games for the Disabled
Stoke Manderville	1984	World Wheelchair Games
Seoul	1988	Paralympics
Barcelona	1992	Paralympics
Madrid	1992	Paralympics
Atlanta	1996	Paralympic Games
Sydney	2000	Paralympic Games
Athens	2004	Paralympic Games
Beijing	2008	Paralympic Games
London	2012	Paralympic Games
Rio de Janeiro	2016	Paralympic Games

1.2 AN INTRODUCTION TO PARA-SWIMMING

Historically, the term '*disability swimming*' has been used to describe all levels of competition for swimmers with an impairment, ranging from beginners through to international standard. In recent years, '*para-swimming'* has become the accepted term used to describe the elite end of the competitive sport and will be used throughout this thesis. When an individual is referred to as a *para-swimmer*, this signifies that they have competed at a Paralympic Games or an equivalent international competition (e.g. IPC Swimming World Championship). All para-swimmers will have an IPC Classification (see Chapter 1.3.3).

Para-swimming made its first appearance at the 1953 Stoke Mandeville Games and has remained one of major sports of the Stoke Mandeville / Paralympic Games. In the 1960 Rome Games, seventy-seven athletes from fifteen countries participated in the swimming events. At that time only 25 m and 50 m freestyle, backstroke and breaststroke races were included. 100 m races were introduced at the 1968 Tel Aviv Games. Butterfly was first seen at the 1976 Toronto Games. The number of participants grew rapidly in the first twenty years (Figure 1.1).

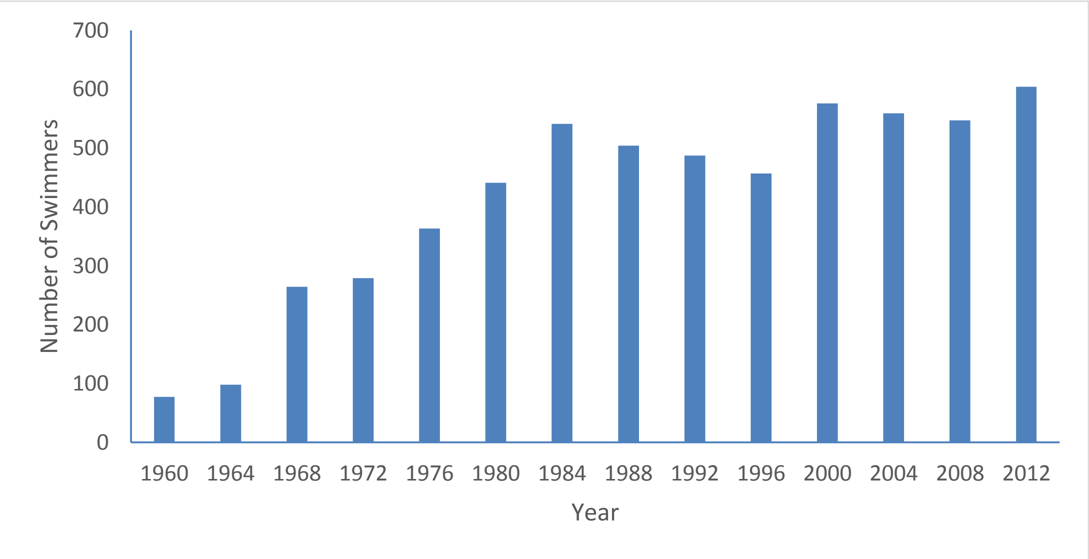

Figure 1.1 Number of participating swimmers from the 1960 to the 2012 Paralympic Games (www.paralympic.org/results/historical).

Table 1.2 Performance differences between the 100 m front crawl swimming time (s) of the male Olympic gold-medallist and the fastest 100 m front crawl male Paralympic gold-medallist.

Year	1968	1972	1976	1980	1984	1988	1992	1996	2000	2004	2008	2012
Paralympic	79.0	72.3	63.3	60.8	56.2	58.3	57.6	56.4	54.3	53.7	51.4	51.1
Olympic	52.2	51.2	50.0	50.4	49.8	48.6	49.0	48.7	48.3	48.2	47.2	47.5
Difference	26.8	21.1	13.3	10.4	6.4	9.7	8.6	7.7	6.0	5.6	4.2	3.6

Five hundred and forty one swimmers from forty-three countries participated in swimming events at the 1984 New York / Stoke Manderville Games. 200 m and 400 m events were introduced at these Games. In London 2012, 604 swimmers from seventy-four countries participated in 148 swimming events. Swimmers currently compete in events ranging from 50 m to 400 m at the Paralympic Games (Brittain, 2012).

The performance times of Para-swimmers continues to improve. Table 1.2 shows the 100 m performance times of the male 100 m freestyle Olympic champion and the fastest male Paralympic gold-medallist. In the 1968 Tel Aviv Games, the time gap between the Olympic gold-medallist and Paralympic gold medallist in the least impaired group was 26.8 s. In the 2012 London Games, the performance time of the fastest Para-swimmer was only 3.6 s slower than that of the Olympic gold medallist. In this period, the performance of Olympic swimmers improved by only 5 s; that of Para-swimmers improved by 27.9 s.

1.3 DISABILITY CLASSIFICATION IN SWIMMING

1.3.1 Early classification systems

Classification of athletes has long been an acceptable practice in sports. For able-bodied athletes, classification by gender, weight, age, and performance level (professional or amateur) is often used. Experts in the field of Paralympic sports have stated that classification is essential for the very existence of sports for athletes with a disability to provide an equitable starting point for competition (Sherrill, Adams-Mushett, & Jones, 1986).

As detailed in Section 1.1, in the early days of disability sport, the ISMGF, which governed sports for those with spinal paralysis, and the ISOD, which governed sports for cerebral palsy, amputees, blind and les autres, developed separately. The Cerebral Palsy International Sports and Recreation Association (CPISRA) and the International Blind Sports Federation (IBSA) separated from the ISOD in 1978 and 1980, respectively. These four organisations established an International Co-coordinating Committee (ICC) in 1982. The International Committee of Sport for the Deaf (CISS) and International Sports Federations for Persons with an Intellectual Disability (INAS-FID) joined in 1986. The IPC currently recognises four IOSDs (CPISRA, IBSA, INAS-FID and the International Wheelchair and Amputee Sports Federation, IWAS). Thus specific impairment groups had their own organisations and these organisations developed classification systems for their own athletes: athletes competed only against others with the same disability. All of these classification systems are commonly called ‘medically-based classification’ because athletes were classified mainly by their medical evaluations. These medically-based systems were used until the Seoul 1988 Paralympic Games. Athletes who had different medical diagnoses competed in separate events and no consideration was given to the fact that impairments resulting from different medical conditions could cause the same activity limitation in a sport (Tweedy & Vanlandewijck, 2011). These systems, therefore, produced a multitude of parallel events and medals whilst limiting the number of athletes able to compete in each one.

1.3.2 The Functional Classification System

When the ISOD joined the 1976 Toronto Paralympics, the number of participating athletes greatly increased. This led to a dramatic improvement in the level of competition (Sherrill, 1989). The Seoul 1988 Paralympics, where 3061 athletes from sixty countries participated, was a good example of this trend (Tiessen, 1997). It hosted twenty-two times more athletes than the 1960 Rome Games. Even though the Seoul Paralympics was successful, it was criticised for having too many separate events and medal winners. Of the 3061 total participants, 2208 (72%) won a medal.

In 1989 the IPC and the Barcelona Paralympic Organising Committee agreed that all the sports at the Barcelona Games would adopt sports-specific functional classification systems (Vanlandewijck & Chappel, 1996; Tweedy & Vanlandewijck, 2011). Event organisers favoured this decision as the fewer number of classes significantly reduced the complexity of event organisation. At this time some sports, such as wheelchair basketball, already had an applicable classification system named 'Player Classification' (Craven, 1990). However, this was not the case for many other sports. For this reason, given the limited time frame, the development of the classification systems was based primarily on expert opinion with a very limited underpinning of scientific evidence (Tweedy & Vanlandewijck, 2011).

1.3.3 The IPC Swimming Functional Classification System

The IPC Swimming Functional Classification System was first introduced in 1985 (Daly & Vanlandewijck, 1999). In this system, there are three distinct swimming categories (IPC Swimming, 2005). The Freestyle, Backstroke and Butterfly are category 'S' strokes, Breaststroke is the 'SB' category, and the Individual Medley is categorised as 'SM' (SM Classification $=\frac{3\times S\ Classification+1\times SB\ Classification}{4}$: In the Individual Medley, the swimmer swims equal distances of the four different strokes within one race. Each physically impaired swimmer is given a classification number from 1 – 10, depending on their level of impairment (1 being the most severe and 10 the least) within each of the three swimming categories. These classifications are established through three specific steps: *Bench Test* (swimming specific examination), *Water Test* (a functional assessment of a swimmer's ability) and *Observation* during competition with the focus on ability. The Bench Test involves assessment of muscle strength, muscle dysfunction (coordination), joint mobility, length of amputated/dysmelic limb, length of lower limb and the drop shoulder test. The Water Test involves an assessment of a swimmer's starting, swimming, floating, kicking and turning ability. Following these procedures up to three classifications are assigned to the athlete (S, SB and SM) along with a classification number (1-10). In addition to the ten physical impairment classes, visually impaired swimmers are denoted S11-S13 and intellectually impaired swimmers are denoted S14 (IPC Swimming, 2005).

Despite its fundamental importance to Paralympic swimming there has been little scientific investigation done to underpin the current functional classification system. There remain many un-answered questions raised by athletes, coaches and researchers relating to the fairness of the classification system (Sherrill, 1993; Wu, 1999). Daly & Vanlandewijck (1999) have questioned what the valid criteria should be for evaluating the fairness of swimming classification. The IPC is currently reviewing its classification process in swimming. In 2010 it approved an international research project "Paralympic swimming classification system - the development of further evidence" and is planning to introduce a more objective, evidence-based system by 2016.

Table 1.3 Landmark events in the evolution of Paralympic sport

Host City	year	Events
	1888	The first sport clubs for the deaf already existed in Berlin.
	1924	The deaf set up their organisation, CISS (Comité International des Sports des Sourds, The International Committee of Sports for the Deaf) in Paris.
	1944	Dr. Ludwig Guttmann opened a spinal injuries centre at the Stoke Mandeville Hospital.
Stoke Manderville	1948	The first Stoke Mandeville Annual Games
Stoke Manderville	1952	The Netherlands joined the Games.
Stoke Manderville	1952	ISMGC (International Stoke Mandeville Games Committee: former name of IWAS) for persons with paraplegia and tetraplegia was founded.
Stoke Manderville	1953	Swimming made its first appearance
Stoke Manderville	1957	The distance in the swimming competitions be as follow: Class A – 20m, Class B & C – 40m.
Stoke Manderville	1958	There were three classes in Table Tennis.
Rome	1960	The first Paralympic Games
	1961	The International Sport Organisation for the Disabled (ISOD) was established.
Tokyo	1964	IOSD offered opportunities for athletes not affiliated to the International Stoke Mandeville Games: visually impaired, amputees, persons with cerebral palsy and paraplegics.
Tel Aviv	1968	
	1969	International Cerebral Palsy Society (ICPS) was founded.
Heidelberg	1972	ISMGC was renamed as ISMGF (International Stoke Manderville Games Federation).
Toronto	1976	ISOD joined the Summer Paralympic Games with athletes with cerebral palsy, amputees and visually impairments in 1976 in Toronto, Canada, which were held under the aegis of ISMGF.
	1978	ICPS developed and renamed as CP-ISRA (Cerebral Palsy International Sports and Recreation Association). ICPS still exists and focuses on Academic seminare. CP-ISRA focuses on the sport and recreational activity.
Arnhem	1980	The International Classification of Impairments, Disabilities, and Handicaps was published by World Health Organization (WHO). It was the first classification of health and functioning which was recognised internationally.
	1981	International Blind Sports Federation (IBSA) was established.
	1982	International Co-ordinating Committee (ICC) was found.
New York / Stoke Mandeville	1984	The '*les autres*' group first participated in this Games.
	1986	INAS-FMH (International Sports Federation for Persons with Intellectual Disability) was founded. It was renamed as INAS-FID in 1994.
	1986	CISS and INAS-FID joined the ICC
Seoul	1988	The term 'Paralympic' was first used officially.
	1988	The last Paralympic Games which used Medical Classification System.
	1989	The International Paralympic Committee (IPC) was founded.
	1989	The IPC and the Barcelona Paralympic Organizing Committee signed an agreement that all Paralympic sports contested at the 1992 Barcelona Paralympic Games were to be conducted using sports-specific functional classification systems.
Barcelona	1992	The first Paralympic Games to use the Functional Classification System.

Madrid	1992	The first Paralympic Games for athletes with Intellectual Disability.
	1993	IPC Sport Science Committee was established.
	1994	INAS-FMH was renamed as INAS-FID.
Atlanta	1996	Athletes with an intellectual disability were first included in the Paralympic Games as a small event program (arranged by INAS-FID).
Sydney	2000	A larger program for athletes with an intellectual disability were included in the Paralympic Games, but suspended from the events because some athletes had cheated the system of determining eligibility.
	2001	The International Classification of Impairments, Disabilities, and Handicaps was revised and renamed the International Classification of Functioning, Disability and Health (ICF) by the World Health Organization (WHO).
Athens	2004	The participation of athletes with Intellectual Disability was prohibited.
	2007	The General Assembly of the IPC approved the IPC Classification Code which explicitly mandates the development of evidence-based classification systems (Code Section 15.2).
Beijing	2008	
	2010	IPC Swimming approved an international research project "Paralympic swimming classification system - the development of further evidence"
London	2012	"Kinematic Analysis of Paralympic swimmers including drag tests" were conducted during the Games as part of the research project of IPC Swimming
	2012	The athletes with Intellectual Disability re-participated in Paralympic Games again.
	2013	"Passive Drag of Paralympic swimmers" were conducted during the Montreal 2013 IPC Swimming World Championships as part of the research project of IPC Swimming.
Rio de Janeiro	2016	Proposed date for introduction of a revised Paralympic swimming classification system.

1.4 FACTORS AFFECTING SWIMMING PERFORMANCE

Scientific research in able-bodied swimming has identified a number of biomechanical and physiological factors that influence performance in competition. It follows that these factors should be taken into consideration when classifying swimmers with a disability.

The key biomechanical factors that influence swimming performance are: buoyancy (Miyashita & Tsunoda, 1978), hydrodynamic drag (Toussaint & Hollander, 1994; Alcock & Mason, 2007), mechanical work (Faulkner, 1968; Miller, 1975), power (Miyashita, 1974), propelling efficiency (Toussaint, van der Helm, Elzerman, Hollander, de Groot & van Ingen Schenau, 1983; Cappaert, Franciosi, Langhand, & Troup, 1992), propulsion (Schleihauf, Gray, & de Rose, 1983; Toussaint & Beek, 1992) and stroke rate and stroke length (Chatard, Collomp, Maglischo, & Maglischo, 1990c; Kjendlie, Ingjer, Stallman, & Stray-Gundersen, 2004). The relationships between each of these factors were introduced in Chapter 2.1. With regard to Para-swimming, only about fifteen studies (Chatard, Lavoie, Ottoz, Randaxhe, Cazorla, & Lacour, 1992; Pelayo, Sidney, Moretto, Wille, & Chollet, 1999; Daly, Malone, Smith, Vanlandewijck, & Steadward, 2001; Bentley, Phillips, McNaughton, & Batterham, 2002; Daly, Djobova, Malone, Vanlandewijck, & Steadward, 2003; Schega, Kunze, & Daly, 2004; Schega, Kunze, & Daly, 2006; Souto, Vilas-Boas, & Costa, 2006; Burkett, Mellifont, & Mason, 2010; Karger, 2012; Oh, Burkett, Osborough, Formosa, & Payton, 2013; Dingley, Pyne, & Burkett, 2014a; Dingley, Pyne, & Burkett, 2014b) have attempted to establish a relationship between any of these factors and the level of physical impairment (IPC class) of a swimmer.

Since the IPC Swimming Classification System was first introduced in 1985, peer-reviewed scientific papers in the area of Biomechanics, Physiology or Psychology examining the performance of disabled swimmers, especially para-swimmers, are scarce.

In contrast, the number of research papers on able-bodied swimming produced in the same period is innumerable. It is clear that more research is required in order to identify the factors that affect the performance of para-swimmers. An increased understanding of how these factors are influenced by the level and type of a swimmer's physical impairment will help in the development of a more evidence-based, objective classification system.

1.5 OVERVIEW OF THE RESEARCH AREA

A swimmer's speed is determined largely by their capacity to produce propulsion effectively whilst minimising the resistive or drag forces from the water (Toussaint & Beek, 1992). A fair classification system should, therefore, evaluate objectively an individual's potential to achieve both of these important determinants of performance within the limitations determined by their physical impairment. It could be argued that the current classification system places too much emphasis on propulsion and allocates insufficient importance to evaluating a swimmer's drag. The IPC Swimming Classification Manual (2005) refers to the term propulsion 150 times in relation to every section of the practical profile used to assign a swimmer to a class (hands, arms, trunk, legs, others and starts & turns). In contrast, a swimmer's drag is assigned in a single, very limited context in the current classification process. Only "leg drag" (no use of legs or swimmer chooses not to use legs) is addressed in the profile. No consideration is given to how other aspects of a specific impairment may impact on the level of drag experienced by a swimmer.

In human swimming, resistive drag (henceforth referred to as drag) is characterised in two ways: *Passive* and *active drag*. *Passive drag* is the retarding force that a swimmer experiences when maintaining a fixed posture. It is usually obtained by measuring the force required to tow a swimmer through water at a constant speed. Studies have demonstrated that passive drag depends on many factors including body position (e.g. Clarys & Jiskoot, 1975), depth and speed of towing (e.g. Lyttle, Blanksby, Elliott, & Lloyd, 1998) and body shape and size (e.g. Clarys, 1979). To date, virtually all passive drag studies have been conducted on able-bodied participants with the exception of two published studies which included swimmers with physical impairments (Chatard, Bourgoin, & Lacour, 1990b; Chatard *et al*., 1992). Chatard *et al*. (1990b) examined the passive drag of eleven male para-swimmers, including four double-leg amputees. The authors provided no information on the anthropometry of the swimmers (other than the mean height and mass) or on the physical impairments of the non-amputee swimmers. As this study was limited to a comparison of 'Double-leg amputees' and 'Non-double-leg amputees', it made only a limited contribution to our understanding of the effect of physical impairment on drag in swimming. The proposed research aims to increase this understanding.

Chatard *et al.* (1992) measured the passive drag of thirty-four swimmers with mild to severe physical impairments. This study provides some valuable insights into the effects of physical impairment on drag. However, no anthropometric data were reported and the swimmers were grouped according to their degree of terrestrial mobility, rather than on their level of swimming-specific impairment, as is done in the IPC Classification System. Consequently, the study does not contribute to our understanding of the link between a swimmer's anthropometry, passive drag and their IPC class. The proposed research will address these areas.

There is no method of measuring active drag during unconstrained swimming. Hollander *et al*., (1986) developed a Measuring Active Drag (MAD)-system for front crawl. The system involves the swimmer progressing down the pool by pushing against underwater pads, with the mean push-off force assumed to equal the mean active drag force, at a constant swimming speed. Kolmogorov & Duplischeva (1992) developed a velocity perturbation method (VPM) to estimate active drag in all four swimming strokes.

Swimmers perform two maximum effort trials; one swim free and one swim while towing a hydrodynamic body of known resistance. The difference in speed between the two conditions is used to estimate active drag assuming an equal power output of the swimmer, in both trials. Alcock & Mason (2007) proposed an Active Towing Method (ATM), a variation of the VPM, in which the swimmer is assisted (towed) whilst swimming, rather than resisted. Most recently, a Naval Architecture Based Approach (NABA) has been proposed (Webb, Banks, Phillips, Hudson, Taunton, & Turnock, 2011) but has not been evaluated fully. The strengths and limitations of the active drag measurement methods will be discussed in Chapter 2. No study has yet attempted to determine active drag in swimmers with physical impairments. The proposed research will critically evaluate the current methods of estimating active drag and then identify and utilise the most reliable method to study the relationship between the severity of physical impairment and active drag, in para-swimmers.

1.6 ACADEMIC AIM AND OBJECTIVE OF THE THESIS

The academic aim of the thesis is to contribute to the development of an objective, evidence-based international classification system for para-swimmers by quantifying the effect of physical impairment on passive and active drag.

This thesis has four objectives: 1) to establish the relationship between swimmers' passive drag, their IPC classification, selected anthropometry (Height, Streamlined Height, Body Mass, Shoulder Width, Chest Depth, Shoulder Girth, Torso Girth, *CSA*, streamlined *CSA*, *LTR*, Streamlined *LTR*, *RPI* and Streamlined *RPI*) and their impairments; 2) to identify the most reliable method of determining active drag for swimmers with a disability; 3) to quantify active drag and its relationship with level of physical impairment (IPC classification), and 4) to establish the relationship between passive and active drag in swimmers with a physical impairment.

1.7 STRUCTURE OF THE THESIS

Following this introduction, this thesis comprises a further seven chapters: a literature review, five experimental studies and a summary. The majority of data for studies 1, 2 and 3 were collected at the London 2012 Paralympic Games and at the Montreal 2013 IPC Swimming World Championships, with approval and support from the International Paralympic Committee. The data for studies 4 and 5 were collected from Manchester-based able-bodied swimmers and the Great Britain Para-swimming World Class Pathway swimmers, respectively.

1.7.1 Chapter 2 – Literature Review

This chapter aims to provide a comprehensive review of the literature relating to passive and active drag in swimming, including relevant theoretical background and a critical appraisal of current measurement techniques. Studies into the passive and active drag of able-bodied swimmers are reviewed. Studies on physically impaired swimmers, and on IPC Swimming Classification, are also evaluated critically.

1.7.2 Chapter 3 – Study 1

This chapter addresses the relationship between passive drag and a para-swimmer's IPC Class. Additionally it examines the relationship between passive drag and Reciprocal Ponderal Index (Height/Mass$^{1/3}$). The possibility of using passive drag as a new criterion in a revised IPC Functional Classification system is also discussed. Chapter 3 relates to academic aim 1.

1.7.3 Chapter 4 – Study 2

This chapter describes the three-fold relationship between passive drag, anthropometric characteristics and IPC Class of para-swimmers. It examines which anthropometric characteristics are most related to passive drag. Possible reasons for within-class variability in drag are also discussed. Chapter 4 relates to academic aim 1.

1.7.4 Chapter 5 – Study 3

This chapter examines the relationship between passive drag and the specific impairments of swimmers. Swimmers are assigned to one of ten passive drag bands (PD1 – PD10) according to their normalised passive drag score (passive drag/body mass). Each swimmer's IPC class integer is compared to their PD integer to establish the extent to which their passive drag score aligns with their current IPC class. Chapter 5 relates to academic aim 1.

1.7.5 Chapter 6 – Study 4

This chapter identifies the most appropriate method of estimating active drag, which is then used in chapter 7. Four different methods for estimating active drag are initially considered. Through pilot work with one able-bodied swimmer, two methods (Active Towing Method and Naval Architecture Based Approach) are short-listed and then compared in the main study. Chapter 6 relates to academic aim 2.

1.7.6 Chapter 7 – Study 5

This chapter describes the relationship between para-swimmers' active drag during front crawl swimming and their IPC Class. Additionally, the chapter examines the relationship between the passive and active drag of para-swimmers and considers how impairment affects this relationship. Chapter 7 relates to academic aims 3 and 4.

1.7.7 Chapter 8 – Summary, applications, recommendations and further research

This chapter summarises the thesis. It considers the applications of the main findings to the development of a new IPC Swimming Classification system and to the development and improvement of competitive swimmers with physical impairment. It concludes by offering some suggestions for further research in para-swimming.

CHAPTER TWO

REVIEW OF RELATED LITERATURE

The aim of this chapter is to provide an extensive review of the literature relating to passive and active drag in swimming. Where possible, research relating to swimmers with a physical impairment will be highlighted. However, the number of published studies for this group is limited. Within the review, established biomechanical data collection techniques are also identified and discussed.

2.1 INTRODUCTION TO SWIMMING BIOMECHANICS

The term ‘biomechanics’ is defined as “the science concerned with the action of forces, internal or external, on the living body” (Farlex Partner Medical Dictionary, 2012). Using this definition, the study of the forces acting on a swimmer whilst swimming is considered ‘swimming biomechanics’. There are four directional components of force that act on a swimmer during the swimming action: propulsion, resistance, buoyancy and weight (Figure 2.1) (Maglischo, 2003). Swimming researchers have generally focused more on propulsion (the forces acting in the swimming direction), and resistance (the forces opposite to the swimming direction, often called drag), than on buoyancy and weight forces. This is understandable as the aim of competitive swimming is to swim a given distance as fast as possible and this is achieved by maximising propulsion whilst at the same time minimising drag (Toussaint, 2011).

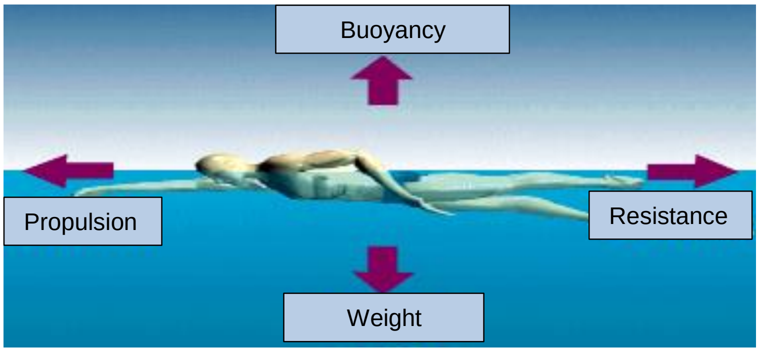

Figure 2.1 The forces acting on a swimmer whilst swimming (adapted from http://scienceforcesport.weebly.com/swimmingbasketball.html).

Another useful way of categorising the forces acting on a swimmer is by their origins and characteristics. Kwon (2001) suggested that three force categories exist: 1) forces created outside the water; 2) forces created inside the water and that exist regardless of the swimming action; and 3) forces created inside the water due to the swimming action. So, when any swimming action stops, the forces in the third category disappear. Forces in first category include the swimmer’s bodyweight (due to gravity) and ‘wall reaction force’ (which acts during the turning action). Bodyweight acts downwards through the swimmer’s centre of gravity so does not have a direct influence on horizontal motion. The ‘wall reaction force’ is created by the interaction between the wall and the swimmer’s pushing action whilst turning (or starting). It is an important force for determining the speed of a swimmer’s gliding phase (Daniel, Klauck, & Bieder, 2003; Araujo, Pereira, Gatti, Freitas, Jacomel, Roesler, & Villas-Boas, 2010) but it does not act during the swimming phase.

Forces in the second and the third category are created inside the water. In the second category is buoyancy. Buoyancy acts vertically upward and so opposes gravity. The magnitude of the buoyancy force is equal to the weight of water displaced by the submersed part of the swimmer (Kwon, 2001). The buoyancy (F_B) is expressed as:

$$F_B = V \cdot \rho \cdot g \tag{2.1}$$

Where V is the volume of the submerged part of the body, ρ is the density of the water and g is acceleration due to gravity. According to Yanai (2004), buoyancy is the primary source of generating bodyroll in front crawl swimming. In able-bodied front crawl swimming, the centre of buoyancy moves symmetrically in an alternating pattern from the right to the left side of the body’s longitudinal axis, and then from the left back to the right. In para-swimming, many swimmers have a considerable bi-lateral asymmetry in body shape, strength and/or coordination. With these swimmers, the centre of buoyancy is unlikely to move symmetrically, making it more difficult to use the buoyancy force for generation body-roll (Payton, Osborough, & Sanders, 2010).

Forces in the third category are the hydrodynamic forces: lift and drag. These forces can act in any direction, including the swimming direction, so they can directly affect swimming performance in a positive (propulsion) or a negative (resistance) way.

Lift Force

The lift force always acts perpendicular to the direction of the water flow over the body or body segment (Barthels, 1979). Lift forces can be created by movements of the hands and feet and if these act in a forwards direction, they will contribute to the propulsion (Berger, de Groot, & Hollander, 1995; Toussaint & Truijens, 2005). The lift force (F_L) is expressed as:

$$F_L = 1/2 \cdot C_L \cdot \rho \cdot A \cdot v^2 \qquad (2.2)$$

where: C_L is the lift coefficient, ρ is the density of the water, A is a reference area and v is the body or body segment's velocity relative to water (Toussaint, 2000).

In swimming, the lift force is influenced by the shape and size of the body segment and its speed and direction of movement (Ungerechts & Arellano, 2011). The generation of lift forces in swimming occurs either when a moving limb is asymmetrical in its shape or the limb presents an angle of attack to the water (Bixler & Riewald, 2002).

Figure 2.2 (a) shows the occurrence of a lift force due to the asymmetry of an object. The upper part of the object is convex and asymmetrical, compared to the lower part. Due to this shape, water traveling over the upper side has to travel further, and therefore, faster than the water flowing over the underside. According to Bernoulli's principle, the faster the speed of the flow, the lower the pressure exerted by the fluid (Toussaint, 2000). For this reason, the upper side has lower pressure than the lower side. This pressure difference creates a lift force in the direction from high pressure to low pressure (Babinsky, 2003). Figure 2.2 (b) shows an example of lift force created by the angle of attack of a symmetrical object. Regardless of the shape of an object (i.e., whether it is symmetrical or asymmetrical), if the object creates an angle (of attack) with its direction of movement, a lift force can be created (Babinsky, 2003).

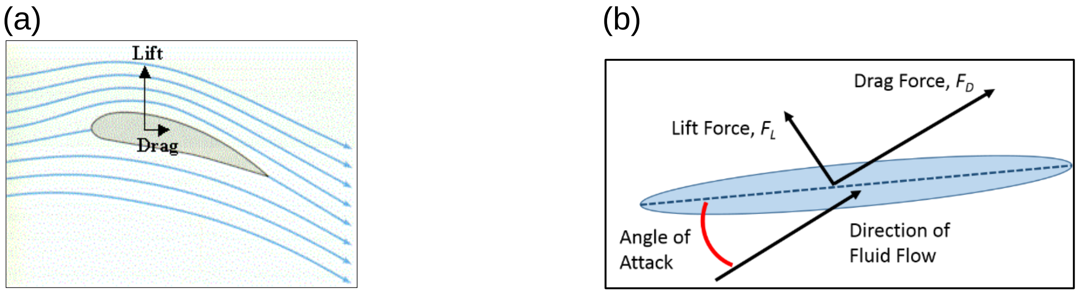

Figure 2.2 The occurrence of the lift force: (a) the asymmetry of the form (taken from taken from http://hydrogen.physik.uni-wuppertal.de/hyperphysics/hyperphysics/hbase/pber.html, (b) angle of attack, flow direction, lift and drag.

In human swimming, researchers in the 1970s emphasised the importance of lift forces for generating propulsion from the hands in swimming (Counsilman, 1971; Brown & Counsilman, 1971). However, researchers in the 1990s and later became sceptical about the benefit of lift forces to propulsion in swimming (Sanders, 1998a). In his research, Sanders (1998b) compared the relative importance of lift and drag to generating propulsion in three aquatic sports: 1) freestyle swimming, 2) flat water kayaking, and 3) water polo, concluding that in freestyle swimming the role of lift forces in generating propulsion must be seriously questioned. However, he acknowledged the importance of lift forces in flat water kayaking and water polo.

Drag Force

The drag force always acts in the opposite direction to the movement of the body, or a body limb, through water. As with the lift force, the drag force can act in a forwards direction to propel the swimmer or a backwards direction to resist them. For example a hand pushed backward through the water will create a forwards (propulsive) drag force (Toussaint & Truijens, 2005) whereas a swimmer's torso gliding through the water will create a backwards (resistive) drag force. The drag force (F_D) is expressed as:

$$F_D = 1/2 \cdot C_D \cdot \rho \cdot A \cdot v^2 \quad (2.3)$$

where C_D is the drag coefficient, ρ is the density of the water, A is a reference area and v is the body or body segment's velocity relative to water (Toussaint, 2000). The total resistive drag (F_D) acting on the whole body, or a body segment, can be broken down into three components: frictional drag (F_f), pressure drag (F_p), and wave making drag (F_w) (Toussaint, Hollander, van der Berg, & Vorontsov, 2000). It is expressed as:

$$F_D = F_f + F_p + F_w \tag{2.4}$$

Frictional drag is created from the shear stress between the fluid and the object. This is produced inside the boundary layer (Prandtl & Tietjens, 1957) which is a thin layer of water that attaches to the moving body (Schlichting, Gersten, & Gersten, 2000). The amount of frictional drag depends on the wetted surface area of the object and the flow conditions inside the boundary layer (Webb, 1975). The flow conditions within the boundary layer can be laminar, turbulent or transitional. The greatest frictional drag occurs when the boundary layer is in turbulent flow (Figure 2.3). In practice, the classification of the laminar and the turbulent flow is made through the Reynolds Number (Re). It is expressed as:

$$Re = v \cdot L \cdot \rho / \mu \tag{2.5}$$

where μ is the viscosity of the water, ρ is the density of the water, v is the swimming velocity and L is the length of the swimmer. The number at which the transition from laminar to turbulent boundary layer flow occurs is called the critical Reynolds number and this varies depending on the nature of flow. For the flow over an object, such as an aerofoil, the critical Reynolds number is about 500,000 (Bone & Moore, 2008). In the case of a swimmer in competition, whose v is 1.8 $m \cdot s^{-1}$, L is 1.8 m, ρ is 1000 $kg \cdot m^{-3}$, and μ is $0.897 \cdot 10^{-3}$ $N \cdot s \cdot m^{-2}$, their Re is about $4.5 \cdot 10^6$. This number signifies that the swimmer will always experience turbulence during competition (Toussaint & Truijens, 2005).

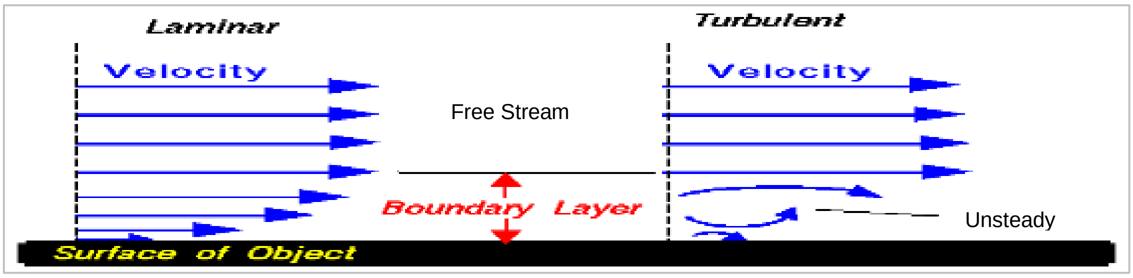

Figure 2.3 Laminar (layered) or turbulent (disordered) flow of boundary layer which is depending the Reynolds number (taken from https://www.grc.nasa.gov/www/k-12/airplane/boundlay.html)

Pressure drag originates from the distortion of flow outside the boundary layer. Steady flow may be separated at a certain point along a swimmer's body, depending on their anthropometry and velocity (Dennis & Walker, 1971). Directly after water passes over a swimmer, its direction may be reversed and roll up at certain points. These flow distortions are called vortices and they create a pressure difference between the front and the rear of the swimmer (Bone & Moore, 2008) resulting in the pressure drag. For this reason, pressure drag is proportional to the pressure difference and the cross sectional area of the swimmer (Toussaint & Truijens, 2005) and is expressed as:

$$F_p = 1/2\, \rho \cdot A_p \cdot v^2 \cdot C_{Db} \qquad (2.6)$$

where F_p is the pressure drag, ρ is the density of water, A_p is the cross sectional area of the body, v is the swimming velocity, C_{Db} is the dimensionless drag coefficient.

Wave making drag is generated when a swimmer moves near the water surface and is forming a wake behind them. The origin of wave drag is the energy required to create these waves (van Manen & van Oossanen, 1988). In elite able-bodied human swimming, wave drag is the largest of the three drag components a swimmer experiences when they swim at the water surface (Vennell, Pease, & Wilson, 2006). Wave drag depends on the Froude number (Fr), which is the ratio of swimming speed to that of a wave with a length equal to the swimmer's length (Toussaint & Truijens, 2005) and is expressed as:

$$Fr = v / \sqrt{g} \cdot L \quad (2.7)$$

where *v* is the swimming velocity, *g* is gravity and *L* is the length of the swimmer. So, the shorter the swimmer, the greater the *Fr*, which leads to a greater wave drag, compared to a taller swimmer. As para-swimmers are more variable in height and streamlined height, than able-bodied swimmers, it is anticipated that the effects of wave drag will be more variable in para-swimming than in able-bodied swimming.

In ship building science, the concept of 'hull speed', which is the vessel's speed, matched with a wave that has a wavelength equal to the length of the vessel, is used. Hull speed occurs when *Fr* is 0.42 (Vennell *et al*., 2006). If *Fr* is over 0.45, the increase in wave drag is less rapid than when *Fr* is 0.25 – 0.44 due to the effect of hydrodynamic lift on the vessel. Elite able-bodied swimmers have been shown to reach their 'hull speed' which indicates that the wave making drag is the predominant contributor to the total drag (Kjendlie & Stallman, 2008). Consequently, in Para-swimming those swimmers with a double-leg amputation or those of extreme short stature may experience greater wave drag than taller swimmers.

Propulsion and Resistance Interaction

During swimming, the sum of all the horizontal force acting on the body will determine its acceleration. This can be is expressed as:

$$\Sigma F \text{ (Horizontal forces)} = m \times a \quad (2.8)$$

$$F_P - F_R = m \times a \quad (2.9)$$

where F_P is the propulsive force (sum of all lift and drag forces acting in swimming direction); F_R is the resistive force (sum of all lift and drag forces acting in direction opposite to swimming), *m* is the swimmer's body mass, and *a* is the horizontal acceleration of the swimmer.

When the swimming speed is constant (*a* = 0), the magnitude of the propulsive and resistive forces are equal. Currently there is no methods for directly measuring the propulsive or resistive (drag) force during swimming. There have been many indirect ways of estimating them. These will be discussed in section 2.4.2.

Work and Power

When a swimmer moves forward, displacement is created due to the net force from both propulsive and drag force and it is said that work has been done upon the swimmer. This can be expressed as:

$$W = F \cdot d \cdot cos\theta \qquad (2.10)$$

where W is the work, F is the force, d is the displacement and the angle (theta) is defined as the angle between the force and the displacement vector. The displacement must be caused by the force. The unit for work is the joule (J).

Power is defined as the rate at which work is done upon the swimmer. As rate is a time based quantity, power is related to how fast the work is done. This can be expressed as:

$$P = W / t \qquad (2.11)$$

where P is the power, W is work and t is time. Combining this equation with the equation for work (2.10), it is transformed as:

$$P = F \cdot cos\theta \cdot (d/t) \qquad (2.12)$$

where the d/t is the constant or average speed. So the equation is expressed as:

$$P = F \cdot V \cdot cos\theta \qquad (2.13)$$

where V is the constant or average speed.

Propelling Efficiency

Propelling efficiency is the ratio of the power to overcome drag (P_d) to the total mechanical power (P_o) including the power wasted in changing the kinetic energy of masses of water (P_k) (Toussaint, Beelen, Rodenburg, Sargeant, de Groot, Hollander & van Ingen Schenau, 1988). P_d at a swimming velocity (V) and drag force (F_d) is expressed as:

$$P_d = F_d \cdot V \qquad (2.14)$$

P_k is given by:

$$P_k = 1/2 \cdot m\,(\Delta u)^2 \cdot f \qquad (2.16)$$

where m is the mass of the pushed water, Δu is the velocity change of the pushed water and f is the stroke frequency (Toussaint, van der Helm, Elzerman, Hollander, de Groot & van Ingen Schenau, 1983).

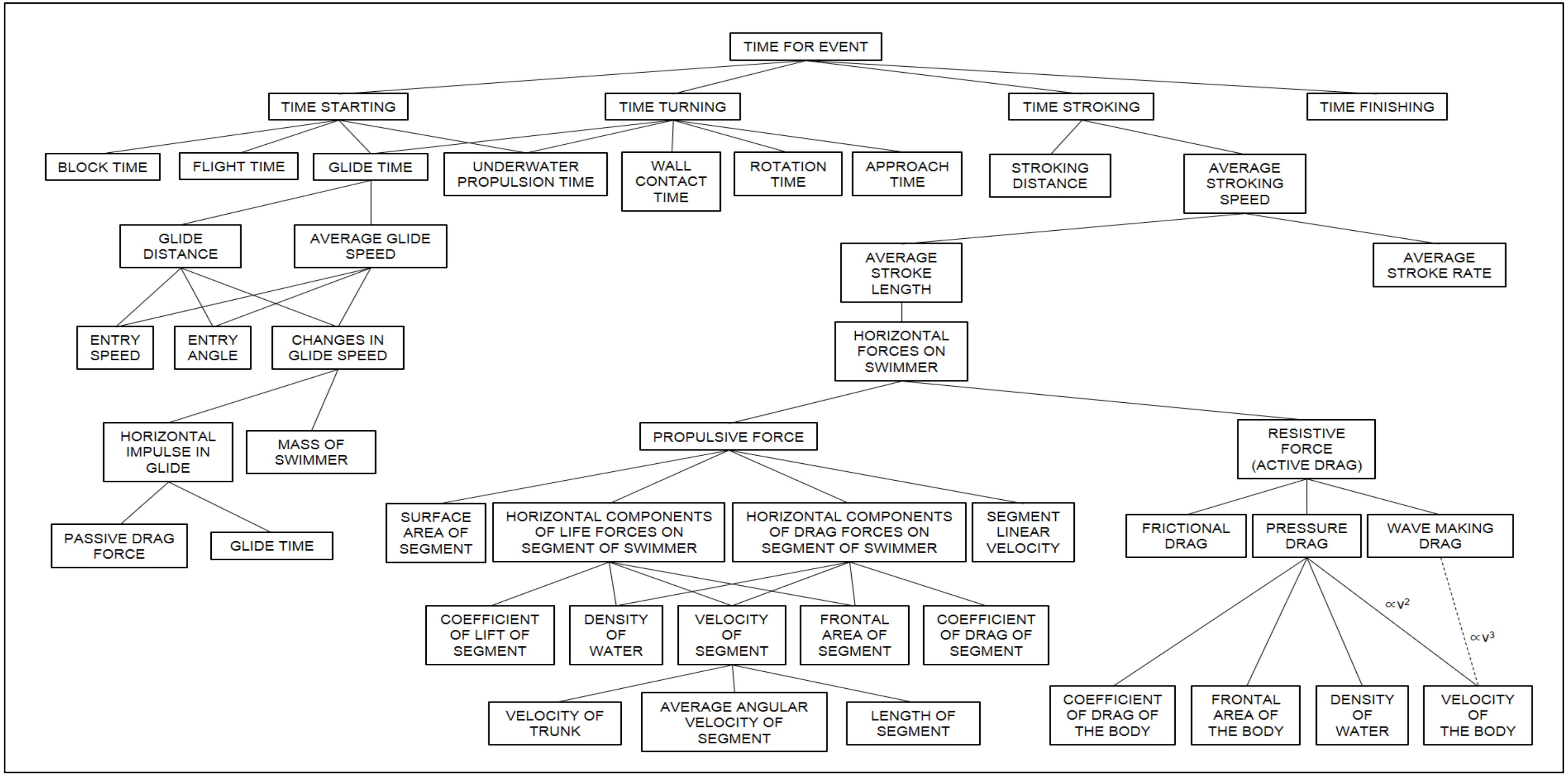

Figure 2.4 Theoretical model identifying the biomechanical factors of swimming (Guimaraes & Hay, 1985; Grimston & Hay, 1986; Mclean *et al.*, 2000).

Figure 2.4 shows a deterministic model of swimming. It shows the relationships between a movement outcome measure and the biomechanical factors that produce such a measure (Chow & Knudson, 2011). This model provides an insight into how anthropometric variables of para-swimmers can influence swimming performance. For example, it can be noted that in the case where a swimmer has higher passive drag force, due to his/her limited joint range of movement, this will influence their Glide Time in Starting and Turning performance. Similarly, if a swimmer has a shortened limb due to an impairment, this will influence the velocity of the segment endpoint which will, in turn, influence the Propulsive Force. Table 2.1 shows the correlation between anthropometric variables and able-bodied front crawl swimming performance. It will be important to observe whether para-athletes would have similar patterns of correlation.

Table 2.1 The correlation between anthropometric variables and performance time for able-bodied front crawl swimming performance

Parameter	Correlation coefficient	Author
Height	-.60 (p<.01)	Duche *et al*., 1993
	-.47 (p<.01)	Siders *et al*., 1993
	-.61 (p<.01)	Geladas *et al*., 2005
	-.67 (p<.01)	Zampagni *et al*., 2008
	-.54 (p<.05)	Lätt *et al*., 2010
Body mass	-.65 (p<.01)	Geladas *et al*., 2005
	-.46 (p<.05)	Zampagni *et al*., 2008
% body fat	.35 (p<.05)	Siders *et al*., 1993
	.47 (p<.05)	Tuuri *et al*., 2002
Upper extremity length	-.55 (p<.05)	Duche *et al*., 1993
	-.64 (p<.01)	Geladas *et al*., 2005
	-.52 (p<.01)	Zampagni *et al*., 2008
Hand length	-.57 (p<.01)	Geladas *et al*., 2005
Foot length	-.49 (p<.01)	Geladas *et al*., 2005
Chest circumference	-.64 (p<.01)	Geladas *et al*., 2005
Biacromial breadth	-.61 (p<.01)	Geladas *et al*., 2005
Biiliac breadth	-.48 (p<.05)	Duche *et al*., 1993
	-.46 (p<.01)	Geladas *et al*., 2005
Arm span	-.56 (p<.05)	Lätt *et al*., 2010

2.2 RESEARCH IN PARA-SWIMMING

'Para-swimming' is the sport of swimming which is adapted for athletes with physical, visual or intellectual impairments. Para-swimmers compete in elite, world-class competitions such as the Paralympic Games and IPC Swimming World championships. These events are governed by the International Paralympic Committee (IPC). In this thesis, the term 'para-swimming' defines the elite subdivision of the broader activity called 'disability swimming' which includes competitive swimming, but also includes other aquatic activities such as swimming for rehabilitation or education of people with an impairment. There are numerous studies in disability swimming (e.g. Dowrick & Dove, 1980; Prins, Hartung, Merritt, Blancq & Goebert, 1994; Yilmaz, Yanardag, Birkan, & Bumin, 2004; Karapolat, Eyigor, Zoghi, Akkoc, Kirazli & Keser, 2009; Rae & White, 2009) but these are peripheral to this thesis which focuses on high level competitive para-swimming.

Para-swimming has been one of the most important events since the first Paralympic Games at Rome in 1960 (Brittain, 2012). Para-swimming adopted its current format when the functional classification system (FCS) was applied at the 1992 Barcelona Paralympic Games (Vanlandewijck & Chappel, 1996; Brittain, 2012).

When the IPC first decided to apply the FCS there were many arguments for and against it, with one of the leading critics of the system being Kenneth Richter (Richter, Adams-Mushett, Ferrara, & McCann, 1992). The main criticism of the FCS was the weakness of the research underpinning it. The developers of the FCS (Blomqwist, 1990) assigned points for parts of the body involved in swimming propulsion, based on data that were, according to Richter et al. (1992), unscientific and subjective. Richter et al. (1992) also highlighted the lack of extensive field-testing to determine the reliability and validity of the swimming FCS and criticised the system from a physiological, sports technique and statistical point of view. Despite these criticisms, opinions supporting the use of the

FCS were already in the majority. Since the system was first used in 1992, researchers have continued to examine the objectivity of it. Four main approaches have been used (Daly & Vanlandewijck, 1999; Daly & Martens, 2011):

1) Comparison of Race Performance Time between Adjacent Classes

Comparing the total race performance time between adjacent classes of well-defined groups of swimmers is the basic step to evaluate the objectivity of the FCS (Daly & Vanlandewijck, 1999; Wu & Williams, 1999). Researchers agree that the world-record swimming speed should decrease as functional impairment increases (Daly & Vanlandewijck, 1999). Using this approach, Gehlsen & Karpuk (1992) undertook a large scale research project (*N*=1,256). However, this research was based on the medical classification system, not the FCS, and all the participants were either Paraplegic or Tetraplegic meaning the results are not relevant to the current system which encompasses a much wider range of impairments.

