MECHANICAL POWER IN WELL TRAINED SWIMMERS WITH A PHYSICAL IMPAIRMENT

CASEY JANE LEE

A thesis submitted in partial fulfilment of the requirements of the Manchester Metropolitan University for the degree of Doctor of Philosophy

Institute for Performance Research

Department of Exercise and Sport Science

Manchester Metropolitan University

JUNE 2012

ACKNOWLEDGEMENTS

First and foremost, I would like to thank Dr Carl Payton, my director of studies, for his endless support, guidance and motivation throughout the duration of my thesis. I would also like to take this opportunity to thank Dr Payton for the wealth of opportunities he has provided me with, in both academic and applied sports science settings.

My sincere thanks go to Dr Adrian Burden (supervisor) for his direction and guidance. I would like to thank UK Sport for funding this Ph.D and British Swimming for funding the development of the ITS Ergometer. For equipment development, I would like to thank Mr Desney Richards. For technical support, I would like to thank Mr Garry Pheasey, who was always ready to help, irrespective of the time of day.

Last and by no means least I would like to thank my family and friends for their support throughout my academic studies: especially my Mum, Granny and Poppa for their continual motivation and belief in my ability to succeed; and friends/ colleagues Conor Osborough and Clare Dadswell for keeping me sane throughout my studies.

ABSTRACT

The aims of this thesis were to: 1) develop and validate tests of propulsive force and mechanical power that can be used to monitor British Disability swimmers; and 2) contribute to the development of an objective, evidence-based international classification system for swimmers with a physical impairment.

The propulsive force produced by unilateral arm amputee and able-bodied swimmers was assessed during a 30 s fully tethered swim (Chapter 3). It was concluded that as a consequence of their physical impairment, arm amputee swimmers produced significantly lower tether forces than able-bodied swimmers. Due to the limitation of the fully tethered method, an Isokinetic Tethered Swimming (ITS) Ergometer was developed (Chapter 4). To establish the setting in which peak power occurs on the device, external power was calculated at a range of tether speeds (Chapter 5). The results demonstrated that peak power occurred at a tether speed of 50 or 60% of the swimmer's maximal swimming speed, and peak power was significantly related to the level of the swimmer's physical impairment (IPC Class). Using the peak power setting, the decline in external power was quantified during a 30 s maximal effort swim (Chapter 6). All swimmers exhibited a decline in external power during the swim; however this decline was not related to the swimmer's IPC Class.

The validity of the movement on the ITS Ergometer was established using electromyography (EMG). The data revealed that muscle activation and recruitment patterns were similar to that of free swimming (Chapter 7). Using EMG the effect of neuromuscular fatigue on the contractile properties of the muscles during a 30 s maximal effort swim was examined (Chapter 8). Of the muscles tested, the muscle which appeared to fatigue the most was different for each swimmer.

LIST OF CONTENTS **PAGE**

Fatigue is a major limiting factor of competitive swimming performance (Toussaint et al., 2006). During a Paralympic 100 m final, across all IPC Classes, swimmers exhibit a ~12% decline in swimming speed (Daly et al., 2003). These values are typical of those reported within able-bodied research (Seifert, Boulesteix, Carter, & Chollet, 2004; Toussaint et al., 2006). Furthermore, the decline in swimming speed is mirrored by decreases in stroke rate in both able-bodied (Toussaint et al., 2006) and disabled swimmers (Daly et al., 2003; Osborough et al., 2009). Seifert et al. (2004) reported a decline in stroke rate of 8.9% over a 100 m swim, in national to international standard male able-bodied swimmers. While Daly et al. (2003) reported a similar decline in stroke rate of 8.4% in male Paralympic swimmers during a 100 m front crawl swim.

LIST OF FIGURES **Page**

LIST OF TABLES **PAGE**

CHAPTER 1

INTRODUCTION

The aim of this chapter is to introduce swimming, propulsion and mechanical power. The chapter then provides a brief description of the history of disability swimming and the current support offered to swimmers who excel at the sport. The final section of the chapter details the academic aims and objectives of the Ph.D.