Using the FCS, Wu & Williams (1999) analysed the relationship between performance and swimming class of 374 para-swimmers who competed at the 1996 Atlanta Paralympics. The results generally reflected the criteria of classification; that the world-record swimming speed should decrease with a decrease in functional class. However, the swimming speed difference between adjacent classes were sometimes too small and the speed range in each class was high. For example, in the female 50 m freestyle, the mean speeds of the S9 and S10 classes were 1.55 $m{\cdot}s^{-1}$ and 1.56 $m{\cdot}s^{-1}$, respectively, with respective standard deviations of 0.03 $m{\cdot}s^{-1}$ and 0.08 $m{\cdot}s^{-1}$. In the female 50 m and 100 m backstroke events, the mean speed of the S9 class (1.25 $m{\cdot}s^{-1}$) was higher than the mean speed of the S10 class (1.24 $m{\cdot}s^{-1}$), even though the S9 swimmers were considered to be less physically impaired than the S10 swimmers. These results showed that good swimmers in more severely impaired classes could swim faster than those in less severely impaired classes.

2) Comparison of Race Component Times and Related Stroke Parameters

Comparisons of race performance times and related stroke parameters (e.g., stroke length & stroke rate) between adjacent classes have been commonly undertaken to examine the objectivity or the validity of the FCS (Daly & Vanlandewijck, 1999; Daly & Martens, 2011). For able-bodied swimmers there have been several studies which report the relationship between speed, stroke length and stroke rate and it is generally agreed that stroke length has a greater correlation with speed than stroke rate (Craig, Skehan, Pawelczyk, & Boomer, 1985; Kennedy, Brown, Chengalur, & Nelson, 1990; Arellano, Brown, Cappaert, & Nelson, 1994). In para-swimming, Pelayo *et al.* (1999) analysed 119 para-swimmers in the 100 m freestyle event and found that speed and stroke length increased significantly with functional class from S3 to S10. Stroke length values had significant differences between male and females in each class, whereas stroke rate did not. Stroke rates did not differ significantly between classes. The study's main finding was the strong relationship between speed and stroke length, with no relationship found between stroke rate and speed. The authors suggested that stroke index (speed × stroke length) be used as a criterion for the purposes of the FCS.

Daly *et al*. (2001) described the contribution of start speed, clean swimming speed, turn speed and finish speed to the total race performance, in all four strokes, for the men's 100m events at the 1996 Atlanta Paralympics. Turn speed (r_s = .63 ~.99; IPC Classes 2 – 10) and finish speed (r_s = .61 ~.97) were highly related to the total race performance. Start speed had the lowest correlation with the total race performance (r_s = .42 ~.82) except for the SB6 class which showed a strong correlation between these two variables (r_s = .81 ~.83).

At the 2000 Sydney Paralympics, Daly *et al*. (2003) analysed the 100-m freestyle performances of 134 para-swimmers for their heats and finals. They found that the winning, or the losing, of the races was decided in the second half of each 50 m lap. Stroke length accounted for more of the differences in speed between swimmers than stroke rate did, but stroke rate changes were still responsible for speed changes between heats and finals. Stroke length was a stronger correlate than stroke rate, for better speed maintenance at the end of the race.

Most of the research detailed above concludes that swimmers across a range of disability groups show similar patterns in their stroke parameters to those of able-bodied swimmers. In other words, stroke length had a stronger correlation with swimming speed than stroke rate (Pelayo *et al.,* 1999; Daly *et al.,* 2003). However a recent study (Osborough, Payton, & Daly, 2009) showed that stroke rate had stronger correlation with swimming speed than did stroke length when a homogenous group of highly trained single-arm amputee swimmers was tested. The study reported inter-swimmer correlations showing maximum swimming speed had a significant correlation with stroke rate (r = .72; p < .01) whereas stroke length did not significantly influence swimming speed. No correlations were found between stroke length and any anthropometric parameters but biacromial breadth, shoulder girth, and upper-arm length all correlated significantly with the stroke rate.

3) Prospect of Any Impairment Group Attaining a Medal or Qualifying for the Final

At the 1996 Atlanta Paralympics, Wu & Williams (1999) examined the prospect of any impairment group attaining a medal or qualifying for a final, based on the classification sheets of 374 swimmers. Swimmers were categorised into one of six physical impairment groups: spinal cord injury, cerebral palsy, poliomyelitis, amputation, dysmelia and les autres (e.g., dwarfism, osteoarthritis, multiple sclerosis, stiff joint, muscular dystrophy and arthrogryposis). Under a valid FCS, para-swimmers in competition should have equal opportunities to qualify for a final and to win medals. Although Wu & Williams (1999) found that female swimmers with cerebral palsy and les autres won relatively more gold medals (65%) relative to the number of their participants (40%), they concluded that the current classification system did not benefit any impairment group because male swimmers showed a different pattern compared to the females. Daly & Martens (2011) noted that similar data to those in the Wu & Williams (1999) study have been collected over the last 20 years, but have unfortunately not been reported in the literature.

4) *Specific Functional Abilities of Para-Swimmers*

To reinforce the scientific basis of the FCS, Daly & Vanlandewijck (1999) suggested comparing specific functional abilities of para-swimmers, which may include physiological capacity, mechanical power output, passive and active drag, propulsion, start and turn abilities.

Chatard *et al*. (1992) was one of the first groups to adopt this approach. They assigned swimmers into three categories (Group I: wheelchair users; Group II: walking with technical aids; Group III: walking without aids) and demonstrated that more severely impaired swimmers had greater passive drag than less severely impaired swimmers. However, the three groups were not aligned with the 10 functional classes currently used by the IPC for physically impaired swimmers.

Burkett *et al.* (2010) compared the 15 m swimming start component of twenty male Olympic and para-swimmers concluding that there were three variables that significantly influenced start time to 15 m: 1) underwater velocity, 2) free swimming velocity, and 3) whether the swimmer had cerebral palsy. The cerebral palsy swimmers had poorer starting performances than other groups. However, it should be noted that only S8-S10 swimmers participated in this study.

As a follow-up study, Dingley *et al.* (2014b) examined how the performance of the swimming start was affected by the severity and type of a swimmer's physical impairment. Clear differences in performance were identified between groups, based on the severity and type of disability and performance level, but the categorisation of disability types was over-simplified (only upper-body, lower-body, and cerebral palsy were defined), due to the difficulty of finding well trained para-swimmers with various impairments.

Recently, Dingley *et al.* (2014a) reported correlations between dry-land bilateral hand force production and swimming performance in three groups (1: S2-S8 [n=8]; 2: S9-S10 [n=8]; 3: S13-14 [n=5]) of physically impaired swimmers. Due to the difficulty of finding well-trained highly impaired swimmers, the number of low classed swimmers was small (S2 = 1, S3 = 1, S6 = 2). Unsurprisingly, swimmers with a greater degree of impairment generated lower force and velocity, compared to less impaired swimmers but there was no difference between groups regarding bilateral asymmetry.

2.3 FACTORS AFFECTING DRAG

In human swimming, resistive drag (henceforth referred to as drag) is described in two ways: *Passive drag*, which is experienced when the swimmer holds a fixed position, for example, during a glide off the wall, and *active drag* which is experienced whilst actively swimming. Researchers have reported that active drag is more dependent on swimming technique, whereas passive drag is more dependent on the anthropometry of an individual swimmer (Toussaint, 1990; Kolmogorov & Duplishcheva, 1992; Kjendlie & Stallman, 2008; Marinho *et al.*, 2010a; Formosa, 2012; Barbosa *et al.*, 2013). The magnitude of drag is easily changed, as it depends on many factors. In the following section, those factors will be categorised as: 1) factors related to the swimmer's movement; and 2) factors unrelated to the swimmer's movement.

2.3.1 Factors affecting drag related to the swimmer's movement

Swimming speed, depth below the water surface, body position and swimming technique are the factors affecting drag that relate to the swimmer's actions (Kjendlie & Stallman, 2008). Many early studies of drag in swimming reported a high correlation between passive drag and speed (Karpovich, 1933; Counsilman, 1955) demonstrating that as a swimmer's speed increases, so does the acting drag.

As a factor affecting drag, the depth below the water surface specifically relates to the wave drag component. Lyttle *et al*. (1998) showed that swimmers who performed underwater glides deeper than 0.4 m reduced their drag, especially when their velocity was above 1.9 $m \cdot s^{-1}$. Vennell *et al*. (2006) reported that, in human swimming, wave drag is the largest drag component (equation 2.4). When swimming at 1.7 $m \cdot s^{-1}$, at the water surface, wave drag comprises up to 60% of the total drag experienced by a swimmer. In contrast, at a depth of 0.5 m at a speed of 1.0 $m \cdot s^{-1}$ and 0.7 m at a speed of 2.0 $m \cdot s^{-1}$, wave drag is less than 5% of the total drag experienced (Vennell *et al*., 2006).

Body position, which is strongly influenced by swimming technique, is another factor that determines drag. Taïar *et al*. (1999) used a mannequin to reproduce three key body positions in the butterfly stroke cycle of a world champion and showed that they had less drag on their legs than a non-elite swimmer (Figure 2.5). Kent & Atha (1971) showed how drag varied from 95 N to 226 N across the phases of the breaststroke technique (Glide – Breathing – Recovery – Pre-thrust – Post-thrust) (Figure 2.6).

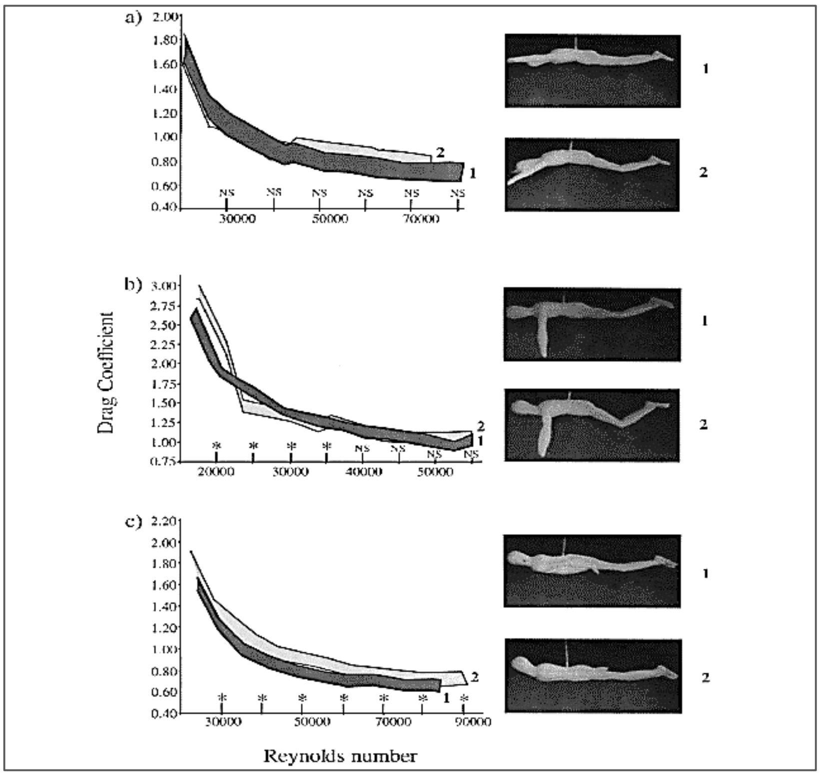

Figure 2.5 Comparison of the drag coefficient of (1) world champion at butterfly swimming and (2) non-elite swimmer, at range of Reynolds numbers. (a) start of arm pull; (d) middle of arm pull; (c) end of arm pull (taken from Taïar *et al*., 1999).

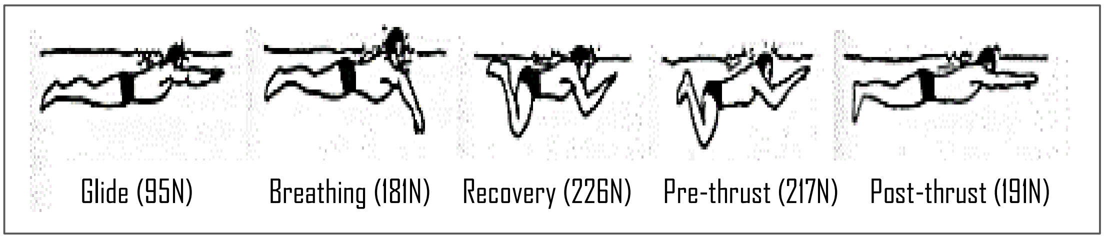

Figure 2.6 Passive drag at key instants in the breaststroke technique (Glide – Breathing – Recovery – Pre-thrust – Post-thrust; taken from Kent & Atha, 1971).

2.3.2 Factors affecting drag unrelated to the swimmer's movement

Drag is affected by, amongst other things, a swimmer's anthropometry which defines their size and the shape (Clarys, Jiskoot, Rijken & Brouwer, 1974; van Tilborgh, Daly & Persyn, 1983). As explained in section 2.1, a swimmer's height is inversely related to their wave drag whereas the cross sectional area (CSA) of a swimmer has a positive association with their pressure drag (Larsen, Yancher & Baer, 1981; Toussaint, de Looze, van Rossem, Leijdekkers & Dignum, 1990). A number of studies have examined the relationships between selected anthropometric characteristics of swimmers and passive (Clarys *et al.*, 1974; van Tilborgh *et al*., 1983; Chatard, Lavoie, Bourgoin & Lacour, 1990a) or active drag (Clarys, 1978; Huijing, Toussaint, Mackay, Vervoon, Clarys & Hollander, 1988; Toussaint *et al*., 1990; Barbosa, Costa, Marques, Silva & Marinho, 2010b).

Clarys *et al.* (1974) wanted to show the effect of anthropometry on passive drag (D_p) so selected participants with extreme body types (i.e. three thin and three heavy types) according to the Health-Carter Somatotyping method (Carter, 1970). The heavy types produced greater D_p than the thin types and their D_p increased more rapidly with increases in speed. The authors concluded that the human form influences total resistance. However, the study did not report correlations between anthropometry and passive drag. The majority of studies that followed have concluded that drag is influenced by anthropometry, particularly body size (Huijing *et al.*, 1988; Chatard *et al*., 1990a; Benjanuvatra, Blanksby, & Elliott, 2001) but some have found no association between passive drag and anthropometry (Miyashita & Tsunoda, 1978; Toussaint *et al.*, 1990).

Clarys *et al.* (1974) suggested that three body slenderness indices: 1) Reciprocal Ponderal Index (RPI) (Height/Mass$^{1/3}$), 2) Length-Thickness Ratio (LTR) (Height^2/body CSA), and 3) Length Surface Ratio (LSR) (Height^2/BSA), could be associated with wave, pressure and frictional drag, respectively (Clarys *et al.*, 1974; Clarys, 1979; Lyttle *et al.*, 1998; Benjanuvatra *et al*., 2001). According to Clarys *et al*. (1974) these slenderness parameters, based on parameters in ship science, might be useful tools in swimming biomechanics, given that the shape of a ship is analogous to that of the human body when swimming. For example, the coefficient of slenderness of a ship model is the Length / Mass$^{-1/3}$ and is known to be influenced by wave drag. The coefficient of slenderness of a ship is analogous to the RPI of the human body. Benjanuvatra *et al.* (2001) reported a significant negative correlation ($p < .05$) between a swimmer's LTR and their passive drag ($r = -.59$) when the towing speed was faster than 1.9 m·s^{-1}, whereas the RPI ($r = -.07$) and LSR ($r = .08$) did not relate to the passive drag.

Most recently, Naemi, Psycharakis, McCabe, Connaboy, & Sanders (2012) examined the effect of swimmers' size and shape parameters on 'gliding efficiency' (the ability of a body to minimise deceleration when gliding; an indirect measure of passive drag). They concluded that gliding efficiency was more dependent on a swimmer's shape characteristics, including the appropriate postural angles, rather than on size parameters.

2.4. Measuring drag in swimming

Swimming is characterised by the successive application of a propulsive force (thrust) to overcome a velocity-dependent water resistance (hydrodynamic drag). Combinations of arm, leg and body movements lead to variations of thrust and velocity (Marinho *et al*., 2010a). Different techniques and levels of skill lead to different fluctuations in thrust, drag and velocity, contributing to the highly variable performances seen in swimming (Barbosa, Bragada, Reis, Marinho, Carvalho & Silva, 2010a). Swimming performance can be studied by analysing the interaction of propelling and resistive (drag) forces. A swimmer will only enhance their performance by minimising resistive forces that act on their body at a given velocity and/or by increasing the propulsive forces produced by the propelling segments (Toussaint *et al*., 2000; Toussaint 2002; Marinho, Barbosa, Kjendlie, Mantripragada, Vilas-Boas, Machado, Alves, Rouboa & Silva, 2010b; Marinho, Barbosa, Mantha, Rouboa, & Silva, 2012).

Hydrodynamic drag can be defined as an external force that acts on a swimmer's body in the opposite direction to their movement (Toussaint *et al.*, 2000). This resistive force is dependent on the anthropometric characteristics of a swimmer, on the characteristics of the equipment used by a swimmer, on the physical characteristics of the water (density, viscosity, temperature, etc.), and on the swimming technique employed (Vilas-Boas, 1996). A swimmer's drag can be measured or estimated under passive conditions (swimmer holding a fixed position) or active conditions (swimmer making movements with their limbs).

2.4.1. Passive drag

Passive drag measurements do not include the drag that a swimmer creates when they move their limbs to generate propulsion. However, passive drag is still extremely relevant in swimming as it provides a direct measure of a swimmer's ability to streamline their body; this is critical in certain phases of a race. For example, during the gliding phase following a dive start or a wall push-off following a turn, the most important requirement is to minimise the hydrodynamic drag (Guimarães & Hay, 2010). Hence, swimmers should adopt their most streamlined position during these phases. With regard to the breaststroke, the gliding phase of the stroke cycle represents 44% of the total swim (D'Acquisto, 1988). Superior breaststroke swimmers spend a greater amount of time in the gliding phase (D'Acquisto, 1988; Chatard *et al.*, 1990a; Vilas-Boas, Costa, Fernandes, Ribeiro, Figueiredo, Marinho, Silva, Rouboa & Machado. (2010), thus must focus on minimising their passive drag.

Measurement of passive drag may also be very relevant in para-swimming According to Vanlandewijck & Chappel (1996), a fair swimming classification system should ensure that para-swimmers win races because of superior talent, training, skill, fitness and motivation, rather than because they are advantaged by their level of impairment. Para-swimmers should therefore be classified using measures that influence swimming performance but that are not unduly influenced by skill level. Kolmogorov & Duplishcheva (1992) found that passive drag was much more dependent on an individual's anthropometry than on their swimming technique (skill) and Mason, Formosa & Rollason (2009) stated that passive drag may be a good indicator of the future capabilities of a swimmer. Thus it could be argued that passive drag could be a very useful measure in any future swimming classification system for para-swimmers.

2.4.1.1. Towing methods (towing devices and towing tank)

Passive drag is generally measured using some form of towing device coupled with a force-transducer. The principle is simple; the force required to tow the swimmer through the water, at a specified speed, is the passive drag. Since Du Bois-Reymond (1905) first towed swimmers behind a rowing boat, towing has remained the most common way to measure passive drag. Karpovich (1933) and Jaeger (1937) used a windlass to demonstrate the relationship between speed and passive drag. Even though the methods of towing swimmers have developed from rowing boat to windlass to electric-driven winches (Figure 2.7). More recently, water flumes have been used to measure passive drag, but the basic approach has remained same (Havriluk, 2007).

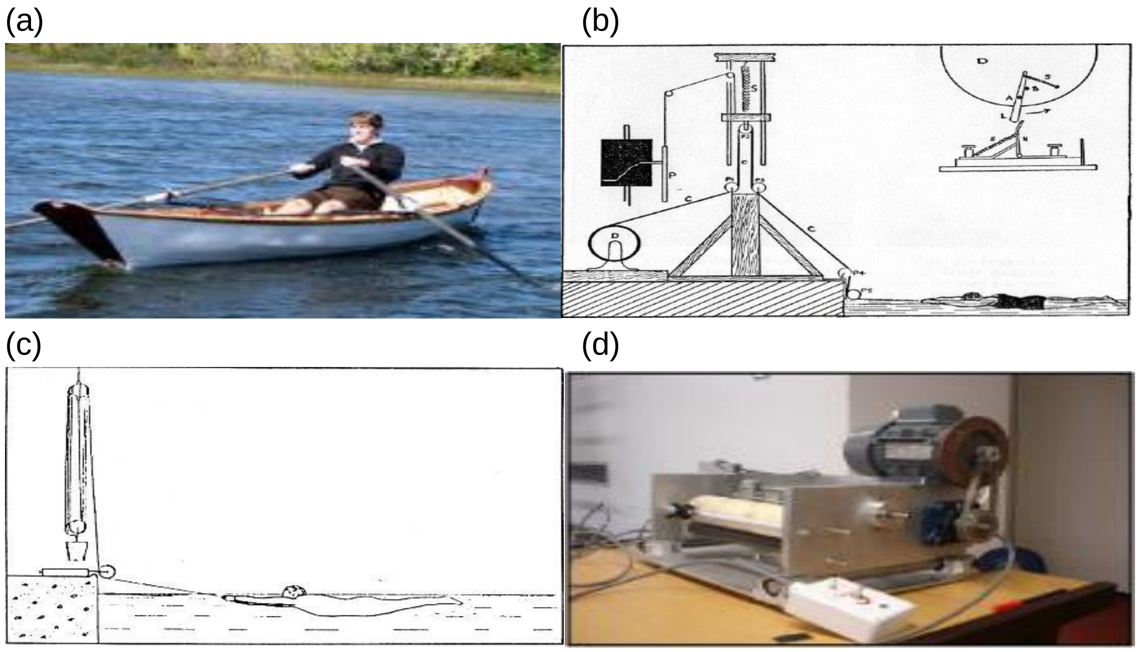

Figure 2.7 Different systems to tow swimmer (a) rowing boat; (b) towing system using windlass (taken from Karpovich, 1933); (c) Towing system using windlass (taken from Jaeger, 1937); (d) Electro-Mechanical towing device (used in the current thesis).

With regard to measuring the towing force, load cells or force platforms are the two most common methods (Chatard *et al.*, 1990b; Lyttle *et al.*, 1998; Benjanuvatra, Dawson, Blanksby & Elliott, 2002). The load cell have been positioned on the towing line, between the swimmer and the towing motor (e.g. Lyttle *et al.*, 1998) or alternatively, the towing device can be mounted on a force platform (Alcock & Mason, 2007; Formosa, Toussaint, Mason & Burkett, 2012).

Figure 2.8 shows the experimental set-up of Lyttle, Blanksby, Elliot & Lloyd (2000). Their system provided a range of towing speeds up to 3.1 $m \cdot s^{-1}$. Towing depth was controlled by a two-pulley system fixed to the pool wall, the lower pulley permitted the towing force vector to be horizontal at the required depth. An underwater video camera was used to ensure that body position and depth was maintained throughout the towing trial. Towing force (passive drag) was recorded using a uni-directional load cell which was calibrated using static weights.

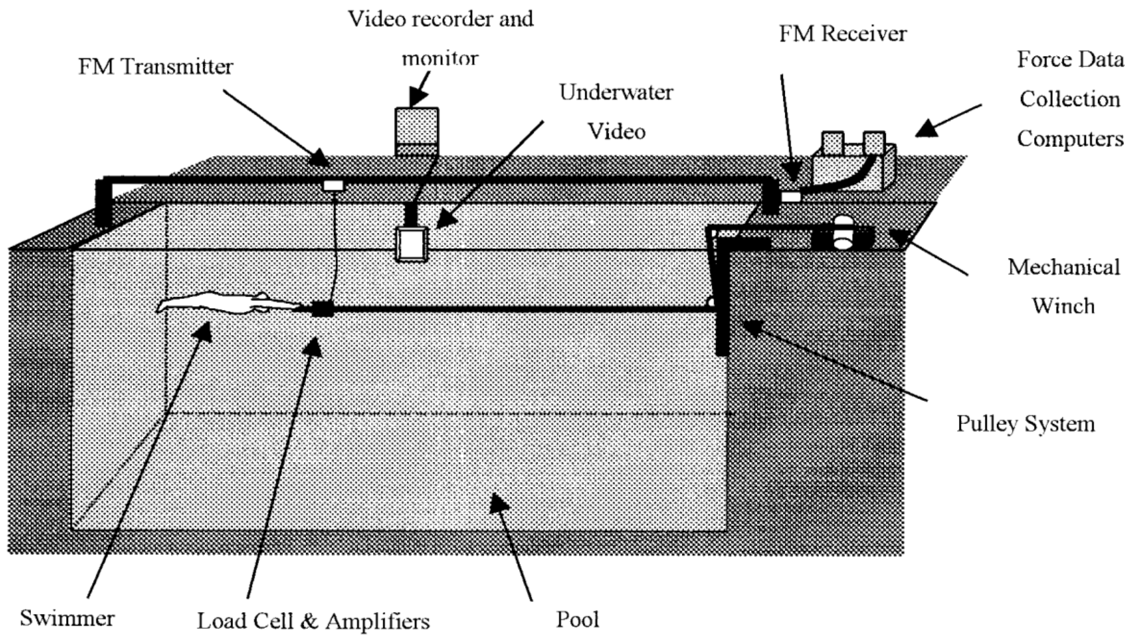

Figure 2.8 Experimental set-up of the towing method (taken from Lyttle *et al.*, 2000).

2.4.1.2. Flume methods

A swimming flume (sometimes called a water treadmill) provides an alternative means of measuring passive drag. In a flume, the swimmer is held in a fixed location by attachment to a handle (Figure 2.6) and the water is driven past them at a specified speed. The passive drag is measured as the horizontal force being transmitted to the handle by the swimmer. The flume method was first used to measure passive drag by Holmér (1974). More recently, Chatard & Wilson (2003) used a flume to measure the effect of drafting (i.e., swimming directly behind or at the side of another swimmer) on drag. Vennell *et al*. (2006) used a flume to demonstrate the effect of wave drag. To accomplish this they measured passive drag at different depths at 10 cm intervals. The equipment consisted of a forward strut joined to a horizontal rod that was connected to an in-line load cell. (Figure 2.8). A mannequin was attached to the rod and the depth was varied by vertically adjusting the horizontal rod. A load cell was placed between the forward strut and the horizontal rod to measure drag force on the mannequin. Measurements were recorded at 100 Hz.

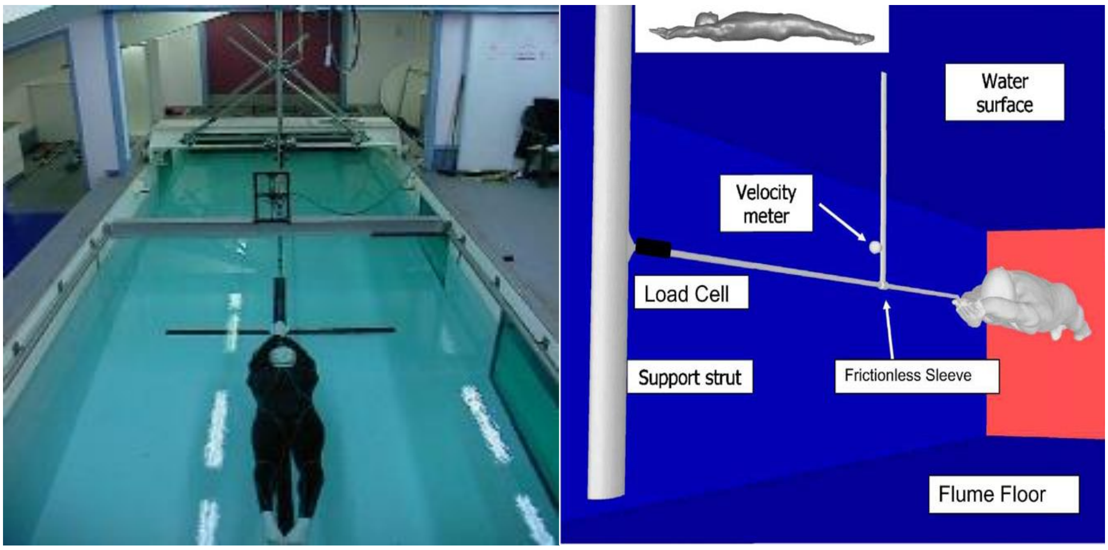

Figure 2.9 Experimental setup of the flume method (taken from Vennell *et al*., 2006).

2.4.1.3. Glide deceleration method

An indirect method for estimating passive drag, the glide deceleration method was suggested by Klauck & Daniel (1976) and used by Mollendorf, Termin, Oppenheim & Pendergast (2004), Kjendlie & Stallman (2008), Webb *et al*. (2015) and Barbosa, Morais, Forte, Neiva, Garrido & Marinho (2015). This method is based on Newton's Second Law of Motion:

$$F = m \cdot a \tag{2.10}$$

where F is force, m is body mass and a is acceleration. Barbosa *et al*. (2015) stated that the forward displacement of a swimmer (derived by the velocity or the acceleration) is the resultant of the external forces acting on the swimmer's body:

$$a = \sum F_i / m \tag{2.11}$$

where a is the acceleration, $\sum F_i$ is the resultant force, and m is the body mass. Equation 2.11 can be simplified to the following, for a swimmer who is passively gliding:

$$a = D_P / m \tag{2.12}$$

where a is the swimmer's deceleration during the glide, D_P is the passive drag force, and m is the total mass (body mass + added mass of the water). Passive drag can thus be calculated by measuring the swimmer's deceleration during the glide and the total mass.

One of the limitations of this method is the difficulty in estimating the added mass of the fluid (Kjendlie & Stallman, 2008; Webb *et al*., 2015; Barbosa *et al*., 2015). Barbosa *et al*. (2015) estimated the added mass to be 27% of the swimmer's body mass based on the equation proposed by Vogel (1996):

$$m_a = C_a \cdot V \cdot d \tag{2.13}$$

where m_a is the added mass, C_a is the coefficient of added mass, V is the volume of the swimmer and d is the water density. Once the added mass is determined, it is added to the swimmer's body mass. So the m in equation 2.12 is:

$$m = \text{body mass} + m_a \tag{2.14}$$

The passive drag is then calculated using equation 2.12.

2.4.1.4. Computational Fluid Dynamics (CFD)

CFD is a branch of fluid mechanics that solves and analyses problems involving a fluid flow with computer-based models and simulations (Marinho *et al*., 2010b). The first attempt to estimate passive drag of swimmers using CFD was performed by Bixler, Pease & Fairhurst (2007). These authors succeeded in establishing a CFD model of a submerged human body and estimated the passive drag. They demonstrated the estimated value was accurate by comparing it with real-world test results. Two years later, Marinho, Reis, Alves, Vilas-Boas, Machado, Silva & Rouboa (2009) used CFD to illustrate how a swimmer's body position influenced the passive drag during underwater gliding. Their CFD model was also used to estimate the relative contributions of frictional drag and pressure drag to the total drag during the gliding phase.

A major benefit of CFD is the ability to obtain results from '*what if*' type scenarios without conducting any physical experiments on swimmers (Lyttle & Keys, 2006). CFD can be very useful in cases when the geometry of the object is known in any flow field and some initial flow conditions are prescribed (Bixler *et al.,* 2007). In order to obtain accurate results it is essential to supply CFD with highly specific data to characterise the study conditions (Marinho *et al*., 2010b). Researchers must recognise the CFD analysis will produce inaccurate results if inaccurate data regarding a specific situation are applied. Prior to any computer simulation is run, analysis and verification of the model is required and the results carefully analysed afterwards (Marinho *et al*., 2010b).

2.4.1.5. Comparison of passive drag measurement techniques

Four main methods for measuring passive drag have been detailed above. As each of those have their own characteristics, it is important to compare their advantages and disadvantages.

The main advantage of the towing and flume methods is that they both provide a direct measure of passive drag. However, during towing, the water maintains a stable laminar flow, whereas the water in a flume is usually turbulent as speed is increased (Chomiak, 1979; Bray, 1990; Bixler & Riewald, 2002). Therefore, the towing method creates a more similar condition to actual swimming than the flume method does. One practical disadvantage of the towing method are the difficulties it presents in controlling the orientation of the swimmer's body and in maintaining a constant depth (see Lyttle *et al.*, 1998; Chatard & Wilson, 2003; Vennell *et al.*, 2006).

Lyttle *et al.* (1998) reported the relationship between passive drag and towing depth. However, only the surface of water and depths of 0.40 and 0.60 m below the surface were compared. Using the flume method, towing depth can be controlled much more precisely. For example, Vennell *et al.* (2006) were able to record the drag on a mannequin in a flume at increments of 0.10 m in the range of 0.0 m to 1.0 m. Chatard & Wilson (2003) showed the effect of drag whilst drafting using a flume and were able to control the distance between the leader and the drafter at 0.50 m steps up to 2 m. These last two studies highlight how a flume allows the researcher to control a swimmer's position accurately. Havriluk (2007) performed a meta-analysis on articles published from 1933 to 2004 to determine the drag differences between studies which used: 1) towing using electro-mechanical motor; 2) flume or 3) towing tank, to measure passive drag. He stated that the passive drag coefficient across the different experimental designs showed remarkable consistency. They found 93% of drag coefficient were between 0.4

and 1.0, and 74% were between 0.5 and 0.9, even though not all the studies measured the drag at the same positions (for example, head under or above water).

Webb, Taunton, Hudson, Forrester & Turnock. (2015) compared the towing method to the glide deceleration method and reported that for five repeat tests, a 1.8% difference in passive drag can be resolved with 95% and 70% confidence levels for the towing method and the glide deceleration method, respectively. Although the glide deceleration method is a relatively simple method of calculating passive drag, it is not a direct measure, the results are based on an assumed amount of additional mass moving with the swimmer, and does not provide as repeatable results the towing method (Webb *et al.,* 2015).

With regard to simulating passive drag using CFD, Bixler *et al*. (2007) compared the numerical results from CFD with experimental results of a swimmer and a mannequin using a flume. They found that the drag of a swimmer measured in a flume was 18% greater than that of mannequin equal in size and shape to the swimmer. The measured passive drag for the mannequin were found to be within 4% of the drag calculated using CFD suggesting that the adopted computational method was appropriate and yielded valid results. However, a 4% discrepancy between the CFD model and reality might not be acceptable if only small changes in drag are being studied.

2.4.2. Active drag

Since the passive drag was first measured by Du Bois-Reymond in 1905 using the towing method, this was considered for decades to be the best measure of the drag which a swimmer encounters (Clarys, 1979). Alley (1949) stated that drag should be considered during active swimming because each moving part of the body creates additional drag and, consequently, should create a drag force dissimilar to the passive drag. Since this observation, virtually in every decade a new approach to estimating active drag has been developed and introduced (di Prampero, Pendergast, Wilson & Rennie, 1974; Clarys, 1979; Hollander *et al*., 1986; Kolmogorov & Duplishcheva, 1992; Alcock & Mason, 2007; Webb *et al*., 2011). This development is still ongoing because, unlike passive drag measurement, there is no method that can measure active drag directly. There is as yet no agreed gold standard approach, with the most current methods producing conflicting data (Toussaint, Roos & Kolmogorov, 2004).

2.4.2.1. Extrapolation technique (1970s)

The earliest approach to measuring active drag was the extrapolation technique used in the 1970s. Di Prampero et al. (1974) first described the active drag of ten well-trained students swimming very slow front crawl (0.55 and 0.90 $m \cdot s^{-1}$) in a ring-shaped swimming pool (depth 2.8 m; width 2.8 m; circumference 58.6m). Their method involved extrapolating the linear relationship between drag and oxygen consumption (VO_{2net}) at constant velocities and determining the drag as a function of VO_{2net}.

The active drag was determined by adding (or subtracting) extra drag loads (or from) swimmers swimming at constant speed. The added drag was related to the swimmer's energy expenditure in order to calculate the active drag as well as the mechanical efficiency.

Figure 2.10 (A) shows the experimental set up. The swimmer was paced at a constant speed. Expired gas was collected when the swimmer reached steady state and the overall energy expenditure was estimated. Known weights (from a few hundred grams to ~1.5 kg) were attached to the swimmer by means of a rope passing through a system of pulleys, allowing the force to act horizontally along the direction of movement. To maintain a constant speed the swimmer was required to supply an overall propulsive force equal to the sum of his body drag and the applied force. Since the swimmer swam at constant speed, the propulsion was equal to the resistance; the added force was equivalent to an increase, or decrease of the body drag by a known amount. Figure 2.10 (B) shows O_2 consumption as a function of added force of one subject. The relationship between O_2 consumption above resting, with added or subtracted drag, appears linear. Using a linear regression, active drag was determined.

The studies using the extrapolation approach yielded active drag values about ~150%-300% greater than those reported at the time for passive drag (Clarys *et al.*, 1974; Holmér, 1975; Rennie, Pendergast & di Prampero, 1975; Kemper, Verschuur, Clarys & Jiskoot., 1983). Toussaint *et al.* (1983) questioned the validity of the method for two reasons: First, that the method inherently assumes that the propelling efficiency (power lost to the water by the swimmer) remained the same when the force values were measured during the experiments. This is unlikely to be the case; Second, that small measurement errors in VO_{2net} values will be propagated significantly by the assumptions of the extrapolation, which is the basis of this approach. Van de Vaart, Savelberg, de Groot, Hollander, Toussaint &van Ingen Schenau (1987) have stated that this active drag value determined by the indirect techniques were overestimated.

(a) (b)

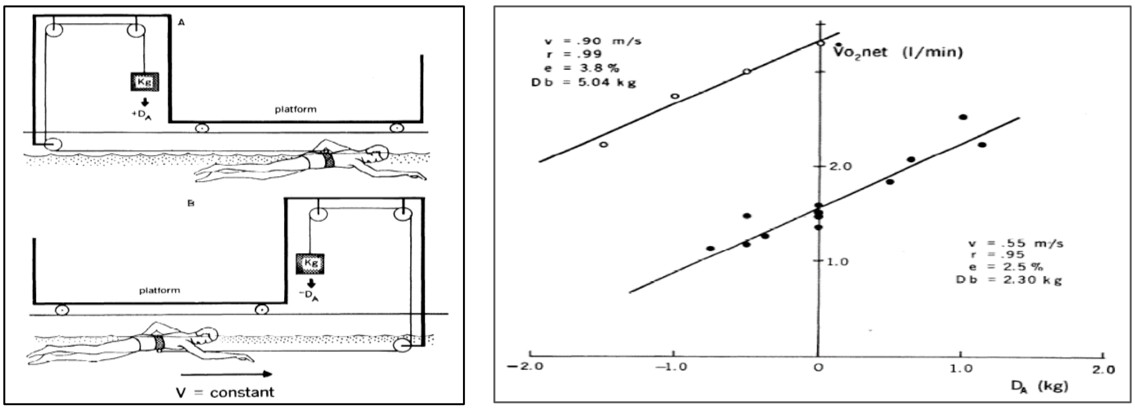

Figure 2.10 (a) The experimental setup of the extrapolation technique; (a) O_2 consumption as a function of added drag of one subject (taken from de Prampero *et al.*, 1974)

2.4.2.2. Measuring Active Drag (MAD) system (1980s)

Following the extrapolation technique, several groups of researchers sought to identify a more direct way of determining active drag. The measuring active drag (MAD) system was developed by Hollander *et al.* (1986) and Toussaint *et al.* (1988). This technique relies on the direct measurement of hand contact forces created when a swimmer pushes off from a series of pads mounted underwater, using a similar technique to front crawl (see figure 2.11). Hence, by calculating the mean push-off forces over a constant speed swim, the mean active drag force can be found as it is assumed to be equal in magnitude to the mean push-off force, the two forces being in equilibrium.

Apparatus

Figure 2.11 shows the experimental set up of Hollander *et al*. (1986). An air filled 23 m tube with 15 push-off pads attached to it (Figure 2.12) is fixed under the water surface. The height of the tube and the space between push-off pads are adjusted to accommodate swimmers of different sizes. One end of the tube is linked to a force transducer mounted on the pool end wall. This measures the push-off forces in the swimming direction. The output signal from the force transducer is transmitted telemetrically and sampled at 100 Hz. The average propulsive force is calculated by integration. Forces on the first and last push-off pad are deleted in order to meet the requirement of constant speed (Hollander *et al*., 1986).

Procedures

Swimmers are required to propel themselves down the pool length at a constant speeds using the push-off pads. The MAD system can only be used for front crawl arm-only swimming. Measurements are therefore performed with the swimmer holding a small buoy between their legs to prevent the use of kicking and to help them maintain a horizontal body position.

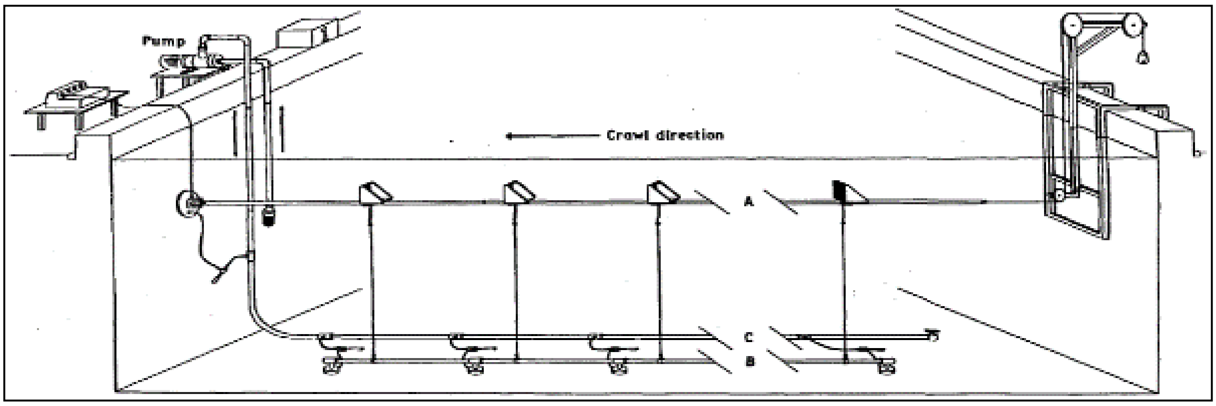

Figure 2.11 System for measuring active drag (MAD) (taken from Hollander *et al.*, 1986).

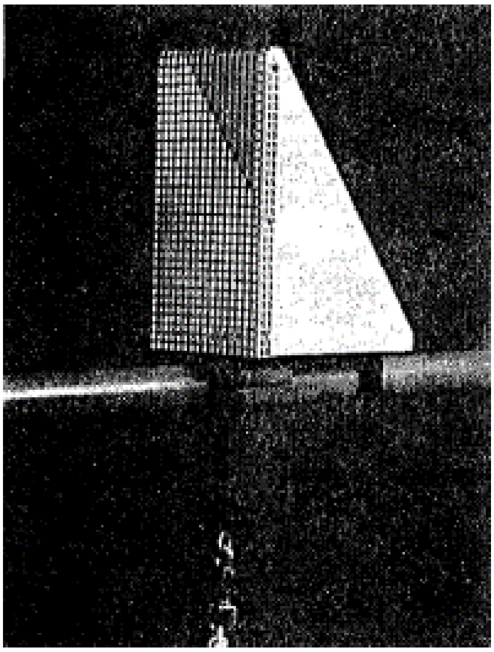

Figure 2.12 A push-off pad from the MAD system (from Hollander *et al.*, 1986).

A considerable number of studies have been undertaken using the MAD system (Hollander *et al.*, 1986; van de Vaart *et al.*, 1987; Toussaint, de Groot, Savelberg, Vervoorn, Hollander & van Ingen Schenau, 1988; Toussaint *et al.*, 1990; Toussaint, Janssen & Kluft, 1991). However there exists several criticisms of the system (Sacilotto, Ball & Mason,2014): 1) the technique which swimmers use on the system is very different from their natural front crawl technique (Xin-Feng, Lian-Ze, Wei-Xing, De-Jian & Xiong, 2007; Alcock & Mason, 2007; Poizat, Ade, Seifert, Toussaint & Gal-Petitfaux, 2010); 2) according to Poizat *et al* (2010), swimmers have reported difficulty in making hand contact with the push-off pads, especially at high swimming speed, and 3) the system can only be used for the analysis of active drag in the front-crawl of individuals capable of using the push-off pads. As such, MAD system would not be a suitable tool for assessing many of the impairment types found in para-swimming.

2.4.2.3. Velocity Perturbation Method (VPM) (1990s)

Kolmogorov & Duplishcheva (1992) developed the Velocity Perturbation Method (VPM). In this method a hydrodynamic body (Figure 2.12) creating an additional known drag, is attached to the swimmer. The maximal velocity when swimming with the hydrodynamic body is compared with the maximal free-swimming velocity. The estimation of active drag relies on the assumption that a swimmer is capable of delivering a constant, useful mechanical power output. Hence, the power output (P_1) when swimming without the hydrodynamic body is equal to the power output delivered when swimming with the hydrodynamic body (P_2) (Kolmogorov & Duplishcheva, 1992):

$$P_1 = P_2, \tag{2.15}$$

The observed difference in velocity (v_1: free swimming, v_2: swimming with the hydrodynamic body) should be due to the effect of the added resistance from the hydrodynamic body. Hence, in the free swimming condition:

$$P_1 = F_{r1} \cdot v_1, \tag{2.16}$$

And in the added resistance condition:

$$P_2 = F_{r2} \cdot v_2, \tag{2.17}$$

Where F_{r1} and F_{r2} is the active drag in the first and second condition, respectively. The active drag is related to the swimming condition according to (Kolmogorov & Duplishcheva, 1992):

$$F_{r1} = \frac{1}{2} C_x \cdot \rho \cdot S \cdot v_1^2 \tag{2.18}$$

$$F_{r2} = \frac{1}{2} C_x \cdot \rho \cdot S \cdot v_2^2 + F_b, \tag{2.19}$$

Where ρ is the density of water and S a characteristic surface area (m^2) of the swimmer. For S, Komologorov & Duplishcheva (1992) used the human body volume (m^3) to the power $\frac{2}{3}$. F_b is the added drag due to the hydrodynamic body. Assuming equal power outputs, combining equations (2.16), (2.17), (2.18) and (2.19) will yield:

$$\frac{1}{2} C_x \cdot \rho \cdot S \cdot v_1^3 = \frac{1}{2} C_x \cdot \rho \cdot S \cdot v_2^3 + F_b \cdot v_2 \tag{2.20}$$

And:

$$C_x = \frac{F_b \cdot v_2}{\frac{1}{2} \rho \cdot S \cdot (v_1^3 - v_2^3)} \tag{2.21}$$

By substituting C_x into equation (2.16) results in:

$$F_{r1} = \frac{F_b \cdot v_2 \cdot v_1^2}{v_1^3 - v_2^3}, \tag{2.22}$$

The maximum velocities when swimming with (v_2) and without the hydrodynamic body (v_1) are determined in maximal 50 m swims. Time to cover 30 m is recorded using an electronic timing system. The structure of the hydrodynamic body (variant 'B') and different ways of fixing it to the swimmer's body are shown in Figure 2.13. The hydrodynamic body is placed at such a distance behind the swimmer that the water is no longer turbulent. This critical distance was found to be 3.5 – 4.5 body lengths, depending on the swimming stroke and the swimmer's proficiency (Kolmogorov & Duplishcheva, 1992).

As a following research, Xin-Feng *et al*. (2007) modified the method with regard to the way the known additional drag was added to the swimmer (Figure 2.14). They used a steel wire and a gliding block, so that the amount of additional drag was controlled by the researcher, rather than being fixed. Under the same assumption of useful mechanical power output and by using the known additional drag, the calculation process for active drag was the same as the VPM.

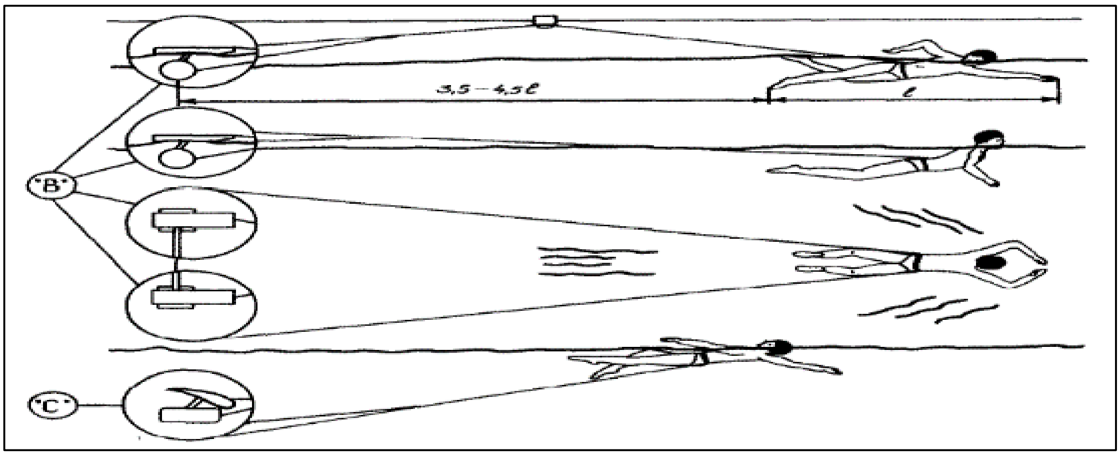

Figure 2.13 Structure of the hydrodynamic body of VPM method (taken from Kolmogorov & Duplishcheva, 1992).

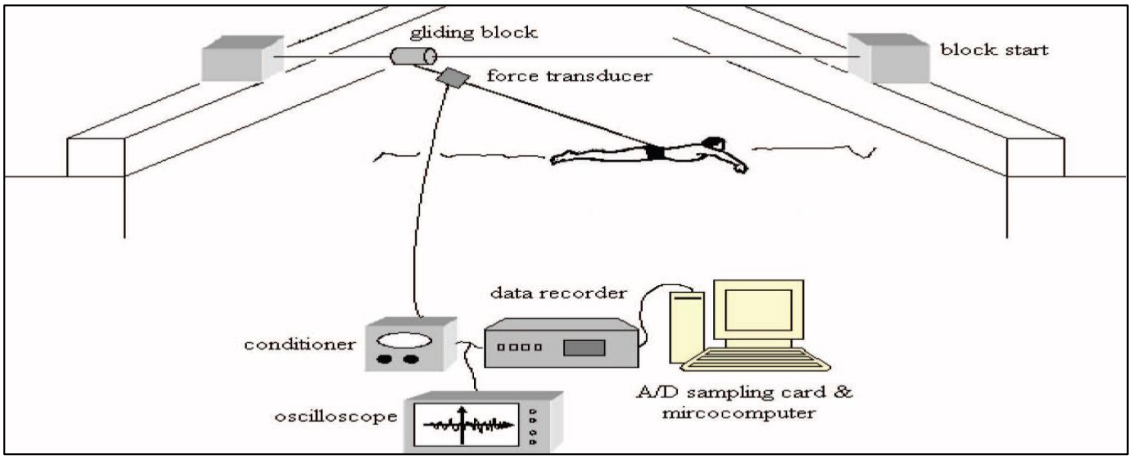

Figure 2.14 Device for VPM using gliding block (taken from Xin-Feng *et al*., 2007).

2.4.2.4. Assisted Towing Method

The Assisted Towing Method (ATM) was developed by Alcock & Mason (2007). This method has a similar theoretical basis to the VPM but its testing protocol is different because a swimmer is assisted by a towing machine rather than resisted by it.

Whilst swimming, participants are towed by an electric motor, which is connected with in-line load cell, at approximately 5 to 10% faster than their maximal swimming speed. This amount is considered to be a small enough not to affect stroke mechanics, yet fast enough so that the towing cable remains taught through all phases of the stroke (Alcock & Mason, 2007). Swimmers are attached to the electric motor, from the front of the body, by an inelastic wire attached to a belt around the waist.

After initial acceleration to constant speed, data from the in-line load cell is typically captured for four full non-breathing stroke cycles, once the swimmer has found their stroke rhythm. Force data are typically sampled at 500 Hz and processed with a Butterworth low pass digital filter (5 Hz) is used to reduce noise. Alcock & Mason, (2007) reported a difference between the mean of the raw and filtered data of less than 0.01 N.

Active drag is expressed as (Alcock & Mason, 2007):

$$D_a = \frac{F_b \cdot v_2 \cdot v_1^2}{v_2^3 - v_1^3} \tag{2.23}$$

where D_a is the active drag during free swimming, F_b is the active towing force measured by an in-line force transducer during 10% faster speed, v_1 is the swimmer's maximum free swimming speed, v_2 is 10% faster than the maximum speed. The calculation process is the same as that in the VPM, but the direction is reversed. One criticism of the ATM approach is its weak reliability (Webb *et al.*, 2011). Chapter 6 of this thesis will address this issue.

2.4.2.5. Naval Architecture Based Approach (NABA)

Recently, Webb *et al*. (2011) proposed a new approach to estimating active drag; the *Naval Architecture Based Approach* (NABA). This method is an adaptation of a test protocol used in scale model ship self-propulsion experiments designed to quantify the interaction effects between the propeller and the naked hull (Molland, Turnock & Hudson, 2011; Webb *et al*., 2011).

When a self-propulsion experiment is carried out, a model with the hull and the propeller connected is towed by an electric motor (connected to a force transducer) at a fixed velocity. The measured towing force with fixed frequency of propeller is *R-P*, where

R is the resistance of the model and P is the propulsion of the propeller. When the hull and propeller are combined, the hull will have a greater resistance because of the accelerated flow over the hull created by the propeller, and the propeller will have a smaller velocity because of the wake produced by the hull (Molland *et al*., 2011).

Applying this approach to a swimmer, Webb *et al*. (2011) assumed that the propelling arms were the propeller and the remaining body was the hull. The swimmer was towed 5%, 10% and 15% faster than their clean swimming speed (CSS), while swimming front crawl, and the towing force ($R\text{-}P_{Measured}$) of each trial was recorded. As the towing speed was faster than the swimmer's CSS, the increased amount of drag was corrected for using a correction value ($\Delta R_{Correction}$). This value is the difference in passive drag recorded at the towed speed and at CSS ($R_{Passive(CSS)}$), when the swimmer's arms are held stationary beside their body. As a result, the active drag is calculated as:

$$R_{Active} = (R - P)_{Measured} - \Delta R_{Correction} + R_{Passive(CSS)} \qquad (2.24)$$

2.4.2.6. Comparison of active drag measurement techniques

Of all the methods previously described, the extrapolation technique has the longest history. However, few researchers currently use this approach because its assumptions are broad and the drag values from this method are considerably higher than those obtained from more recent techniques (van de Vaart *et al.,* 1987; Toussaint & Hollander, 1994).

The MAD system's main advantage is that its results come from the direct measurement of push-off forces during front crawl swimming (Sacilotto *et al*., 2014). However this method can only be applied to arms-only front crawl swimming. Also, it requires specialist equipment that is huge and difficult to transport to venues.

The apparatus used in the VPM is much simpler than in the MAD system. Furthermore, the fact that it can be applied to all swimming strokes is an advantage. In this method, to get a meaningful value of active drag, it is essential that the swimmer's maximum speed must be recorded as accurately as possible. Toussaint *et al*. (2004) compared active drag results from the MAD and VPM techniques, concluding that the results of the VPM technique were significantly lower than from the MAD system. The difference in results could be attributable to a violation of the VPM constant power assumption. Toussaint *et al*. (2004) challenged the validity of this assumption but indicated that the VPM may still provide a meaningful estimation of active drag. Xin-Feng *et al.* (2007) concluded that the addition of a fixed amount of additional drag in the VPM, regardless of each swimmer's different swimming speed, may increase the level to which the constant power assumption is violated. Hence, they introduced the 'steel wire and gliding block' system, to allow adjustment of the amount of additional drag.

Alcock & Mason (2007) proposed that assisting (actively towing) a swimmer, rather than resisting them might be a preferred approach. They named this the Active Towing Method (ATM). Even though the ATM methodology creates the required additional drag in a different way to the VPM and Xin-Feng's sliding block method, the basic principle and calculation procedures of all three methods is the same. They can therefore be considered as three variations of one method, but that just use different apparatus. Interestingly, the active drag values estimated using these methods have shown large discrepancies and inconsistencies. For example, in study which compared MAD and VPM (Toussaint et al., 2004), the active drag estimated from VPM (53.2 N) was smaller than MAD (66.9 N), whereas in study which compared MAD and ATM (Formosa et al., 2004), ATM produced far greater active drag values (148.3 N) than the MAD (82.3 N).

Some researchers who have used these methods have reported active drag data for individual, repeated swimming trials. Where this has been done, there have generally been surprising high inter-trial variations in active drag, indicating that the methods may have limitations relating to their reliability (Kolmogorov & Duplishcheva, 1992; Alcock & Mason, 2007; Mason, Kolmogorov, Wilson, Toussaint, Sinclair, Schreven, Sacilotto, Dominguez & Hazrati, 2013). The NABA uses towing apparatus similar to that used in the ATM but can be considered an entirely separate method, as evidenced by the different theoretical background and calculation procedures involved. Based on testing of a single recreational swimmer, Webb *et al.* (2011) concluded that the NABA produced more repeatable results than the ATM.

2.4.3. Comparison of passive and active drag

The comparison between passive and active drag is of interest to swimming biomechanists. In early studies, it was assumed that the active drag was equal to the passive drag (Karpovich, 1933; Karpovich & Pestrecov, 1939; Alley, 1952; Faulkner, 1968). But di Prampero *et al* (1974) first estimated that active drag was double that of passive drag, using the extrapolation technique. Studies using the MAD system have shown active drag in front crawl to be of similar magnitude to passive drag, at the same test speed (van de Vaart *et al.*, 1987). In contrast, using the VPM, Kolmogorov & Duplishcheva (1992) reported the active drag of top-level front-crawl swimmers to be 60 – 162 % of their passive drag. This study introduced the concept of an active-to-passive drag ratio, defining it as the Technique Drag Index (TDI). Later, Kjendlie & Stallman (2008) showed that the active drag of adult male front crawl swimmers was 1.15 times that of their passive drag whereas the same ratio for 11 year old male swimmers was only 0.7.

Webb *et al*. (2011) suggested that the 'Thrust Deduction' (passive/active drag) could be used to represent the effectiveness of a swimmer's propulsion. They reported a mean value of approximately 0.8 for this ratio. This value cannot be compared directly to those from previous studies (Kolmogorov & Duplishcheva, 1992; Kjendlie & Stallman, 2008) as the NABA used by Webb *et al.* requires the passive drag to be measured with the swimmer's arms held by their sides. The other studies recorded passive drag with the arms extended above the head in a streamlined position.

In all of these studies, the participants were able-bodied swimmers. No attention was given to swimmers with physical impairments. For swimmers with physical impairments, the ratio between passive and active drag may provide a valuable insight into the swimmer's ability to reduce active drag but it might also shed some light on how various physical impairments influence the passive – active drag relationship. These ideas will be examined further in Chapter 7 of this thesis.

In summary, the four main methods of measuring passive drag (towing, flume, glide deceleration and CFD) each has its advantages and limitations. Taking all of these into account, the towing method (using an electro-mechanical motor) will be used to examine the passive drag of para-swimmers (studies 1-3).

Of the five main approaches to estimating active drag (extrapolation, MAD, VPM, ATM and NABA), no gold standard method is apparent. The evidence indicates that the extrapolation approach may not be valid and the MAD system cannot be used with many para-swimmers. The ATM can be considered a development of the VPM (Alcock & Mason, 2007) and warrants further research. The ATM and NABA will be compared in study 4. The preferred method will then be used to examine the active drag of elite para-swimmers.

CHAPTER THREE

EXPERIMENTAL STUDY 1

RELATIONSHIP BETWEEN PASSIVE DRAG OF PARA-SWIMMERS AND THEIR IPC FUNCTIONAL CLASS

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The aim of this chapter is to determine the relationship between passive drag and the level of physical impairment as defined by IPC class. The chapter tests the hypothesis that those swimmers with the highest level of physical impairment (low IPC class) exhibit the highest passive drag, and vice-versa. Chapter 3 relates to academic aim 1.

3.1 INTRODUCTION

Over the last fifty years the number of participants in Paralympic games has increased dramatically. At the first Paralympic games, held in Rome in 1960, there were 400 athletes from only 23 different countries, compared with about 4200 athletes from 164 different countries who competed in London 2012. The Paralympic Games is now the world's second largest multi-sports event, after the Olympic Games. One of the key differences between the Olympic and Paralympic Games is that the latter event hosts participants with a wide range of physical, visual and intellectual impairments. In the Paralympic sports, perhaps the greatest challenge is to provide all athletes with an equal starting point through the implementation of a fair classification system. Sherrill (1999) asserted that in Paralympic sports, classification is the area where research is most required.

Prior to the Seoul Paralympic Games in 1988, athlete classification was solely medically based, such that athletes with different medical diagnoses competed in separate events. No consideration was given to the fact that impairments resulting from different medical conditions could cause the same activity limitation in a sport. This medically based approach produced a multitude of parallel events and medals whilst limiting the number of athletes able to compete in each one. To overcome these issues, the International Paralympic Committee (IPC) introduced the Functional Classification System at the 1992 Barcelona Paralympic Games. In Paralympic Swimming, competitors now undergo a medical and a technical classification to assess their functional abilities. They are then allocated a class ranging from S1 to S10 (S1 denoting the most severely impaired swimmers, S10 the least impaired). Additionally, visually impaired swimmers are denoted S11-S13 and intellectual disability swimmers are denoted S14 (Chapter 1 Section 3.1).

The current IPC Swimming Functional Classification System, however, has been challenged on its objectivity (fairness) because there is insufficient scientific evidence to underpin its basis. For example, the point systems of the Bench test and Water test are based on the relative contributions made to propulsion by the arms and the legs quoted in Counsilman's *Competitive Swimming Manual for Coaches and Swimmers* (1977). For example, Counsilman suggests that in the breaststroke 55% of the propulsion comes from the legs and 45% from the arms. However, there is no scientific evidence to support these figures (Richter *et al*., 1992). Even Counsilman rejected this approach to the analysis of propulsion considering it unscientific and based on subjective evaluation (Counsilman, 1977).

Various research methods have been used to evaluate the suitability of the Swimming Functional Classification System (Daly & Vanlandwijck, 1999). Comparisons of the race performances of swimmers in adjacent classes are most often used to judge the system's validity (Gehlsen & Karpuk, 1992; Wu & Williams, 1999). In such studies, the results are dependent on the sample of athletes and the statistical techniques employed. Using a different approach, Pelayo, Sidney, Kherif, Chollet & Tourny (1996) compared stroke rates and stroke lengths across functional classes at the 1995 European Championships. Stroke index (stroke length × swim speed), an indicator of swimming efficiency (Costill, Kovaleski, Porter, Kirwan, Fielding & King, 1985), was also calculated. The authors concluded that their results supported the logic of the Functional Classification System even though the differences in the stroke index between adjacent classes were not always significant.

Wu & Williams (1999) examined whether any particular impairment group (e.g. Cerebral Palsy, Poliomyelitis, Amputation, Spinal Cord Injury, Dysmelia, and *Les Autres*) had a greater chance of success at the 1996 Atlanta Paralympics. They found that there was equal opportunity for all impairment groups to qualify for a final but that the Poliomyelitis group had relatively less opportunity to win a medal than the other groups.

Another approach suggested for evaluating the swimming classification system is to compare specific functional abilities such strength, coordination, flexibility, VO_2max and muscle function, across the classes (Daly & Vanlandwijck, 1999). Although some of these are already considered in the current classification, additional functional abilities may have to be included if the validity of the system is to be improved. According to Vanlandewijck & Chappel (1996), any classification system should ensure that winning or losing an event depends on talent, training, skill, fitness and motivation, rather than a lack of parity among competitors on disability-related variables. Therefore, any functional abilities used to classify swimmers must be direct or indirect determinants of swimming performance. The classification process must consider how the swimmer's impairment limits each of these abilities and, consequently, their potential swimming performance. It must not be influenced by a swimmer's skill level.

A swimmer's speed is determined largely by their capacity to produce propulsion effectively whilst minimising the resistive or drag forces from the water (van Tilborgh *et al*., 1983). A fair classification system should, therefore, evaluate objectively an individual's potential to achieve both of these things within the limitations determined by their physical impairments. The current classification system, however, places too much emphasis on propulsion and allocates insufficient importance to a swimmer's drag. The IPC Swimming Classification Manual (2005) uses the term *propulsion* 150 times in the document in relation to every section of the practical profile (hands, arms, trunk, legs, others and starts & turns) used to assign a swimmer to a class. The manual states that the classification system is expressed in profiles showing the variation in *propulsion* effectiveness of swimmers with different loco-motor abilities. In contrast, a swimmer's drag is assessed in a single, very limited context in the current classification process. Only 'leg drag' (no use of legs or swimmer chooses not to use legs) is addressed in the profile. No consideration is given to how other aspects of a specific impairment may affect the level of drag a swimmer experiences. Furthermore, with regard to research into the fairness of swimming classification, studies have focused on propulsion or speed (Gehlsen & Karpuk, 1992; Wu & Williams, 1999; Daly & Vanlandewijck, 1999) but there has been no examination of how drag relates to the current classification system.

Drag can be measured under two general conditions: passive and active (Toussaint & Hollander, 1994): Passive drag is the resistive force encountered when moving through the water while holding a fixed body position, for example, when gliding; active drag is the resistance experienced when making movements with the arms and legs. Passive drag can be measured directly by recording the force required to tow the swimmer at a constant speed. It has been suggested that passive drag can contribute significantly to the prediction of swimming performance in able-bodied swimmers (Chatard *et al*., 1990a). Measurement of active drag still remains a complex and controversial issue, with the most current methods still producing conflicting data (Toussaint *et al*., 2004). Researchers have found that active drag, in able-bodied swimming, is more dependent on swimming skill and less on an individual's anthropometry (Kolmogorov & Duplishcheva, 1992). As the fundamental philosophy of the classification system is to evaluate impairment, not skill, passive drag seems the more appropriate measure for classification purposes. Mason *et al*. (2009) found that passive drag reflected the amount of propulsion required for a swimmer to swim at maximal speed, and suggested that it may be a good indicator of the future capabilities of a swimmer.

Previous studies on able-bodied swimmers have demonstrated that passive drag depends on many factors including body position (e.g. Clarys & Jiskoot, 1975), depth and speed of towing (e.g. Lyttle *et al.*, 1998) and body shape and size (e.g. Clarys, 1979). To date, only two published studies have examined the passive drag of swimmers with physical impairments (Chatard *et al*., 1990b; Chatard *et al.*, 1992). Although these studies provide some valuable insights into the effects of physical impairment on drag, neither attempted to to relate their passive drag measurements to the level of impairment, as defined by the current IPC classification system. Chatard *et al* (1990b)examined the influence of height and mass on the passive drag of eleven male para-swimmers, including four double-leg amputees. The impairments of the remaining seven was unspecified. In 1992 the same group demonstrated that passive drag is influenced by level of physical impairment. However, critically, they divided their thirty-four physically impaired participants into three groups based their degree of terrestrial mobility, not on their level of swimming-specific impairment, as is done in the IPC Classification System. Consequently, research to date has not contributed to our understanding of the link between passive drag and IPC class. The aim of this study, therefore, is to determine the relationship between passive drag and the level of physical impairment as defined by IPC Class. The study will test the hypothesis that those swimmers with the highest level of physical impairment (low IPC class) will exhibit the highest passive drag, and vice-versa.

3.2 METHODS

3.2.1 Participants

A total of 210 trained competitive swimmers (122 male and 88 female), each with an official IPC Para-swimming classification, participated in this study (Table 3.1). Testing procedures were approved by the University's ethics committee and all swimmers provided written informed consent prior to participating. Of the swimmers, 117 competed at the Montreal 2013 IPC World Championships and 106 competed at the London 2012 Paralympic Games. Twenty-seven swimmers competed in both events. The remaining fourteen swimmers were members of the Great Britain World Class Performance and had competed at national or international level. As most swimmers had three classifications (S, SB and SM), their lowest class integer was used in all statistical analyses. For example, the integer 4 was used for a swimmer classified S5, SB4, SM5. The rationale for this was that the lowest integer best represented each swimmer's level of swimming specific impairment.

In addition to the physically impaired swimmers (1-10), visually impaired (11-13) and intellectually impaired (S14) swimmers participated in the study. The S11-S13 swimmers were combined into a single group for statistical purposes. Swimmers' height and body mass data are presented by class in Table 3.1.

Table 3.1 Participant information.

IPC Class	Male				Female				Total			
	N	Age (yrs)	Height (m)	Mass (kg)	N	Age (yrs)	Height (m)	Mass (kg)	N	Age (yrs)	Height (m)	Mass (kg)
		Mean(SD)	*Mean(SD)*	*Mean(SD)*		*Mean(SD)*	*Mean(SD)*	*Mean(SD)*		*Mean(SD)*	*Mean(SD)*	*Mean(SD)*
1	4	31.7(10.3)	1.77(.07)	67.9(8.7)	1	17	0.82	33.2	5	28.8(11.1)	1.58(.43)	60.9(17.2)
2	4	29.7(0.5)	1.47(.45)	62.6(11.8)	4	23.5(2.9)	1.55(.08)	46.9(10.4)	8	26.1(8.2)	1.51(.30)	54.8(13.3)
3	12	25.6(0.7)	1.43(.30)	55.1(10.2)	5	25.0(11.9)	1.46(.32)	50.0(11.1)	17	25.4(8.2)	1.44(.29)	53.5(10.4)
4	7	30.1(8.2)	1.62(.26)	63.0(11.1)	7	26.6(10.0)	1.51(.23)	54.2(5.4)	14	28.4(9.0)	1.57(.24)	58.6(9.6)
5	10	28.1(11.2)	1.46(.31)	62.1(12.3)	7	25.6(10.2)	1.49(.24)	49.9(7.5)	17	27.1(10.6)	1.47(.28)	57.1(12.0)
6	15	24.1(5.3)	1.58(.24)	60.3(11.4)	15	23.7(6.4)	1.33(.20)	47.9(9.3)	30	23.9(5.7)	1.52(.26)	54.8(12.4)
7	10	24.0(7.0)	1.79(.11)	72.5(10.0)	8	20.9(4.8)	1.63(.14)	61.4(9.7)	18	22.6(6.1)	1.71(.14)	67.6(11.1)
8	16	24.3(5.7)	1.78(.09)	69.0(8.2)	5	25.4(6.0)	1.69(.06)	59.7(6.0)	21	24.6(5.7)	1.76(.09)	66.8(8.6)
9	7	22.7(6.7)	1.77(.09)	68.4(10.2)	3	18.7(3.8)	1.61(.03)	51.7(10.0)	10	21.5(6.1)	1.72(.10)	63.4(12.5)
10	11	25.6(6.4)	1.81(.08)	73.4(10.9)	10	18.8(4.9)	1.64(.08)	55.3(5.8)	21	22.4(6.6)	1.73(.12)	64.8(12.7)
11-13	15	25.2(6.7)	1.78(.07)	71.8(12.8)	13	21.8(3.8)	1.66(.07)	59.9(6.4)	28	23.6(5.7)	1.72(.09)	66.2(11.8)
14	11	22.3(3.2)	1.83(.09)	76.2(8.9)	10	22.9(5.2)	1.68(.76)	60.9(6.3)	21	22.6(4.2)	1.76(.12)	68.9(10.9)
Mean	122	25.4(7.1)	1.69(.24)	67.1(11.9)	88	22.8(6.7)	1.57(.20)	55.0(9.4)	210	24.3(7.0)	1.64(.23)	62.0(12.5)

3.2.2 Experimental Set-up

Passive drag was measured while swimmers were being towed using an electro-mechanical device located at the end of a 50 m swimming pool. The device consisted of a drum winch driven by a 0.75 kW electric motor (ABB Ltd, UK) that was controlled by a hand-held unit enabling the towing speed to be set to ± 0.01 $m \cdot s^{-1}$ up to 2.0 $m \cdot s^{-1}$. Swimmers were attached via an inelastic steel cable. An in-line submersible load cell (DDEN, Applied Measurements Ltd, UK) was attached approximately 5 m in front of the swimmer to measure directly the towing force. Foam fairings were attached on either side of the load cell to make it neutrally buoyant and to reduce the form drag. The load cell was linked to an amplifier (Model ICA, Applied Measurements Ltd, UK) and a 12-bit A-D converter (PicoLog 1216, Pico Technology, UK) mounted on a pole which was carried by a researcher above the load cell. Force data were sampled at 100 Hz by the A-D converter and captured on a tablet PC (LE1700, Motion Computing, Inc, USA) in real time using custom-built software.

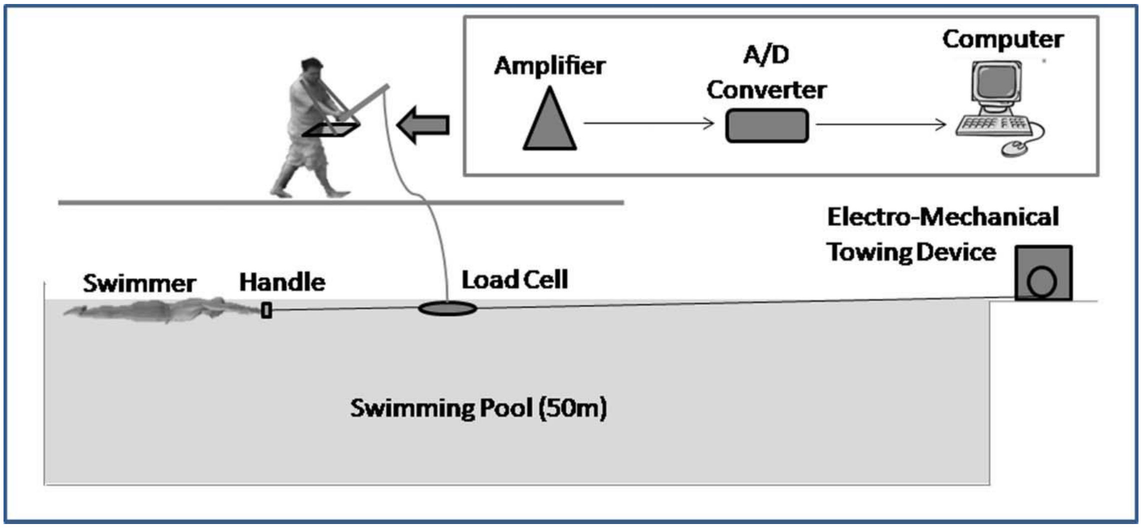


Figure 3.1 Schematic of equipment setup for passive drag measurement

Figure 3.2 Electro-Mechanical towing device.

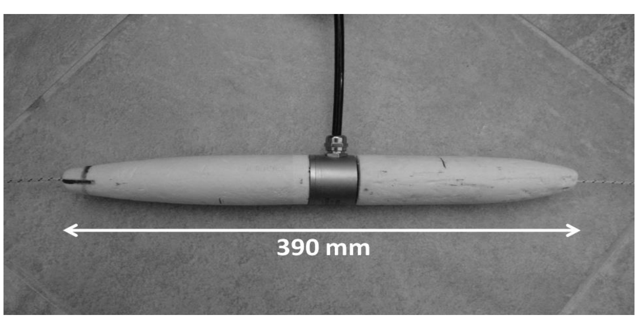


Figure 3.3 Submersible load cell with foam fairings.

3.2.3 Calibration

Load cell

A static calibration of the load cell was performed before each testing session by suspending it vertically and adding known masses incrementally, recording the output for each increment. The linearity of the load cell was always less than 0.5% and its resolution better than 0.25 N. Figure 3.4 shows a typical calibration curve and calibration equation for the load cell. The calibration equation was re-arranged to allow the force, *F*, in newtons to be calculated from the ADC units. In the example shown below, the calibration equation would re-arrange as follows:

$$F = [(\text{ADC units} - 57.1) / 245.4] \cdot 9.81 \quad (3.1)$$

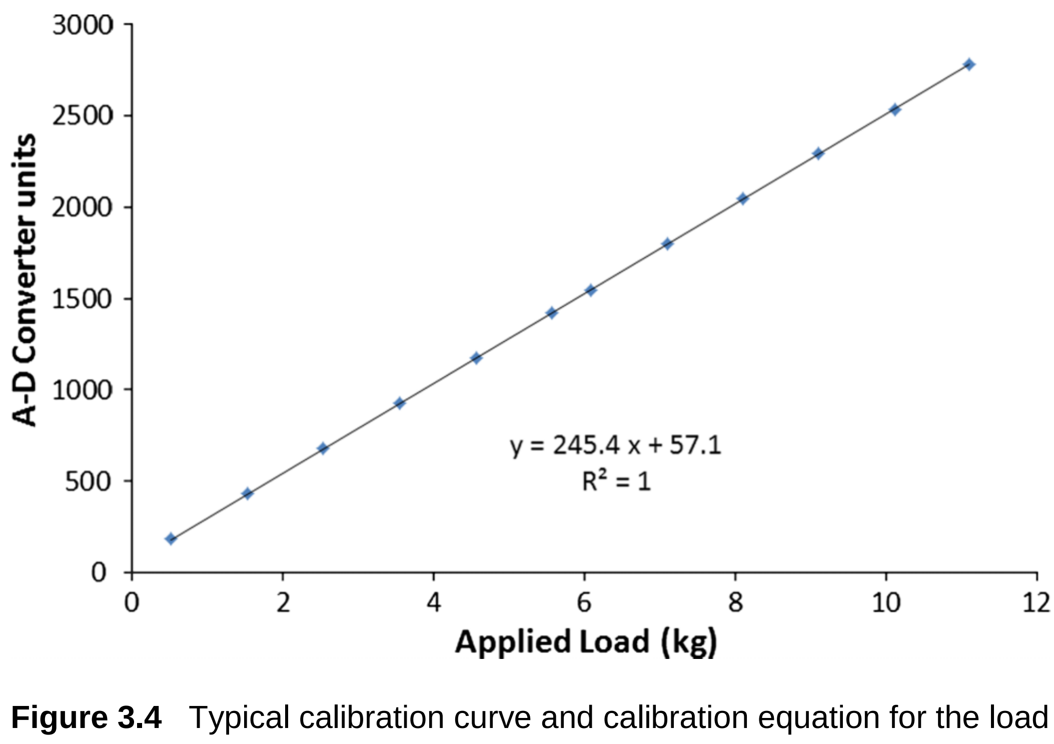


Figure 3.4 Typical calibration curve and calibration equation for the load cell.

Electric motor towing speed

Calibrations of the towing speed were performed before each testing session either on land, using infrared timing gates 10 m apart, or in water, using standard 2D video protocol with calibration markers in the plane of motion 10 m apart. A volunteer was attached to the towing device via a waist belt (land-based calibration) or handle (water-based calibration). In the land-based calibration, the volunteer walked toward the towing device but provided some resistance in the towing cable; in the water-based calibration, the volunteer was towed in a passive, streamlined position. In both formats, the person was towed at motor frequencies between 10 and 50 Hz in 5 Hz increments. The time, t, to cover the set distance, d, was recorded and the towing speed (v) for each trial obtained ($v = d/t$). Through this procedure the relationship between the motor frequency and the towing speed was calculated. Figure 3.5 shows a typical calibration curve and calibration equation for motor frequency versus towing speed. Linearity was always 0.25% or better and the calibration curve was unaffected by how much resistance was applied during towing.

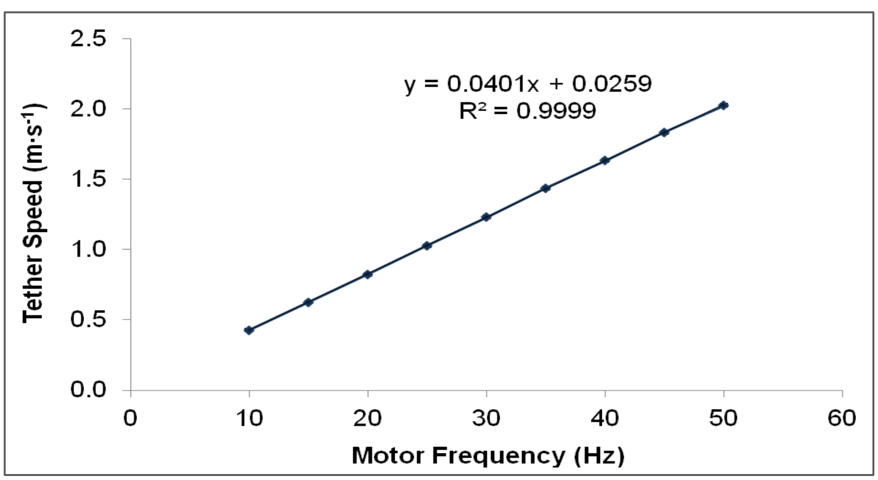


Figure 3.5 Typical calibration curve and calibration equation for motor frequency versus towing speed.

3.2.4 Data collection protocol and processing

Swimmers were drag tested in their preferred swimming costume and swim cap. Depending on the nature of their impairment, swimmers were attached to the towing cable using: (1) a small handle, (2) a belt secured under the arms or (3) rubber tubing wrapped around the upper arms. Swimmers were instructed to maintain their most streamlined prone position in the water while holding their breath. All swimmers were towed approximately 35 m at the surface of the water, at a standardised speed of 1.50 $m \cdot s^{-1}$. Pilot studies demonstrated that this was a speed that swimmers were comfortable being towed at and at which they were able to maintain a stable, horizontal body position in the water. Each swimmer completed between three and six trials. A time window in which the passive drag force remained reasonably constant for at least 4 s was identified (Figure 3.6) and the mean passive drag force value (D_P) was calculated using equation 3.1. The lowest drag value for each participant was used for the subsequent analysis.

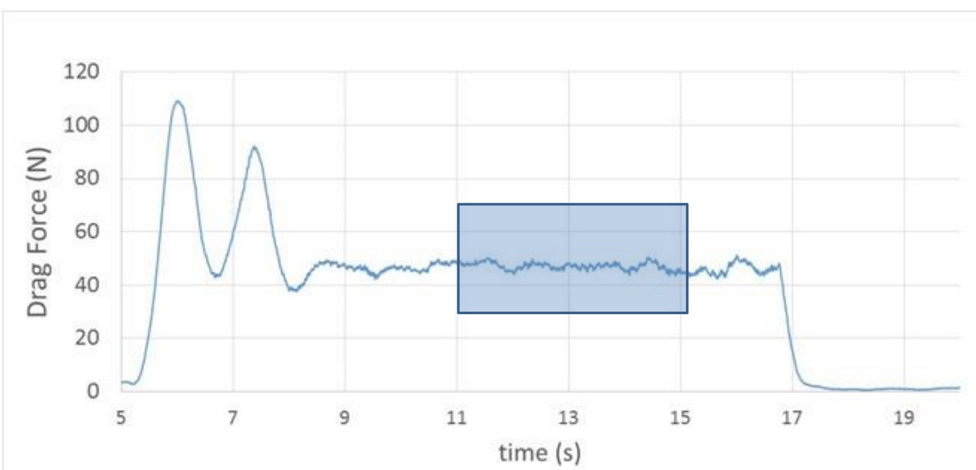


Figure 3.6 Sample passive drag curve showing acceleration phase (t=5-8 s) and the constant speed phase (t=9-16 s).

3.2.5 Normalisation of passive drag force

To account for the anthropometric profile between swimmers of different size, the passive drag force was divided by body mass (D_P/m) on the assumption that mass was a suitable variable for reflecting a swimmer's size. D_P/m was deemed to be a particularly relevant variable as it provided an approximation of the deceleration (force/mass) which, according to Newton's second law of motion, the swimmer would experience if the towing force were suddenly removed. In order to evaluate the effect of swimmer shape on the drag measures, the Reciprocal Ponderal Index, RPI (Singh & Mehta, 2009) was calculated using equation 3.2.

$$\text{Reciprocal Ponderal Index} = \text{Height} / \text{Mass}^{1/3} \tag{3.2}$$

3.2.6 Statistical Analysis

The descriptive statistics (mean and 95% CI) were determined for each classification group according to Hopkins (2000). Any significant differences (p<.05) between classifications were identified using a one-way analysis of variance. Scheffe's post hoc analysis was conducted to identify whether there were significant differences between each classification. The strength of the relationship between the passive drag measures and the swimming classification group was determined using Kendall's tau coefficient. The strength of the relationship between the passive drag measures and the RPI was determined using the Pearson Product coefficient (r_P). Correlations were defined as: weak <0.3, moderate 0.3–0.6 or strong >0.6. Note that classes 11-13 were combined into a single, non-physically impaired group for the interclass correlations.

3.3 RESULTS

The passive drag force ranged from 24.9 N to 120.0 N with a mean of 47.4 ± 13.5 N. The mean passive drag for the male para-swimmers was 49.9 ± 13.4 N (range: 32.2-120.0 N); for the female para-swimmers the mean was 44.0 ± 13.0 N (range: 24.9-93.9 N). Figure 3.7 shows the relationship between the swimmers' passive drag and their IPC Class. A significant negative association was found between passive drag and IPC class (τ = -.43, p <.01).

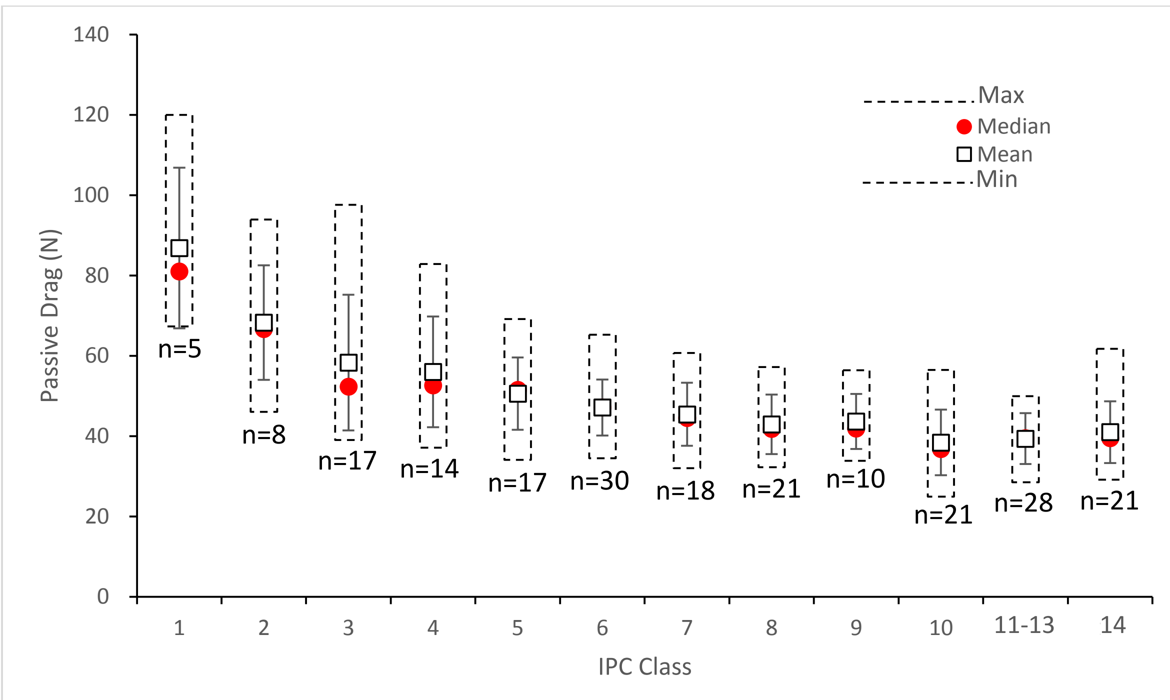


Figure 3.7 Passive drag for physical impairment classes (1-10), visual impairment classes (11-13) and intellectual impairment classes (14). For each class, the sample size, mean, *SD*, median and range are displayed.

Passive drag normalised for body mass (D_P/m) ranged from 0.43 N·kg^{-1} to 2.03 N·kg^{-1} with a mean value of 0.76 ± 0.28 N·kg^{-1}. The mean D_P/m for males was 0.76 ± 0.23 N·kg^{-1} (range: 0.43 N·kg^{-1} to 1.62 N·kg^{-1}) and for females it was 0.83 ± 0.33 N·kg^{-1} (range: 0.45 N·kg^{-1} to 2.03 N·kg^{-1}). The highest normalised drag recorded was 2.03 N·kg^{-1} for one of the most impaired (class 1) females; the lowest recorded normalised drag was 0.43 N·kg^{-1} for a visually impaired (class 11) male. Figure 3.8 shows the relationship between D_P/m and the IPC class. The strength of the negative association between passive drag and IPC class was increased when passive drag was normalised for body mass (τ = -.59, p <.01).

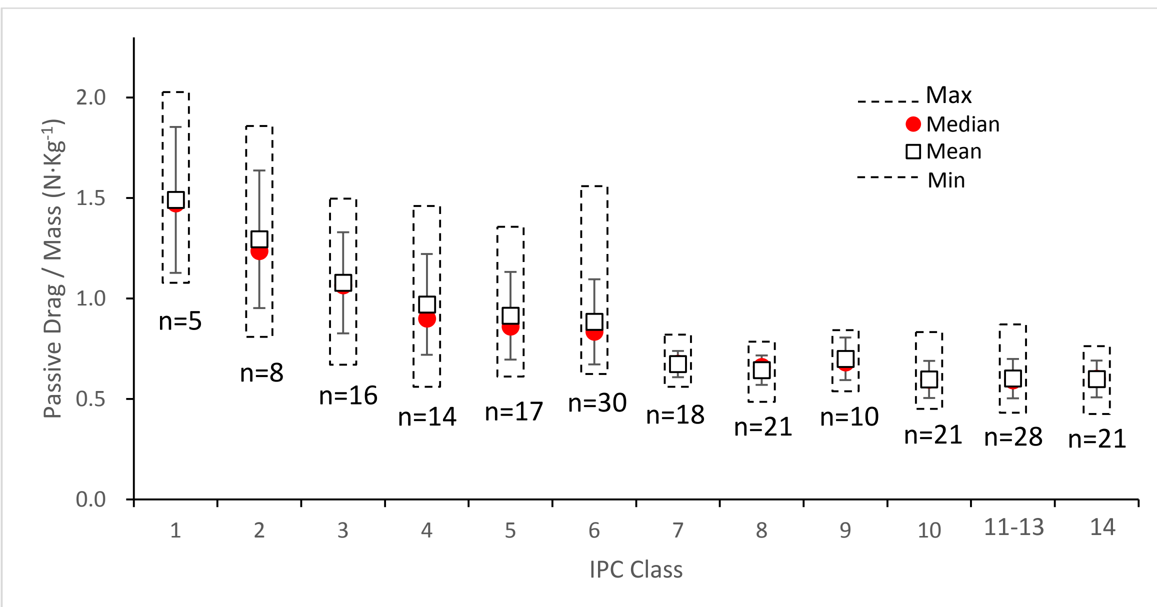


Figure 3.8 Normalised Drag (passive drag/mass) for physical impairment classes (1-10), visual impairment classes (11-13) and intellectual impairment classes (14). For each class, the sample size, mean, *SD*, median and range are displayed.

ANOVA Post-Hoc analysis testing revealed that there were no significant differences ($p > .05$) in passive drag force, between the majority of the physical (classes 1-10), visual (11-13) and intellectual (14) impairment classes (Table 3.2 top section).

Table 3.2 Scheffe Post Hoc Analysis, reporting significant differences (*p<.05) between IPC classes.

□	Physical Impairment										Visual Impairment			Intellectual
Passive Drag	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	□	0.62	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*
2	0.62	□	0.96	0.84	0.18	0.01*	0.01*	0.00*	0.01*	0.00*	0.00*	0.00*	0.00*	0.00*
3	0.00*	0.96	□	1.00	0.97	0.38	0.32	0.05	0.38	0.00*	0.15	0.05*	0.03*	0.01*
4	0.00*	0.84	1.00	□	1.00	0.85	0.76	0.33	0.75	0.03	0.41	0.23	0.19	0.12
5	0.00*	0.18	0.97	1.00	□	1.00	1.00	0.96	1.00	0.43	0.92	0.83	0.80	0.78
6	0.00*	0.01*	0.38	0.85	1.00	□	1.00	1.00	1.00	0.79	0.99	0.98	0.97	0.98
7	0.00*	0.01*	0.32	0.76	1.00	1.00	□	1.00	1.00	0.99	1.00	1.00	1.00	1.00
8	0.00*	0.00*	0.05	0.33	0.96	1.00	1.00	□	1.00	1.00	1.00	1.00	1.00	1.00
9	0.00*	0.01*	0.38	0.75	1.00	1.00	1.00	1.00	□	1.00	1.00	1.00	1.00	1.00
10	0.00*	0.00*	0.00*	0.03	0.43	0.79	0.99	1.00	1.00	□	1.00	1.00	1.00	1.00
11	0.00*	0.00*	0.15	0.41	0.92	0.99	1.00	1.00	1.00	1.00	□	1.00	1.00	1.00
12	0.00*	0.00*	0.05*	0.23	0.83	0.98	1.00	1.00	1.00	1.00	1.00	□	1.00	1.00
13	0.00*	0.00*	0.03*	0.19	0.80	0.97	1.00	1.00	1.00	1.00	1.00	1.00	□	1.00
14	0.00*	0.00*	0.01*	0.12	0.78	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	□
PD / Mass	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	□	0.99	0.09	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*
2	0.99	□	0.83	0.20	0.03*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*
3	0.09	0.83	□	1.00	0.89	0.49	0.00*	0.00*	0.01*	0.00*	0.00*	0.00*	0.00*	0.00*
4	0.00*	0.20	1.00	□	1.00	1.00	0.06	0.01*	0.40	0.00*	0.14	0.02*	0.02*	0.00*
5	0.00*	0.03*	0.89	1.00	□	1.00	0.25	0.06	0.75	0.01*	0.36	0.10	0.07	0.01*
6	0.00*	0.00*	0.49	1.00	1.00	□	0.26	0.05*	0.83	0.01*	0.43	0.11	0.08	0.00*
7	0.00*	0.00*	0.00*	0.06	0.25	0.26	□	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	0.00*	0.00*	0.00*	0.01*	0.06	0.05*	1.00	□	1.00	1.00	1.00	1.00	1.00	1.00
9	0.00*	0.00*	0.01*	0.40	0.75	0.83	1.00	1.00	□	1.00	1.00	1.00	1.00	1.00
10	0.00*	0.00*	0.00*	0.00*	0.01*	0.01*	1.00	1.00	1.00	□	1.00	1.00	1.00	1.00
11	0.00*	0.00*	0.00*	0.14	0.36	0.43	1.00	1.00	1.00	1.00	□	1.00	1.00	1.00
12	0.00*	0.00*	0.00*	0.02*	0.10	0.11	1.00	1.00	1.00	1.00	1.00	□	1.00	1.00
13	0.00*	0.00*	0.00*	0.02*	0.07	0.08	1.00	1.00	1.00	1.00	1.00	1.00	□	1.00
14	0.00*	0.00*	0.00*	0.00*	0.01*	0.00*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	□

There were significant differences ($p < .05$) in passive drag between class 1 and classes 3-14; between class 2 and classes 6-14; and between class 3 and classes 10 and 12-14. Regarding normalised drag, D_P/m (Table 3.2 bottom section), ANOVA Post-Hoc testing identified significant differences ($p < .05$) between class 1 and classes 4-14; between class 2 and classes 5-14; between classes 3 and classes 7-14; between class 4 and classes 1, 8, 10, 12-14; between class 5 and classes 1, 2, 10 & 14; and between class 6 and classes 1-2, 8, 10 & 14.

There was considerable within-class variability in the passive drag, as evidenced by the SDs and ranges presented in Figure 3.7. When the drag was normalised for body mass, the within-class variability reduced substantially in classes 7–14 but remained relatively high in the lower classes (1-6). Effect statistics comparing adjacent classes reveal that there was an inconsistent difference between each class (Table 3.3). The inter-class difference in passive drag ranged from 0.7 N (between classes 8 and 9) to 18.5 N (between classes 1 and 2).

The swimmers' slenderness measure, *RPI*, ranged from 0.25 to 0.56 $m \cdot kg^{-1/3}$, with a mean of 0.41 $m \cdot kg^{-1/3}$. The within-class variability in *RPI* was considerably greater in classes 1–6 than in classes 7–14. There was a slight trend for the mean *RPI*s in swimming classes 1-6 to be lower than the mean *RPI*s for classes 7-14.