1.1 INTRODUCTION TO SWIMMING

Swimming is unique as, unlike land based sports, the athlete is suspended in a watery medium and must propel their body forwards by pushing against liquid (Maglischo, 2003). Competitive swimmers propel themselves through the water using one of four different swimming strokes; front crawl, backstroke, breaststroke and butterfly. Front crawl is the fastest of the four strokes and will be the stroke focused on for the remainder of this thesis, unless specified otherwise. The speed of the swimmer is determined largely by two horizontal forces; the drag force (resistive) and the propulsive force (propelling). The latter will be one of the focal points of this thesis.

1.1.1 Propulsive Force and Mechanical Power

Propulsion is the force from the water that drives the swimmer forward. In front crawl, propulsion is predominantly produced by movements of the hand and forearm (Counsilman, 1968). Due to the continual displacement of water, the generation of propulsive force always leads to a loss of mechanical energy (Toussaint & Truijens, 2005). The loss occurs as mechanical energy is transferred, in the form of kinetic energy, to the fluid (Toussaint & Truijens, 2005). Thus, only a proportion of the total mechanical energy the swimmer produces is used effectively to overcome the drag force. Therefore, it is important not just to consider the propulsive force produced by the swimmer, but also the time derivative of the work they produce, that is, the mechanical power (Toussaint & Truijens, 2005).

1.1.2 Disability Swimming

Disability swimming as a movement originates back to 1948 when the first organised competition for people with a disability took place. The competition was organised by Sir Ludwig Guttmann for World War II veterans with spinal cord injuries. Since the very first Paralympics Games (an international sporting event for elite disabled athletes) in Rome in 1960, swimming has been one of the main events at the Paralympics. A total of 400 athletes from 23 different countries, took part in the first Paralympics. Through the years the Paralympic movement has grown tremendously and additional disability groups have been included. At the 2008 Beijing Games, 560 swimmers from more than 80 countries competed in 140 swimming events, while in the 2012 London Games, 600 swimmers will compete in 148 events. Swimmers with a disability who compete at the Paralympics must be classified by the International Paralympic Committee (IPC) based on the level of their physical impairment. The current IPC classification procedure has come under much scrutiny due to the perceived subjectivity of the classification process (Keogh, 2011; Souto, Vilas-Boas, & Costa, 2006).

1.1.3 Monitoring Athlete Development within Disability Swimming

British swimmers with a disability who show their potential to be World Class are eligible to enter the 'World Class Development' programme, while those swimmers who have a strong medal winning potential at the next Paralympic Games are eligible to enter the 'World Class Podium' programme. These programmes are designed to ensure that athletes, coaching science and medicine staff, work together in a coordinated manner to facilitate peak swimming performance. Swimmers on these programmes are offered a wealth of support including: medical support (e.g., access to physiotherapists, injury and illness management and medical and musculo-skeletal profiling) and sports science support (e.g., biomechanics, physiology, and psychology). In return, athletes must comply with the programme's monitoring procedures; failure to do so will lead to the suspension of the swimmer from that programme. When on a programme, swimmers are required to provide a detailed weekly log, complete a monthly monitoring form and attend a macro-cycle review. In addition, the athlete's coach must submit the results from two Aerobic Step Tests during each macro-cycle. The Aerobic Step Test is a physiological test used to assess and monitor aerobic capacity. The Aerobic Step Test is typically set to 7 × 200 m swims, although the number of sets and distance can vary depending on the swimmer's IPC Class.