Table 3.3 Differences (Δ) in passive drag (D_P) and normalised drag (D_P/m) between adjacent swimming classes (mean difference (95% CI)) for impairment classes 1-10.

	Class 1 & 2	Classes 2 & 3	Classes 3 & 4	Classes 4 & 5	Classes 5 & 6	Classe 6 & 7	Classes 7 & 8	Classes 8 & 9	Classes 9 & 10
ΔD_P	18.5	9.7	1.1	8.8	1.6	1.7	2.5	0.7	5.2
$\Delta D_P/m$	0.19	0.10	0.13	0.09	0.09	0.21	0.03	0.06	0.10

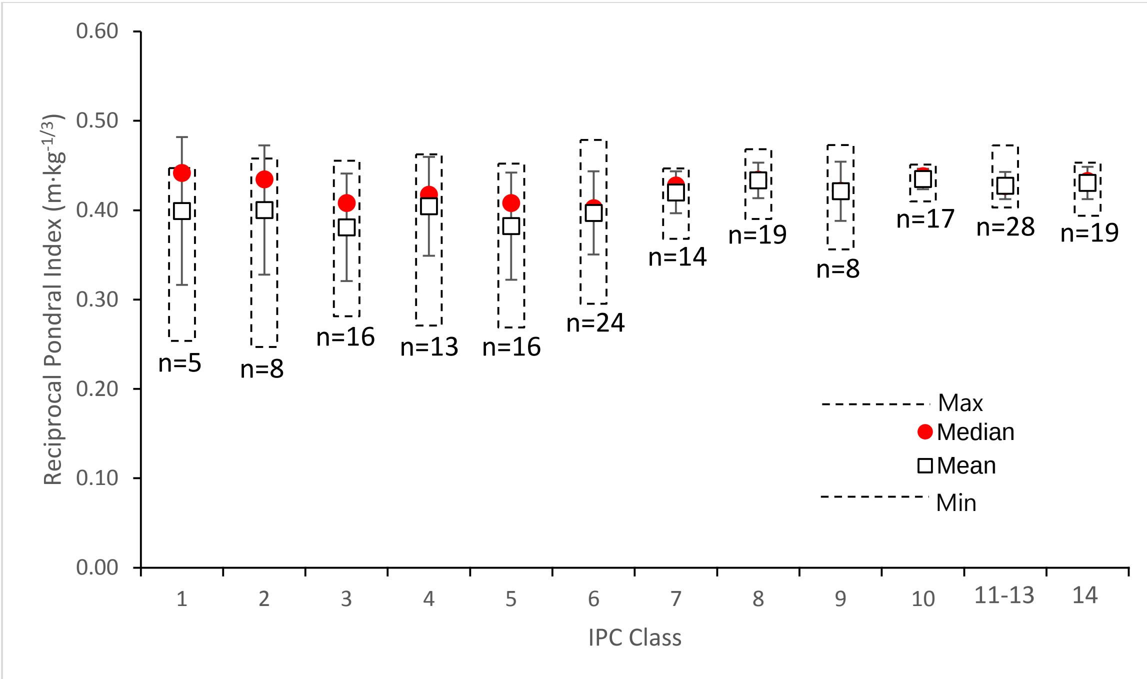


Figure 3.9 Reciprocal Pondral Index for physical impairment classes (1-10), visual impairment classes (11-13) and intellectual impairment classes (14). For each class, the sample size, mean, *SD*, median and range are displayed.

A weak negative relationship was found between passive drag and *RPI* ($r_p = -.14$, $p < .05$). The strength of the association increased to moderate when drag was normalised for body mass ($r_p = -.22$, $p < .01$).

3.4 DISCUSSION

The Paralympic sport classification systems determine the eligibility of athletes with disabilities to compete in the Paralympic Games and in which categories they can compete. The aim of this study was to assess objectively the swimming classification system by determining the relationship between passive drag and the level of swimming-specific impairment, as defined by the current Paralympic swimming class. It was hypothesised that: (1) swimmers with the highest level of swimming-specific impairment would exhibit the highest passive drag and vice versa and (2) the classification system would differentiate passive drag measures between classes. The study found significant correlations (moderate—strong) between the passive drag measures and the swimmer's current classification. That is, as the severity of swimming-specific impairment decreased, so did the passive drag measures. The first part of the hypothesis was therefore accepted. The second part of the hypothesis was rejected as there were inconsistent differences in the passive drag measures between classes.

The mean passive drag recorded in this study was 47.4 N. This falls within the range of values reported in previous studies of able-bodied swimmers at the same speed (1.5 $m \cdot s^{-1}$), for example, Bixler *et al.*, (2007) 37.2 N; Mason *et al.*, (2010) 43.8 N and Takagi, Shimizu & Kodan (1999) 59.2 N. However, the range of the drag scores in the current study (24.9–120.0 N) is higher than those typically observed in able-bodied studies. One of the key findings of this study was the considerable within-class variability in passive drag, as evidenced by the *SD*s and ranges. When drag was corrected for body mass, this variability decreased substantially in classes 7–14, but remained relatively high in classes 1–6. As all the drag measures were made on international-level athletes, these results are unlikely to be due to differences in levels of training within and between the classes. High within-class variability in drag exists mainly because different impairment types compete within a single class (eg, amputee, spinal cord injury, cerebral palsy). The lower classes may incorporate a greater diversity of impairment types than the higher classes. Hence they may be more variable in factors that influence drag, such as body shape, strength, coordination and joint range of motion. Within classes 1–6 in particular, some athletes appear to have a substantial advantage over others with regard to passive drag, which in turn may translate to a performance advantage (Chatard *et al*., 1990a; Mason *et al*., 2009). Whether this is an unfair advantage depends critically on whether the swimmer's relatively low drag is a consequence of superior training or whether their impairment type predisposes them to a lower drag than others in their class. If it is the latter, then the current classification system is more advantageous for certain swimmers by placing insufficient weighting on drag assessment. If drag was assigned more importance in the classification process, the within-class variability in drag would be reduced, increasing the likelihood of there being significant differences in drag between adjacent classes.

Despite the athletes in classes 7–10 having very similar normalised drag scores to each other, as well as to elite able-bodied swimmers (Bixler *et al*., 2007; Mason *et al.*, 2010), the swimming speeds of athletes in these classes are not generally comparable (Daly *et al*., 2003). It seems that the capacity to generate propulsion, rather than to reduce drag, is what separates the performances of these groups. Conversely, drag may be more important in discriminating between performances across the lower classes.

Although the visually impaired swimmers in this study could be considered able-bodied athletes physically, their limited vision might have been expected to reduce their spatial awareness and adversely affect their ability to hold a streamline position. This does not appear to have been the case as the passive drag scores for this group were comparable to those found for elite able-bodied swimmers. Similarly, there was no evidence to suggest that the intellectually impaired swimmers were less able to streamline their bodies than elite, non-impaired swimmers.

The *RPI* results indicate that swimmers in classes 7–14 were generally slightly more slender than those in the lower classes. As with the passive drag measures, the *RPI* presented greater variability in the lower classes, reflecting the greater diversity of impairment types and body shapes in these classes. A previous study reported a very strong correlation (r = .93) between passive drag and mass:height ratio for swimmers with physical impairments (Chatard *et al*., 1990b). In contrast the current study found only a moderate association when passive drag was related to a combination of height and mass (the *RPI*). The statistical results of the previous study may be explained by the small sample size (n=11), four of whom were of very small stature as they were double-leg amputees.

The purpose of classification should be to minimise the impact of impairment on the outcome of competition. That is, the aim is to ensure that the athletes who win are those with the best combination of anthropometry, physiology and psychology, enhanced to best effect through training and legal technical aids. Therefore, any system must be based on a method of classification that correctly measures and classifies impairments according to the degree to which they limit the relevant activity (in this case, swimming).

A swimmer’s body shape and body position in the water will have a significant influence on the amount of drag they experience. This study measured objectively how much drag each swimmer produced when holding their most streamlined position and thus contributed to the body of existing knowledge on how people with impairments move through the water. Furthermore, the results presented provide a database of passive drag relationships that researchers can compare their Paralympic swimming group with and help guide any intervention on changing the swimmers' body position where possible.

This study's limitations must be acknowledged. First, the small sample size in some classes limits the scope to generalise the results to a wider population. A larger scale confirmatory study would be the logical next step. Second, the authors were unable to collect impairment-specific data such as strength, range of motion and coordination. These data would have helped explain the observed within and between class variability in the drag measures. Finally, it was not possible to obtain anthropometric measurements on all of the athletes due to the testing environment. Height and mass data allowed a slenderness index to be calculated but further measurements would have allowed a more detailed assessment of body shape and size.

3.5 CONCLUSION

This chapter has reported passive drag measures for a range of para-swimmers. There exists a strong relationship between a swimmer's normalised passive drag and their current swimming class. However, there is an inconsistent and often an almost negligible difference in normalised passive drag measures between adjacent classes, indicating that the current system does not differentiate clearly between classes. High within-class variability in passive drag, in the lower classes, indicates that some athletes in these classes may have a substantial advantage over others with regard to this performance-related parameter. Since the only swimmer dimensions included in this study were height and body mass, further research and analysis is necessary to gain a fuller understanding of the relationship between anthropometry and drag in para-swimmers. The next chapter will address this.

CHAPTER FOUR

EXPERIMENTAL STUDY 2

RELATIONSHIP BETWEEN SELECTED ANTHROPOMETRIC PARAMETERS, IPC SWIMMING CLASS AND PASSIVE DRAG OF PARA-SWIMMERS

This chapter describes the three-fold relationship between passive drag, anthropometric parameters (Height, Streamlined Height, Body Mass, Shoulder Width, Chest Depth, Shoulder Girth, Torso Girth, *CSA*, streamlined *CSA*, *LTR*, Streamlined *LTR*, *RPI* and Streamlined *RPI*) and IPC Class of para-swimmers. It examines which anthropometric parameters are affected by IPC Class and how those anthropometric parameters affect the passive drag of para-swimmers. Linear regression is also performed to predict passive drag through the anthropometric parameters (Torso Girth and Streamlined *RPI*). Chapter 4 relates to academic aim 1.

4.1 INTRODUCTION

Swimming performance is influenced by anthropometry. Adult competitive swimmers are generally taller than the normal population (e.g. Carter, 1984) and elite swimmers are generally taller than sub-elite swimmers. The mean height and mass of 474 male swimmers at the London 2012 Olympics was 1.86 m and 79.8 kg, respectively. The corresponding values for nineteen male gold-medallists were 1.92 m and 87.2 kg (http://www.topendsports.com/events/summer/science/anthropometry.htm).

Olympic level male swimmers have a greater height, body mass, arm length and leg length, but a smaller pelvic circumference and abdomen circumference, than non-swimming trained individuals (Clarys, 1979). Additionally, male and female Olympic swimmers have greater height, seated-height, torso circumference and torso-to-waist ratio than sub-Olympic swimmers (Dunman, Morris, Nevill & Peyrebrune, 2006). These studies generally support the notion that successful able-bodied swimmers are relatively tall, long-limbed with narrow waist and hips. To date, no study has reported the anthropometry of highly trained para-swimmers.

Studies have demonstrated significant relationships between selected anthropometric measures and a number of swimming performance variables including swimming speed (e.g. Zampagni, Casino, Benelli, Visani, Marcacci, & de Vito, 2008), stroke rate and stroke length (e.g. Morais, Garrido, Marques, Silva, Marinho & Barbosa, 2013), propelling limb size and swimming efficiency (e.g. Gourgoulis, Aggeloussis, Vezos, Kasimatis, Antoniou & Mavromatis, 2008) and hydrodynamic drag (e.g. van Tilborgh *et al*., 1983). The vast majority of studies that have examined the relationship between a swimmer's anthropometry and the drag they create have focussed on able-bodied swimmers. Van Tilborgh *et al*. (1983) examined the relationship between the drag coefficient, determined from a passive glide test, and selected anthropometric measures taken on thirty-two female competitive swimmers. The passive drag coefficient correlated significantly (p<.01) with a number of measures including: height (r =.54), body mass (r =.63), bi-acromial width (r = .59), chest depth (r =.55), latissimus circumference (r =.54), arm length (r =.47) and body surface area (*BSA*) (r =.63).

A swimmer's anthropometry also influences the drag experienced during active freestyle swimming. Huijing *et al*. (1988) found significant (p <.05) positive correlations between active drag and twelve anthropometric measures taken from seventeen well trained male able-bodied swimmers. These included: height (r =.55), body mass (r =.82), arm length (r =.54), leg length (r =.57), body surface area (r =.82), *CSA* with arms by side (r =.74) and *CSA* with both arms above head (r =.87). A more recent study by Benjanuvatra *et al.* (2001) on thirty-six male and female swimmers (aged 9 to 13 years) demonstrated that height (r =.55), body mass (r =.62), chest girth (r =.54), thorax *CSA* (r =.61) and *BSA* (r =.61) correlated significantly (p<.05) with passive drag, when the towing speed was faster than 1.9 $m \cdot s^{-1}$. Interestingly, these anthropometric measures did not correlate significantly with passive drag when the towing speed was below 1.6 $m \cdot s^{-1}$. Benjanuvatra *et al*. (2001) calculated three 'slenderness' indexes (Clarys *et al*., 1974) to represent the swimmer's body shape: 1) reciprocal ponderal index, *RPI* (height/mass$^{1/3}$); 2) length-thickness ratio, *LTR* (height^2/body CSA), and 3) length-surface ratio (height^2/*BSA*). They found *LTR* had a significant negative correlation (p<.05) with passive drag (r =-.59) whereas the *RPI* (r = -.07) and *LSR* (r =.08) did not.

The findings of van Tilborgh *et al*. (1983), Huijing *et al*. (1988) and Benjanuvatra *et al*. (2001) are supported by a study of eighty-four swimmers able-bodied swimmers conducted by Chatard *et al.* (1990a). Significant (p<.01) correlations were found between passive drag and height (males: r = .80; females: r= .60) and body mass (males: r = .78; females: r= .54).

Whilst most studies conclude that drag is significantly related to a swimmer's anthropometry, not all do. Miyashita & Tsunoda (1978) correlated passive drag with the body surface area of child and adult swimmers. Although a wide range of body surface areas (1.00 – 2.21 m^2) were involved, no significant correlation with passive drag was found. No difference in passive drag was found between a 1.90 m well trained swimmer and 1.30 m ten year old swimmers. This was thought to be due to the younger participant's inferior ability to hold a stable body position while being towed.

Toussaint *et al*. (1990) monitored active drag over a 2.5-year period of growth in a group of children (12.9 years, mean age at start of study). During this period, mean height increased from 1.52 to 1.60 m and body mass from 40.0 to 54.7 kg. Additionally, the body *CSA* of the children increased by 16%. Despite these anthropometric changes, the active drag at 1.25 $m \cdot s^{-1}$ remained the same (30.1 ± 2.4 N in 1985 vs 30.8 ± 4.5 N in 1988). The authors suggested that the increase in height resulted in a lower Froude number and an associated reduction in the wave-making drag component (see Chapter 2.1). This effectively cancelled out the increases in the frictional and pressure drag components that were likely to have occurred due to the children's increased *BSA* and body *CSA*.

To date most of the studies that have related anthropometry with drag have focussed on able-bodied swimmers. Only two published peer-reviewed studies and one unpublished study have examined the relationship between the anthropometry of physically impaired swimmers and passive drag. Within a large study, which included 207 able-bodied swimmers, Chatard *et al*. (1990b) examined the passive drag of eleven male para-swimmers, including four double-leg amputees. For these para-swimmers, passive drag was negatively related to height (r = -.87, p<.01) and positively related to body mass:height ratio (r = .93, p<.01). No significant correlation existed between passive drag and body mass (r = .22). The finding of a strong negative correlation between swimmer height and passive drag is in direct conflict with the results from studies of able-bodied swimmers (van Tilborgh *et al*., 1983; Huijing *et al*., 1988; Benjanuvatra *et al*., 2001). This apparent contradiction may be explained by the small and heterogeneous sample of para-swimmers studied, four of whom were likely to be of very small stature being double-leg amputees. As the authors provided no information on the anthropometry of the swimmers (other than the mean height and mass) or on the physical impairments of the non-amputee swimmers, the study made only a limited contribution to our understanding of the relationship between drag and anthropometry in physically impaired swimmers.

Chatard *et al*. (1992) measured the passive drag of thirty-four swimmers with mild to severe physical impairments and reported a strong significant correlation (r = .71, p<.01) between the passive drag and ratio between mass and height without amyotrophia; a significant but weaker correlation was also found with thoracic *CSA* (r = .38, p<.05). In contrast with previous studies of able-bodied swimmers (van Tilborgh *et al*., 1983; Huijing *et al*.,1988; Benjanuvatra *et al*., 2001; Chatard *et al*., 1990a), neither height (r = .25) or mass (r = .34) correlated with the passive drag, when the group were considered as a whole. Although this study provides some valuable insights into the effects of physical impairment on drag, the results do not contribute significantly to our understanding of the link between anthropometry, passive drag and IPC class. No anthropometric data were reported for any specific physical impairment groups and the swimmers were assigned to one of only three groups based their degree of terrestrial mobility, not on their level of swimming-specific impairment, as is done in the IPC Classification System.

Schega *et al*. (2004), which is in the proceedings of a examined the relationship between the height, mass and projected frontal area of 103 physically impaired swimmers with their passive drag. Although their abstract provided very little detail on the level of the swimmers or the testing methods, and reported no data or statistical results, it presented an interesting observation; that the level of a swimmer's impairment might have a greater influence on passive drag than their anthropometry has.

The current study was designed to increase our understanding of how the anthropometry of para-swimmers relates to their level of swimming impairment and passive drag. Thus, the aim of this study was to establish the relationships between selected anthropometric measures of highly-trained para-swimmers, their current IPC Class and passive drag. It is hypothesised that: 1) the anthropometric features of para-swimmers will differ significantly between IPC classes and 2) selected anthropometric characteristics of para-swimmers will have a significant association with their passive drag.

4.2 METHODS

4.2.1 Participants

One hundred and eighty five (105 male and 80 female; IPC Classes 1 – 14) para-swimmers (height 1.64 ± 0.23 m; mass 61.9 ± 12.4 kg; mean ± SD) participated in this study. Ninety were competitors at the London 2012 Paralympic games and eighty-nine were competitors at the Montreal 2013 IPC Swimming World Championships. The remaining six had competed at national or international level (Table 4.1 and 4.2). The study was approved by the University's Ethics Committee and written informed consent was obtained from all participants prior to testing.

Table 4.1 Characteristics of the participants (mean (SD))

Characteristic	Male (N=105)	Female (N=80)	Combined (N=185)
Age (years)	25.1 (7.6)	22.0 (6.8)	23.6 (7.4)
Height (m)	1.70 (0.22)	1.56 (0.20)	1.64 (0.23)
Body Mass (kg)	67.5 (11.6)	54.6 (9.4)	61.9 (12.4)

Table 4.2 Number of participants for swimming class

Class	1	2	3	4	5	6	7	8	9	10	11-13	14	Total
Male	4	4	10	6	9	11	7	15	6	8	15	10	105
Female	1	4	4	7	6	15	7	4	2	8	13	9	80
Total	5	8	14	13	15	26	14	19	8	16	28	19	185

4. 2. 2 Data Collection Procedure

Measuring Anthropometric Parameters

Seven anthropometric variables, height, streamlined-height, body mass, shoulder width, chest depth, shoulder girth, torso girth were collected according to Lohman *et al*. (1988). All measurements were taken with the participant barefoot wearing their swimming costume (images of measurement protocols are shown in Appendix A).

Height (m): Participants stood with their arms by their sides, with their heels, buttocks, shoulder-blades and head against a wall. Height was recorded from the floor to the top of the head to the nearest 0.01 m. When there was a possibility of instability in the standing posture, or standing was not possible, this measurement was taken with them lying supine on the floor.

Streamlined Height (m): Participants stood with their arms raised above their head in a streamlined position, with their heels, buttocks, shoulder-blades, head and hands against a wall. Streamlined height was recorded from the floor to the highest point where their hands touched the wall, to the nearest 0.01 m. When there was a possibility of instability in the standing posture, or standing was not possible, this measurement was taken with them lying supine on the floor.

Body Mass (kg): Participants were dry, barefoot and wearing only their swimming costume. Participants stood or sat on a set of calibrated scales. Body mass was recorded to the nearest 0.1 kg.

Shoulder Width (cm): Participants stood or sat upright with their arms by their sides hanging freely. A sliding anthropometric calliper (Cescorf, Paquímetro 60cm, Brazil) was used to measure the distance between the most lateral points of the acromial processes of the shoulders. Shoulder width was recorded to the nearest 0.1 cm.

Chest Depth (cm): Participants stood or sat upright with their arms by their sides hanging freely. The sliding anthropometric calliper was used to measure the distance between the most anterior points of the xiphoid process to the most posterior point of the C7 spine, at the level of the nipples. Chest depth was recorded to the nearest 0.1 cm.

Shoulder Girth (cm): Participants stood or sat upright with their arms by their sides hanging freely. An inelastic measuring tape was used to measure the circumference of the shoulders at the maximum bulge of the deltoid muscles inferior to each acromion. Shoulder girth was recorded to the nearest 0.1 cm.

Torso Girth (cm): Participants stood or sat upright with their arms raised above their head in a streamlined position. An inelastic measuring tape was used to measure the circumference of the torso at the widest point (when viewed from the front). Torso girth was recorded to the nearest 0.1 cm.

Calculating Anthropometric Parameters

Cross sectional area, reciprocal ponderal index and length-thickness ratio in the anatomical standing position, and in the streamlined position, were calculated using the anthropometric measurements. The cross sectional areas were estimated by representing the transverse plane through the thorax as a stadium shape as proposed by Yeadon (1990). The reciprocal ponderal indexes and length- thickness ratios were calculated according to Benjanuvatra *et al*. (2001).

① Cross sectional area in anatomical standing position (*CSA*) (cm^2):

$$CSA = (\text{chest depth}/2)^2 \cdot \pi + ((\text{shoulder girth} - \text{chest depth} \cdot \pi)/2) \cdot \text{chest depth}$$

② Cross sectional area in streamlined position (Streamlined *CSA*) (cm^2):

$$\text{Streamlined } CSA = (\text{chest depth}/2)^2 \cdot \pi + ((\text{torso girth} - \text{chest depth} \cdot \pi)/2) \cdot \text{chest depth}$$

③ Length-thickness ratio in anatomical standing position (*LTR*):

$$LTR = \text{Height}^2 / CSA$$

④ Length-thickness ratio in streamlined position (Streamlined *LTR*):

$$\text{Streamlined } LTR = \text{Streamlined Height}^2 / \text{Streamlined } CSA$$

⑤ Reciprocal ponderal index in anatomical standing position (*RPI*):

$$RPI = \text{Height} / \text{Body Mass}^{1/3}$$

⑥ Reciprocal ponderal index in streamlined position (Streamlined *RPI*):

$$\text{Streamlined } RPI = \text{Streamlined Height} / \text{Body Mass}^{1/3}$$

Passive drag measurements

The passive drag of each participant was measured in their most streamlined position at a speed of 1.5 $m \cdot s^{-1}$ using the methods detailed Chapter 3 Section 3.2.4.

4. 2. 3 Statistical Analysis

IPC Class vs Anthropometric Parameters

The Kolgomorov-Smirnov test was applied to check the distribution of the data and Levene's test was applied to check the equality of variance. To identify the differences in anthropometry between each IPC class, non-parametric data were analysed using the Kruskal Wallis test with post hoc Mann Whitney U. Parametric data were analysed using a one way ANOVA with Bonferroni-corrected post-hoc pairwise comparisons. Greenhouse Geisser corrections were applied to normally distributed but heterogeneously variant datasets on ANOVA outputs. Correlations between IPC Class and all anthropometric parameters were obtained using Kendal's tau_b.

Anthropometric Parameters vs Passive Drag

Spearman's Rho was utilised to determine the correlation between anthropometric parameters and passive drag, as the latter was found to be non-parametric. Multiple correlations were applied to determine any collinearity between key anthropometric parameters before multiple linear regressions were applied to predict passive drag from anthropometry. Spearman's Rho was utilised for non-parametric data and Pearson Moment correlation used for parametric data. Correlations were defined as: weak <0.3, moderate 0.3–0.6 or strong >0.6.

Before determining the final linear regression model, multiple correlations were performed to identify any collinearity between key anthropometric parameters. After all the collinear parameters were removed from the analysis, only 12 pairs remained which were composed of one parameter of slenderness and one thorax parameter (i.e. *RPI* versus shoulder width, shoulder girth, torso girth, *CSA* or streamlined *CSA*; Streamlined *RPI* versus chest depth, torso girth, *CSA* or streamlined *CSA*; *LTR* vs shoulder width; Streamlined *LTR* vs chest depth or streamlined *CSA*) (see Appendix B). Each of these pairs were entered in the regression analysis using SPSS Version 12. In the equations made by these paired-parameters, if there existed any parameter for which the p values of t or F were greater than 0.05, the parameter was deemed to cause instability and was therefore rejected.

4.3 RESULTS

IPC Class vs Anthropometric Parameters

The comparison of the IPC classes using Kruskal Wallis revealed significant main effects of IPC class on height, streamlined height, chest depth, *RPI*, streamlined *RPI*, *LTR* and streamlined *LTR*. There was no effect of IPC class on shoulder width. The results of the parametricity checks on each parameter are reported in Appendix C. Comparisons of the IPC classes by one-way ANOVA revealed significant main effects of IPC class in terms of body mass [with this effect due to the difference between Classes 3 and 14 (p=.021); 6 and 14 (p=.013)] and *LTR* [with this effect due to the difference between Class 3 and 8 (p=.006); 3 and 10 (p=.001); 3 and 12 (p=.014); 3 and 13 (p=.016); 3 and 14 (p<.001); 5 and 8 (p=.042); 5 and 10 (p=.009); 5 and 14 (p=.003); 6 and 14 (p=.050)]. There was no effect of IPC Class on shoulder girth, torso girth, *CSA* and streamlined *CSA*. Overall, IPC Class had a significant main effect on all the parameters which are related with height and ratios calculated using height but it had no effect on thorax size parameters, except for chest depth. The results of the post hoc pairwise comparisons, where data showed a significant group effect, are reported in Appendix C.

Figure 4.1 is the scatter plot for IPC Class and height for the male and female para-swimmers.

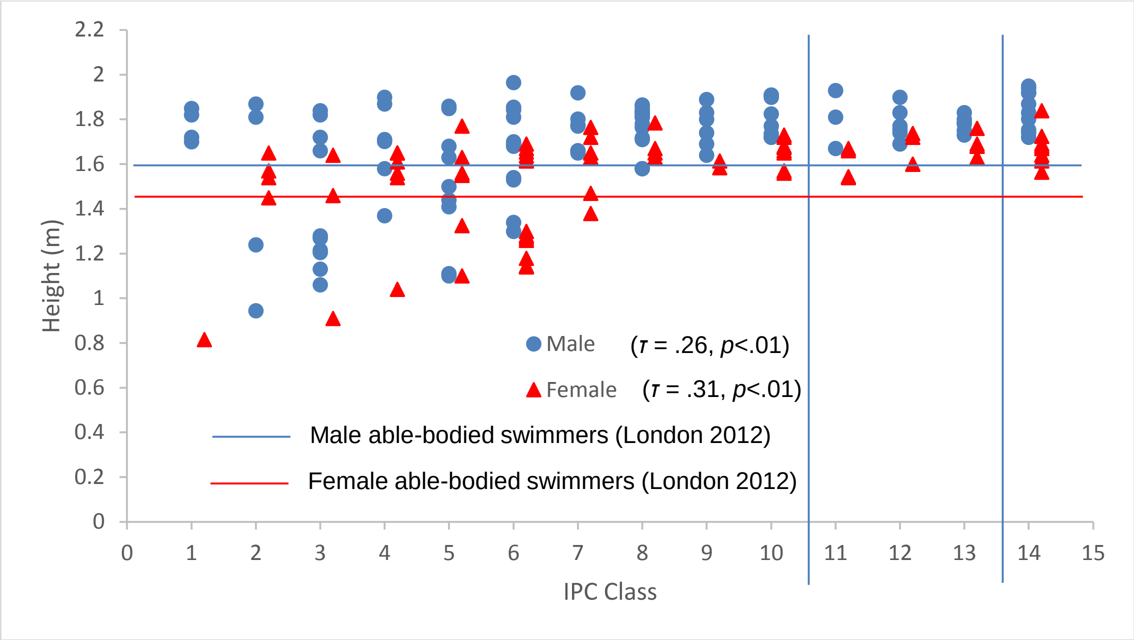


Figure 4.1 Scatter plot for IPC Class versus Height for male (*n*=105) and female (*n*=80) para-swimmers.

The para-swimmers' height ranged from 0.95 to 1.97 m and from 0.82 to 1.84 m for males and females, respectively. The lower classes (1 – 6) showed considerably greater within-class variability, and smaller mean height, than the higher classes (7 – 10), visually impaired (Class 11 – 13) and intellectually impaired swimmers (Class 14). Both male and female groups showed a significant positive association between height and IPC class (M: τ = .26, p<.01; F: τ = .31, p<.01, Class 1 – 10), meaning that the less impaired swimmers were taller than the more severely impaired swimmers. Blue and red horizontal lines show the mean heights of the 474 male (1.86 m) and 433 female (1.73 m) swimmers, respectively, who participated in 2012 London Olympic Games. Of the 105 male para-swimmers, only eighteen (17%) were taller than the mean height of the male Olympic swimmers. From the eighty female para-swimmers, only six (7.5%) were taller than the mean height of female Olympic swimmers.

Figure 4.2 is the scatter plot for IPC Class and streamlined height for the male and female para-swimmers.

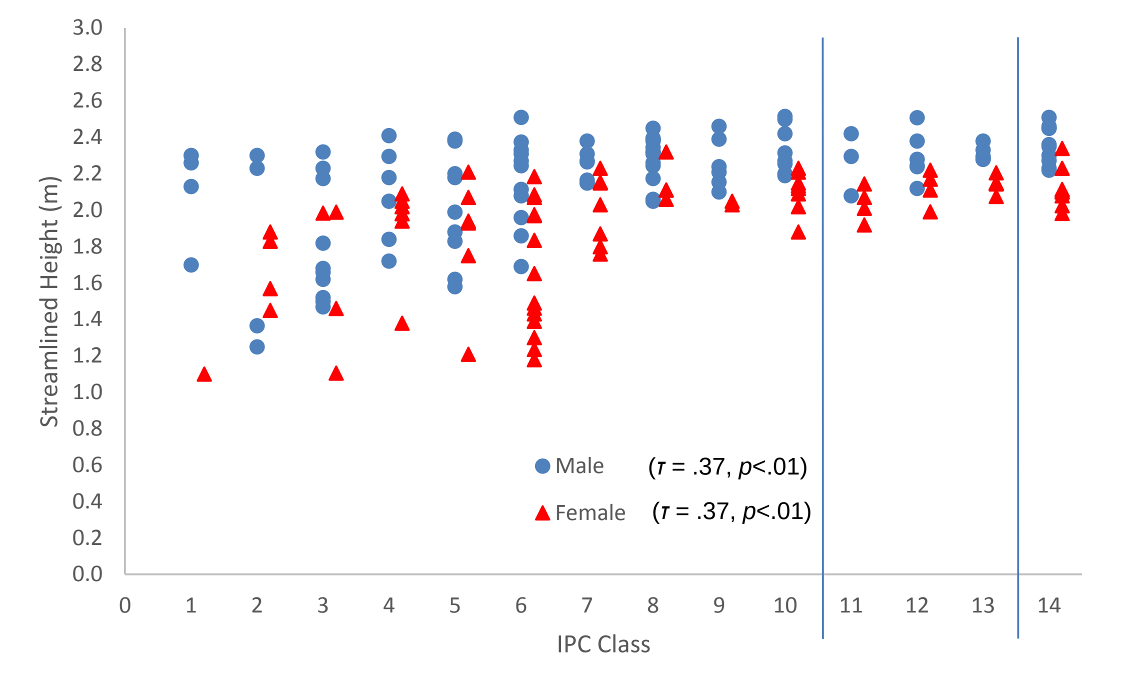


Figure 4.2. Scatter plot for IPC Class versus Streamlined Height for male (n=105) and female (n=80) para-swimmers.

The males' streamlined height ranged from 1.25 to 2.52 m and for females it ranged from 1.10 to 2.34 m. Classes 1 - 6 showed considerably lower streamlined heights and greater within-class variability than Classes 7-10, visually impaired (Class 11-13) and intellectually impaired swimmers (Class 14). Both male and female groups showed a significant positive association between streamlined height and IPC Class (M: τ = .37, p<.01; F: τ = .37, p<.01, Class 1 – 10).

Figure 4.3 is the scatter plot for IPC Class and body mass for the male and female para-swimmers. Body mass ranged from 41.2 to 105.0 kg for the males and from 27.0 to 72.2 kg for the females. There was a weak but significant association between IPC class and body mass for both groups (M: τ = .21, p<.01; F: τ = .21, p<.01). There was no clear difference in within-class variability in body mass, between the lower and higher classes. Blue and red horizontal lines show the mean body masses of 474 male (79.8 kg) and 433 female (62.8 kg) swimmers, respectively, who participated in 2012 London Olympic Games. Among the 105 male Class 1 – 14 swimmers only 12 swimmers (11.4%) were heavier than the mean body mass of male Olympic swimmers. Among the 80 female Class 1 – 14 swimmers only 15 swimmers (18.8%) were heavier than the mean body mass of female Olympic swimmers.

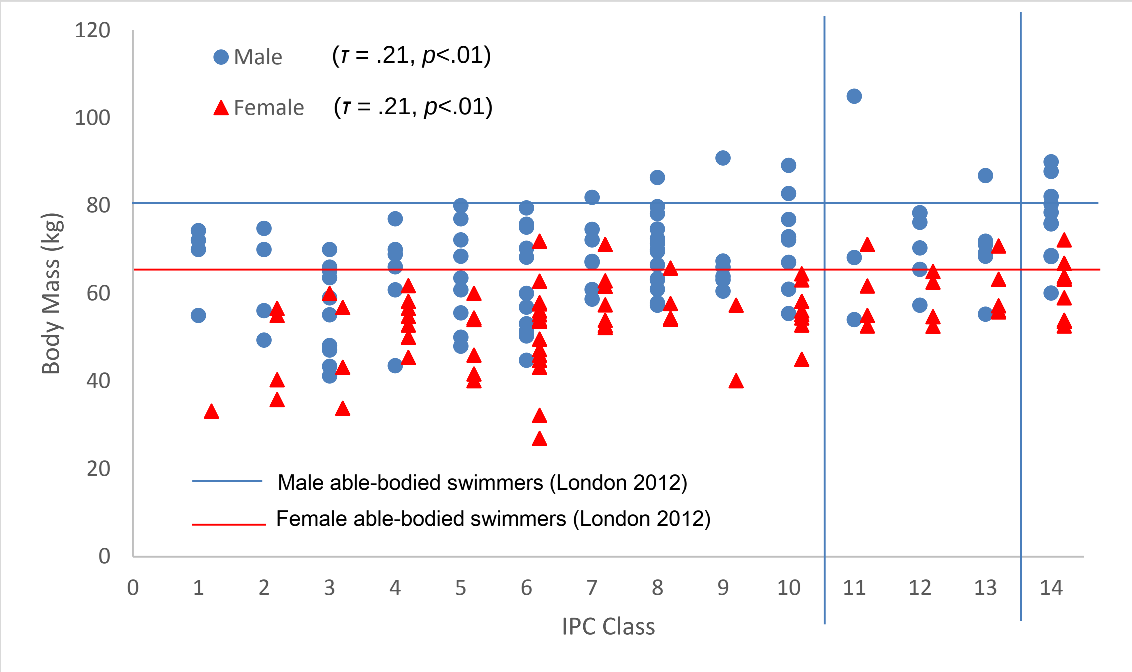


Figure 4.3 Scatter plot for IPC Class versus Body Mass for male (*n*=105) and female (*n*=80) para-swimmers.

Figure 4.4 is the scatter plot for IPC Class and shoulder girth for the male and female para-swimmers. Shoulder girth ranged from 98.2 to 132.5 cm for the males and from 83.5 to 123.0 cm for the females. No significant association existed between IPC class and shoulder girth (M: τ = .06; F: τ = .09, Class 1 – 10) and there were no apparent differences in within-class variability in shoulder girth, between the lower and higher classes. Other measurements on the swimmers' thorax: shoulder width (M: 33.0 – 49.0 cm; F: 29.0 – 41.3 cm), chest depth (M: 17.0 – 27.7 cm; F: 14.0 – 24.0 cm), torso girth (M: 84.5 – 130.5 cm; F: 69.0 – 103.0 cm), CSA (M: 693 – 1209 cm^2; F: 450 – 973 cm^2) and streamlined CSA (M: 538 – 1034 cm^2; F: 329 – 731 cm^2) showed no significant association with IPC Class.

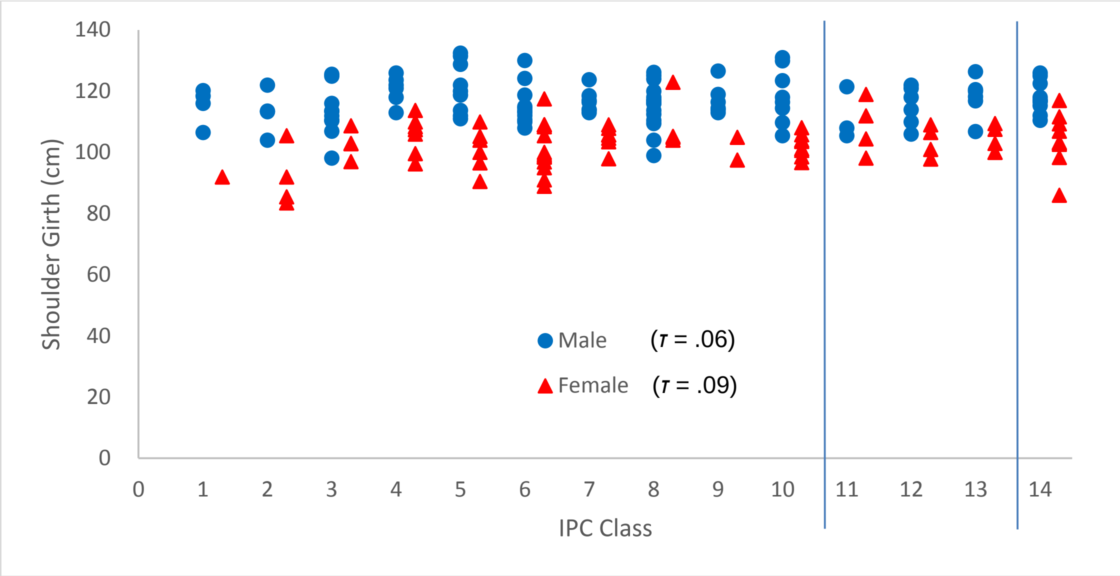


Figure 4.4 Scatter plot for IPC Class versus Shoulder Girth for male (n=105) and female (n=80) para-swimmers.

Figure 4.5 is the scatter plot for IPC Class and streamlined *RPI* for the male and female para-swimmers. Male streamlined *RPI* ranged from 34.1 to 61.5 m·kg$^{-1/3}$ and for the females it ranged from 34.2 to 59.9 m·kg$^{-1/3}$.

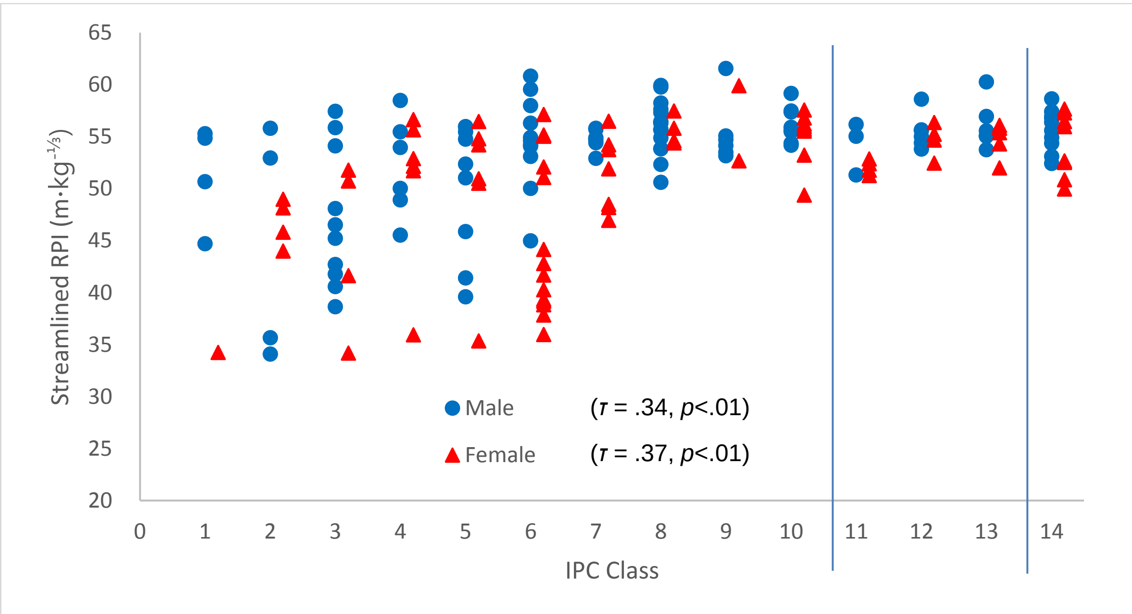


Figure 4.5 The scatter plot for IPC Class versus Reciprocal Ponderal Index in streamlined position for male (n=105) and female (n=80) para-swimmers.

The within-class variability of streamlined *RPI* in Classes 1 - 6 was considerably greater than in Classes 7-10, visually impaired (Class 11-13) and intellectually impaired swimmers (Class 14). The streamlined *RPI* (M: τ = .34, p<.01; F: τ = .37, p<.01), *LTR* (M: τ = .24, p<.01; F: τ = .20, p<.01) and streamlined *LTR* (M: τ = .39, p<.01; F: τ = .36, p<.01), of both the male and female groups had a significant, moderate correlation with IPC Class. Among the scatter plots for other anthropometric parameters, streamlined *RPI*, *LTR* and streamlined *LTR* had similar trend with the scatter plot of *RPI*; Shoulder width, chest depth, torso girth, *CSA* and streamlined *CSA* had similar trend with the scatter plot of shoulder girth. The scatter plots for these anthropometric parameters versus IPC Class are shown in Appendix D.

Anthropometry vs Passive Drag

Spearman's Rho revealed that passive drag had no significant correlation with height (.06), streamlined height (-.04), shoulder width (.13), *RPI* (-.12) or streamlined *LTR* (-.10); significant positive correlations with body mass (.18), chest depth (.27), shoulder girth (.24), torso girth (.33), *CSA* (.28) and streamlined *CSA* (.36); and significant negative correlations with streamlined *RPI* (-.24) and *LTR* (-.19). Figures 4.6, 4.7, 4.8 and 4.9 show the scatter plots between passive drag and height, streamlined *CSA*, *RPI* and *LTR*, respectively. The scatter plots for passive drag and the other anthropometric parameters are reported in Appendix E.

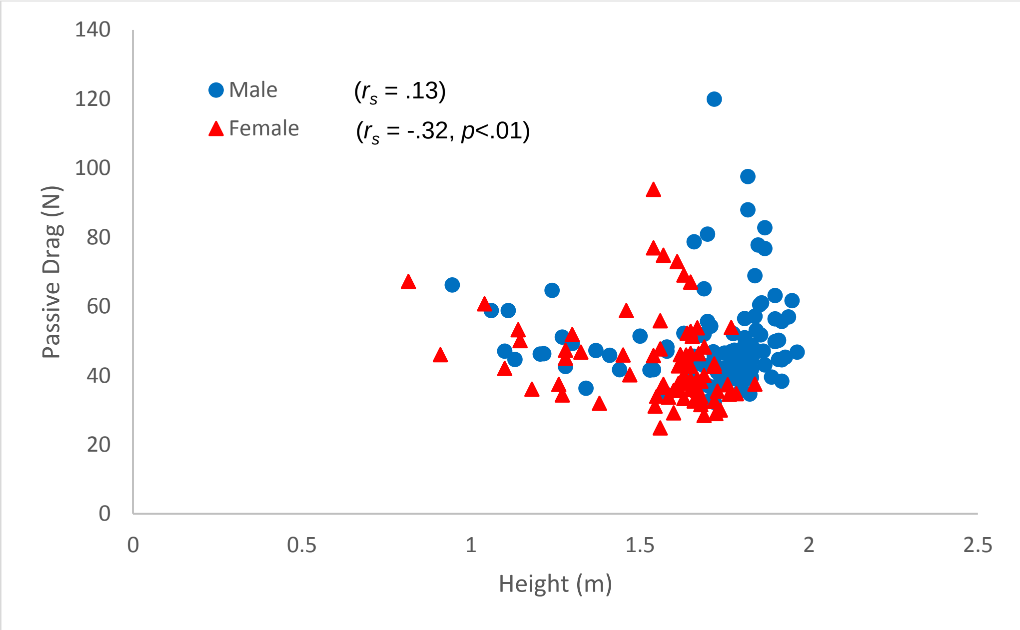


Figure 4.6 Scatterplot for Height versus Passive Drag for male (n=105) and female (n=80) para-swimmers.

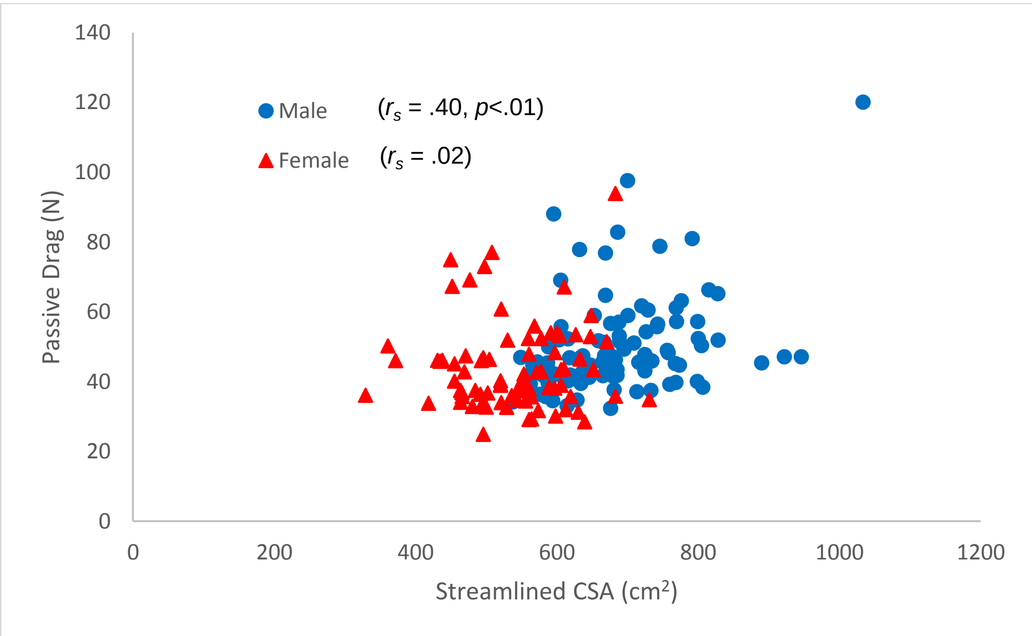


Figure 4.7 Scatterplot for Cross-Sectional Area in streamlined position versus Passive Drag for male (n=105) and female (n=80) para-swimmers.

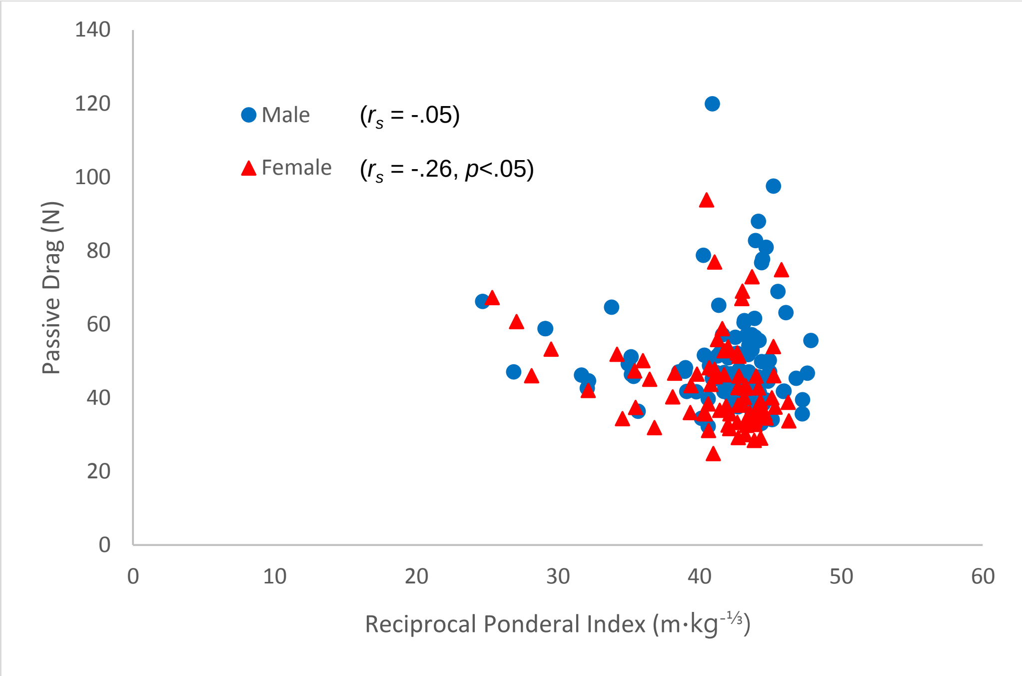


Figure 4.8 Scatterplot for Reciprocal Ponderal Index versus Passive Drag for male (*n*=105) and female (*n*=80) para-swimmers.

Figure 4.9 Scatterplot for Length Thickness Ratio versus Passive Drag for male (*n*=105) and female (*n*=80) para-swimmers.

The final linear regression model (*F* = 20.111; *p*<.001) included the torso girth (*t* = 5.618; *p*<.001) and the streamlined *RPI* (*t* = -3.755; *p*<.001) in order to predict the passive drag. The equation (R^2 = .183; R_a^2 = .174; *p*<.01) was:

$$\text{Passive Drag} = 0.591 \cdot \text{torso girth} - 58.587 \cdot \text{streamlined } RPI + 23.072$$

4.4 DISCUSSION

The IPC Swimming Classification system determines the category in which swimmers with physical impairment can compete in the Paralympic Games. This study set-out to establish whether the anthropometric features of highly trained para-swimmers were related to their IPC class and whether those anthropometric characteristics had a significant association with their passive drag.

The study found IPC Class correlated significantly with height, streamlined height, body mass, chest depth and the slenderness indices (*RPI*, streamlined *RPI*, *LTR* and streamlined *LTR*). There was no significant association between IPC Class and shoulder width, shoulder girth, torso girth, *CSA* and streamlined *CSA*. This indicates that the less impaired para-swimmers tended to be taller and heavier than those with more severely impairments, but their torso dimensions did not change systematically with IPC Class.

The mean height of the para-swimmers in this study was 1.70 ± 0.22 m for males and 1.56 ± 0.20 m for females. These values are considerably lower than those typically reported for high-level, able-bodied swimmers (Arellano *et al.*, 1994: males:1.84 ± 0.10 m; females: 1.73 ± 0.08 m; Pelayo *et al.*, 1996: males: 1.86 ± 0.06 m; females: 1.73 ± 0.06 m; Naemi *et al.*, 2012: males: 1.86 ± 0.06 m; females:1.74 ± 0.08 m). The range of heights in the current study (males: 0.95-1.97 m; females: 0.82-1.84 m) is larger than those reported in able-bodied studies. The significant positive association found between height and IPC Class indicates that the swimmers with less severe impairments were generally taller than those with more severe impairments. The mean heights of the male and female para-swimmers in the higher classes (Class 7 – 14) were 1.79 m and 1.65 m, respectively. These swimmers were, on average, shorter than the male (1.86 m) and female (1.73 m) swimmers at the London Olympics. The wide range of heights observed in the lower classes (Class 1 – 6) reflects the great diversity of impairment types found in these classes. In these classes, athletes with double-leg amputation, dysmelia or short stature may compete against swimmers whose impairments affect their coordination or muscle function, but not their stature.

The mean body masses of the male and female para-swimmers in this study were 67.5 ± 11.6 kg and 54.6 ±9.4 kg, respectively. As with height, these mean values are lower than those reported for high-level, able-bodied swimmers (Pelayo *et al*., 1996: male: 76.7 ± 1.4 kg; female: 61.2 ± 4.4 kg; Naemi *et al*., 2012: male: 77.5 ± 4.9 kg; female: 66.8 ± 5.2 kg) and the range of values are higher (males: 41.2-105.0 kg; females: 27.0-72.2 kg). For both the male and female groups, the more impaired para-swimmers tended to be lighter than the less impaired para-swimmers, as evidenced by the significant positive correlations between IPC Class and body mass. This observation can be explained by the lower classes comprising athletes with multiple limb loss, short stature, dysmelia and poor muscle development.

The mean height of the non-physically impaired para-swimmers (the visually and intellectually impaired participants, Class 11-14) was 1.81 m and 1.66 m, for the males and females, respectively and the mean body mass of these groups was 73.8 kg and 60.3 kg, respectively. These swimmers were shorter and lighter than competitors at the London Olympics. The world-wide populations of visually impaired and intellectually impaired swimmers will be considerably smaller than the population of non-impaired swimmers. These swimmers therefore face less competition than Olympic swimmers to achieve International standards and thus may succeed with a physique that may not be ideal for Olympic competition.

A particularly interesting finding in this study was that, unlike for height and body mass, most of the torso measures (shoulder girth, torso girth, *CSA* and streamlined *CSA*) did not change systematically across IPC Classes. The mean *CSA* recorded in this study was 684 ± 90 cm^2 for males and 540 ± 77 cm^2 for females. These values are ~5-15% smaller than those reported for able-bodied swimmers (Clarys, 1979: M: 767 ± 124 cm^2; Morais, Costa, Mejias, Marinho, Silva & Barbosa, 2011: M: 748 ± 185 cm^2; F: 634 ± 145 cm^2; Barbosa, Morais, Costa, Mejias, Marinho & Silva, 2012: M: 716 ±176 cm^2: F: 643 ± 154 cm^2).

The mean *RPI* values for the male and female para-swimmers in this study were 0.42 ± 0.04 $m\cdot kg^{⅓}$ and 0.41 ± 0.04 $m\cdot kg^{⅓}$, respectively. These are similar to values reported for able-bodied swimmers (Lyttle *et al*., 1998: 0.43 ± 0.01 $m\cdot kg^{⅓}$ for male adult swimmers; Benjanuvatra *et al*., 2001: 0.45 ± 0.02 $m\cdot kg^{⅓}$ for 13 year old male and female swimmers). However, the ranges for *RPI* observed in this study (males: 0.25-0.48 $m\cdot kg^{⅓}$; females: 0.25-0.46 $m\cdot kg^{⅓}$) are greater than those reported in the able-bodied studies.

The mean *LTR* values for the male and female para-swimmers were 33.6 ± 8.2 and 35.7 ± 8.6, respectively. These values are smaller than the 50.4 ± 2.8 reported by Benjanuvatra *et al*. (2001) for 13 year old male and female swimmers indicating that, on average, the para-swimmers were considerably less slender than the able-bodied swimmers. As anticipated, the ranges of *LTR* in the current study (9.0-48.6 for male and 11.0-59.0 for female) were much greater than the range reported by Benjananuvatra *et al*. (2001).

Overall, the para-swimmers in this study were shorter, lighter, with a smaller torso circumference and less slender than able-bodied swimmers. However, the concept of a mean or 'typical' shape for a para-swimmer is rather meaningless due to the diverse range of impairments, and associated body shapes and sizes, present in this population.

It was hypothesised in this study that selected anthropometric characteristics of para-swimmers would have a significant association with passive drag such that passive drag could be predicted from a para-swimmer's anthropometry. Only eight of the thirteen anthropometric measures were significantly correlated with passive drag. The strength of these correlations were, at best, moderate, the highest coefficients being found with torso girth (r = .33) and streamlined *CSA* (r = .36). The best linear regression, which combined torso girth and streamlined *RPI*, produced an R^2 of .183. Thus only 18% of the variability in passive drag could be explained by the para-swimmers' anthropometric measures. Studies of able-bodied swimmers have generally shown much higher associations between anthropometry and drag than studies of impaired swimmers have (e.g. van Tilborgh *et al*., 1983; Huijing *et al*., 1988; and Benjanuvatra *et al*., 2001). One of the most notable differences between the current study and previous ones is the relationship between passive drag and height. Correlation coefficients ranging from 0.54 (van Tilborgh *et al*., 1983) to 0.80 (Chatard *et al*., 1990a) have been reported for these two variables, whereas in the current study there was no apparent relationship (r = .06). In the two previous studies involving physically impaired swimmers, height has either shown no correlation with passive drag (Chatard *et al*., 1992), which is in agreement with the current study, or a very strong negative relationship (Chatard *et al*., 1990b). Similar conflicting findings exist when considering the effect of body mass on drag. The weak relationship (r = .18) found between these two variables in the current study is not consistent with the findings of able-bodied swimmer studies which have shown correlation coefficients from 0.54 (Chatard *et al*., 1990a) to as high as 0.82 (Huijing *et al*., 1988). The group of para-swimmers in the current study had much greater variability in height and mass than the groups used in the able-bodied studies had. This is to be expected given the nature of some of the swimmers included in this study, e.g. double leg amputees, dwarves. It could be argued that having such a heterogeneous sample should enhance the strength of the correlation between passive drag and height (and other anthropometric measures), compared to the more homogenous able-bodied groups. It is likely that during testing, the para-swimmers had a far greater range of Froude numbers than the able-bodied groups. Given that the Froude number is directly proportional to wave-making drag and inversely proportional to swimmer height, a strong negative relationship between passive drag and height, such as that reported by Chatard *et al*. (1990b), might have been anticipated. However, this was not case in the current study.

There are a number of possible reasons for the lack of consensus regarding the relationship between passive drag and swimmer height (and certain other anthropometric measures): 1) *Participant characteristics*- differences exist between studies in terms of the types of physical impairments included, age, skill level and the homogeneity of the anthropometric measures. The current study is the first to examine the anthropometry of highly-trained para-swimmers. This is a unique population and, as such, was always likely to produce findings not consistent with previous studies; 2) *Statistical power*- the two previous studies involving physically impaired swimmers had relatively low sample sizes (eleven and thirty-four) which increased their probability of making a Type II error, when compared to the larger-grouped studies, such as the current one which had 185 participants, 3) *Test speed* – a wide range of speeds have been used in passive drag studies. The current study used a towing speed of 1.5 $m \cdot s^{-1}$. For speeds up to ~ 1.5 $m \cdot s^{-1}$, pressure drag is the main component of the total drag whilst at higher speeds, wave-making drag becomes predominant (Toussaint & Truijens, 2005). Thus, high test speeds are more likely to reveal a relationship between passive drag and swimmer height (a measurement related to wave-making drag), whereas low test speeds are more likely to show relationships between passive drag and those anthropometric measures associated with pressure drag (e.g. chest depth, shoulder width, *CSA*). This may partially explain why, in the current study, the strongest correlations were found with shoulder girth and Streamlined *CSA* and not with height or streamlined height; 4) *Stability and body alignment* – passive drag, by definition, involves the swimmer maintaining a fixed body position during measurement. In the current study, it was quite apparent that some para-swimmers, as a consequence of their impairment, were less stable, or were more poorly aligned than others, during towing. The additional drag caused by an unstable or poorly aligned body position could outweigh any anthropometric influences on drag.

Even though passive drag correlated significantly with a number of anthropometric measures in this study, the strength of the relationships were never strong. The linear regression model showed that only 18% of the variability in passive drag could be explained by the para-swimmers' anthropometry, leaving 82% unaccounted for. Much of the remaining variability in passive drag could be due to the lack of uniform body position in the water. All swimmers were instructed to maintain their most streamlined position. However, some para-swimmers clearly had impairments preventing them from achieving an ideal position (joints fully extended and body horizontally aligned). A swimmer with a limited joint range of movement, e.g. at the elbow, pelvis or knee, would experience greater pressure drag than a swimmer with the same anthropometry but with no joint restrictions. For example, Kent & Atha (1971) demonstrated that passive drag measured with the hip in approximately 90° flexion was more than double the passive drag in a streamlined position. Similarly, Naemi *et al*. (2012) concluded that a swimmer's joint angles had a significant effect on their glide efficiency, an indirect measure of passive drag.

4. 5 CONCLUSION

This study has reported selected anthropometries and passive drag of a large group of para-swimmers representing the fourteen IPC functional classes. Significant inter-class differences were found with regard to height, streamlined height, body mass, chest depth, *RPI*, streamlined *RPI*, *LTR* and streamlined *LTR*, whereas shoulder width, shoulder girth, torso girth and *CSA* did not differ significantly between classes. Therefore there was only partial evidence to support the first hypothesis, that the anthropometry features of para-swimmers will differ significantly between IPC classes.

Six anthropometric measures (body mass, chest depth, shoulder girth, torso girth, *CSA* and streamlined *CSA*) showed a significant positive correlation with passive drag; two measures (streamlined *RPI* and streamlined *LTR*) had a significant negative correlation, and the remaining five (height, streamlined height, shoulder width, *RPI* and *LTR*) did not correlate significantly with passive drag. The strength of the significant correlations were, at best, moderate. The best linear regression, which combined torso girth and streamlined *RPI*, indicated that only 18% of the variability in passive drag could be explained by the para-swimmers' anthropometric measures. Thus, the study provided little evidence to support the hypothesis that the anthropometric characteristics of para-swimmers are significantly associated with their passive drag.

The weak associations found between anthropometry and passive drag in this study are in conflict with the results from studies on able-bodied swimmers. In para-swimming, athletes with similar anthropometric measurements can experience quite different passive drag forces due to differences in the nature of their impairment. For this reason, further research and analysis is necessary to gain an understanding of the relationship between passive drag and the specific impairments of para-swimmers. The next chapter will address this.

CHAPTER FIVE

EXPERIMENTAL STUDY 3

INFLUENCE OF SPECIFIC IMPAIRMENTS ON PASSIVE DRAG

This chapter considers how the specific impairments of para-swimmers influence passive drag. Forty-six impairment groups were identified and a Passive Drag Band (PDB) ranking system was then used to identify whether certain impairments can advantage or disadvantage a para-swimmer, with respect to drag, under the current classification system.

5.1. INTRODUCTION

The passive drag experienced by para-swimmers has been linked with their level of physical impairment (Oh *et al*., 2013). However, study 1 of this thesis found that the current IPC Swimming Classification System does not discriminate swimmer's passive drag clearly between adjacent classes. The relatively high within-class variability in passive drag found in the lower classes (1-6) remained when drag was normalised for size (body mass). This led to the conclusion that some athletes may be substantially advantaged or disadvantaged over others in their class with regard to drag, which may give them a corresponding performance advantage or disadvantage.

The drag created by able-bodied swimmers has been closely linked with their anthropometry (e.g. Chatard *et al*., 1990a; Benjanuvatra *et al*., 2001). In contrast, study 2 of this thesis has shown that, for para-swimmers, the association between anthropometry and passive drag is relatively weak, indicating that para-swimmers with similar anthropometric measurements can experience quite different passive drag forces. As anthropometric measures could only explain 18% of the variability observed in para-swimmers' passive drag, it seems likely that the nature of the swimmer's impairment may be a more important determinant of passive drag than their anthropometry per se.

From when para-swimming started at the 1953 Stoke Mandeville Games until the 1972 Heidelberg Games, only swimmers with spinal-cord injuries were eligible to participate in this competition. The opportunity to participate was extended to swimmers with amputations and visually impairment in the 1976 Toronto Games. Swimmers with cerebral palsy were included from Arnhem 1980 and those who qualified for the 'les autres' group were invited to compete at the 1984 New York Games (Brittain, 2012). Up until and including the 1988 Seoul Paralympics, these swimmers with different medical diagnoses or impairments competed in separate races. The 1992 Barcelona Paralympics saw a fundamental change in the organisation of the swimming races; swimmers with different medical diagnoses and impairments competed in races together under the new functional classification system. Since Barcelona, offering an equitable starting point for athletes in all Paralympic sport, through fair classification systems, has become one of the most important challenges the IPC faces (Vanlandewijck & Chappell, 1996).

Para-swimmers with wide range of impairments may be allocated the same IPC Class and therefore compete in the same race, yet the amount of drag resisting progress during the race can vary considerably between the competing swimmers. Some physical impairments may severely limit a swimmer's ability to achieve or maintain an 'ideal' streamlined position, i.e. with the body fully extended and horizontal aligned in the water. For example, swimmers with a limited joint range of motion or with paralysis of the lower extremity will not achieve perfect streamlining and will, consequently, encounter greater drag than those who can. Kent and Atha (1971) demonstrated that passive drag measured with the hip flexed ~90° was more than double that in a streamlined position. The influence of body position was also highlighted by Naemi *et al*. (2012) who concluded that a swimmer's joint angles and posture in the water had a greater effect on glide efficiency, an indirect measure of passive drag, than the dimensions of the swimmer.

No study has yet to examine how specific physical impairments or medical conditions (e.g. cerebral palsy, achondroplasia) may influence the magnitude of passive drag and, consequently, advantage or disadvantage a para-swimmer with respect to this performance variable. The aims of this study therefore were: 1) to determine whether para-swimmers' passive drag changes in accordance with their impairment type, and 2) to identify whether para-swimmers with certain impairments have an advantage or disadvantage, with respect to passive drag, under the current classification system. The two corresponding hypotheses were: 1) a para-swimmer's passive drag can be related to their impairment type, and 2) certain impairments can advantage or disadvantage a para-swimmer, with respect to drag, under the current classification system.

5.2. METHODS

5.2.1. Participants

A total of 153 para-swimmers (93 males and 60 females) representing IPC Classes 1 to 10 participated in this study (height 1.60 ± 0.25 m; mass 60.7 ± 12.4 kg; mean ± SD). Eighty-nine competed at the London 2012 Paralympics, sixty competed at the Montreal 2013 IPC Swimming World Championships and the remaining four were from the GB squad who competed at national level. Testing procedures were approved by the University's ethics committee and all swimmers provided written informed consent prior to participating.

5.2.2. Data Collection Procedures

Passive drag

The passive drag of each participant was measured in their most streamlined position, at a speed of 1.5 $m \cdot s^{-1}$, using the methods detailed in Chapter 3 Section 3.2.4.

Impairment

Details of each participant's impairments was ascertained either from on-line profiles or directly from the swimmer. They were then categorised into five impairment groups: 1) Spinal Cord Injury or Polio; 2) Cerebral Palsy; 3) *Les Autres*; 4) Short Stature; 5) Amputee or Dysmelia. To visualise the specific types and severity of the impairments, a modified version of the *Code for Disability Profile* from the IPC Swimming Classification Manual (IPC, 2005) was used. Figure 5.1 illustrates the basic principle of how the type and severity of an impairment is represented by a coloured illustration.

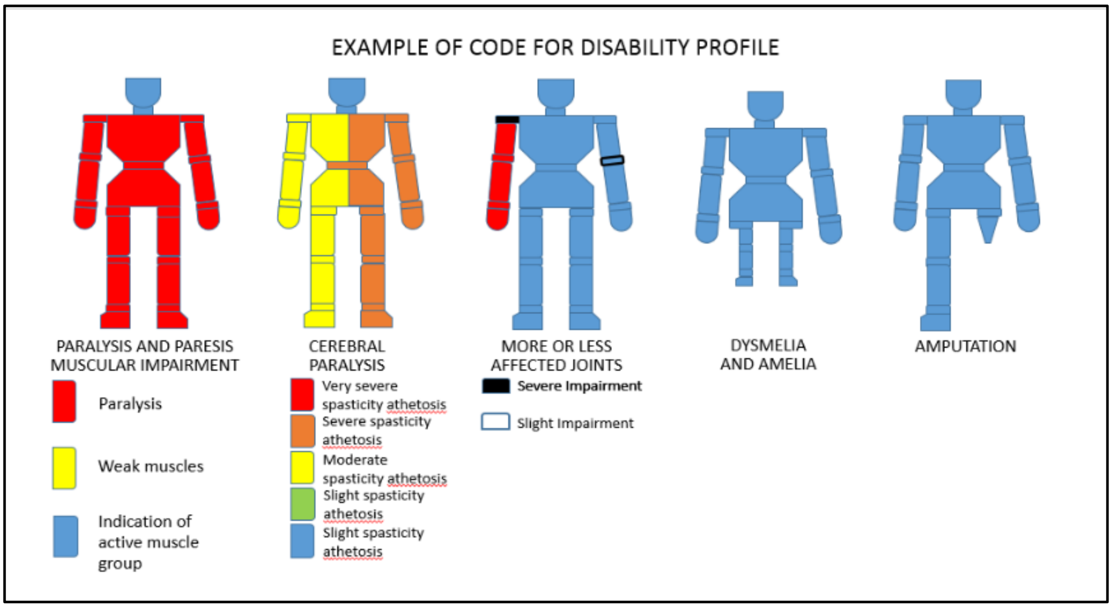


Figure 5.1 Code for Disability Profile used in IPC Swimming Classification Manual (IPC, 2005).

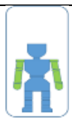
The twenty-one para-swimmers with spinal cord injury or polio were split into eight sub-groups according to the severity of their impairment. These sub-groups were labelled SP1 – SP8, with SP1 generally representing the most severely impaired and SP8 the least severely impaired. Table 5.1 shows each sub-group name, impairment illustration, number of participants (N) and impairment description.

The fourteen short stature para-swimmers were split into two sub-groups, SS1 and SS2, according to the severity of their impairment. Table 5.2 shows each sub-group name, impairment illustration, number of participants (N) and impairment description.

Table 5.1 Illustration and description of impairments in the spinal cord injury or polio sub-groups (SP1 – SP8).

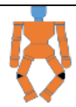
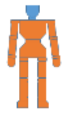
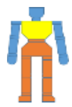
NAME	ILLUSTRATION	N	DESCRIPTION
SP1		1	Tetraplegia or Polio comparable to a complete lesion below C6 with restricted knee function (Class 1).
SP2		1	Tetraplegia comparable to a complete lesion below C7 with additional plexus paralysis or restriction in one arm (Class 1).
SP3		2	Tetraplegia or Polio comparable to a complete lesion below C8 with good finger extension (Class 3).
SP4		3	Complete paraplegia or polio comparable to lesion at T1-T8 with restricted knee function (Class 3-5).
SP5		5	Complete paraplegia or polio comparable to lesion at T1-T8 (Class 4-5).
SP6		3	Complete paraplegia or polio comparable to lesion at T9-L1 with no leg function suitable for swimming (Class 5).
SP7		5	Complete paraplegia or polio comparable to lesion at L2-L3 (Class 5-6).
SP8		1	Walking paraplegia with minimal involvement in limbs or Polio with one non-functional leg (Class 8).
		21	

Table 5.2 Illustration and description of impairments in the short stature sub-groups (SS1 and SS2).

NAME	ILLUSTRATION	N	DESCRIPTION
SS1		3	Achondroplasia: not more than 130 cm for women and 137 cm for men with additional handicap that causes propulsion problems (Class 2-5).
SS2		11	Achondroplasia: not more than 130 cm for women and 137 cm for men (Class 6).
		14	

The thirty-one para-swimmers with cerebral palsy were split into eight sub-groups according to the severity of their impairment. These sub-groups were labelled CP1 – CP8, with CP1 generally representing the most severely impaired and CP8 the least severely impaired. Table 5.3 shows each sub-group name, impairment illustration, number of participants (N) and impairment description.

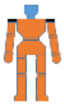
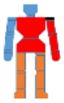
Table 5.3 Illustration and description of impairments in the cerebral palsy sub-groups (CP1 – CP8).

NAME	ILLUSTRATION	N	DESCRIPTION
CP1		2	Severe spastic quadriplegia with poor trunk control and asymmetrical movement of the upper limbs for propulsion with restricted legs (Class 2).
CP2		1	Severe quadriplegia with spasticity and athetosis involving poor head and trunk control, limited co-ordination for propulsion in all four limbs (Class 2).
CP3		2	Severe diplegia with involvement of the trunk and limited propulsion in shoulders and elbows (Class 3-4).
CP4		2	1) Severe diplegia with fair trunk control and fair propulsion in shoulders and elbows, 2) Severe hemiplegia, or 3) Severe to moderate athetosis / ataxia and spasticity (Class 4-5).
CP5		8	Moderate hemiplegia with severe restriction in the more affected side (Class 5-6).
CP6		8	Moderate or minimal hemiplegia (Class 7).
CP7		4	Minimal diplegia with minimal trunk involvement (Class 7-9).
CP8		4	Weak paresis on two legs (Class 10).
		31	

The twenty-three para-swimmers in the *Les Autres* group were split into ten sub-groups according to the severity of their impairment. These sub-groups were labelled LA1

– LA10, with LA1 generally representing the most severely impaired and LA10 the least severely impaired. Table 5.4 shows each sub-group name, impairment illustration, number of participants (N) and impairment description.

Table 5.4 Illustration and description of impairments in the Les Autres sub-groups (LA1 – LA10).

NAME	ILLUSTRATION	N	DESCRIPTION
LA1		1	Severe muscular atrophy of both upper and lower limbs with very poor leg function comparable to complete to tetraplegia below C6 (Class 1).
LA2		3	Musculoskeletal impairment with very poor shoulder function comparable to tetraplegia below C7 (Class 2-3).
LA3		1	Musculoskeletal impairment with very poor shoulder function for one side comparable to tetraplegia below C8 (Class 2).
LA4		4	Arthrogryposis affecting all four limbs with moderate to fair propulsion from the upper limbs with a possible restricted movement in the lower limbs (Class 4-6).
LA5		3	Swimmers unable to use both legs due to the effect of congenial arthrogryposis with misalignment of the hip or congenial malformation of the spine and lower limbs, etc. (Class 6).
LA6		6	Swimmers with impairments on both legs, such as congenial malformation of the spine and lower limbs, neuromuscular myopathy, cancer, spina bifida, etc. (Class 7-8).
LA7		1	Swimmers with impairments of one arm (Class 8).
LA8		2	Slight overall functional co-ordination problems (Class 9-10).
LA9		1	Swimmers with leg length differences combined with minimal weakness of the leg.
LA10		1	Severe hip joint restriction with further dysfunction of the leg.
		23	

The sixty-three para-swimmers with amputations were first divided into three categories and then sub-grouped as follows:

1) Double-leg Amputees (DLA) – eight sub-groups (DLA1 – DLA8) (Table 5.5).

2) Single-leg Amputees (SLA) – five sub-groups (SLA1 – SLA5) (Table 5.6).

3) Arm-Amputees (AA) – five sub-groups (AA1 – AA5) (Table 5.7).

Table 5.5 Illustration and description of impairments in the double-leg amputee (DLA) sub-groups (DLA1 – DLA8).

NAME	ILLUSTRATION	N	DESCRIPTION
DLA1		1	Severe dysmelia or amputation of four limbs (Class 2).
DLA2		4	Severe dysmelia or amputation of three limbs (Class 2-3).
DLA3		4	Severe amputation of both legs and one arm amputation below elbow level (Class 3-5).
DLA4		1	Severe dysmelia of both legs and missing arm and hand.
DLA5		4	Double-leg Amputation at knee or shank level and double arm amputee below elbow level (Class 3-5).
DLA6		2	Severe amputation of both legs (Class 4-5).
DLA7		4	Double-leg Amputation of knee level (Class 5-6).
DLA8		4	Double-leg Amputation below knee level (Class 7-8).
		23	

Table 5.6 Illustration and description of impairments in the single-leg amputee (SLA) sub-groups (SLA1 – SLA5).

NAME	FIGURE	N	DESCRIPTION
SLA1		1	Amputation of three limbs above knee and elbow level (Class 2).
SLA2		1	Amputation or Dysmelia of three limbs below knee or elbow level (Class 4).
SLA3		1	Amputation of one arm and one leg on different sides (Class 6).
SLA4		6	Single-leg amputation above knee level (Class 8).
SLA5		4	Single-leg amputation below knee level (Class 10).
		13	

Table 5.7 Illustration and description of impairments in the arm amputee (AA) sub-groups (AA1 – AA5).

NAME	FIGURE	N	DESCRIPTION
AA1		1	Double-arm amputee at elbow level (Class 7).
AA2		1	Double-arm amputee below wrist level (Class 7).
AA3		5	Single-arm amputee above elbow level (Class 7-8).
AA4		10	Single-arm amputee below elbow level (Class 8-9).
AA5		10	Hand amputation, loss of 1/2 of the hand (Class 10).
		27	

Passive Drag Band (PDB)

The para-swimmers were assigned to one of ten passive drag bands (PD1 – PD10) according to their normalised passive drag score (passive drag/body mass). Those with the highest normalised passive drag were in band PD1; those with the lowest were in band PD10. The distribution of the 153 para-swimmers across the ten bands was kept the same as the distribution across the 10 IPC physical impairment classes. Table 5.8 shows the number of para-swimmers in each Class and Passive Drag Band (PDB). The numerical difference between each para-swimmer's IPC Class integer and their PDB integer was computed (PDB – IPC Class) to establish the extent to which their passive drag score was aligned with their current IPC class.

The magnitude and direction of the difference between a swimmer's IPC Class and their PDB was colour coded as follows:

Navy : IPC Class greater than PDB by 3 or more.

Blue : IPC Class greater than PDB by 2.

Green : IPC Class greater than PDB by 1.

Yellow : IPC Class equals PDB.

Orange : PDB greater than IPC Class by 1.

Scarlet : PDB greater than IPC Class by 2.

Red : PDB greater than IPC Class by 3 or more.

Table 5.8 Distribution of 153 para-swimmers across the ten IPC Classes / Passive Drag Bands (PDB)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
Class	5	7	15	12	17	28	19	20	9	21	153
PDB	5	7	15	12	17	28	19	20	9	21	153

5.3. RESULTS

5.3.1 Impairment vs Passive Drag

The para-swimmers in this study experienced passive drag ranging from 24.9 to 120.0 N with a mean 49.2 N. When passive drag (D_P) was normalised for body mass (m), the normalised passive drag (D_P/m) ranged from 0.45 – 2.03 N·kg^{-1} with the mean of 0.84 N·kg^{-1}. Swimmers with restricted joint range of movement at two segments (sub-groups SP1, CP1 and LA1: 1.3 – 1.7 N·kg^{-1}), Swimmers with no joint range of movement at one segment (SP4: 1.0 – 1.5 N·kg^{-1}) and with a double leg amputation at crotch level (sub-groups DLA1, DLA2, DLA3 and DLA6: 0.9 – 2.0 N·kg^{-1}) generally showed greater D_P/m than the other impairment groups.

Figure 5.2 shows the distribution of D_P/m when swimmers were grouped according to their impairment. The D_P/m of the Spinal Cord Injury or Polio (SP) group ranged from 0.61 to 1.62 N·kg^{-1} (mean 0.94 ± 0.25 N·kg^{-1}). The mean D_P/m of sub-group SP4 was about 1.2 and 1.5 times greater than that of sub-groups SP2 and SP3, respectively, despite the SP4 swimmers being regarded as less impaired according to their IPC Class.

The D_P/m of the Cerebral Palsy (CP) group ranged from 0.49 to 1.71 N·kg^{-1} (mean 0.78 ± 0.24 N·kg^{-1}). Even though CP2 and CP3 swimmers are classified as being similarly impaired or more impaired than the SP4 swimmers, the mean D_P/m of the CP2 and CP3 swimmers were lower than the mean for the SP4 group.

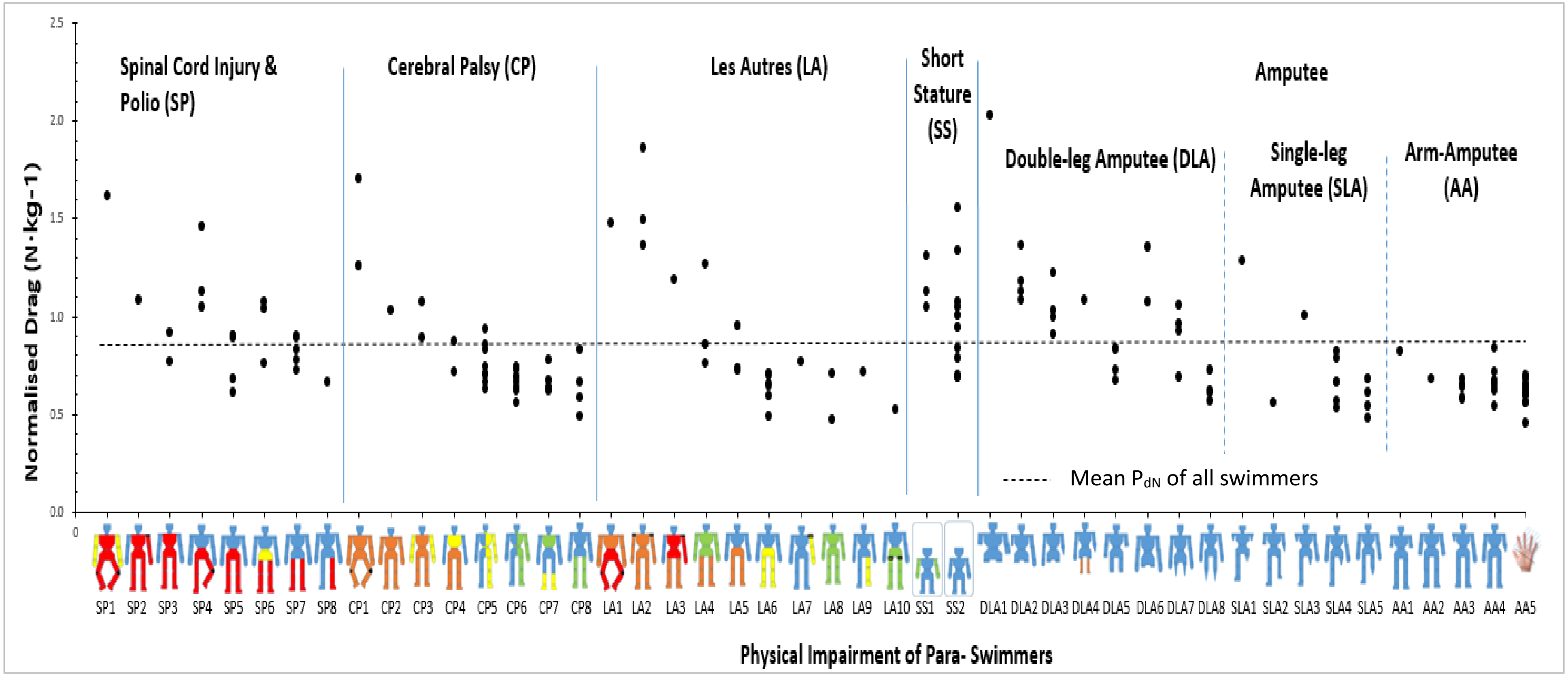
The D_P/m of the Les Autres (LA) group ranged from 0.47 to 1.86 N·kg^{-1} (mean 0.89 ± 0.37 N·kg^{-1}). The mean D_P/m of sub-group LA2 was nearly two times greater than the combined mean D_P/m of all the swimmers participating in this study.

The D_P/m of the Short Stature (SS) group ranged from 0.69 to 1.31 N·kg^{-1} (mean 1.01 ± 0.26 N·kg^{-1}). Sub-group SS1 created a greater mean D_P/m (1.16 N·kg^{-1}) than sub-group SS2 (mean 0.97 N·kg^{-1}).

The D_P/m of the Double-leg amputee (DLA) group ranged from 0.57 to 2.03 $N \cdot kg^{-1}$ (mean 0.99 ± 0.32 $N \cdot kg^{-1}$). The mean D_P/m of sub-group DLA4 was smaller than that for sub-groups DLA5 and DLA6, despite the swimmers in DLA4 being more severely impaired according to their IPC Class.

The D_P/m of the Single-leg amputee (SLA) group ranged from 0.48 to 1.28 $N \cdot kg^{-1}$ (mean 0.71 ± 0.24 $N \cdot kg^{-1}$). The D_P/m of sub-group SLA2 was smaller than that for sub-groups SLA3, SLA4 and SLA5, but note that sub-group SLA2 contained only a single participant. The D_P/m of the Arm-amputee (AA) ranged from 0.45 to 0.84 $N \cdot kg^{-1}$ (mean 0.64 ± 0.08 $N \cdot kg^{-1}$).

Figure 5.2 Scatter plot of normalised passive drag versus para-swimmer physical impairment groups.



5.3.2 Passive Drag Band (PDB)

Figure 5.3 shows the normalised passive drag (D_P/m) of each Passive Drag Band. The variability of D_P/m within each PDB is very small compared to the within- IPC Class variability illustrated in Figure 3.8 (Chapter 3) and, by definition, there is a clear delineation of D_P/m between successive Bands.

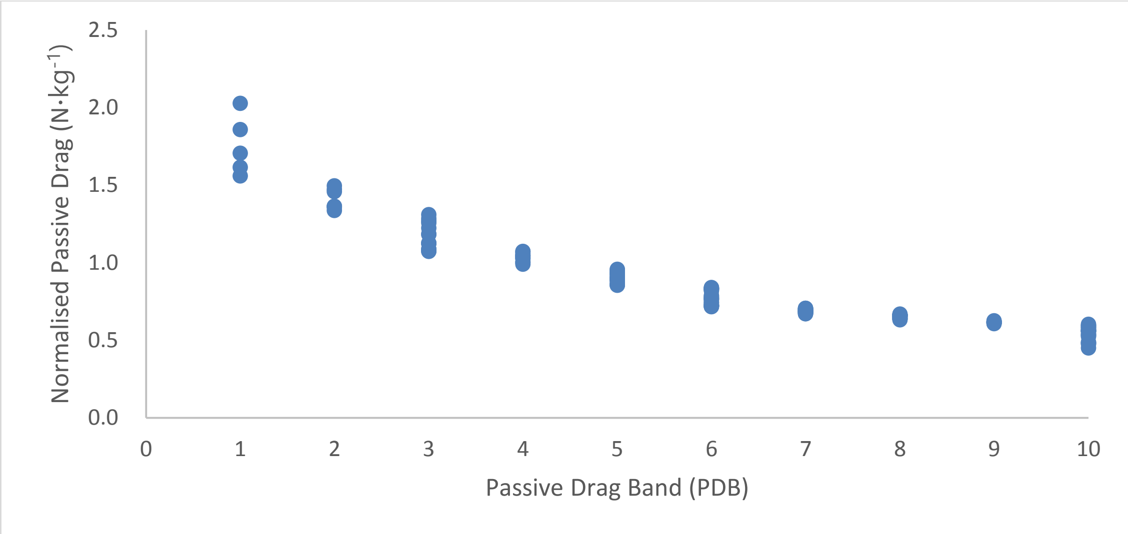


Figure 5.3 Normalised passive drag of each Passive Drag Band.

Figure 5.4 summarises the differences found between the IPC Class and PDB for the 153 para-swimmers. Forty-two (27.5%) swimmers had a PDB that matched their IPC Class (yellow); one hundred eleven (72.5%) therefore had a PDB that differed from their IPC Class. Twenty-one (13.7%) had differences of 3 or more (navy and red); thirty-three (21.6%) had a difference of 2 (blue and scarlet); Fifty-seven (37.3%) had differences of 1 (green and orange).

PDB<IPC			IPC=PDB	PDB>IPC		
-<3	-2	-1		+1	+2	+>3
11	17	31	42	26	16	10

Figure 5.4 Difference between IPC Class and Passive Drag Band (PDB) for 153 para-swimmers.

Figure 5.5 shows the physical impairment type of the para-swimmers in each of the ten IPC Classes. Figure 5.6 shows how the physical impairment types of the para-swimmers distributed across the ten Passive Drag Bands (PDBs).

Figure 5.5 Physical impairment type of para-swimmers in each of the ten IPC Classes.

5.3.3 Summary of the para-swimmers whose passive drag band was much greater than their IPC Class.

The para-swimmers represented by scarlet and red cells in Figure 5.6 are those whose passive drag ranking placed them in a band whose integer was 2 or higher than that of their IPC Class. Note that this automatically excluded swimmers in IPC Classes 9 and 10.

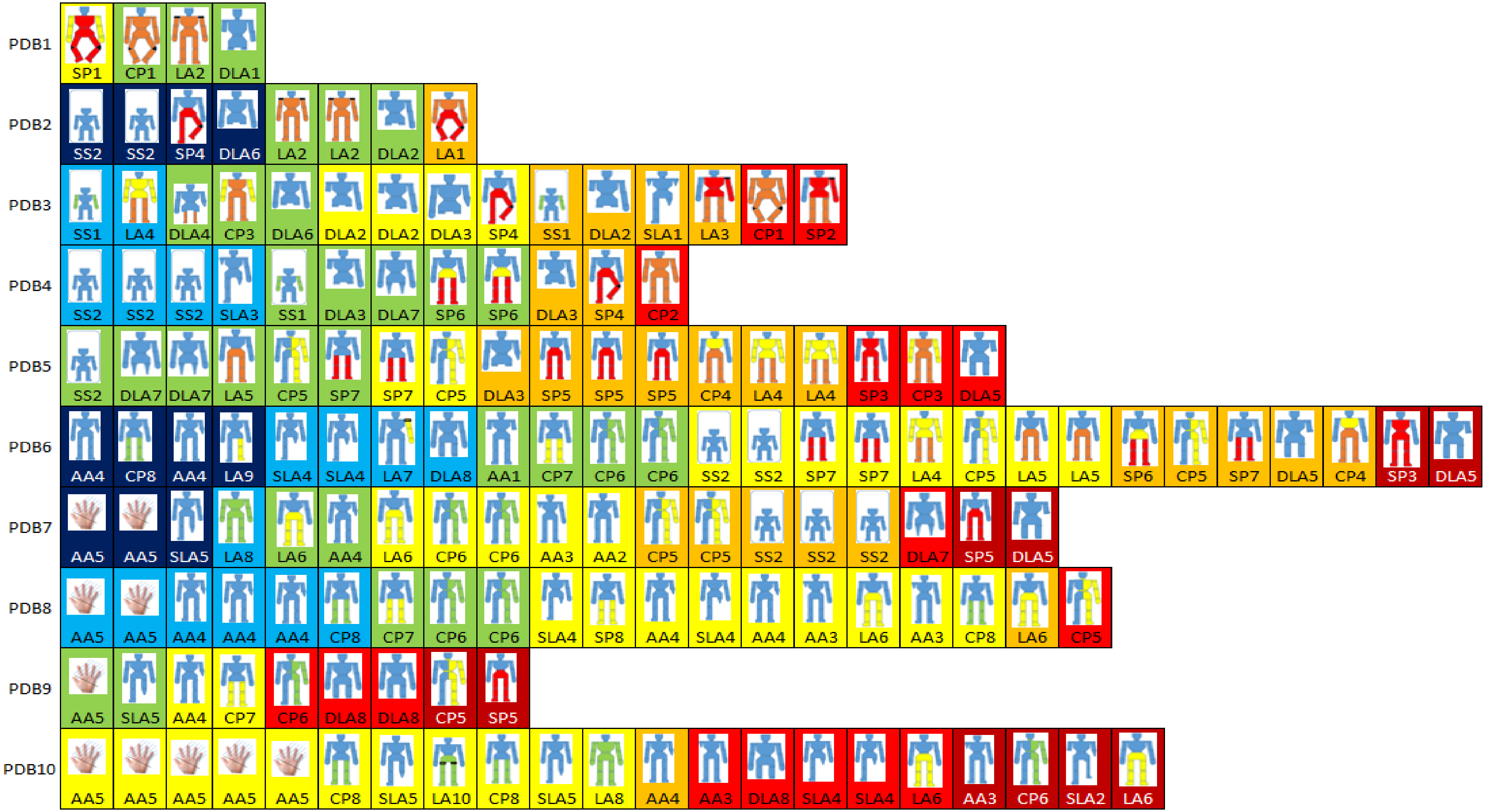
Two swimmers in PDB 3 were from IPC Class 1: one had severe spastic quadriplegia with restricted legs; one had tetraplegia with a complete lesion below C6 with restricted knee function. One CP2 swimmer in PDB 4 was from IPC Class 2; who had poor head and trunk control, limited co-ordination for propulsion in all four limbs. Eight swimmers in PDB 5 – 7 were from IPC Class 3 – 5: three DLA5s had a double-leg amputation at knee or shank level and a double arm amputation below elbow level; two SP3s had tetraplegia or polio comparable to a lesion below C8 with good finger extension; one CP3 had severe diplegia with involvement of the trunk and limited propulsion in shoulders and elbows; one SP5 had complete paraplegia lesion T1-T8 and one DLA7 had a double-leg amputation of knee level. Six swimmers in PDB 8 and 9 were from IPC Class 6 – 7: two CP5s had moderate hemiplegia with severe restriction in the more affected side; two DLA8s had a double-leg amputation below knee level; one SP5 had complete paraplegia comparable to a lesion at T1-T8 and one CP6 had minimal hemiplegia. Among the nine swimmers in PDB 10, eight swimmers came from IPC Class 7 – 8: two AA3; two SA4; two LA6; one had minimal hemiplegia; one DA8. One swimmer came from IPC Class 4. He had single-leg amputation and a double-arm amputation below elbow level.

5.3.4 Summary of the para-swimmers whose passive drag band was much lower than their IPC Class.

The para-swimmers represented by the blue and navy cells in Figure 5.6 are those whose passive drag ranking placed them in a band whose integer was 2 or lower than that of their IPC Class. Note that this automatically excluded swimmers in IPC Classes 1 and 2.

Four swimmers in PDB 2 were from IPC Class 5 or higher: one had a complete paraplegia lesion at T1-T8 with restricted knee function (SP4); one had a double-leg amputation at crotch level (DLA6) and two had short stature (SS2). Six swimmers in PDB 3 and 4 were from IPC Classes 5 and 6: four had short statures (SS1-2); one had restricted movement in the lower limbs (LA4) and one had an amputation of one arm and one leg (SLA3). Eighteen swimmers in PDB 6 – 8 were from IPC Class 8 – 10: nine had a single-arm amputation at forearm (AA4) or hand level (AA5); three had a single-leg amputation at thigh (SLA4) or shank level (SLA5); one had a double-leg amputation at shank level (DLA8); two had weak paresis in two legs (CP8) and three had moderate or minimal impairments of one arm (LA7), one leg (LA9) or the whole body (LA8).

Figure 5.6 Physical impairment type of para-swimmers in each of the ten Passive Drag Bands (PDB).



5.4 DISCUSSION

Impairment versus Passive Drag

In able-bodied swimmers, the passive drag is strongly influenced by the shape of the swimmer (Naemi et al., 2012). The body shape of many physically impaired para-swimmers is determined by the nature of their impairment or medical condition, so it was hypothesised that a para-swimmer's passive drag can be related to their impairment type. It would then follow that certain impairments can advantage or disadvantage a para-swimmer, with respect to drag, under the current classification system.

The study found a large variation of normalised passive drag (D_P/m) between certain impairment categories. A particularly interesting finding in this study was relatively high D_P/m of the swimmers who could not fully extend one or more of their joints/limbs. The inability to fully extend one or more limb joint led to: 1) a greater frontal area presented to the water, 2) limbs presenting a greater angle of attack to the water, and 3) an asymmetrical body shape in the water. An increase in frontal area will result in an increase passive drag, as evidenced by the significant association between passive drag and chest depth, shoulder girth, torso girth, CSA and streamlined CSA found in Study 2. The angle between a limb's longitudinal axis and the flow direction is called the angle of attack (Bixler & Riewald, 2012). According to Bixler & Riewald, (2012), when the angle of attack of a hand is 90°, it creates four times more drag than when the angle is 0°. In the current study, for example, swimmers with complete paraplegia or polio comparable to lesion at T1-T8 with restricted knee function (SP4) had 34% greater normalised drag than the swimmers with same condition but without restriction of knee function (SP5). The asymmetry of the body shape, created by a fixed joint angle can create further additional drag (e.g. swimmers with hemiplegia). The shape asymmetry can make the flow conditions down one side of the body different to the other side. Thus, according to Bernoulli's principle (see section 2.1), a sideward lift force can be created on the swimmer during towing, forcing their longitudinal axis out of alignment with their direction of travel, causing them to be towed in an oblique position. In Chapter 4, the swimmer's frontal area was not measured during towing, but was approximated using the swimmer's torso girth. Swimmers whose impairment caused them to be towed in an oblique position will have presented a frontal area to the water that was unrelated to their torso girth (or any other anthropometric measure). It was observed during the drag testing that a number of swimmers had to make small corrective movements with a limb to maintain a stable position in the water.