Swimming fast is highly dependent upon a swimmer's ability to produce high mechanical power output, enabling the production of high propulsive forces (Toussaint and Truijens, 2005). In order to increase propulsive force and mechanical power, swimmers incorporate power training into their training programme, much of which is performed on dry-land (e.g., swim bench and weights). The rationale for this dry-land approach is that these exercises should provide a greater resistance against the working muscles, increasing mechanical power output more effectively than water based training alone (Toussaint & Vervoorn, 1990). However, as the movements performed on dry-land do not directly replicate those experienced within the water, it is unclear how much of the power gains developed on dry-land, are transferred into power gains within the water. Furthermore, anecdotal evidence obtained through discussions with coaches and through observation, has raised some concerns that strength and power gains developed on dry-land do not necessarily transfer effectively into power gains and performance gains in the water. Currently, there are no standardised tests or devices to evaluate mechanical power within the water. The ability to accurately monitor a swimmer's mechanical power output in the water, throughout the year, would provide an objective measure of the effectiveness of training and thus would clearly be of considerable value to the coach and swimmer.

1.2 ACADEMIC AIMS AND OBJECTIVES

The aims of this Ph.D thesis were to:

- To develop and validate tests of propulsive force and mechanical power that can be used to monitor swimmers on British Disability Swimming World Class Programmes.

- To contribute to the development of an objective, evidence-based international classification system for swimmers with a physical impairment.

The objectives of the Ph.D were to:

- To develop systems to measure propulsive force and mechanical power during swimming;
- To assess the reliability, validity and muscle specificity of swimming on a device to measure mechanical power;
- To establish the relationship between mechanical power and the level of physical impairment of a swimmer (IPC Class);
- To examine the effect of fatigue on propulsive force production, mechanical power output and the contractile properties of the muscles, in swimmers with a physical impairment.

1.3 STRUCTURE OF THE THESIS

The remainder of this thesis is comprised of eight chapters: a review of literature, a preliminary experimental study, an equipment development study, four further experimental studies, finishing with a summary and practical applications section.

1.3.1 Chapter 2 – Literature Review.

The aim of this chapter was to provide an extensive review of the literature in relation to the overall aims and objectives of the thesis. The chapter will begin by outlining the current IPC classification system followed by a summary of recent research in the area of disability swimming. The main body of the literature review will identify and critique research methodologies and findings with respect to propulsive force, mechanical power and fatigue during swimming. Where possible the literature review will highlight research in the area of disability swimming, however, the number of published studies in this area is quite limited.

1.3.2 Chapter 3 – Experimental Study 1

The aim of this study was to examine changes in the tether (propulsive) force produced by trained unilateral arm amputee swimmers during a 30 s maximal effort swim, and to compare the results to those of a group of well-matched able-bodied swimmers. The experimental hypotheses were: 1) that the arm amputee group will produce significantly lower mean tether forces than the able-bodied group, and 2) the arm amputee group will exhibit a significantly greater decline in force (fatigue index) than the able-bodied group.

1.3.3 Chapter 4 – Equipment Development

This chapter outlines the development of a swimming specific ergometer designed to measure the mechanical power produced by both able-bodied swimmers and swimmers with a physical impairment. The development of the ergometer was a pivotal part of the Ph.D as it was the main measurement tool used in the experimental studies 2-5. This chapter details the performance characteristics and construction of the device. In addition, this chapter explores the reliability and validity of the ergometer. Finally, the chapter discusses additional items of peripheral equipment which were developed and tested in conjunction with the ergometer.

1.3.4 Chapter 5 – Experimental Study 2

The aims of the study were: 1) to calculate the external power produced by competitive swimmers with a physical impairment at a range of tether speeds in order to identify the setting at which peak power occurred, and 2) to examine the relationship between peak power and IPC Class. The experimental hypotheses were: 1) there will be an optimum tether speed setting in which peak power occurs, and 2) there will be a significant positive relationship between IPC Class and peak power.

1.3.5 Chapter 6 – Experimental Study 3

The aims of the study were to: 1) examine changes in external power during a 30 s maximal effort swim on the Isokinetic Tethered Swimming (ITS) Ergometer; and 2) establish the relationship between the decline in external power and IPC Class. The experimental hypotheses were: 1) there will be a decline in external power during the

30 s test; and 2) there will be no relationship between the decline in external power and IPC Class.

1.3.6 Chapter 7 – Experimental Study 4

The primary aims of this study were to establish whether: 1) the level of muscle activity and, 2) the muscle recruitment patterns, exhibited when swimming maximally on the ITS Ergometer, at various tether speeds, differ from those during free swimming. A secondary aim was to gain a better understanding of the relationship between muscle activity and the external power produced by the swimmer. In order to achieve this, the power to overcome drag was estimated and combined with the measures of external power. The primary hypotheses were, as tethered swimming speed increases: 1) the level of muscle activity and, 2) muscle recruitment patterns will match more closely to those found during free swimming. The secondary hypothesis was: an increase in tether speed setting would affect the level of muscle activity but would not affect the power output of the swimmer, when drag is accounted for.

1.3.7 Chapter 8 – Experimental Study 5

The aims of this study were twofold: First, to examine the effect of neuromuscular fatigue on the frequency content of the EMG signal during a 30 s maximal effort swim on the ITS Ergometer. Second, to establish whether there was a relationship between changes in the frequency content of the EMG signal and the decline in external power during the 30 s test. The experimental hypotheses were: 1) that the frequency of the EMG signal would decrease significantly between the beginning and the end of the test; and 2) that there would be a significant relationship between the decline in the frequency of the EMG signal and the decline in external power.

1.3.8 Chapter 9: Summary and Practical Applications

The aim of this chapter was to provide a summary of the key findings of the Ph.D thesis in relation to the academic aims. Practical applications based on these findings are discussed.

CHAPTER 2

LITERATURE REVIEW

The aim of this chapter is to provide an extensive review of the literature in relation to the overall aims and objectives of the thesis. The chapter will begin by outlining the current IPC classification system followed by a summary of recent research in the area of disability swimming. The main body of the literature review will identify and critique research methodologies and findings with respect to propulsive force, mechanical power and fatigue during swimming. Where possible the literature review will highlight research in the area of disability swimming, however, the number of published studies in this area is quite limited.

2.1 INTRODUCTION

2.1.1 Classification of Swimmers with a Physical Impairment

Swimmers with a disability who wish to compete in swimming events must be classified based on their physical impairment(s) by the IPC. The IPC classification system is designed to ensure that swimmers compete against other swimmers with the same functional ability, thus creating a 'level playing field'. During the classification process, swimmers are assessed via a series of water-based and land-based tests to evaluate the level of their physical impairment and performance potential. There must be at least one medical and one technical qualified classifier present during the assessment.

There are three main components of the classification procedure: a land-based assessment (bench test), a water-based assessment and finally, an observation during competition. The land-based assessment is performed in a prone position on a medical testing bench. Tests performed on the bench include: muscle testing, joint coordination, joint mobility, measurement of amputation(s), measurement of the trunk and the shoulder drop test. Once the bench test is completed a provisional classification is submitted. Swimmers then undergo a water-based test in which the key race components (starts and turns) of the 'S strokes' (front-crawl, backstroke and butterfly) are examined. A basic breakdown of points awarded for the 'S strokes' are as follows: for the arms (130 points), legs (100 points), trunk (50 points), starts (10 points) and turns (10 points). The points accumulated throughout the three assessments (land assessment, water assessment and observation during performance) are calculated and the swimmer is then placed within the relevant IPC Class. With regards to physical impairment, the classification scale ranges from S1 (40-60 points) to S10 (266 – 285 points), with S1 being the most and S10 being the least physically impaired.

The IPC classification procedure has come under much scrutiny due to the perceived subjectivity of the classification process (Keogh, 2011; Souto et al., 2006). Keogh (2011) stated that due to the nuances of the IPC classification process and the considerable between- and within-class variability, the most appropriate method of classification has yet to be defined. As previously outlined, during the IPC classification procedure swimmers are assessed during water-based and performance observations. The limitations of these tests are that they do not differentiate between physical impairment and the effect of training, therefore some athletes may be penalised for having a higher trained status, than others (Keogh, 2011). It would appear future research is required to increase the objectivity of the IPC classification procedure (Souto et al., 2006).