Another impairment group who created a large normalised passive drag were the double leg amputees. Importantly, in this group the passive drag appeared to be influenced by the length of remaining stumps. According to Figure 5.2, the swimmers whose double leg amputation was at crotch level (sub-groups DLA1, DLA2, DLA3, DLA4 and DLA6) experienced greater drag than the mean for the whole study sample, whereas the sub-group DLA5 and DLA8 swimmers, whose double leg amputation was below knee level, created less drag than the mean for the whole study sample. These observations are supported by Chatard et al. (1990b) who reported a strong negative correlation (r = -.87, p<.01) between height and passive drag for eleven para-swimmers including four double-leg amputee swimmers. Shorter swimmers have a higher Froude number (equation 2.7) than taller swimmers which means they experience greater wave drag and thus total drag at a comparable speed. The swimmers with a double leg amputation at crotch level had similar body lengths to the short stature swimmers (SS1 and SS2). The double leg amputee at crotch level swimmers were about 15 cm shorter in height (1.11 m vs 1.26 m; DLA vs SS), but the short stature swimmers were about 9 cm shorter in streamlined height (1.48 m vs 1.39 m; DLA vs SS). Short stature swimmers also had relatively greater normalised passive drag than the mean value for the whole study sample but interestingly, this group had the greatest passive drag range among all the categories. Many double leg amputee swimmers also had arm amputations (except for two in this study) which may have adversely influenced their pressure drag due to the asymmetry of body shape. For example, the DLA1 swimmer, who was a double leg amputee at crotch level and also had a missing arm and hand, would have the disadvantage of both a greater wave drag (high Froude number) and greater pressure drag (asymmetrical shape) than a similar size and shape swimmer without these impairments. Most of the short stature swimmers did not have body asymmetry, so it is anticipated that the short stature swimmers may also have the disadvantage of relatively high wave drag, but not the disadvantage of asymmetry-related pressure drag.

Passive Drag Band

The Passive Drag Band effectively revealed the swimmers who are currently being advantaged or disadvantaged, in terms of passive drag, due to the lack of consideration of drag in the functional classification system. In this section, para-swimmers in the lower-bands (PDB 1-5) and higher bands (PDB 6-10) will be discussed separately.

In PDB 1-5, swimmers with short stature, with double leg amputations, and with fixed or limited joint ranges of motion were coded green and blue, indicating that they had moved down to PDBs that were lower than their IPC class; whereas swimmers able to fully extend at least one shoulder (even though having severe SCI) or amputation on all four limbs (but below knee level), were coded orange or red, indicating a move up to PDBs higher than their IPC class.

One of the most noteworthy results in this study was the substantial shift down (code Navy Blue: PDB < IPC) of two short stature swimmers (SS2). They were both IPC classified as S6 but were categorised in Passive Drag Band PDB 2. This can probably be explained by the relatively high Froude number and therefore wave drag associated with these swimmers (see Section 2.1).

Spinal Cord Injured swimmers (SCI) with a fixed or limited joint range of motion also made a big down (code Navy Blue (PDB < IPC). These swimmers were usually hidden by other SCI swimmers without fixed knee joints within the same IPC Class. Thus the disadvantage of the additional drag caused by fixed knee joints was revealed by the PDB.

Among the swimmers coded red (PDB>IPC) were those with severe SCI (Tetraplegia lesion below C7) but still able to fully extend at least one arm (SP2 and SP3) and those with amputation of all four limbs but with stumps below knee (DA5). Although these swimmers are defined as quite severely impaired by the IPC classification system, their passive drag is not highly affected by their impairment.

In PDB 6-10 there was a substantial step up for an SA2 swimmer to PDB 10 from IPC class 4. As this swimmer had amputation on three limbs, it is difficult to explain why he had such a relatively low normalised passive drag to cause such a shift. It was observed that this swimmer had one strong and healthy leg and one arm which extended beyond the elbow. It may be that, despite his impairment, he did not create excessive wave drag, as he was quite tall (height 1.70 m) and, with respect to pressure drag, he may have developed a strategy for maintaining a good balance and body orientation in the water.

In terms of other swimmers, two with hand amputations (AA5) or minor leg impairments (LA9) were coded green or blue (PDB < IPC), whereas others with moderate hemiplegia (CP6) or single arm amputees (AA3) were coded red (PDB>IPC). However, within each of these groups, there was quite high inter-swimmer variability in the passive drag. The two hand-amputee swimmers were coded blue, not because they created considerably more drag than the other S10 swimmers, rather it happened because the swimmers in the higher classes were very homogenous with respect to normalised passive drag. This example highlights one of the limitations of the Passive Drag Band approach. A numerical difference of 1 between IPC Class integer and PDB integer is not equivalent when considering the higher (IPC 7-10) and lower (IPC 1-6) classes. This is because, as the mean normalised passive drag was so similar across the higher classes (see Figure 3.8), only a small difference in normalised passive drag between two higher IPC class swimmers could still put them in two very different Passive Drag Bands. This was not the case for the lower classes.

5.5 CONCLUSION

This study has related the normalised passive drag to the specific impairments of para-swimmers. The para-swimmers with a fixed or limited joint range of movement, short stature and double leg amputation at crotch level created greater normalised passive drag than the other impairment groups.

The extent to which a swimmer's passive drag integer differs from their current IPC class integer illustrated that: 1) swimmers with short stature (SS2) and with SCI with fixed or limited joint range of movement (SP4) are currently disadvantaged with respect to passive drag, and 2) swimmers with an amputation of three or more limbs with the leg amputation below knee level (DA5, SA2), and swimmers with severe SCI with fully extended shoulder and arm (SP2, SP3) may currently have an advantage, as the existing classification system does not take into account how physical impairment influences drag. The first three studies (Chapters 3 - 5) investigated the passive drag of Para-swimmers and how physical impairment influences drag in a fixed, streamlined position. The next two studies (Chapters 6 - 7) will investigate the active drag of Para-swimmers. These will provide an insight into how the swimmers' movement patterns, and their impairments, affect the drag they experience.

CHAPTER SIX

EXPERIMENTAL STUDY 4

COMPARISON OF TWO METHODS OF ESTIMATING THE ACTIVE DRAG IN FRONT CRAWL SWIMMING

This chapter compares two methods of estimating active drag during front crawl swimming: the Naval Architecture Based Approach (NABA) and the Active Towing Method (ATM). The reliability of each is examined by looking at the variability of active drag scores from repeat trials. A sensitivity analysis is conducted to help identify why one method is more reliable than the other. Chapter 6 relates to academic aim 3.

6.1 INTRODUCTION

The hydrodynamic resistance experienced during swimming is called active drag. The ability of a swimmer to minimise their active drag during a race is one of the most important determinants of swimming performance (Toussaint & Beek, 1992; Yanai, 2003). Unlike passive drag, active drag cannot be measured directly. A number of methods for estimating active drag have been proposed (see Chapter 2.4.2.1) but there is no agreed gold standard approach, with the most current methods producing conflicting data (Toussaint *et al*., 2004).

Techniques for determining active drag were first introduced in the 1970s. These approaches, based on so called extrapolation techniques, yielded active drag values that were ~150-300% greater than those reported at the time for passive drag (Clarys *et al*., 1974; di Prampero *et al*., 1974; Holmér, 1974; Rennie *et al*., 1975). In the mid- 1980s, the Measuring Active Drag (MAD) system was developed (Hollander *et al*., 1986). This involved measuring hand push-off forces during front crawl swimming using underwater pads linked to a load cell. The mean push-off force was then assumed to equal the mean active drag force. The MAD system has several practical limitations: 1) the apparatus involved is extremely bulky, 2) the system is limited to front-crawl arms-only swimming, 3) the underwater arm motion is not representative of free swimming, and 4) the system would not accommodate many impairments groups, e.g., arm amputees, achondroplasia and athletes who swim freestyle on their backs.

In the 1990s, the Velocity Perturbation Method (VPM) was introduced by Kolmogorov & Duplishcheva (1992). This method required little apparatus (a small hydrodynamic body towed by the swimmer) and in theory could be applied to all four competitive strokes. Their study of seventy-three members of the Soviet national team swimming found that active drag during front crawl was 60 – 162% of the passive drag. Such a large range is surprising given that the swimmers were all of a very high standard and that by normalising each swimmer's active drag relative to their passive drag, many factors that influence active drag, e.g. speed, swimmer size, are controlled for. The VPM is underpinned by two critical assumptions: 1) that the swimmer creates equal power output when swimming with and without the added constant resistance, and 2) the active drag is proportional to the swimmer's maximum swimming squared (v_{MAX}^2). Toussaint *et al*. (2004) challenged the validity of the first assumption but indicated that the VPM may still provide a meaningful estimation of active drag. Xin-Feng *et al*. (2007) asserted that a towed hydrodynamic body did not provide a constant resistance and proposed the use of a sliding friction block to achieve this. In the same year, an Assisted Towing Method (ATM_{TOW}) was proposed (Alcock & Mason, 2007) that adopted the same calculation procedures and assumptions as the VPM, but involved towing the swimmer instead of resisting them. This approach has its merits as it is easier to maintain normal stroke technique while being towed than it is while being during resisted (Girold, Calmels, Maurin, Milhau & Chatard, 2006).

The assumption that drag is proportional to the square of the swimming velocity has also been questioned. At high swimming speeds, wave formation and the associated wave drag can become the dominant source of drag (Toussaint, van Stralen & Stevens, 2002; Toussaint *et al*., 2004; Toussaint & Truijens, 2005) and wave drag is not proportional to the square of the swimming speed (Toussaint *et al*., 2000; Vorontsov & Rumyantsev, 2000). On a practical level, the VPM and ATM_{TOW} may be prone to substantial error propagation. As both methods calculate active drag from squared and cubed values of the velocities v_1 and v_2, small measurement errors in these velocities could propagate into large errors in the active drag estimate (Webb *et al*., 2011). Active drag, D_a is estimated for the VPM and ATM using equations 6.1 and 6.2, respectively (see Chapter 2. 4.2.3 for the full derivation):

$$D_a \text{ (VPM)} = (F_b \cdot v_2 \cdot v_1^2) / (v_1^3 - v_2^3) \qquad (6.1)$$

$$D_a \text{ (ATM}_{\text{TOW}}) = (F_b \cdot v_2 \cdot v_1^2) / (v_2^3 - v_1^3) \quad (6.2)$$

Where F_b is the resisting (VPM) or towing (ATM_{TOW}) force measured during the resisted or towed trials, v_1 is the swimmer's maximum freestyle speed and v_2 is the swimmer's speed during the resisted or towed trials. Previous studies using the VPM and ATM_{TOW} have not reported estimates of the errors in their measurements (Alcock & Mason, 2007; Mason, Sacilotto, & Menzies, 2011; Formosa *et al*., 2012; Mason *et al*., 2013) and very few have provided details of the test-retest reliability of their protocols (Xin-Feng *et al.*, 2007; Marinho *et al*., 2010a).

Mason *et al*. (2013) compared the VPM and ATM_{TOW} with an ATM-resisted protocol (ATM_{RES}). This new approach differed from the VPM in the way resistance was applied to the swimmer. Where the VPM used a 'hydrodynamic body' of known drag, the ATM_{RES} used a mechanical motor to fix the swimmer's speed at 10% below their maximum speed. The ATM_{RES} active drag results correlated only moderately (r = .72) with the VPM whereas the ATM_{TOW} and VPM results were strongly correlated (r = .94). Most notable was that the active drag resulting from the ATM_{RES} was approximately half that from the VPM and ATM_{TOW}. The authors did not offer a clear reason for why the ATM_{RES} produced such different active drag results.

Recently, Webb *et al.* (2011) proposed a new approach to estimating active drag; the *Naval Architecture Based Approach* (NABA). This method is an adaptation of a test protocol used in scale model ship self-propulsion experiments designed to quantify the interaction effects between the propeller and the naked hull (Molland *et al.,* 2011; Webb *et al.,* 2011). Webb *et al.* (2011) determined the active drag of a single, untrained participant using the NABA and ATM_{TOW} using towing speeds 5%, 10% and 15% above maximum swimming speed. Mean active drag values was similar in the two methods (NABA: 133.9 N; ATM_{TOW}: 131.4 N) but their standard deviations were far higher in the ATM_{TOW} (*SD*: ±6.0 to ±15.2 N) than in the NABA (*SD*: ±1.5 N to ±3.0 N). The authors concluded that the ATM_{TOW} measurements had a much higher uncertainty associated with them and that the NABA was a more robust method of estimating active drag. Although the NABA appears to give reliable results and offer a credible alternative to existing methods, to date only a single participant case study has been published (Webb *et al.*, 2011). Further examination of this method is necessary.

The aim of this study was to compare the ATM and NABA to determine the most reliable method of estimating active drag among those approaches which were applicable to all Para-swimming strokes. This study was necessary in order to identify the preferred method to use with para-swimmers in the final study of this thesis. It was hypothesised that: 1) the ATM and NABA provide similar estimates of active drag, 2) the NABA will produce more repeatable between-trial measurements than the ATM.

6.2 METHODS

6.2.1 Pilot Study

The two main methods, ATM and NABA, can be implemented in two modes: assisted (towing) and resisted. A pilot study was conducted with a single male competitive swimmer to compare the four protocols, ATM_{TOW}; ATM_{RES}; $NABA_{TOW}$; $NABA_{RES}$, to ascertain whether any of these could be excluded from the main study.

6.2.1.1 Theoretical Background

Assistant Towing Methods (ATM$_{TOW}$ and ATM$_{RES}$)

Active drag, D_a at the swimmer's maximum front crawl speed is estimated for the ATM_{TOW} and ATM_{RES} using equations 6.3 and 6.4, respectively (see Chapter 2.4.2.3 for the full derivation). Note that the equation nomenclature used in the original articles has been changed in this chapter to improve clarity when comparing between the methods.

$$D_a\ (\mathrm{ATM_{TOW}}) = (F_{TOW} \cdot v_{TOW} \cdot v_{MAX}^2) / (v_{TOW}^3 - v_{MAX}^3) \qquad (6.3)$$

$$D_a\ (\mathrm{ATM_{RES}}) = (F_{RES} \cdot v_{RES} \cdot v_{MAX}^2) / (v_{MAX}^3 - v_{RES}^3) \tag{6.4}$$

where F_{RES} is the mean resisting force and F_{TOW} is the mean towing force, measured during the resisted and towed trials, respectively; v_{MAX} is the swimmer's maximum freestyle speed; v_{RES} and v_{TOW} are the swimmer's speeds during the resisted and towed trials, respectively.

Naval Architecture Based Approaches (NABA$_{TOW}$ and NABA$_{RES}$)

Active drag, D_a at swimmer's maximum front crawl speed is estimated for the $\mathrm{NABA_{TOW}}$ and $\mathrm{NABA_{RES}}$ using equations 6.5 and 6.6, respectively (see Chapter 2.4.2.5 for detail):

$$D_a\ (\mathrm{NABA_{TOW}}) = F_{TOW} - (D_{p}\_v_{TOW} - D_{p}\_v_{MAX}) + D_{p}\_v_{MAX} \tag{6.5}$$

$$D_a\ (\mathrm{NABA_{RES}}) = F_{RES} + (D_{p}\_v_{MAX} - D_{p}\_v_{RES}) + D_{p}\_v_{MAX} \tag{6.6}$$

where F_{RES} is the mean resisting force and F_{TOW} is the mean towing force, measured during the resisted and assisted trials, respectively; $D_{p}\_v_{MAX}$ is the swimmer's passive drag (towed with arms held at side) measured at their maximum freestyle speed (v_{MAX}); $D_{p}\_v_{RES}$ is the swimmer's passive drag measured at the speed used in the resisted trials (v_{RES}) and $D_{p}\_v_{TOW}$ is the swimmer's passive drag measured at the speed used in the assisted trials (v_{RES}).

6.2.1.2 Pilot Study Data Collection

The pilot test was conducted in a 50 m indoor swimming pool. The participant's maximum swimming speed (v_{MAX}) through a 7.5 m calibrated test zone (Figure 6.1) was determined from video footage using standard two-dimensional video analysis procedures. Output from a 50 Hz video camera (Sony HDR HC9, Sony Corporation, Japan) placed perpendicular to the swimmer's direction of travel was captured using commercial software (Dartfish TeamPro version 7.0, Dartfish UK). The participant performed three maximal effort 20 m front crawl sprints separated by 3 minutes rest. His fastest time, t, to cover the 7.5 m was used to compute his maximum speed (v_{MAX} = 7.5 m / t).

The participant was towed using an electro-mechanical towing device (Chapter 3.2.2) while holding a fixed 'passive' position with his arms held at his side. Passive drag was measured using an in-line waterproof load cell (Chapter 3.2.2) at three towing speeds: 1) maximum swimming speed v_{MAX} ($D_p\_v_{MAX}$); 2) v_{MAX} + 10% ($D_p\_v_{TOW}$) and 3) v_{MAX} – 10% ($D_p\_v_{RES}$). Three towing trials were completed at each of these speeds.

Finally, the cable force during assisted towing (F_{TOW}) and resisted towing (F_{RES}) were recorded as participant swam maximal effort freestyle trials while being assisted (towed) at v_{TOW} (Figure 6.1) and being resisted at v_{RES} (Figure 6.2). A minimum of 3 minutes rest was taken after every trial. Assisted and resisted swimming trials were repeated three times to assess the repeatability (R) of each methods. The repeatability (R) of the active drag (D_a) was assessed using equation 6.7:

$$R = [(\text{Max } D_a - \text{Min } D_a) / \text{Mean } D_a] \times 100\% \quad (6.7)$$

Active drag (D_a) was calculated using equations 6.3, 6.4, 6.5 and 6.6 for ATM_{TOW}, ATM_{RES}, $NABA_{TOW}$ and $NABA_{RES}$, respectively.

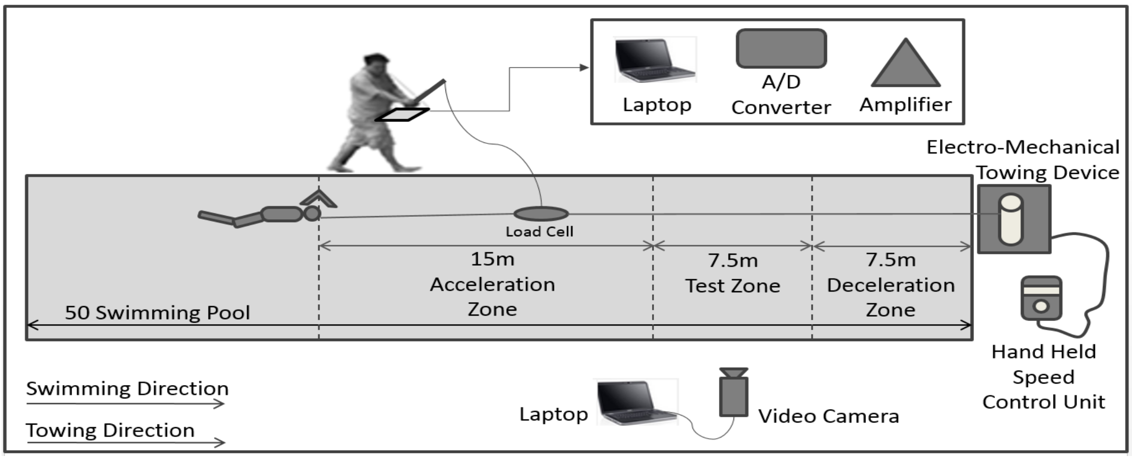


Figure 6.1 Set-up for active drag measurement using ATM_{TOW} and $NABA_{TOW}$.

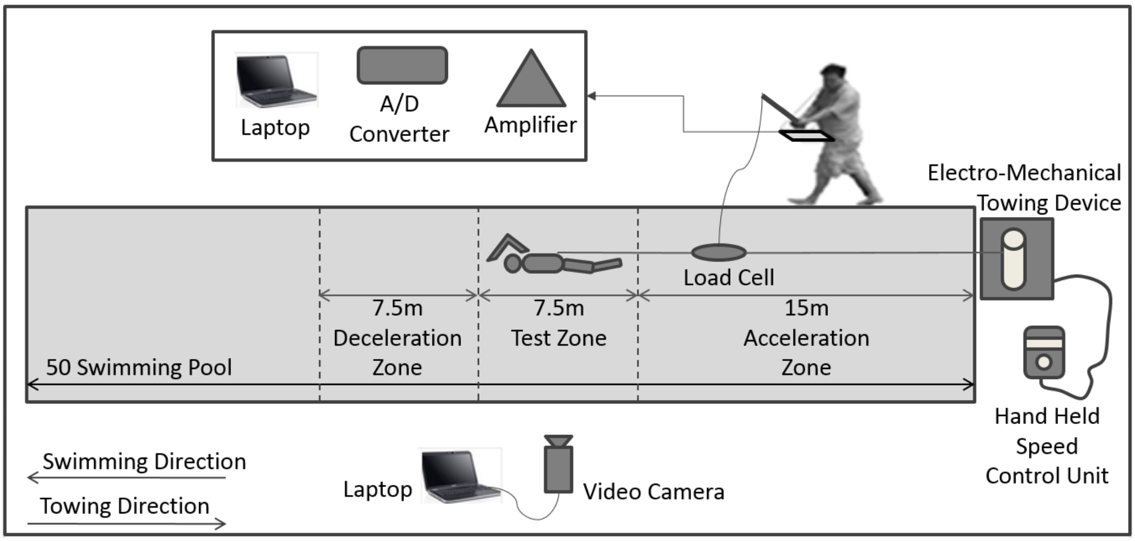


Figure 6.2 Set-up for active drag measurement using ATM_{RES} and $NABA_{RES}$.

6.2.1.3 Pilot Study Results

Figure 6.3 shows the active drag data from the pilot study. ATM_{TOW} (175.7 N), $NABA_{TOW}$ (161.9 N) and $NABA_{RES}$ (173.9 N) produced similar mean active drag values, whereas ATM_{RES} gave a much smaller mean active drag of 56.7 N at the maximum speed of 2.0 m·s^{-1}. The $NABA_{TOW}$ had the best repeatability (3.5%) but $NABA_{RES}$ was similar (4.0%). The repeatability of the ATM_{TOW} was 10.6%. The ATM_{RES} had by far the weakest repeatability (58.4%).

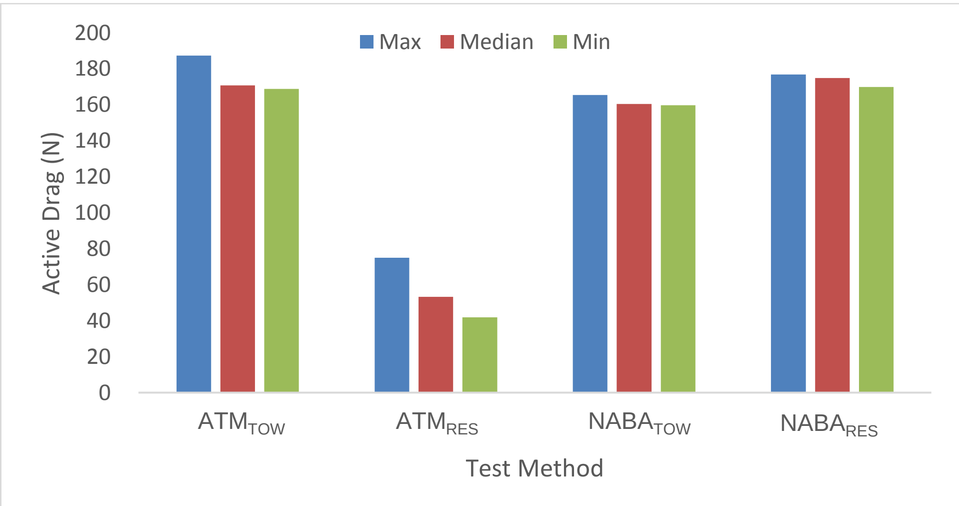


Figure 6.3 Active drag estimated by the four approaches: ATM_{TOW}, ATM_{RES}, $NABA_{TOW}$ and $NABA_{RES}$. Data are for a single able-bodied participant performing three trials. The maximum swimming speed was 2.0 m·s^{-1}.

6.2.1.4 Pilot Study Key Findings

The $NABA_{TOW}$, $NABA_{RES}$ and ATM_{TOW} protocols predicted similar mean active drag forces but the two NABA protocols had markedly better repeatability than the two ATM methods. The repeatability of the ATM_{RES} was unacceptably poor and the method produced active drag values that were unrealistically low when compared to the literature (Kolmogorov & Duplishcheva, 1992; Toussaint *et al*., 2004; Formosa *et al.,* 2012). Only the ATM_{RES} of Mason *et al.* (2013) which showed weak correlation with ATM_{TOW} and VPM of their study showed similar value with the ATM_{RES} of current study.

In previously published VPM resisted active drag protocols (e.g. Kolmogorov & Duplisheva, 1992; Xin-Feng *et al*., 2007) the swimmer's resisted speed (v_{RES}) is a function of the resistive load applied and how much effort the swimmer makes. In the current study, the swimmer's resisted speed was set on the electro-mechanical rig. Consequently it was independent both of the resistive force and the amount of effort applied. As the resisted speed of the swimmer (v_{RES}) is used directly in ATM_{RES} method (equation 6.4), test conditions in which the speed remains fixed, regardless of how much force the swimmer produces, may invalidate the assumptions inherent in the method.

Based on the pilot study results, the assumptions inherent in the four methods and practical considerations, the two towing approaches, $NABA_{TOW}$ and ATM_{TOW}, were selected for the main study. The main reasons for including them were:

- $NABA_{TOW}$ produced the most repeatable results, it does not make the false assumption that drag is proportional to velocity-squared, and it uses assisted swimming, which is considered more valid than resisted swimming (Girold *et al.,* 2006).
- ATM_{TOW} produced reasonably repeatable results and uses assisted towing. Since its introduction (Alcock & Mason, 2007) that it has been used extensively and so merits comparison to the more recently proposed $NABA_{TOW}$ method (Webb *et al*., 2011).

The two resisted methods were excluded from further study primarily on the basis that the electro-mechanical rig, not the swimmer, defined the resisted speed and that resisted swimming was less realistic than assisted swimming.

6.2.2 Main Study

6.2.2.1 Participants

Eleven female able bodied swimmers (Height: 1.70±.03 m; Mass: 61.9±4.7 kg) participated in this study. Two competed at international level; the other nine at national level. The University ethics committee approved the procedures prior to testing and written informed consent was obtained from all participants.

6.2.2.2 Data Collection Procedure

Active drag measurements

The active drag (D_a) of each participant was estimated at their maximum front crawl swimming speed using the ATM_{TOW} and $NABA_{TOW}$. Testing was conducted in a 50 m indoor swimming pool following the procedures detailed in section 6.2.1.2. As in the pilot study, swimmers completed three trials of each element of the test protocol, i.e. maximum swimming speed trials, passive drag (towing) trials and assisted swimming (towing) trials.

Active drag (D_a) was calculated by applying equations 6.3 and 6.5 for the ATM_{TOW} and $NABA_{TOW}$, respectively. The repeatability of the active drag scores, for each swimmer in both tests, was assessed using equation 6.7. This was used to represent the variability (range) of each swimmer's active drag scores relative to their mean value.

6.2.2.3 Sensitivity Analysis

A sensitivity analysis was conducted on each of the measurements used in the ATM_{TOW} and $NABA_{TOW}$ equations to examine how measurement errors propagated and affected the calculated active drag value. The ATM_{TOW} requires three measurements: (equation 6.3): maximum swimming speed (v_{MAX}), assisted swimming towing speed (v_{TOW}) and assisted swimming towing force (F_{TOW}). The $NABA_{TOW}$ also requires three measurements (equation 6.5): assisted swimming towing force (F_{TOW}), passive drag at maximum speed ($D_p\_v_{MAX}$) and passive drag at assisted swimming towing speed ($D_p\_v_{TOW}$). The effect of adding a 1% and 3% measurement error to of each of these variables was examined.

6.2.2.4 Statistical Analysis

Kolmogorov-Smirnov test and Shapiro-Wilks test were performed to check the normal distribution of the active drag (D_a) and repeatability (R) of the ATM_{TOW} and $NABA_{TOW.}$ Paired *t*-tests were performed to the test for differences in the mean D_a and the mean R between the ATM_{TOW} and $NABA_{TOW}$. Pearson Product coefficient (r_P) was used to assess the association between D_a scores from the ATM_{TOW} and $NABA_{TOW}$. All these statistics were performed using IBM SPSS Version 12. After this, the agreement of the values of the two methods were checked using a Bland-Altman plot.

6.3 RESULTS

Active Drag

The swimmers' maximum front crawl speed, v_{MAX} ranged from 1.50 – 1.68 m·s^{-1}. The swimmers' active drag (mean of three trials) estimated by the ATM_{TOW} ranged from 54.8 to 125.9 N; for the $NABA_{TOW}$ it ranged from 66.9 to 111.9 N. The mean active drag estimated by the ATM_{TOW} and $NABA_{TOW}$ were 93.1 ± 19.4 N and 87.6 ± 13.5 N, respectively. Paired t-test showed that the active drag values from the two methods were not significantly different (t= .63, p=.54) and Pearson correlation showed them to be significantly associated (r_P = .83, p<.01). Figure 6.4 shows active drag (N) of each trials estimated by using ATM and NABA. Each swimmer's repeatability (R) was calculated for their three trials in both methods. The ATM_{TOW} had an R ranging from 4.8 – 33.6%; the $NABA_{TOW}$ range for R was 1.6 – 9.5%. Paired t-test showed that repeatability, R, of the active drag estimates from the ATM_{TOW} was significantly higher (worse) (p<.01) than it was for the $NABA_{TOW}$. Figure 6.4 shows that the $NABA_{TOW}$ produced more repeatable results than the ATM_{TOW} for each of the eleven participants. In Figure 6.5, a Bland-Altman plot shows the active drag calculated by ATM is 5.5 N greater than that of NABA. All but one of the values are within the lower and upper limitations (95% confidence).

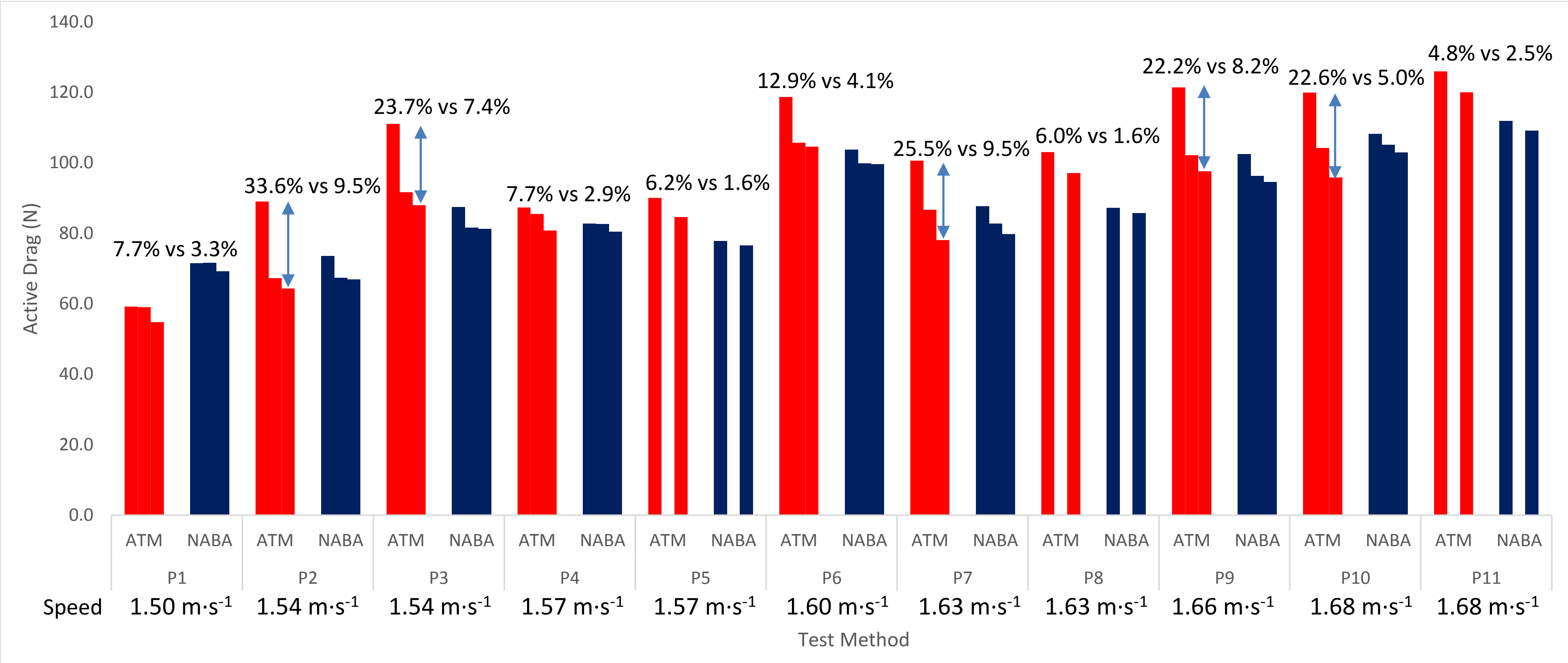


Figure 6.4 Active drag (D_a) of all three trials of the ATM_{TOW} and $NABA_{TOW}$ for each participant. The repeatability of each swimmer's active drag score [(max D_a – min D_a) / mean D_a] × 100% for both methods is shown at the top of each group of bars. The speed at which D_a was tested (v_{MAX}) is shown at the bottom of the figure.

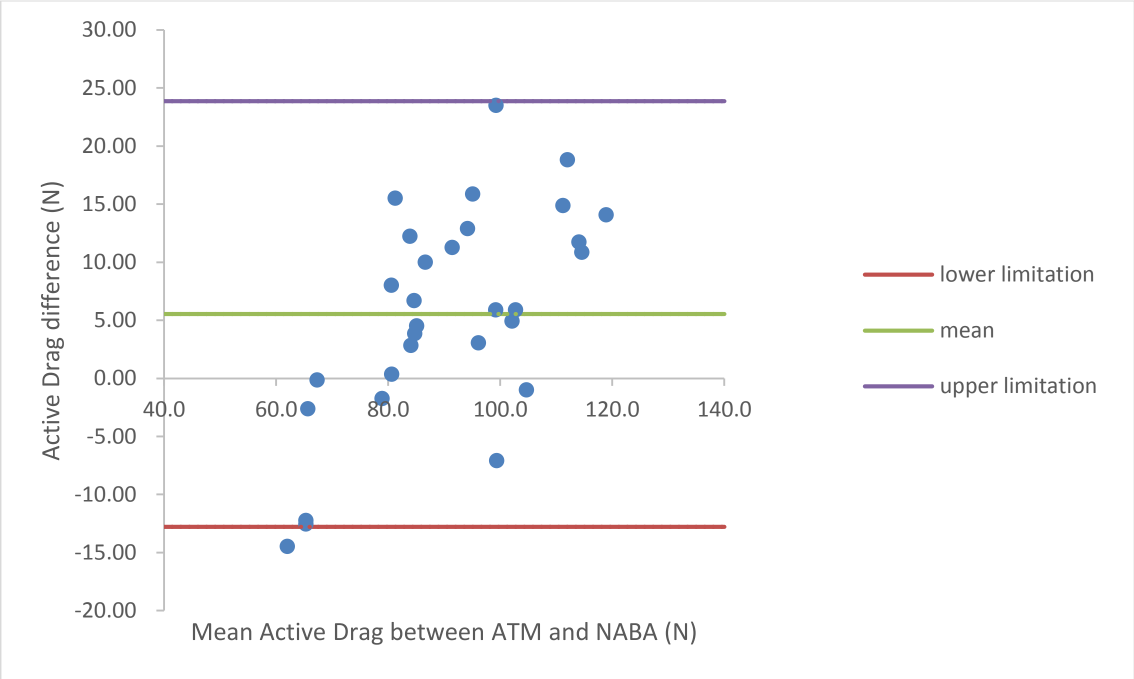


Figure 6.5 Bland-Altman plot of all three trials of the ATM$_{TOW}$ and NABA$_{TOW}$ for each participant.

Sensitivity Analysis

The sensitivity of the ATM$_{TOW}$ and NABA$_{TOW}$ to measurement errors was examined. Table 6.1 illustrates how the measurement errors propagate. In the ATM$_{TOW}$, the introduction of errors produced values of D_a ranging from 64.0 – 126.2 N. This equates to -24.3% to 49.2% difference from the original, error free value of 84.6 N. In contrast, when the same magnitude of measurement errors were introduced to the NABA$_{TOW}$, D_a ranged from 74.2 – 81.2 N which represents a -3.1% to 6.1% difference from the original, error free value of 76.6 N.

Table 6.1 Effect on active drag (D_a) of introducing errors of 1% and 3% to the measures used in the ATM$_{TOW}$ and NABA$_{TOW}$ equations. Values highlighted in red are the largest resulting positive and negative errors in D_a. Values highlighted in blue are the original, error free values.

	ATM$_{TOW}$					NABA$_{TOW}$				
	v_{TOW}	v_{MAX}	F_{TOW}	D_a	Error (%)	D_{p_vMAX}	F_{TOW}	D_{p_vTOW}	D_a	Error (%)
0% + 0% +0%	1.736	1.572	26.5	**84.6**	0.0	64.1	26.5	78.1	**76.6**	0.0
0% + 0% + 1%	1.736	1.572	26.8	85.4	1.0	64.1	26.5	78.9	75.8	-1.0
0% + 0% + 3%	1.736	1.572	27.3	87.1	3.0	64.1	26.5	80.5	74.2	-3.1
0% + 1% + 0%	1.736	1.588	26.5	94.6	11.8	64.1	26.8	78.1	76.8	0.3
0% + 1% + 1%	1.736	1.588	26.8	95.5	12.9	64.1	26.8	78.9	76.0	-0.7
0% + 1% + 3%	1.736	1.588	27.3	97.4	15.1	64.1	26.8	80.5	74.5	-2.7
0% + 3% + 0%	1.736	1.619	26.5	122.6	44.9	64.1	27.3	78.1	77.4	1.0
0% + 3% + 1%	1.736	1.619	26.8	123.8	46.3	64.1	27.3	78.9	76.6	0.0
0% + 3% + 3%	1.736	1.619	27.3	126.2	49.2	64.1	27.3	80.5	75.0	-2.0
1% + 0% +0%	1.753	1.572	26.5	76.4	-9.6	64.7	26.5	78.1	77.8	1.7
1% + 0% + 1%	1.753	1.572	26.8	77.2	-8.7	64.7	26.5	78.9	77.1	0.7
1% + 0% + 3%	1.753	1.572	27.3	78.7	-6.9	64.7	26.5	80.5	75.5	-1.4
1% + 1% + 0%	1.753	1.588	26.5	84.6	0.0	64.7	26.8	78.1	78.1	2.0
1% + 1% + 1%	1.753	1.588	26.8	85.4	1.0	64.7	26.8	78.9	77.3	1.0
1% + 1% + 3%	1.753	1.588	27.3	87.1	3.0	64.7	26.8	80.5	75.8	-1.0
1% + 3% + 0%	1.753	1.619	26.5	106.6	26.1	64.7	27.3	78.1	78.6	2.7
1% + 3% + 1%	1.753	1.619	26.8	107.7	27.3	64.7	27.3	78.9	77.9	1.7
1% + 3% + 3%	1.753	1.619	27.3	109.8	29.8	64.7	27.3	80.5	76.3	-0.3
3% + 0% +0%	1.788	1.572	26.5	64.0	-24.3	66.0	26.5	78.1	80.4	5.0
3% + 0% + 1%	1.788	1.572	26.8	64.7	-23.5	66.0	26.5	78.9	79.6	4.0
3% + 0% + 3%	1.788	1.572	27.3	65.9	-22.0	66.0	26.5	80.5	78.1	2.0
3% + 1% + 0%	1.788	1.588	26.5	69.8	-17.5	66.0	26.8	78.1	80.7	5.4
3% + 1% + 1%	1.788	1.588	26.8	70.5	-16.6	66.0	26.8	78.9	79.9	4.3
3% + 1% + 3%	1.788	1.588	27.3	71.9	-15.0	66.0	26.8	80.5	78.3	2.3
3% + 3% + 0%	1.788	1.619	26.5	84.6	0.0	66.0	27.3	78.1	81.2	6.1
3% + 3% + 1%	1.788	1.619	26.8	85.4	1.0	66.0	27.3	78.9	80.4	5.0
3% + 3% + 3%	1.788	1.619	27.3	87.1	3.0	66.0	27.3	80.5	78.9	3.0

6.4. DISCUSSION

Active drag is an important consideration in any biomechanical analysis of swimming as it is a strong predictor of swimming performance (Toussaint & Beek, 1992; Yanai, 2003). Unfortunately, active drag cannot be measured directly and there is no agreed method of estimating it, with the most current methods still producing conflicting data (Toussaint *et al*., 2004). The aim of this study was to compare two current methods, the ATM and NABA, to determine which the most reliable method of estimating active drag was. This study was necessary in order to identify the preferred method to use with para-swimmers in the final study of this thesis. It was hypothesised that: 1) the ATM and NABA will provide similar estimates of active drag, 2) the NABA will produce more repeatable between-trial measurements than the ATM. The two methods were evaluated using their assisted swimming protocols.

The ATM_{TOW} and $NABA_{TOW}$ produced active drag values of 93.1 ± 19.4 N and 87.6 ± 13.5 N, respectively. As the t-test and Bland-Altman plot show the means were not statistically different, the first hypothesis was therefore accepted. This result is supported by Webb *et al.* (2011). They obtained active drag estimates on a single swimmer at 1.53 $m \cdot s^{-1}$ using both the ATM_{TOW} and $NABA_{TOW}$ and reported mean values of 131.4 N and 133.9 N, respectively.

The second hypothesis was also accepted as the $NABA_{TOW}$ had significantly lower (better) repeatability (*R*) values than the ATM_{TOW}. All eleven swimmers showed more consistent active drag scores in their three $NABA_{TOW}$ trials, compared to their three ATM_{TOW} trials. This finding is consistent with the results of Webb *et al*. (2011) that showed the $NABA_{TOW}$ active drag scores had considerably smaller standard deviations (1.5 – 3.0 N) than the ATM_{TOW} active drag scores (6.0 – 15.2 N). The ATM_{TOW} and $NABA_{TOW}$ provide two fundamentally different approaches to estimating active drag as shown by their equations and underlying assumptions. The greater repeatability of the

$NABA_{TOW}$ may be due to a number of factors including: 1) the $NABA_{TOW}$ was less sensitive to errors in the assisted swimming towing force, F_{TOW} than the ATM_{TOW} was. For example, a 3% measurement error in F_{TOW} led to errors in D_a of 1% and 3% for the $NABA_{TOW}$ and ATM_{TOW}, respectively; 2) the ATM_{TOW} was extremely sensitive to measurement errors in the two velocities (v_{TOW} and v_{MAX}) used in its calculation procedure. For example, an error of only 1% in v_{MAX}, propagated to an error of 11.8% in D_a. This can be explained with reference to the ATM_{TOW} equation (6.3) that uses squared and cubed functions of v_{MAX}, thus magnifying any error in this measure.

The eleven highly-trained female swimmers in this study produced active drag values ranging from 54.8 – 125.9 N, for the ATM_{TOW}, and from 66.9 – 111.9 N for the $NABA_{TOW}$. Their maximum front crawl speeds ranged from 1.50 – 1.68 $m \cdot s^{-1}$. The participant in the Webb *et al.* (2011) study was an untrained male which might explain why he created greater active drag (D_a ~134 N) than any of the swimmers in the current study, despite being slower than them. This suggestion is supported by Toussaint (1990) who reported that the active drag of trained but non-swimming specialists (triathletes) swimming front crawl was, on average, 36% higher than that of trained swimmers.

Using the ATM_{TOW}, Mason *et al.* (2011) found active drag values ranging from 112 – 253 N for eight well-trained male and female swimmers who had a maximum speed ranging from 1.61 – 1.83 $m \cdot s^{-1}$. Mason's active drag values are notably higher than those found in the current study; this will be partly due to the higher test speeds used but also the inclusion of males in their study who, presumably, will be have been larger than the females in the current study. In direct contrast to Mason *et al.* (2011), Kolmogorov & Duplicheva (1992) and Xin-Feng *et al.* (2007) both reported much lower active drag values than the current study (Kolmogorov & Duplicheva D_a range: 43.6 – 69.8 N; Xin-Feng *et al.* D_a range: 36.3 – 50.3 N) for swimmers tested using the Velocity Perturbation Method. Both of these VPM studies tested participants at swimming speeds very similar to those used in the current study and so the lower active drag values cannot be explained by the use of lower test speeds. Fundamental differences between the test protocols, swimmer anthropometry and skill level may be some of the factors responsible for the lower drag estimates from the VPM.

6.5 CONCLUSION

This study has considered two different approaches to estimating active drag. The $NABA_{TOW}$ provided active drag values that were not significantly different to those from the ATM_{TOW} but the $NABA_{TOW}$ produced significantly more repeatable results. A sensitivity analysis highlighted the propagation of measurement errors in the two methods and demonstrated that the ATM_{TOW} was prone to higher errors than the $NABA_{TOW}$. Errors of 3% in the pool-based measurements used in the ATM_{TOW} (velocity and towing force) could lead to errors of up to 49% in the active drag. In contrast, errors of 3% in the pool-based measurements used in the $NABA_{TOW}$ (towing force, passive drag) could only result in a 6% error in the active drag. For these reasons, along with the $NABA_{TOW}$ being considered to have a more valid theoretical basis than the ATM_{TOW}, the $NABA_{TOW}$ was selected as the most appropriate method for examining active drag in para-swimmers during front crawl swimming. This will be the focus of the final study.

CHAPTER SEVEN

EXPERIMENTAL STUDY 5

ACTIVE DRAG OF ELITE PARA-SWIMMERS DURING FRONT CRAWL SWIMMING

As a consequence of the results in the previous chapter the NABA method was valid and was deemed to most reliable method for measuring active drag. In this chapter the active drag of elite para-swimmers during front crawl will be measured using the Naval Architecture Based Approach ($NABA_{TOW}$) and the relationship between active drag and IPC Class will be investigated. A Technical Effectiveness Ratio (TER), which is the ratio between the passive and active drag, will also be discussed. Chapter 7 relates to academic aims 3 and 4.

7.1 INTRODUCTION

Swimming is characterised by the repetitive action of generating propulsive force in order to overcome the hydrodynamic drag which acts in the opposite direction to the movement of the swimmer (Marinho *et al.*, 2010a). This hydrodynamic drag is influenced by many factors including the velocity, depth, shape and size of the swimmer (Kjendlie & Stallman, 2008). Hydrodynamic drag in human swimming can be evaluated under two conditions; passive and active drag (Toussaint & Hollander, 1994). Passive drag is the resistance the swimmer produces when moving through the water while holding a fixed body position; active drag is the resistance produced when performing a swimming stroke. Oh *et al.* (2013) reported a significant correlation between para-swimmers' passive drag and their IPC classification, that is, as the severity of swimming-specific impairment decreased, so did the passive drag. No study has yet attempted to determine the active drag of physically impaired swimmers.

Researchers have demonstrated that, in able-bodied swimming, active drag is highly influenced by the swimmer's technique whereas with passive drag, swimming technique is far less relevant (Toussaint, 1990; Kolmogorov & Duplishcheva, 1992; Kjendlie & Stallman, 2008; Marinho *et al*., 2010a; Formosa, 2012; Barbosa *et al.*, 2013).

Using the Measuring Active Drag system, Toussaint (1990) compared the propelling efficiencies of six highly trained swimmers to five highly trained triathletes. Based on an analysis of the raw data presented in their paper, it can be concluded that the triathletes created 34% more active drag than the swimmers at a sub-maximal swimming speed. It seems likely that the superior technique of the swimmers must account for much of the drag difference found between the two groups.

Using the Velocity Perturbation Method, Marinho *et al.* (2010a) found that after eight weeks of training, young male and female swimmers reduced their active drag by $5.3 \pm 0.5\%$, although this decrease was not statistically significant. The authors suggested that the lack of a significant reduction in active drag could be attributed to the heterogeneity of the sample (different skill levels of the swimmers) and an insufficient training period (eight weeks). It should be noted that after the training, the swimmers' maximum front crawl speed increased by 1.5 ± 0.1 %, meaning that the active drag at the end of the training period was measured at a higher test speed than at the beginning, making a direct comparison difficult. This highlights the importance of normalising active drag for test speed when conducting inter-trial, inter-swimmer and inter-study comparisons. In most studies, this is achieved by assuming a velocity-squared relationship with active drag (D_a) and calculating a k-value ($k = D_a / v^2$) or a dimensionless drag coefficient (Toussaint *et al*., 1988; Kjendlie & Stallman, 2008).

To demonstrate the relationship between active drag and skill level, a *Technique Drag Index* (TDI), which is the ratio of active to passive drag measures, has been used by several researchers (Kolmogorov & Duplicheva, 1999; Kjendlie & Stallman, 2008). In both studies the *TDI* was calculated as:

$$\mathrm{TDI} = (k_{\mathrm{Da}} / k_{\mathrm{Dp}}) \times 100\% \qquad (7.1)$$

Where, k_{Da} was the *k*-value of the active drag and k_{Dp} was the *k* value of the passive drag.

Kolmogorov & Duplicheva (1992) reported front crawl TDIs that ranged from 62 – 162% for males and from 60 – 145% for females. They attributed the variability in TDI to differences in technique, despite all seventy-three participants being national team members. In their study, 41.7% of the swimmers produced less drag when swimming front crawl than when being passively towed at the same speed, resulting in TDIs below 100%. The authors described this result as "Paradoxical" (Kolmogorov & Duplishcheva, 1992, p316) but did not offer any reasons to explain it. Another interesting finding in this study was the lack of a relationship between the passive and active drag coefficients. This showed that those swimmers who had the most streamlined shapes during the towing trials were not those who were the most streamlined when swimming front crawl.

Kjendlie & Stallman (2008) compared the TDI of nine children to thirteen adult swimmers, hypothesising that the children would have a greater TDI due to a lower skill level. Their hypothesis was rejected as groups were not significantly different, in fact there was a clear trend towards the adults having a greater TDI (Adult TDI: 115 ± 60%; Child TDI: 70 ± 18%). The authors suggested that differences in TDI could be explained by the Froude number (*Fr*) which is the ratio between the swimmer's speed and that of a water wave with a wavelength equal to the swimmer's length, i.e. height or streamlined height (see section 2.1). Wave drag starts to increase rapidly above *Fr* = .25. Around *Fr* = .42, the 'hull speed', the swimmer's speed matches that of a wave which has a wavelength equal to the swimmer's length. The wave drag increases less rapidly above *Fr* = .45 (Vennell *et al.,* 2006). Kjendlie & Stallman (2008) found that the adults generally achieved their hull speed (*Fr* =.42) but the children did not (*Fr* = .37). They proposed that the greater *Fr* increased the wave drag of adult swimmers, thus TDI was increased. They also asserted that the TDI may be suitable as a parameter for evaluating technique, as previously suggested (Kolmogorov & Duplicheva, 1992), but only if swimmers were compared at equal Froude numbers (Kjendlie & Stallman, 2008).

The *Fr* will vary far more in para-swimming than in able-bodied swimming as it depends on (streamlined) height, which has a much greater range in para-swimmers than in able-bodied swimmers (See Chapter 4). Thus *Fr* needs to be considered when considering passive drag, active drag and TDI of para-swimmers. For example, Study 2 included two S5 swimmers with very different streamlined heights (2.18 m vs 1.58 m). The taller swimmer had a much lower normalised passive drag (0.72 $N \cdot kg^{-1}$) than the shorter swimmer (1.06 $N \cdot kg^{-1}$). As the two swimmers had identical torso girths, their pressure drag could be similar but the taller swimmer would have experienced less wave drag due to a 17% lower *Fr* (0.32 vs 0.38). This illustrates one of the advantages of being tall in swimming.

A similar concept to the TDI is the 'thrust deduction', a term used in ship science (Webb *et al.,* 2011). The thrust deduction represents the additional thrust (propulsion) required to overcome the increase in a hull's resistance from the flow generated by the propeller. Webb *et al.* (2011) applied this concept to swimming, with the swimmer's arms representing the propeller and their body (minus the arms) representing the hull. The thrust deduction was expressed as:

$$\text{Thrust deduction} = D_p \,/\, D_a \tag{7.2}$$

Where D_p was the passive drag with the arms held at side (analogous to the ship's hull) and D_a was the active drag; the combined drag of the body (hull) and propeller (arms).

In tests on a single un-trained swimmer using the $NABA_{TOW}$, Webb *et al*. (2011) obtained thrust deductions ranging from 0.75 – 0.80. Note that in equations 7.1 and 7.2 the numerator and denominator are reversed so a higher thrust deduction means a lower TDI. Even if this is accounted for, a direct comparison of TDI and thrust deduction data is difficult. The TDI studies (Kolmogorov & Duplishcheva, 1992; Kjendlie & Stallman, 2008) measured passive drag with the arms extended above the head whereas Webb *et al*. (2011) measured it with the arms at the side, which will produce a higher force.

The TDI and thrust deduction both quantify the ratio of an active drag measure relative to a passive drag measure (equations 7.1 and 7.2). The fundamental difference between active drag and passive drag is that the former is strongly affected by the movements of the arms and legs, the latter is not. Able-bodied swimmers who perform their arm strokes and leg kicks while causing minimal disturbance to the water may be considered to have a better 'technique' or a higher 'skill level' than swimmers whose movements cause more disturbance. Thus, both TDI and thrust deduction could both be a measure of technique effectiveness. However, highly trained swimmers with physical impairments often have to use adapted versions of ‘standard’ swimming techniques to maximise their performance within the constraints imposed on them by their impairment. Restrictions in strength, joint range of movement or coordination may dictate how the swimmer moves their limbs. For example, single arm-amputee front crawl swimmers use a very different inter-arm coordination pattern when compared to able-bodied swimmers (Osborough, Payton & Daly, 2010). In para-swimming, a swimmer’s impairment will inevitably have an effect on their swimming technique. In many cases this effect could be substantial and may have a detrimental influence on the swimmers’ active drag. As active drag is an important determinant of swimming performance, information on how physical impairment affects active drag, and how active drag relates to passive drag, should be of value to swimming teachers, coaches and classifiers. To date, no study has reported the active drag of physically impaired swimmers.

The aims of this study were to: 1) establish the relationship between active drag, passive drag and IPC Class of elite para-swimmers performing front crawl; 2) determine the relationship between the para-swimmers’ IPC Class and their active-to-passive drag ratio. The corresponding two hypotheses were: 1) there will be an inverse relationship between the para-swimmers’ active drag and their level of physical impairment defined by their IPC Class, and 2) the para-swimmers’ passive-active drag ratio will be positively related to their IPC Class.

7.2 METHODS

7.2.1 Participants

Sixteen elite para-swimmers (seven male and nine female) from IPC Classes S5 to S14 participated in this study. The University ethics committee approved the procedures prior to testing. Written informed consent was obtained from all participants. Table 7.1 summarises the participant details.

Participants were considered elite para-swimmers as the group comprised ten Gold medallists, two Silver medallists, three Bronze medallists and one finalist (top 5) at either the London 2012 Paralympics, Montreal 2013 World Championships or Glasgow 2015 World Championships. As this study focussed exclusively on the front crawl stroke, each swimmer's IPC S Class was used in all statistical analyses.

7.2.2 Data Collection and Processing

Active & Passive Drag

The active drag (D_a) of each participant was estimated at their maximum front crawl speed (v_{MAX}) using the $NABA_{TOW}$. The test protocol is detailed in Chapter 6 Section 6.2.2. To enable inter-swimmer comparisons, the active drag was normalised relative to the swimmer's v_{MAX} and their body mass (BM) as follows: $D_{a\_NORM} = D_a \cdot BM^{-1} \cdot v_{MAX}^{-2}$. Passive drag was similarly normalised (D_{p_NORM}).

Technique Effectiveness Ratio (TER)

A Technique Effectiveness Ratio (TER), analogous to the naval architecture's thrust deduction, was calculated using the equation 7.3:

$$TER = D_p / D_a \qquad (7.3)$$

7.2.3 Statistical Analysis

The strength of the relationship between the swimmers' normalised active (D_{a_NORM}) and normalised passive drag (D_{p_NORM}) and between TER and maximum speed were determined using Pearson correlation, after parametricity was checked using Kolgomorov-smirnov test and Levene's test (p<.05). The strength of the relationships of the swimmers' D_{a_NORM}, D_{p_NORM} and TER with their IPC S Class were determined using Kendall's tau coefficient. Correlations were defined as: weak <0.3, moderate 0.3–0.6 or strong >0.6. All statistics were performed using IBM SPSS Version 12.

Table 7.1 Participant information.

Swimmer Code	IPC S Class	Age (years)	Height (m)	Mass (kg)
S5a	S5	22	1.37	43.5
S5b	S5	19	1.70	63.1
S6a	S6	21	1.43	67.6
S6b	S6	21	1.27	49.6
S7a	S7	32	1.61	54.0
S7b	S7	18	1.80	70.3
S8a	S8	28	1.10	57.6
S8b	S8	24	1.66	55.2
S8c	S8	21	1.72	70.4
S8d	S8	22	1.81	79.8
S9a	S9	17	1.62	58.5
S9b	S9	20	1.65	57.7
S9c	S9	23	1.58	66.5
S10	S10	16	1.63	49.4
S12	S12	19	1.74	65.6
S14	S14	19	1.79	71.4

7.3. RESULTS

Maximum swimming speeds ranged from 1.22 – 1.74 m·s^{-1}. Active and passive drag ranged from 35.7-117.6 N and 34.3-110.4 N, respectively. D_{a_NORM} and D_{p_NORM} ranged from 0.43-0.77 m^{-1} and 0.38 to 0.78 m^{-1}, respectively. A high, significant association was found between D_{p_NORM} and D_{a_NORM} (Pearson's r=.94, p<.01, Figure 7.1). A moderate, significant association existed between D_{p_NORM} and IPC S Class (Kendall's tau (τ) = -.56, p< .01, Figure 7.2). No relationship was found between D_{a_NORM} and IPC S Class (Kendall's tau (τ) = -.33, p=.09, Figure 7.3).

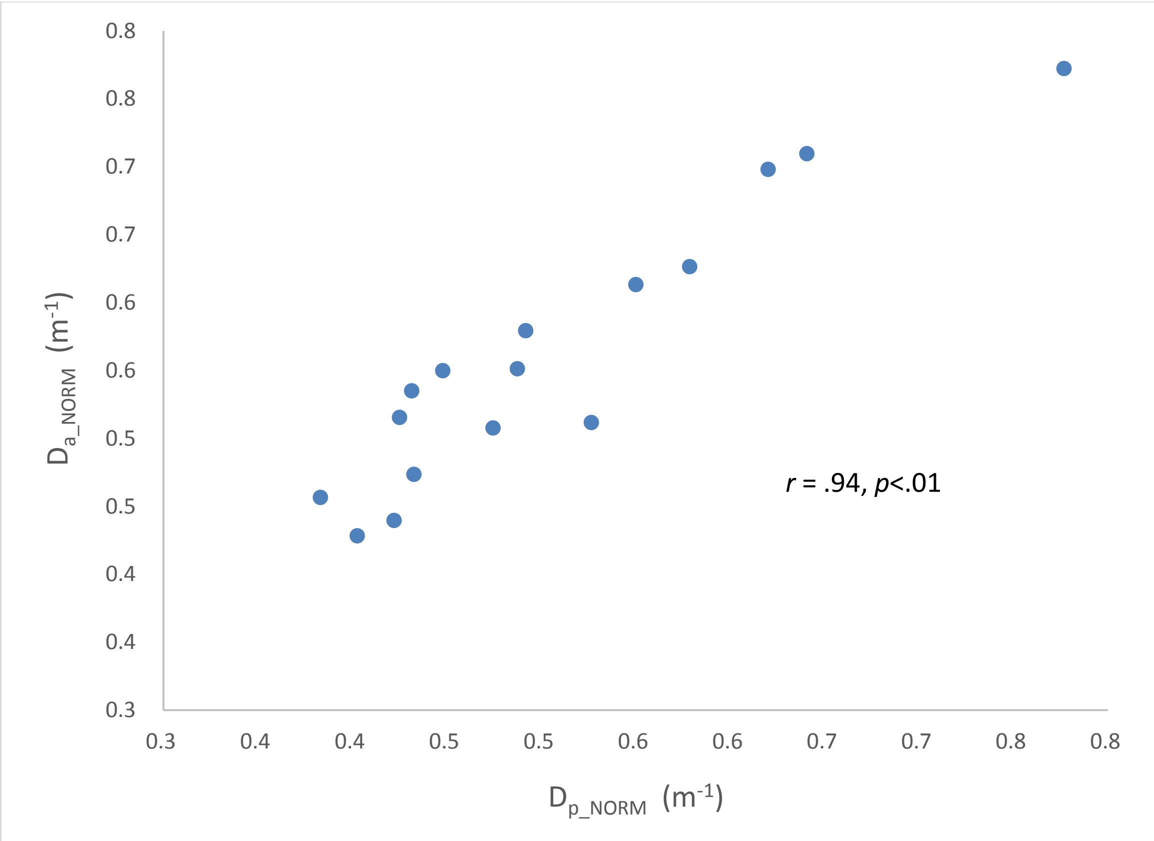


Figure 7.1 Scatter plot showing para-swimmers' normalised passive drag (D_{p_NORM}) versus their normalised active drag (D_{a_NORM}).

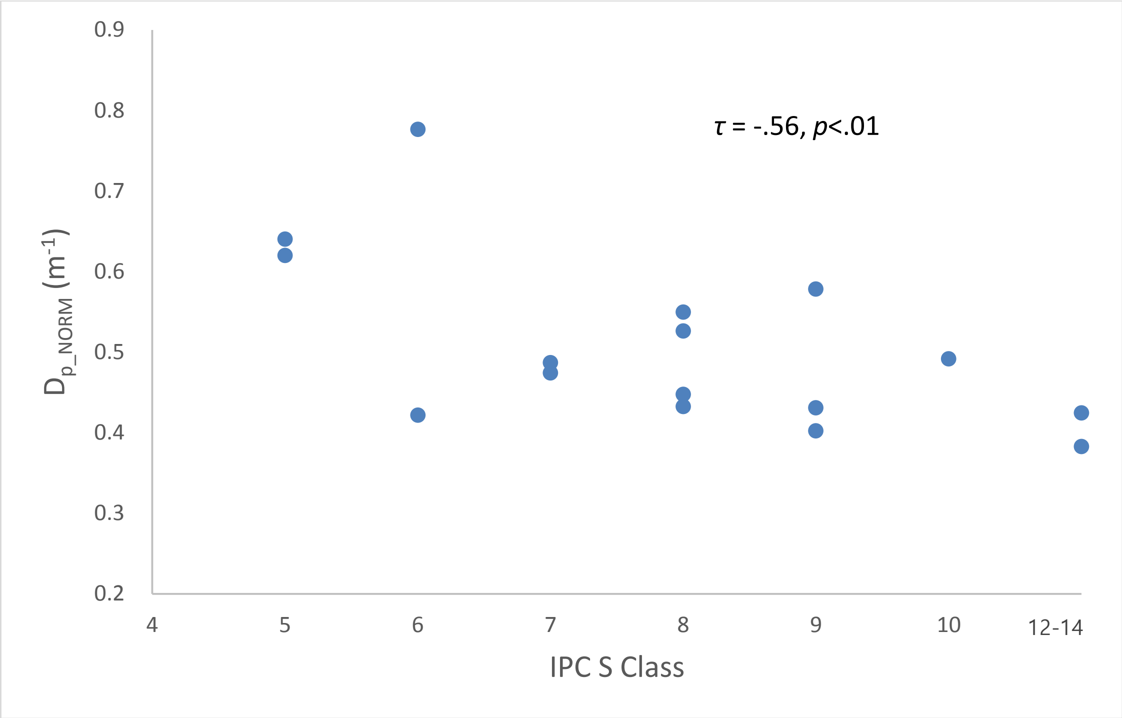


Figure 7.2 Scatter plot showing para-swimmers' IPC S Class versus their normalised passive drag (D_{p_NORM}).

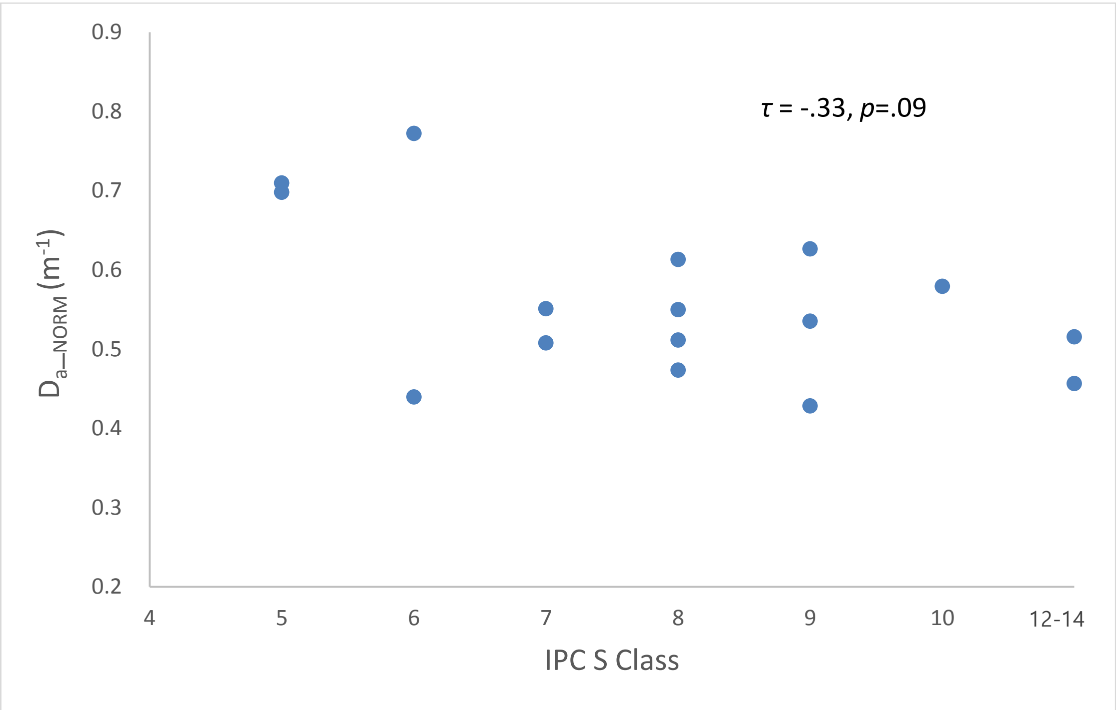


Figure 7.3 Scatter plot showing para-swimmers' IPC S Class versus their normalised active drag (D_{a_NORM}).

Technical Effectiveness Ratio (TER) ranged from 0.81 – 1.03 with the Froude number ranging from 0.30 – 0.37. A strong negative association existed between TER and speed (Kendall's tau (τ) = -.70, p<.01, Figure 7.4). In Figure 7.4, the TERs of S5a, S5b and S9a (Red circles: swimmers with arm-amputations) were lower than the trend line, whereas S6a, S8a and S9c (Blue circles: swimmers with double-leg amputations) were higher than the trend line. A moderate, negative association existed between the TER and the IPC S class of the swimmers (Kendall's tau (τ) = -.40, p<.05, Figure 7.5).

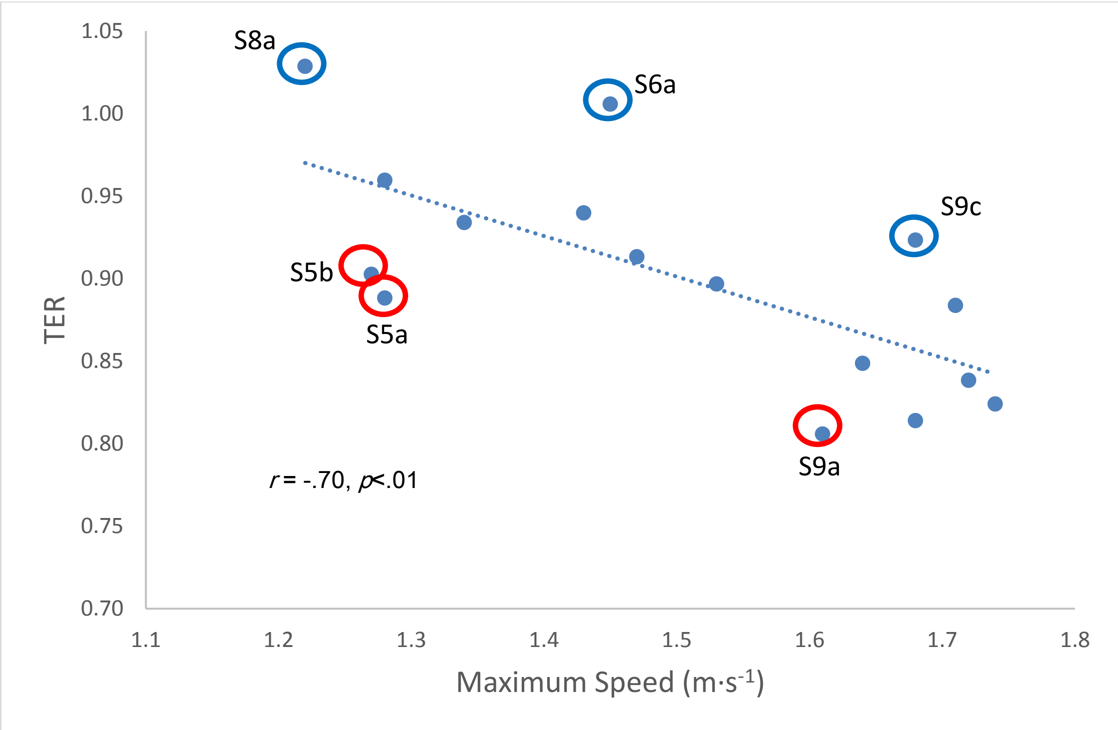


Figure 7.4 Scatter plot showing para-swimmers' maximum speed versus Technical Effectiveness Ratio (TER). Red circles indicate arm-amputees; blue circles indicate double leg amputees.

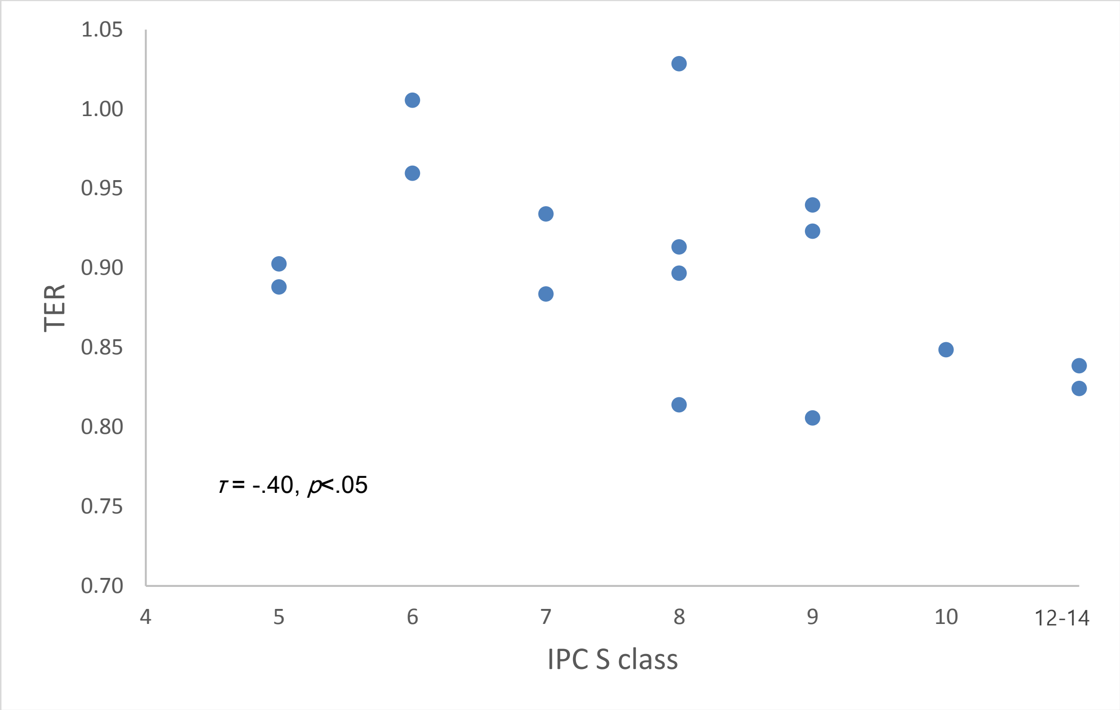


Figure 7.5 Scatter plot showing swimmer's IPC S Class versus their Technical Effectiveness Ratio (TER).

7.4. DISCUSSION

The aim of this study was to establish the relationship between active drag, passive drag and IPC S class for elite para-swimmers performing front crawl. The active drag and passive drag ranged from 35.7-117.6 N and 34.3-110.4 N, respectively, within the maximum swimming speed range of 1.22 – 1.74 m·s^{-1}. As anticipated, this range of speeds is wider than is typically reported in studies of able bodied swimmers. The mean active drag estimated in the current study was 79.3 N. This compares well with active drag values published on able-bodied swimmers tested at similar or higher speeds, for example, Kolmogorov & Duplishcheva (1992) 54.7 N, 1.52 – 1.74 m·s^{-1}; Toussaint *et al.* (2004) 53.2 N, 1.81 – 2.02 m·s^{-1}; Mason *et al.* (2013) 139.6 N, 1.61 – 1.75 m·s^{-1}; Webb *et al.* (2011) 133.9 N, 1.69 – 1.74 m·s^{-1}. Formosa *et al.* (2012) 148.3 N, 1.40 – 1.87 m·s^{-1}.

Normalised passive drag had a significant negative association with IPC class, which supports the findings of a previous study (Oh *et al*., 2013). It also had a very strong positive association with normalised active drag, which was expected as the $NABA_{TOW}$ considers passive drag to be a large component of the active drag (see equation 6.5). This result contrasted with the findings of Kolmogorov & Duplishcheva (1992) who reported no relationship between the active and passive drag of able-bodied swimmers. Despite the strong link between active and passive drag in the current study, normalised active drag did not have a significant inverse relationship with IPC S Class, that is, the more physically impaired swimmers did not create more drag during front crawl swimming. The first hypothesis was therefore rejected. It should be noted however that the correlation between IPC S Class and normalised active drag approached a significant level (-.33, p=.09) and a larger sample size may have strengthened the relationship. It is also noteworthy that the three lowest class swimmers (S5-S6) created the highest normalised active drag. The non-significant relationship between normalised active drag and IPC S Class indicates that factors other than impairment level may be more important in determining active drag in para-swimming. A para-swimmer's specific impairment type, anthropometry and swimming technique will all influence the amount of active drag created and should be considered in any future analysis.

The range of TER in the current study (0.81 – 1.03) is smaller than that reported by Kolmogorov & Duplicheva (1992). They observed TDIs in front crawl ranging from 0.60 – 1.62 for high level male and female swimmers (note TDIs have been converted from percentage values to allow a direct comparison with TERs). This is a surprising finding as it could be expected that high level able-bodied swimmers would be far more homogenous in their front crawl technique and therefore have less variable TDIs than para-swimmers. The wide range of TDI values recorded in the Kolmogorov & Duplicheva study may be due to their method of estimating active drag; the VPM. As was demonstrated in Chapter 6, the equations used in the VPM are very sensitive to small measurement errors and the $NABA_{TOW}$ used in the current study provides more reliable results.

The para-swimmers' TER scores (passive-active drag ratio) were negatively related to the level of physical impairment as defined by IPC S class. This indicates that the more physically impaired swimmers generally created relatively less disturbance with their arm and leg movements in front crawl than the less impaired swimmers. The second hypothesis of this study was therefore also rejected. It is interesting to note that two of the double leg amputees (S6a and S8a) produced less drag when they were swimming front crawl than when they were being passively towed, resulting in TER scores greater than 1.0. Kolmogorov & Duplishcheva (1992) reported the same phenomenon in able-bodied swimmers, describing it as 'paradoxical' but offering no explanation. One possible explanation can be found by considering the effect of the Froude Number (*Fr*). The double-leg amputee swimmers will be affected by wave drag, under passive and active conditions, to a greater extent than other, taller, para-swimmers, because their smaller height is associated with a higher *Fr* ($Fr \propto 1/\sqrt{\text{body length}}$). In the current study, passive drag was measured with the arms held at the side and so the *Fr* in the passive trials would relate to the swimmers' standing height. In the active swimming trials, all the para-swimmers effectively increased their body length at the water surface, due to the arms being stretched overhead. Consequently, the *Fr* in the swimming trials would be related to the swimmers' streamlined height. Thus, in theory, the wave drag component during active swimming could have been lower than it was during the passive towing. The double leg amputees could benefit more from this phenomenon, than the non-leg-amputee swimmers, as they had a greater increase from standing height to streamlined height, and consequently, a greater drop in *Fr*. For example, the height and streamlined height of the double leg amputee S8a were 1.10 m and 1.65 m, respectively, a difference of 50%. In contrast, swimmer S9a's streamlined height (2.10 m) was only 30% greater than their height (1.62 m). This would have the effect of bringing the passive and active drag closer together and, in the case of the double leg amputees (S6a and S8a) making the active drag less than the passive drag. This example illustrates that a swimmer's physical impairment, rather than their technique, can directly influence the relationship between their passive and active drag and, consequently, their Technical Effectiveness Ratio. Several authors have proposed that a passive-to-active drag ratio (Technique Drag Index, Thrust Deduction) may be a useful parameter for evaluating a swimmer's skill level or technical effectiveness (Kolmogorov & Duplishcheva, 1992; Kjendlie & Stallman, 2008; Webb *et al*., 2011). The results of the current study show that this may not be a valid approach with para-swimmers due to the potential effects of impairment on passive drag, active drag and the Froude Number. It should be noted that this study adopted the test protocol of Webb *et al*. (2011) in which passive drag was measured with the arms held beside the body. If the passive drag had been measured in the streamlined position, the effect of *Fr* on the TER would be reduced, as the body length in the passive and active conditions would be similar. It would also lead to lower TER values by increasing the discrepancy between the passive and active drag.

7.5. CONCLUSION

This study has established the relationship between active drag, passive drag and IPC S class for elite para-swimmers performing front crawl. Active and passive drag of elite para-swimmers are highly correlated but no relationship exists between their active drag and their IPC S class, indicating that factors other than impairment level may be more important in determining active drag. A para-swimmer's impairment type, anthropometry and swimming technique will all influence the amount of active drag created and should be considered in any future analysis.

The Technical Effectiveness Ratio (passive drag/active drag) was negatively related to the para-swimmers' level of physical impairment, as defined by IPC S class. This indicates that the more physically impaired swimmers created relatively less disturbance with their arm and legs when swimming front crawl than the less impaired swimmers. The validity of using the TER as a parameter for evaluating a para-swimmer's skill level or technical ability was questioned as the TER can also be influenced by the para-swimmer's impairment type.

CHAPTER EIGHT

SUMMARY AND PRACTICAL APPLICATIONS

8.1 SUMMARY

The academic aim of this thesis was to contribute to the development of an objective, evidence-based international classification system for para-swimmers by quantifying the effect of physical impairment on passive and active drag. The objectives of this thesis were: 1) to establish the relationship between swimmers' passive drag, their IPC classification, selected anthropometry, and their impairments; 2) to identify the most reliable method of determining active drag for swimmers with a disability; 3) to quantify active drag and its relationship with severity of physical impairment (IPC classification); and 4) to establish the relationship between passive and active drag in swimmers with a physical impairment. To achieve these objectives, five experimental studies were undertaken.

Studies 1, 2 and 3 were designed to achieve the first objective. Study 1 supported the overall premise of this thesis, which was that 'the more severely impaired swimmers would experience greater drag than the less severely impaired swimmers', by showing a strong correlation between normalised passive drag and IPC class (τ = -.59, p <.01). However, the observation of an inconsistent and often an almost negligible difference in normalised passive drag measures between adjacent classes indicated that the current classification system does not differentiate clearly between classes. High within-class variability in passive drag, in the lower classes, indicated that some para-swimmers in these classes may have had a substantial advantage over others competing in the same class in respect of this performance-related parameter.

Study 2 described the three-fold relationship between passive drag, anthropometry and IPC class of para-swimmers. In contrast to results from studies on able-bodied swimmers, only weak associations were evident between para-swimmers' anthropometry and passive drag. This suggests that in para-swimming, swimmers with similar anthropometric measurements can experience quite different passive drag forces due to the effect of other factors, for example, differences in the nature of their impairment.

Study 3 examined the influence of specific impairments on passive drag. To identify the para-swimmers who had a substantial advantage or disadvantage with respect to passive drag, each was assigned to one of ten passive drag bands (PD1 – PD10) according to their normalised passive drag score. The numerical difference between each para-swimmer's IPC Class integer and their PDB integer was computed to establish the extent to which their passive drag score was aligned with their current IPC class. Using this approach it was shown that: 1) swimmers with short stature, and those with SCI and with fixed or limited joint ranges of movement were at a disadvantage in respect of passive drag; 2) swimmers with three limb amputations, those with a leg amputation below knee level, and those with severe SCI with a fully extended shoulder and arm, may be advantaged under the current classification system due to their relatively low passive drag for their IPC Class.

Study 4 compared the active drag values estimated by two methods: the Naval Architecture Based Approach ($NABA_{TOW}$) and the Assisted Towing Method (ATM_{TOW}). The active drag values estimated by the two methods correlated strongly with each other (r_P = .83, p<.01) and were not statistically different (t= .63, p=.54). However, the ATM_{TOW} produced far less repeatable results than the $NABA_{TOW}$. Furthermore, the ATM_{TOW} was shown to have errors of up to 44.9% in the active drag, based on only small errors in the measurements used in its calculation procedures. For these reasons, it was concluded that the $NABA_{TOW}$ was a more reliable method than the ATM_{TOW}, for the estimation of active drag.

Study 5 established the relationship between active drag, passive drag and IPC class for elite para-swimmers performing front crawl. Active drag and passive drag of these swimmers were highly correlated but no relationship existed between the active drag of the swimmers and their IPC S class. This absence of a significant relationship indicated that the severity of a para-swimmer's impairment is not the most important determinant of active drag. The para-swimmers' Technical Effectiveness Ratio (passive drag/active drag) was negatively related to the para-swimmers' level of physical impairment, as defined by IPC S class. This indicates that the more physically impaired swimmers created relatively less disturbance with their arm and legs when swimming front crawl than the less impaired swimmers. The validity of using the TER as a parameter for evaluating a para-swimmer's skill level or technical ability was questioned as the TER can also be influenced by the para-swimmer's impairment type.

8.2 PRACTICAL APPLICATIONS AND FUTURE DIRECTIONS

8.2.1 Contribution to the development of an objective, evidence-based IPC classification system for para-swimmers

In Chapter 3 of this thesis, passive drag was proposed as potential key criterion that should be included in a new or revised Para-swimming classification system, due to its fundamental importance in swimming performance. The key benefit of using passive drag as a criterion for swimming classification is the possibility of quantifying the swimming-specific potential of a swimmer, regardless of their skill level or practice. Chapter 4 and 5 show that some swimmers with certain impairments have a substantial advantage or disadvantage over others in the same class. These findings can be applied to the future classification system.

Chapter 6 showed the NABA method for estimating active drag is more reliable than the VPM. Even though it is difficult to exclude skill level from the evaluation of active drag, it is still an extremely useful measure that can be used to quantify the impact certain types of impairment have on drag during the swimming stroke. For example, in the case where a front crawl para-swimmer has limited range of movement at their shoulder, their ability to recover the arm effectively over the water may be restricted. By conducting an active drag assessment of that swimmer and comparing the results to data obtained on able-bodied swimmers, the performance impact of the impairment could be determined and appropriately accounted for in classification. For these reasons, the author of this thesis would strongly recommend the introduction of passive and active drag as key assessment criteria in any new or revised Para-swimming classification system.

The small sample of swimmers for each impairment should be considered as a limitation. Even though 210 swimmers participated in Chapter 5, when they were sub-categorised into 46 sub-categories, there were 11 sub-categories which had only one participant. In chapter 7, whilst the data from a gold-medallist was included in each class future studies would ideally include a greater number of swimmers.

An important consideration is how much weighting should be assigned to the assessment of drag in a revised Para-swimming classification system. The current system, which combines a bench test and a water test, uses a point system which allocates points 1 – 5 to each criteria (e.g., muscle testing, coordination, length of amputated limb, etc., see Section 1.3.3). The criteria in the current system focuses almost exclusively on propulsion. It is proposed that the new system should have two categorical sections: one for propulsion, which will include many sub-criteria, and the other for drag, which will also contain many sub-criteria.

Even though the current thesis offers some compelling scientific evidence to justify the inclusion of drag assessment in the new revised IPC classification, a considerable amount of further research is required to provide a complete understanding of drag in para-swimming. For example, the relationships between joint range of movement, drag and propulsion have yet to be studied. In addition to further experimental studies on para-swimmers, other approaches, such as computational fluid dynamics and musculo-skeletal modelling are likely to prove valuable sources of new knowledge.

8.2.2 Monitoring elite para-swimmers on World Class Programmes.

In Britain, UK Sport funds World Class Swimming Programmes for the UK's most talented para-swimmers in order to achieve maximum medal potential for the current Paralympic cycle and beyond (http://www.swimming.org/britishswimming/swimming/world-class/). One of the important features of the World Class Swimming Programme is that it provides the swimmers with sports medicine and sport science support, including biomechanics.

One of important findings of this thesis was the emergence of the Naval Architecture Based Approach (NABA) as a useful method of estimating active drag in para-swimmers. Chapter 6 of this thesis showed that the NABA was a far more reliable method of estimating active drag than the Assisted Towing Method (ATM); one of the most widely used methods. The NABA appears to be the most viable method to use with para-swimmers given that the Measuring Active Drag (MAD) system is unsuitable for many para-swimmers.

Together with the measurement of passive drag, regular assessment of swimmer's active drag using the NABA would allow for the continuous monitoring of any drag reduction or improvement in skill level. This would be of benefit to swimmers, coaches and sports scientists involved in elite swimming, such as those on the British Para-swimming's 'World Class Development' and 'World Class Podium' programmes.

8.3 CONCLUSION

This thesis has contributed to the very limited body of knowledge relating to the passive and active drag of para-swimmers. The findings of this thesis suggest the following: (a) normalised passive drag and the current IPC swimming class are closely associated; (b) the current IPC classification system does not differentiate clearly between classes. High within-class variability in passive drag, in the lower classes, indicates that some swimmers in these classes may have a substantial advantage over others with regard to this performance-related parameter; (c) IPC class has only a weak association with a para-swimmer's anthropometry, indicating that para-swimmers with similar anthropometric measurements can experience quite different passive drag forces due to differences in the nature of their impairment; (d) the implementation of a Passive Drag Band (PDB) was able to identify swimmers either a substantial advantage or disadvantage in regards to passive drag; (e) the NABA is more reliable method of estimating active drag than the ATM; (f) normalised active drag does not correlate with a swimmer's IPC class; (g) the validity of using the TER (ratio between passive and active drag) as a parameter for evaluating a para-swimmer's skill level or technical ability must be questioned as the TER can also be influenced by the para-swimmer's impairment type.

The findings of this thesis can contribute: 1) to the development of an objective, evidence-based international classification system for para-swimmers and 2) to the existing body of knowledge pertaining to factors affecting passive and active drag in swimming. The findings will also be of interest to scientists working in the area of swimming biomechanics and should be of some practical benefit to para-swimmers and to those who coach and teach them.

CHAPTER NINE

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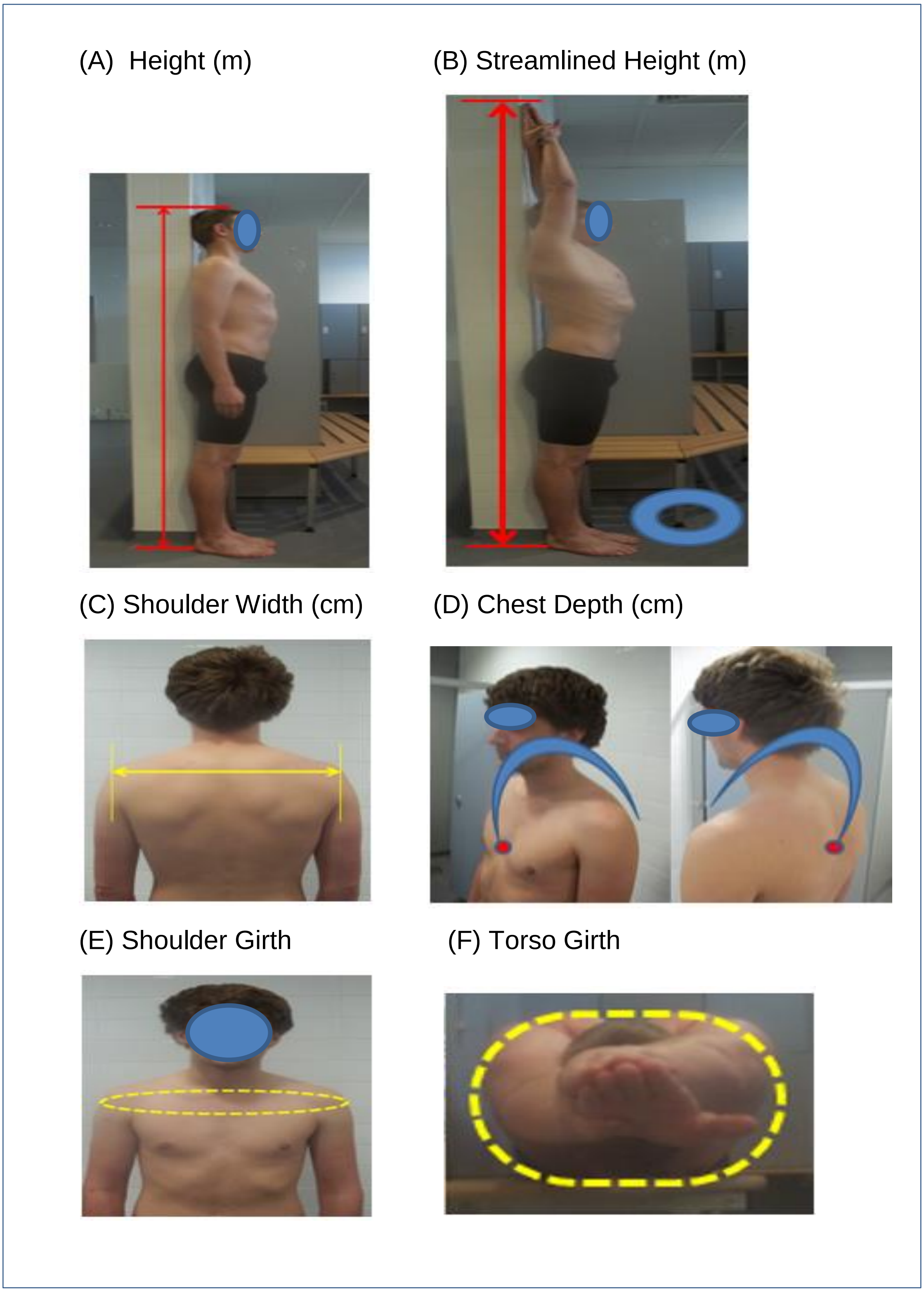
APPENDIX – A

IMAGES OF MEASUREMENT PROTOCOLS

Figure A.1 Seven anthropometric variables were collected according to Lohman *et al.* (1988). (A) Height, (B) Streamlined Height, (C) Shoulder Width, (D) Chest Depth, (E) Shoulder Girth, (F) Torso Girth



APPENDIX – B

COLLINEARITY CHECK BETWEEN ANTHROPOMETRIC PARAMETERS FOR LINEAR REGRESSION

To check any collinearity between anthropometric parameters Spearman's Rho was utilised for non-parametric variables whereas a Pearson Moment correlation was run for the parametric correlations.

Table B.1 Spearman's Rho between non-parametric parameters

	H_S	**BM**	**SW**	**CD**	**SG**	**TG**	**CSA**	**CSA_S**	**RPI**	**RPI_S**	**LTR**	**LTR_S**
H	.90**	.80**	.41**	.21**	.46**	.43**	.43**	.42**	.68**	.69**	.56**	.80**
H_S		.77**	.47**	.22**	.52**	.43**	.48**	.42**	.59**	.78**	.50**	.84**
BM			.51**	.43**	.70**	.62**	.68**	.64**	.20**	.33**	.18*	.58**
SW				.25**	.64**	.57**	.55**	.54**	.07	.27**	-.04	.33**
CD					.47**	.46**	.75**	.68**	-.16*	-.02	-.38**	-.05
SG						.79**	.92**	.79**	-.05	.20**	-.31**	.33*
TG							.75**	.96**	-.02	.10	-.22**	.17**
CSA								.85**	-.13	.11	-.39**	.22**
CSA_S									-.12	-.00	-.29**	.13
RPI										.80**	.81**	.66**
RPI_S											.59**	.79**
LTR												.62**

**. P<.01 (2-tailed); *. P<.05 (2-tailed).

Table B.2 Pearson correlation between parametric parameters

	SG	**TG**	**CSA**	**CSA_S**
BM	.70**	.64**	.69**	.66**
SG		.78**	.93**	.78**
TG			.74**	.96**
CSA				.85**

**. P<.01 (2-tailed); *. P<.05 (2-tailed).

APPENDIX – C

PARAMETRICITY CHECKS ON EACH PARAMETER

AND THE POST HOC PAIRWISE COMPARISONS

Table C.1 Parametricity of parameters was identified using Kolgomorov-smirnov test for checking the normal distribution and Levene's test for checking the equal variance.

	Kolgomorov-smirnov; p≤0.05 **(Non-normally distributed are listed)**	**Levene's; p≤0.05**	**Parametricity**
Passive drag (P_d)	Classes 10 & 14	Non-equal variance	Non-Parametric
Height (H)	Classes 1 & 10	Non-equal variance	Non-Parametric
Streamline Height (H_S)	Classes 7 & 8	Non-equal variance	Non-Parametric
Body Mass (BM)	N/A	Equal variance	Parametric
Shoulder Width (SW)	Class 9	Equal variance	Non-Parametric
Chest Depth (CD)	Classes 3, 12, 13	Equal variance	Non-Parametric
Shoulder Girth (SG)	N/A	Equal variance	Parametric
Torso Girth (TG)	N/A	Equal variance	Parametric
Cross Sectional Area (CSA)	N/A	Equal variance	Parametric
RPI	Classes 1, 2, 4, 7, 10	Non-equal variance	Non-Parametric
RPI_S	Classes 5, 7, 9, 10, 14	Non-equal variance	Non-Parametric
LTR		Non-equal variance	Non-Parametric
LTR_S	Classes 7 & 10	Non-equal variance	Non-Parametric

Table 4.4 post hoc pairwise comparisons between each class where data showed a significant effect of group (differences where the statistical significance of 1-tailed comparisons is present, are specified; otherwise, the cell is marked with a cross).