2.1.2 Current Research in the area of Disability Swimming

Within disability swimming each athlete is unique, therefore in order to enhance performance coaches and sports scientists must understand the physical impairment(s) of each individual swimmer (Keogh, 2011). This understanding allows an individual's training programme to be correctly modified and reduces the risk of injury (Keogh, 2011). The main body of scientific literature regarding performance characteristics of well-trained disabled swimmers is still in its infancy, with research focusing on three main areas; race analysis (Burkett & Mellifont, 2008; Daly, Djobova, Malone, Vanlandewijick, & Steadward, 2003), upper body kinematics and kinetics (Lecrivain, Slaouti, Payton, & Kennedy, 2008; Osborough, Payton, & Daly, 2009) and lower body kinematics (Fulton, Pyne, & Burkett, 2009).

Daly et al. (2003) conducted video race analysis to examine stroke rate, stroke length and swimming speed in 72 male and 62 female 100 m finalists at the Sydney 2000 Paralympic games. The key finding of the study was that, Paralympic swimmers exhibited similar race patterns to Olympic swimmers with clean swimming, turning and finishing speed being correlated highly with race performance (r = 0.61). To gain an understanding of the affect an upper limb amputation has on stroking kinematics, Osborough et al. (2009) examined the relationship between stroke length, stroke rate and swimming speed in thirteen unilateral arm amputee swimmers. The authors found that an increase in swimming speed was strongly associated with stroke rate (r = 0.86), but not stroke length (r = 0.01). Fulton et al. (2009) examined the kicking pattern of fourteen Paralympic swimmers and concluded that kick rate was a strong determinant of swimming speed.

2.2 PROPULSIVE FORCE

2.2.1 Definitions and Background Theory

Propulsion can be defined as the force which propels the swimmer in a forward direction, and results from the muscle force being applied, by mainly the hand and forearm, to the water (Arellano, 1999). Theories on how swimmers produce propulsion have been developed and debated upon since the early 1900s. During the 1900s it was thought that swimmers propelled themselves through the water in a similar manner to that of oars and paddle-wheels (paddle-wheel theory). It was believed that swimmers pulled the arm, whilst fully extended, through the water and under the body (Maglischo, 2003). Based on Newton’s third law of motion, it was thought that the drag force created by moving the hand backwards would propel the swimmer forwards. It was not until the late 1960's with the use of underwater cameras that this paddle-wheel theory was further developed. From underwater observations it was clear that swimmers did not push the water backwards in a straight line but instead, pushed water backwards by extending and bending the arms creating a three dimensional (3D) 'S' shape pulling pattern (Counsilman, 1968). It was believed that this 3D 'S' shape pulling pattern was used to push handfuls of slowly moving water, mostly backwards, a short distance (Counsilman, 1968).

The 'S' shape pulling pattern was thought to create important lift and drag forces for the generation of propulsive force (Arellano, 1999). Based on Bernoulli's principle, Counsilman (1968) concluded that swimmers created a foil shape with the hand and produce sculling movements, to create a lift force. The lift force created by the hand was thought to be similar to that created by an aircraft wing. It was observed that during the sculling movements the upper surface of the hand was slightly arched causing the water over the top of the surface on the hand to move more quickly, than below it. This was thought to create lower pressure on the superior surface, compared to the inferior surface of the hand. This pressure differential was believed to result in a lift force directed at right angles to the line of motion of the hand (Toussaint & Truijens, 2005).

Many authors argued that the concept of the human hand as a foil was over simplistic and that the application of Bernoulli's principle to a non foil-shaped structure, such as the human hand, was unrealistic (Bixler & Riewald, 2002; Toussaint, Van Der Berg, & Beek, 2002). Bixler and Riewald (2002) examined the fluid flow around the hand and arm using a computer based simulation method, referred to as Computational Fluid Dynamics (CFD). The study revealed that the simulated hand and arm produced large drag forces and very minimal coefficients of lift. Furthermore, the author stated that the hand lacked many characteristics of an airfoil making the adaptation of

Bernoulli's principle to propulsion very limited. Toussaint et al. (2002) concluded that during swimming the boundary layer running over the hand does not remain intact and therefore, Bernoulli's principle only plays, at best, a very minor role in the generation of propulsive force.

Although the exact theory behind the swimmer's ability to generate propulsive force is still unknown, what is clear is that elite swimmers use sculling motions with their hand and forearm to create a 3D 'S' shape pulling pattern to propel themselves forwards. As the pulling pattern of the hand was not realised until the use of underwater cameras, it would appear the pulling pattern of the hand and arm is not a taught learned skill but rather a self-learned instinctive movement. High propulsive forces produced by world class swimmers are not simply due to muscular strength but attributed to the swimmers' '*feel'* of the water through a specific kinaesthetic and tactile sense . The importance of this tactile sense in producing propulsion provides a strong rationale for measuring propulsive force in the water, as opposed to measuring it using other methods (e.g., CFD and dry-land ergometers).

2.2.2 Quantifying Propulsive Force

2.2.2.1 Indirect Methods

Schleihauf (1979) calculated propulsive force through a combination of three-dimensional kinematic analysis and data from fluid laboratories. The advantage of this method was that it allowed for the calculation of propulsive force without restricting the swimmer in anyway. The limitation of this method was that the values of propulsive force were not direct measurements, but calculations based upon data from fluid laboratories, which assume that the flow under steady conditions (constant velocity, angle of attack and sweep back angle). During actual swimming, unsteady flow conditions exist (Toussaint et al., 2002). Thus, Schleihauf's model was restrictive, in that it did not account for the accelerated movements of the hand nor the water around it.

In recent years, propulsive force has been calculated using CFD to simulate the fluid flow around a computer simulated three-dimensional arm. The use of CFD allows for a complete computation of all the hydrodynamic forces (i.e., propulsive force) involved in swimming, and unlike the method proposed by Schleihauf (1979; Schleihauf, Gray, & DeRose, 1983), CFD allows for the determination of hydrodynamic forces during steady and unsteady state flow conditions (Lecrivain et al., 2008). Bixler and Riewald (2002) stated that through the use of CFD it will one day be possible to design the optimal pulling pattern for the production of propulsive force. More recently CFD was used to investigate the performance of the affected side of a uni-lateral arm amputee swimmer (Lecrivain et al., 2008). Lecrivain et al. (2008) identified that although able-bodied research had demonstrated that the majority of propulsive force is produced by the hand and forearm, the effect of the upper arm was generally not taken into consideration. The study found that the affected arm did produce propulsive force (3.2 N) at a simulated swimming speed of 1 $m \cdot s^{-1}$. An advantage of CFD is it enables visualisation of the fluid flow around the swimmer at any time during the swimming stroke. The contribution of different arm segments to propulsive and resistive forces can also be assessed numerically and compared qualitatively to the flow patterns from experimental tests (Lecrivain et al., 2008). Furthermore, CFD provides realistic values of propulsive force and presents high intra-study reliability (Berger & Riewald, 2002; Lecrivain et al., 2008). Unfortunately, the use of CFD within an applied setting is problematic as the method is both time consuming and costly. It relies heavily on expensive equipment and specialist expertise.

2.2.2.2 Direct Methods

The MAD system was originally designed to measure active drag (Hollander et al., 1986), but has been used further to assess propelling efficiency (Toussaint, 1990; Toussaint et al., 1988), mechanical power (Toussaint & Vervoorn, 1990) and fatigue during swimming (Toussaint, Carol, Kranenborg, & Truijens, 2006). The MAD system is comprised of fixed pads situated under the surface of the water (Figure 2.1). Swimmers propel themselves forwards by pushing off the fixed pads. A force transducer measures the push-off force produced by the swimmer.