C1 vs	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
P_d	.023	.004	.002	<.001	<.001	<.001	<.001	<.001	<.001	.002	<.001	<.001	<.001
H	X	.001	.001	<.001	<.001	<.001	<.001	.001	<.001	.002	<.001	<.001	<.001
H_s	X	X	X	X	X	X	X	X	X	X	X	X	X
CD	X	X	X	X	X	X	X	X	X	X	X	X	X
RPI	X	X	X	X	X	X	X	X	X	X	X	X	X
RPI_S	X	X	X	X	X	X	.005	X	.006	X	.028	.019	.018
LTR	X	X	X	X	X	X	X	X	X	X	X	X	X
LTR_S	X	X	X	X	X	X	X	X	X	X	X	X	X

C2 vs	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
P_d	.039	X	.002	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
H	X	X	X	X	X	.009	.044	.014	X	.032	.032	.007
H_s	X	X	X	X	.021	<.001	.013	.004	.027	.008	.006	.001
CD	X	X	X	X	X	X	X	X	X	X	X	X
RPI	X	X	X	X	X	X	X	X	X	X	X	X
RPI_S	X	.031	X	X	.009	<.001	.003	<.001	.025	.002	.001	<.001
LTR	X	X	X	X	X	X	X	X	X	X	X	X
LTR_S	X	X	X	X	.048	.006	.008	.003	X	.003	.006	.004

C3 vs	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
P_d	X	X	.032	.001	.002	.001	<.001	<.001	<.001	<.001	<.001
H	X	X	X	.012	.001	.022	.001	.045	.006	.005	.001
H_s	.041	X	X	.003	<.001	.001	<.001	.010	<.001	<.001	<.001
CD	X	X	X	X	.042	X	.013	X	.070	X	X
RPI	X	X	X	.033	.004	.025	.003	X	.024	.018	.009
RPI_S	.027	X	X	.004	<.001	.002	<.001	.024	.001	<.001	<.001
LTR	X	X	X	.009	.008	.018	<.001	.015	.002	.001	.001
LTR_S	X	X	X	.004	<.001	.001	<.001	.008	<.001	<.001	<.001

C4 vs	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
P_d	X	.018	.002	.002	.008	<.001	.001	.001	<.001	<.001
H	X	X	X	.012	X	.014	X	.026	.018	.006
H_s	X	X	X	<.001	.018	.004	X	.010	.004	.003
CD	X	X	X	.039	X	X	X	X	X	X
RPI	X	X	X	X	X	.047	X	X	X	X
RPI_S	X	X	X	.007	X	.011	X	.044	.030	.042
LTR	X	X	X	X	X	.009	X	.039	.045	.026
LTR_S	X	X	X	.006	.008	.001	X	.001	.003	.004

C5 vs	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
P_d	X	.004	.009	.011	.001	.001	.001	<.001	<.001
H	X	.020	.001	.019	.002	X	.009	.003	.001
H_s	X	.031	<.001	.005	.001	.040	.002	.001	<.001
CD	.005	X	X	X	.003	X	.030	X	X
RPI	X	.023	.001	.012	<.001	X	.004	.004	.002
RPI_S	X	X	.001	X	.001	X	.020	.010	.007
LTR	X	.013	.007	.032	<.001	.019	.002	.005	.001
LTR_S	X	.042	.001	.002	<.001	X	<.001	.001	<.001

C6 vs	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
P_d	.042	.070	X	.001	.005	.005	.002	.003
H	.027	<.001	.025	<.001	X	.005	.002	<.001
H_s	.041	<.001	.018	.003	X	.007	.003	.001
CD	X	<.001	X	X	X	X	X	X
RPI	.048	.003	.049	.001	X	.023	.019	.007
RPI_S	X	.001	.047	.002	X	.020	.011	.011
LTR	.046	.015	X	<.001	.038	.001	.003	.001
LTR_S	X	.003	.005	.002	X	.003	.006	.001

C7 vs	C8	C9	C10	C11	C12	C13	C14
P_d	X	X	X	X	X	X	X
H	.036	X	X	X	X	X	X
H_s	.010	X	X	X	X	X	X
CD	.046	X	.023	X	X	X	X

RPI	X	X	.030	X	X	X	X
RPI_S	.004	X	.003	X	X	.032	X
LTR	X	X	.029	X	X	X	X
LTR_S	X	X	.030	X	.022	X	.039
C8 vs	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	
P_d	X	.039	X	X	X	X	
H	X	X	X	X	X	X	
H_s	X	X	.045	X	X	X	
CD	X	<.001	.048	.006	.013	X	
RPI	X	X	.049	X	X	X	
RPI_S	X	X	.004	X	X	X	
LTR	X	.012	X	X	X	X	
LTR_S	X	X	X	X	X	X	
C9 vs	**C10**	**C11**	**C12**	**C13**	**C14**		
P_d	X	X	X	X	X		
H	X	X	X	X	X		
H_s	X	X	X	X	X		
CD	X	X	X	X	X		
RPI	X	X	X	X	X		
RPI_S	X	.034	X	X	X		
LTR	X	X	X	X	X		
LTR_S	X	X	X	X	X		
C10 vs	**C11**	**C12**	**C13**	**C14**			
P_d	X	X	X	X			
H	X	X	X	X			
H_s	X	X	X	X			
CD	X	X	X	.035			
RPI	.011	X	X	X			
RPI_S	.004	X	X	X			
LTR	X	X	X	X			
LTR_S	.033	X	X	X			
C11 vs	**C12**	**C13**	**C14**				
P_d	X	X	X				
H	X	X	X				
H_s	X	X	X				
CD	X	X	X				
RPI	X	X	X				
RPI_S	.020	.012	.029				
LTR	X	X	X				
LTR_S	X	X	X				
C12 vs	**C13**	**C14**					
P_d	X	X					
H	X	X					
H_s	X	X					
CD	X	X					
RPI	X	X					
RPI_S	X	X					
LTR	X	X					
LTR_S	X	X					
C13 vs	**C14**						
P_d	X						
H	X						
H_s	X						
CD	X						
RPI	X						
RPI_S	X						
LTR	X						
LTR_S	X						

APPENDIX – D

SCATTER PLOTS FOR ANTHROPOMETRIC PARAMETERS

VERSUS IPC CLASS

Figure D.1 The scatter plot for IPC Class versus Shoulder Width for male and female para-swimmers.

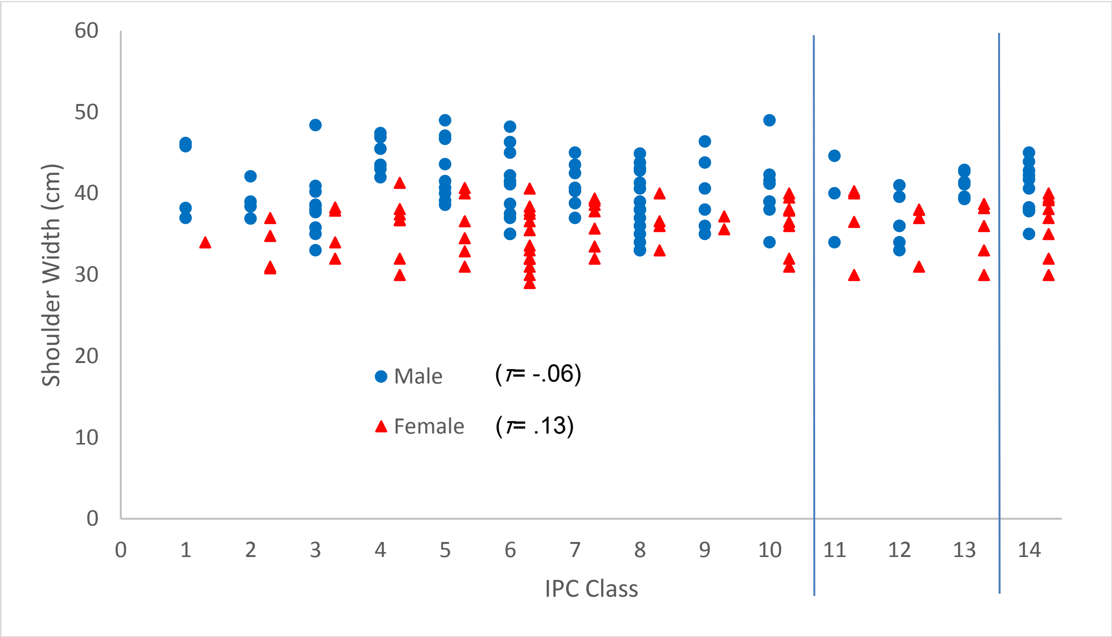


Figure D.2 The scatter plot for IPC Class versus Chest Depth for male and female para-swimmers.

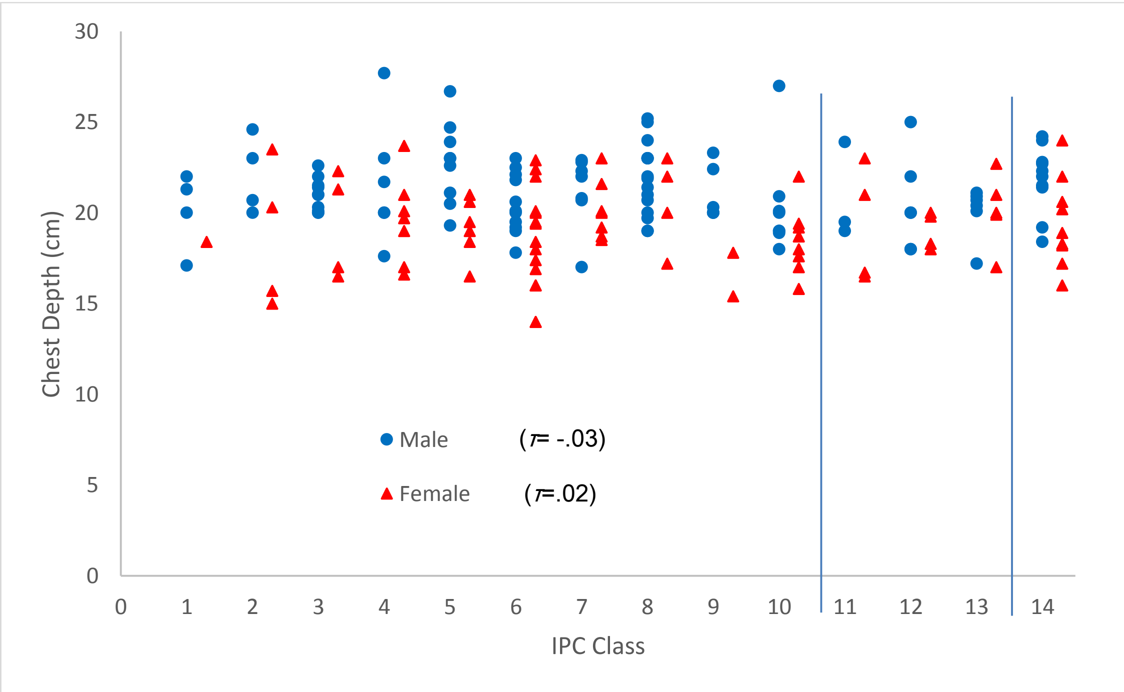


Figure D.3 The scatter plot for IPC Class versus Torso Girth for male and female para-swimmers.

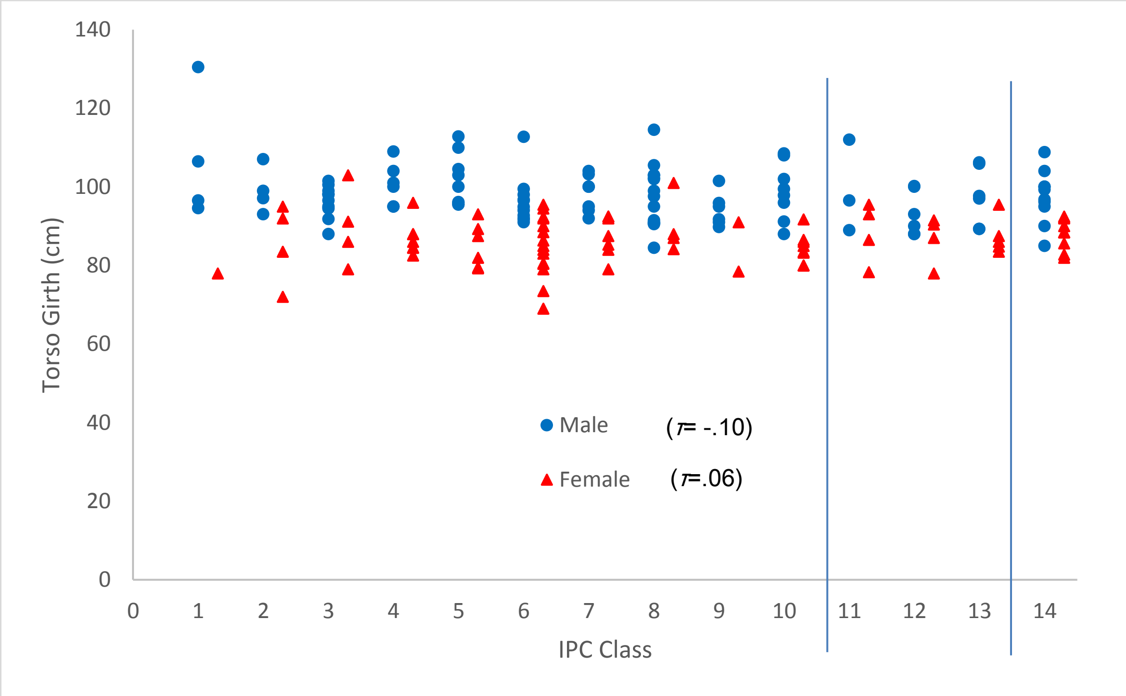


Figure D.4 The scatter plot for IPC Class versus RPI for male and female para-swimmers.

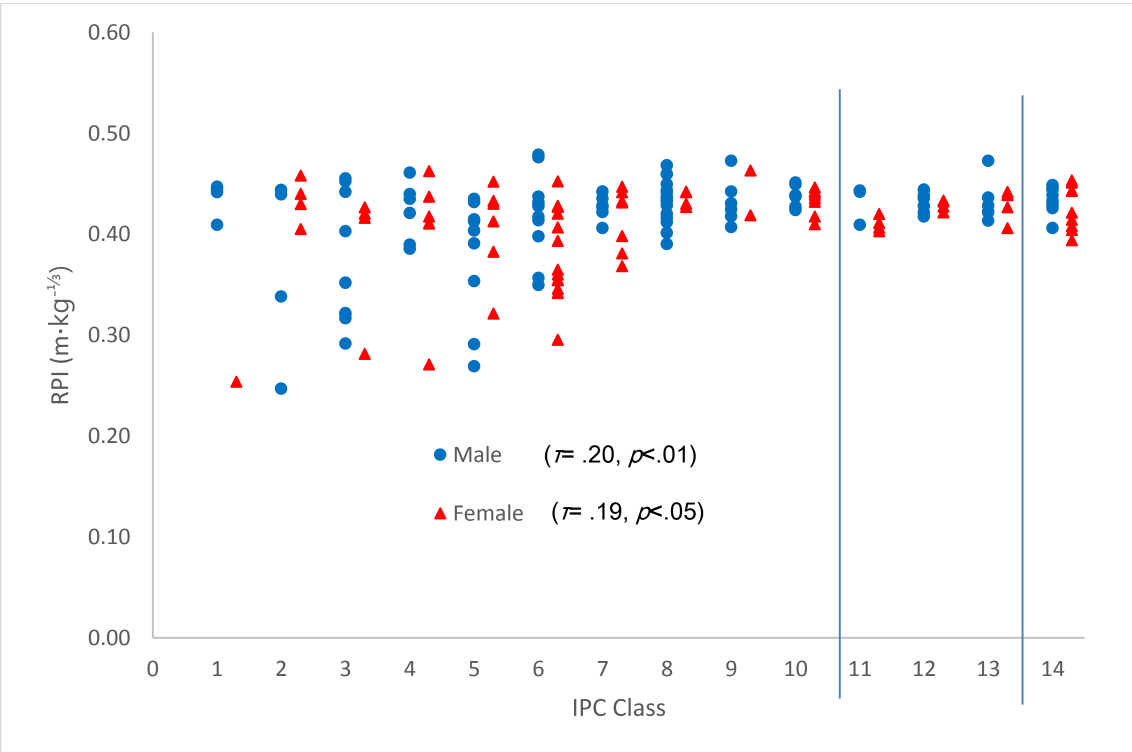


Figure D.5 The scatter plot for IPC Class versus CSA for male and female para-swimmers.

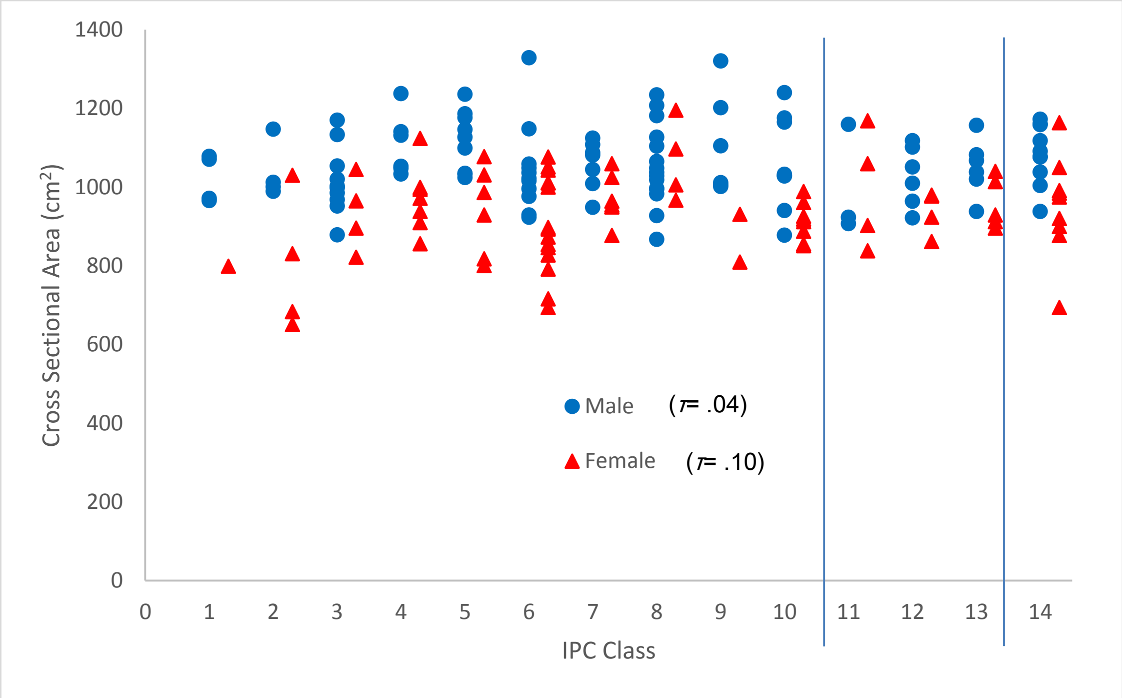


Figure D.6 The scatter plot for IPC Class versus Streamlined CSA for male and female para-swimmers.

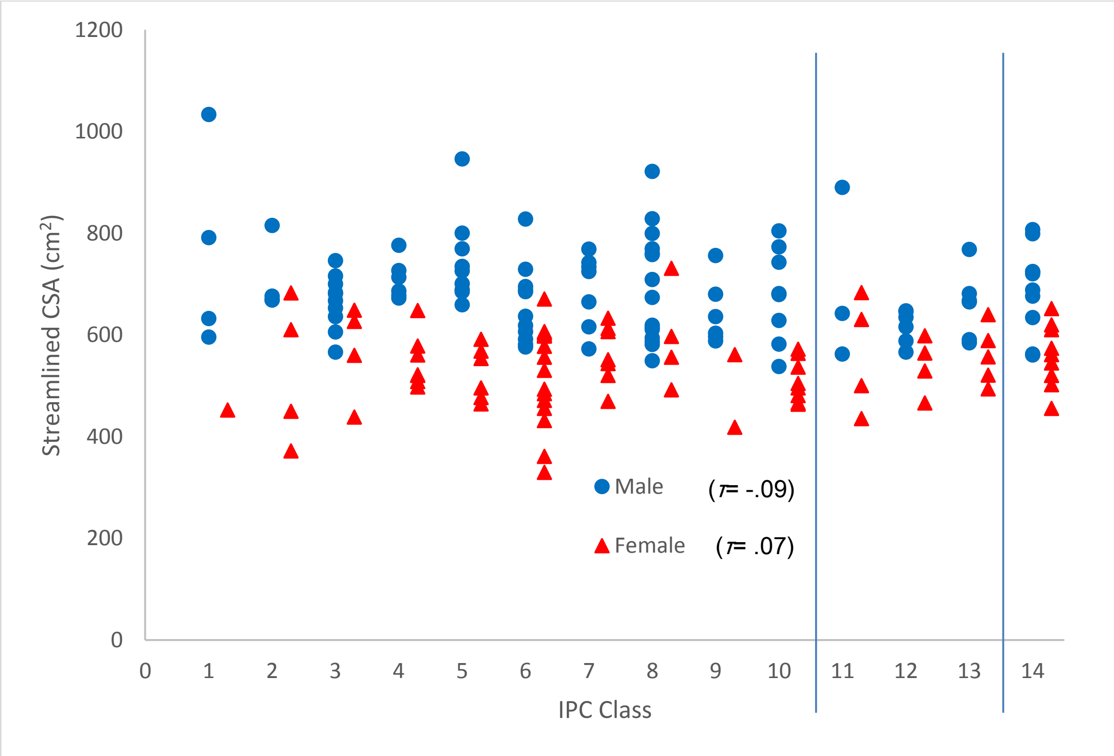


Figure D.7 The scatter plot for IPC Class versus Length Thickness Ratio for male and female para-swimmers.

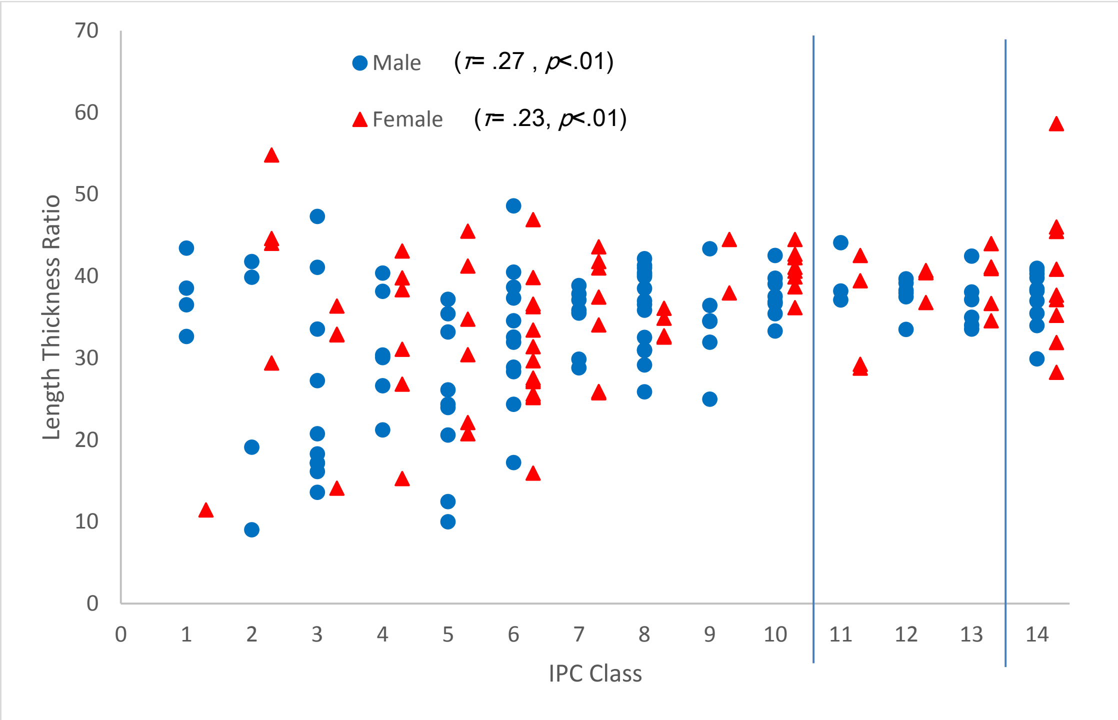
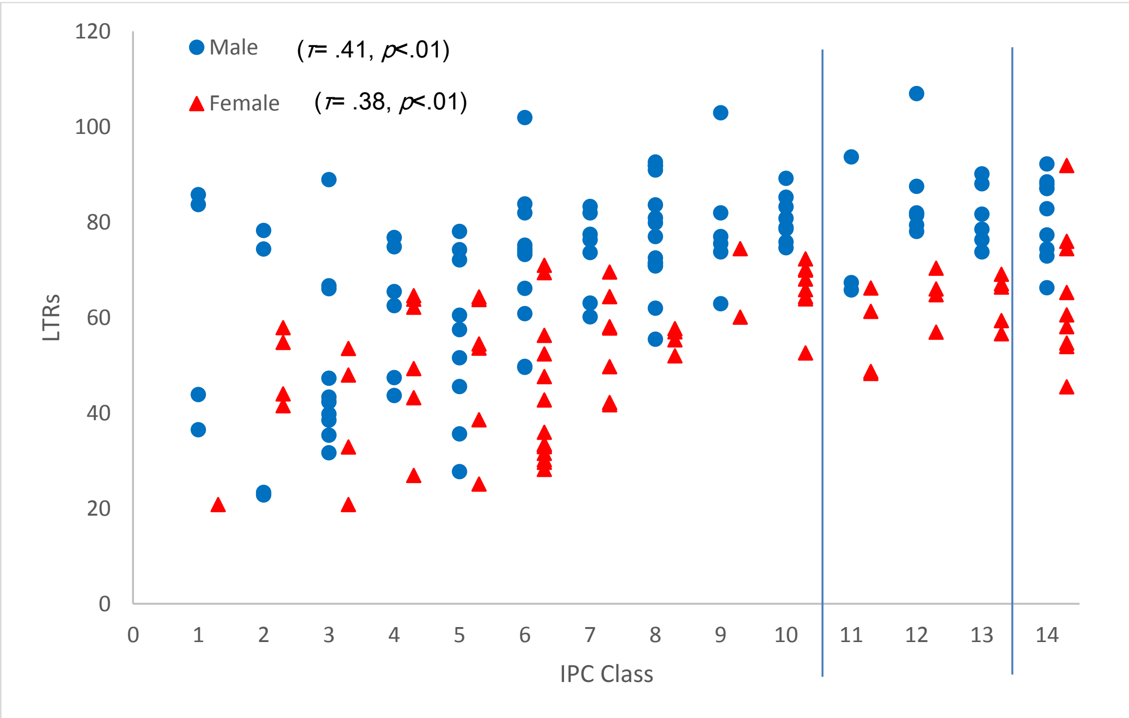


Figure D.8 The scatter plot for IPC Class versus Streamlined LTR for male and female para-swimmers.



APPENDIX – E

SCATTER PLOTS FOR PASSIVE DRAG

AND ANTHROPOMETRIC PARAMETERS

Figure E.1 The scatter plot for Passive Drag versus Streamlined Height for male and female para-swimmers.

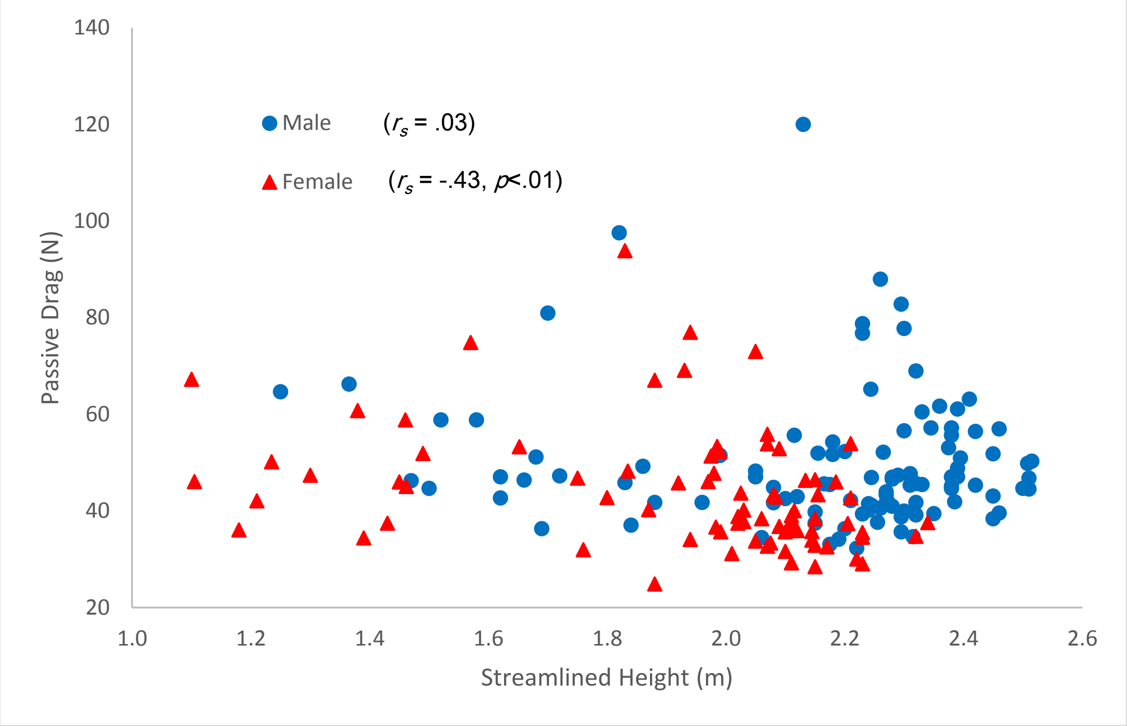


Figure E.2 The scatter plot for Passive Drag versus Body Mass for male and female para-swimmers.

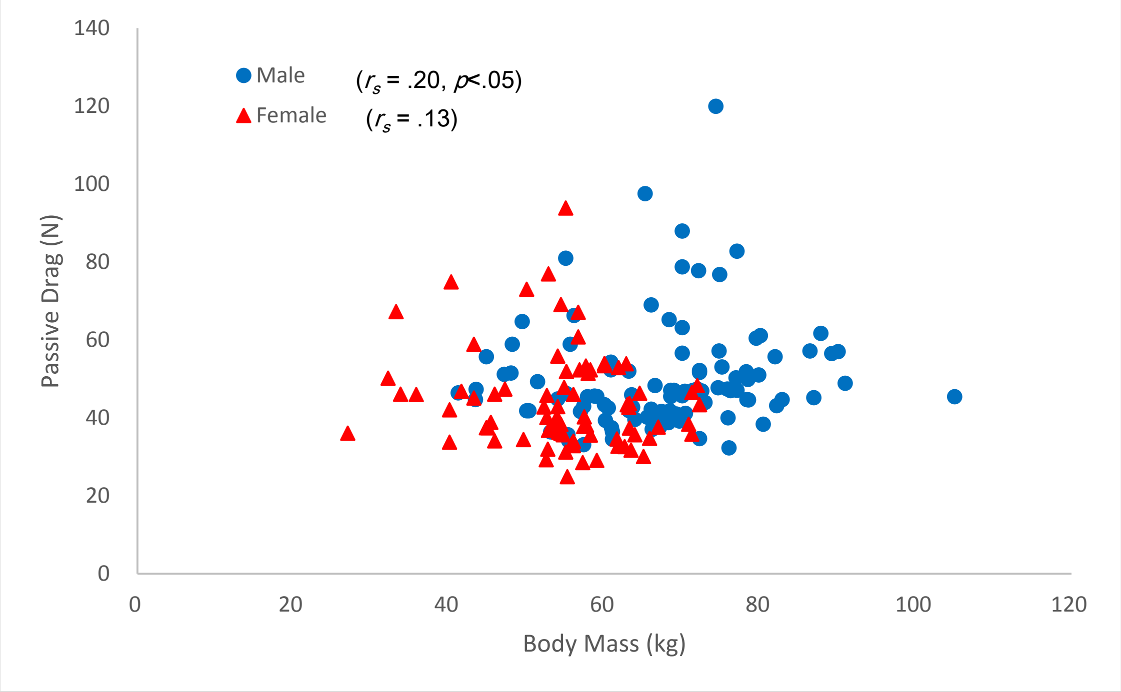


Figure E.3 The scatter plot for Passive Drag versus Shoulder Width for male and female para-swimmers.

Figure E.4 The scatter plot for Passive Drag versus Chest Depth for male and female para-swimmers.

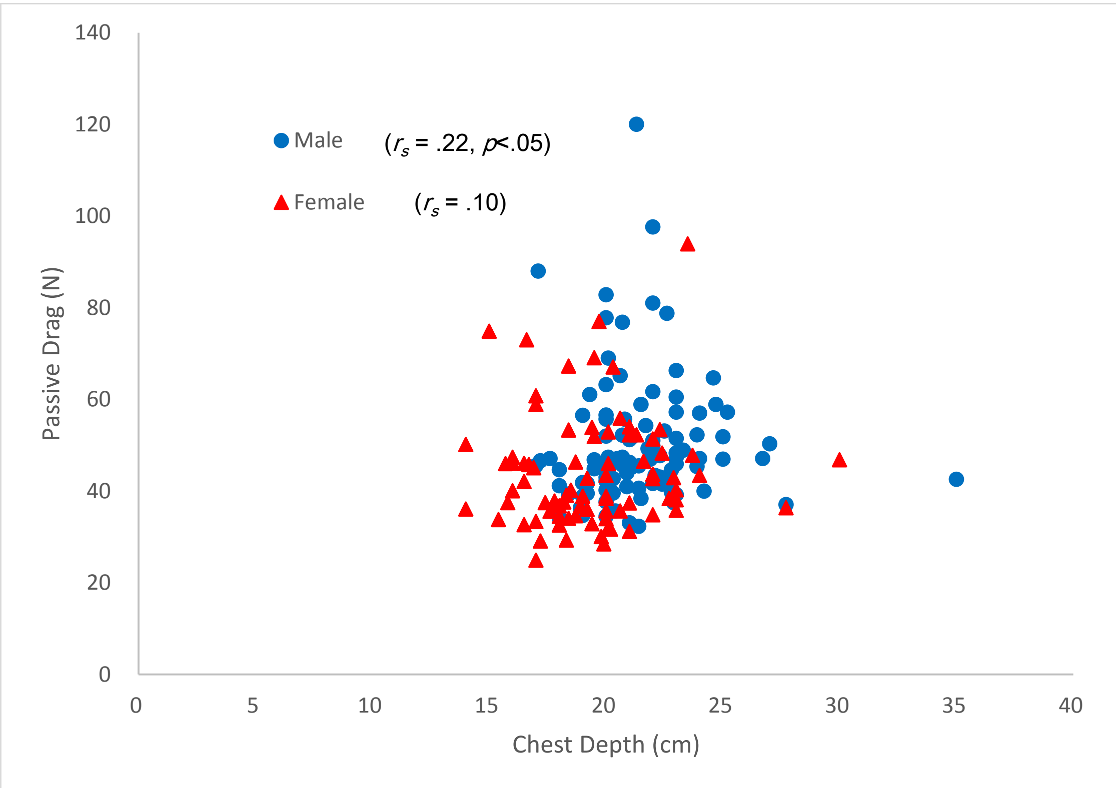


Figure E.5 The scatter plot for Passive Drag versus Shoulder Girth for male and female para-swimmers.

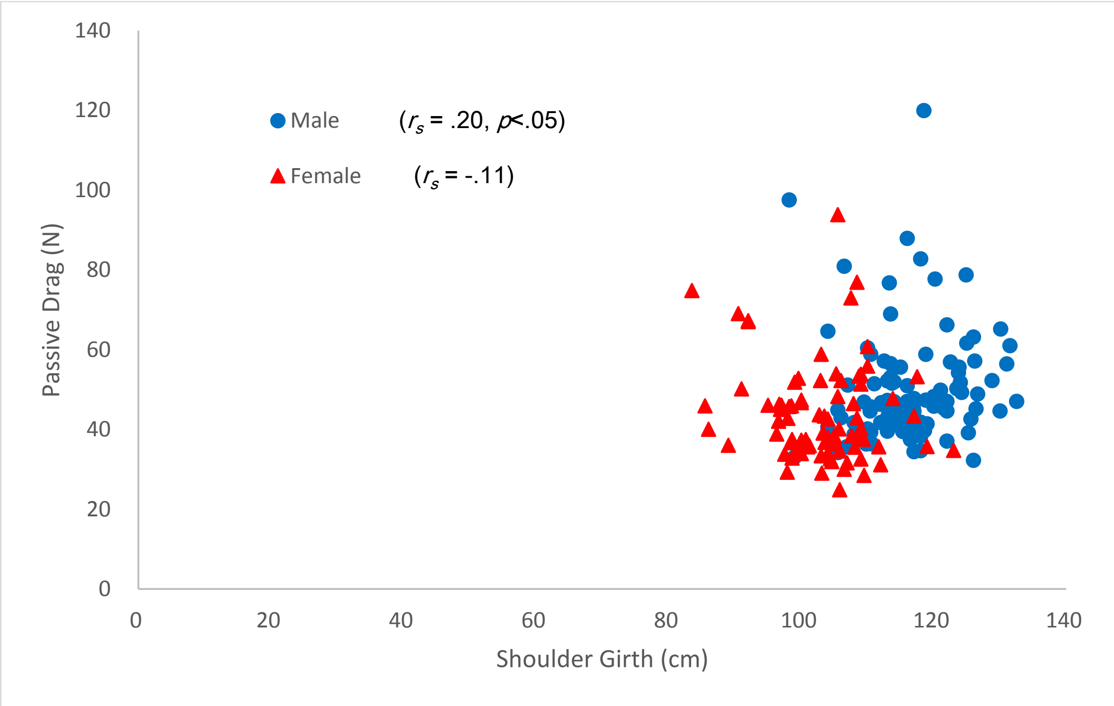


Figure E.6 The scatter plot for Passive Drag versus Torso Girth for male and female para-swimmers.

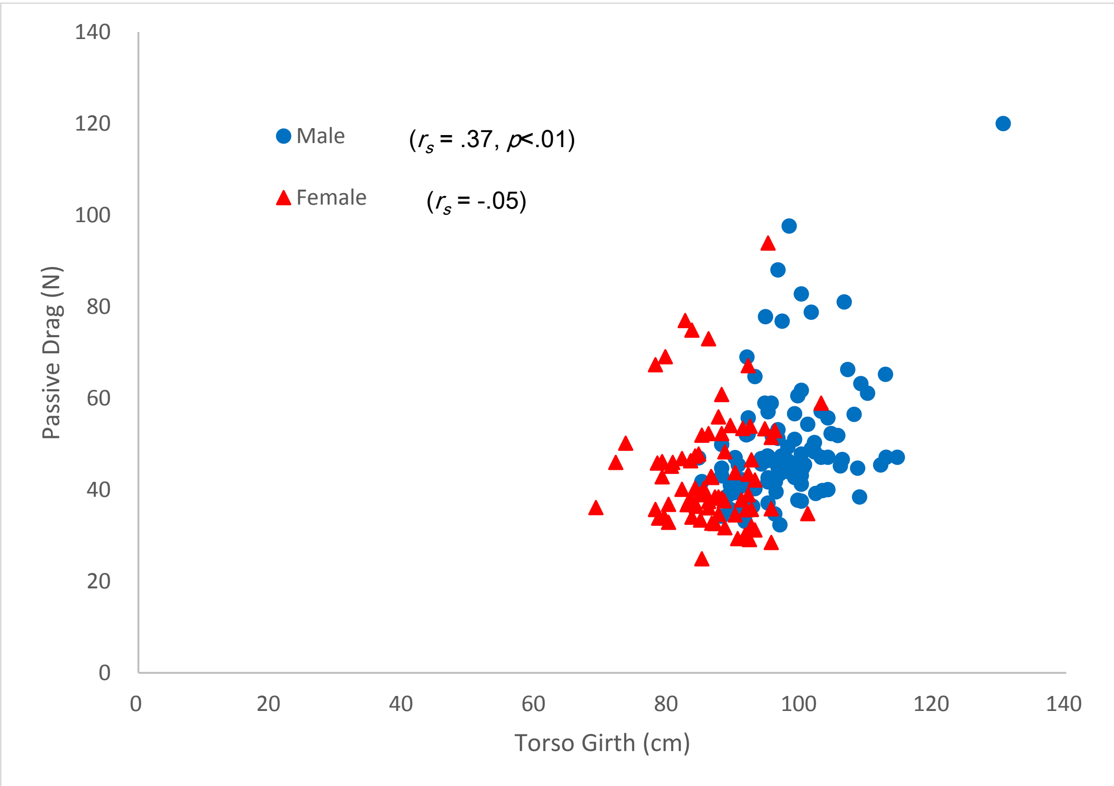


Figure E.7 The scatter plot for Passive Drag versus RPI for male and female para-swimmers.

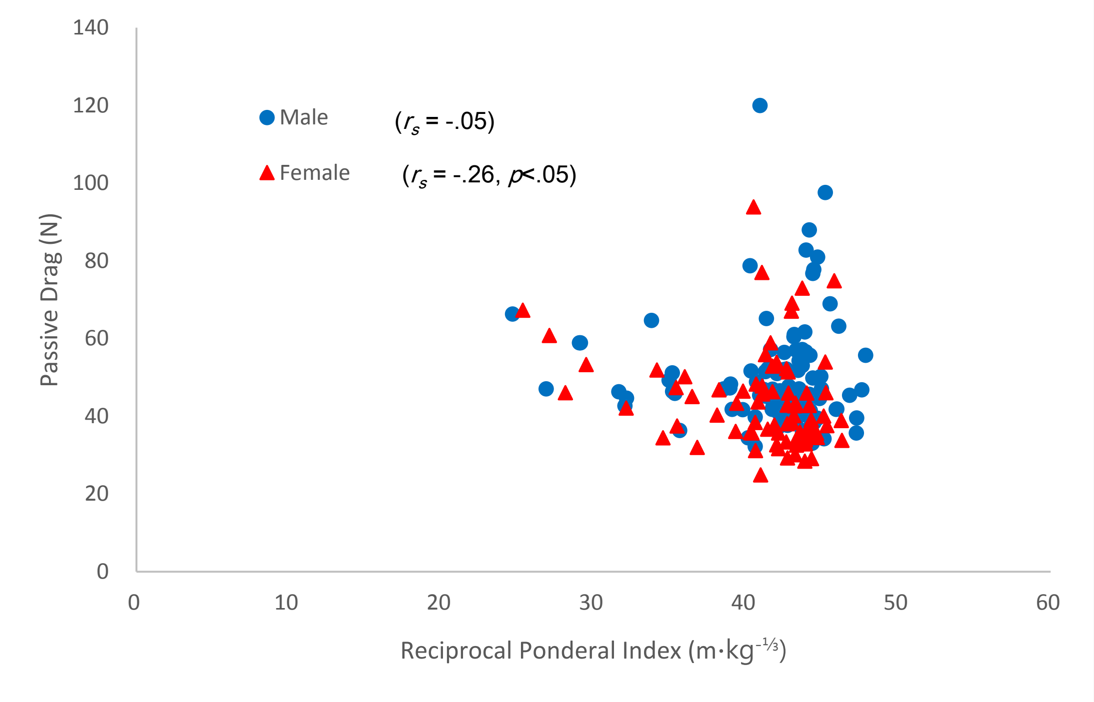


Figure E.8 The scatter plot for Passive Drag versus Streamlined RPI for male and female para-swimmers.

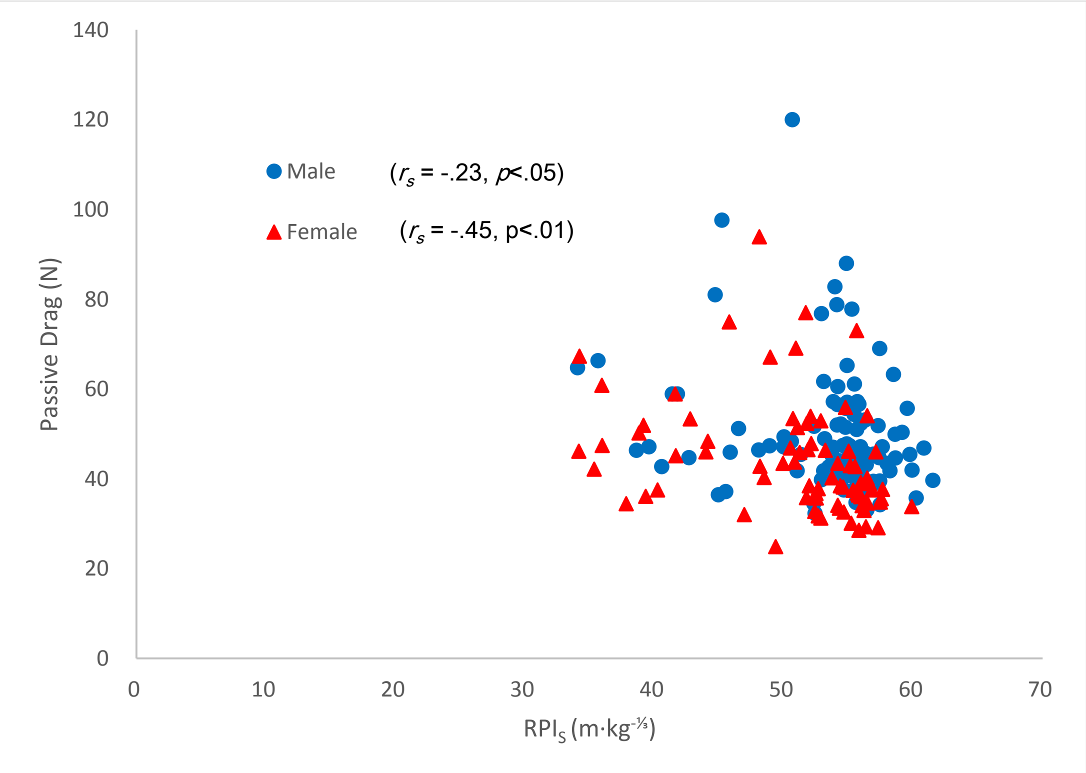


Figure E.9 The scatter plot for Passive Drag versus Cross Sectional Area for male and female para-swimmers.

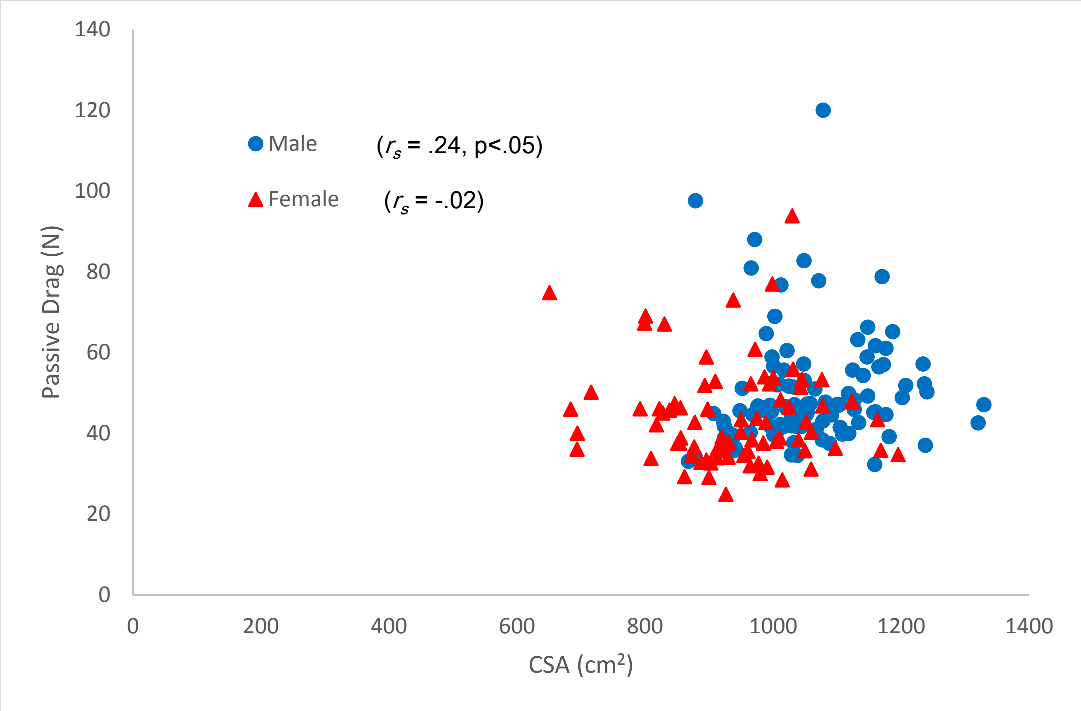


Figure E.10 The scatter plot for Passive Drag versus Length Thickness Ratio for male and female para-swimmers.