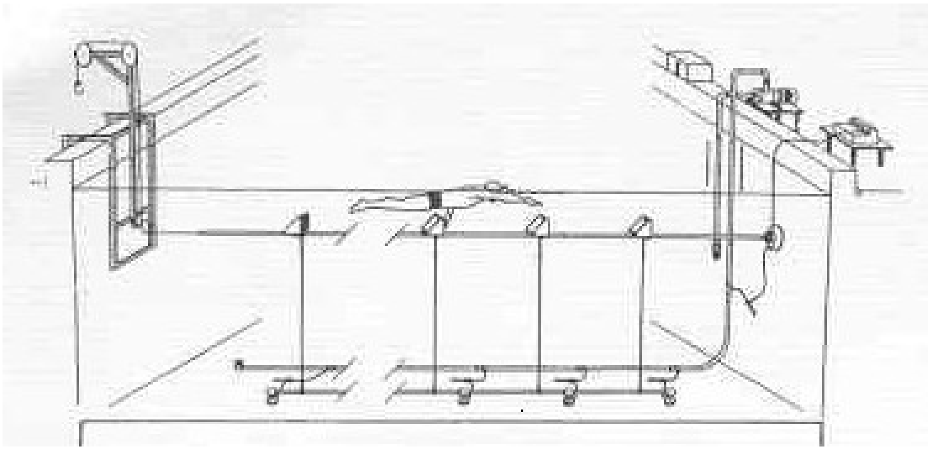


Figure 2.1: Diagrammatical representation of the MAD system taken from Toussaint, Knops, De Groot and Hollander (1990).

In order to determine whether swimming on the MAD system was similar to free swimming, Hollander et al. (1986) filmed two swimmers simultaneously swimming down the pool, with one swimmer on the MAD system and the other free swimming. The video clips were shown to 140 skilled swim coaches affiliated to the Royal Dutch Swimming Association, who were asked to identify which swimmer was using the MAD system and which swimmer was free swimming. Of the 140 coaches, only 50%

could identify which swimmer was swimming on the MAD system. In a later study, using electromyography the muscle activity exhibited on the MAD system was explored and compared with that of free swimming (Clarys et al., 1988). Electromyography (EMG) is the recording of electrical signals generated by the muscles. Clarys et al. (1988) examined the similarity of muscle activity (triceps brachii, pectoralis major, latissimus dorsi and flexor digitorum) between swimming on the MAD system and free swimming. The similarity in muscle timing and amplitude was determined using the 'IDANCO system' (Identical, Analogue and Conform) described by Bollens, Annemans, Vaes, and Clarys (1988). Based on the percentage difference in the timing and amplitude of the EMG recordings, the movement on the MAD system was categorised as being either 'identical' (0-10%), 'analogue' (11-20%), 'conform' (21-30%) or 'different' (unequal number of peaks or disproportion of dynamic contraction) to free swimming. The study by Clarys et al. (1988) found a high level of muscle specificity with 83% of the EMG recordings being of either 'analogue' or 'identical' patterns, 9% were found to be of 'conform' patterns and 7.2% of the patterns were found to be 'different' (Clarys et al., 1988). The muscle patterns which were found to be 'different' to free swimming were all observed in the flexor digitorum. In addition, the flexor digitorum presented high inter-individual differences. Based on the muscle activity from the flexor digitorum, the authors concluded that the push-off pads on the MAD system create individual specific movements of the hand and forearm. As the hand and forearm are key in producing propulsive force (Berger, Hollander, & De Groot, 1995), the ecological validity of the MAD system appears limited as a measure of propulsive force.

Unlike the MAD system, tethered swimming is a measure of the force produced by the hand and forearm against the water rather than against a fixed surface. During tethered swimming, the swimmer is attached via a waist belt to a tether line (or pole) which is connected to a force measuring device (e.g., force transducer or weight stack). There are two main forms of tethered swimming; fully tethered and semi-tethered. During fully tethered swimming the tether line is secured to the side of the pool and the swimmer remains stationary. During semi-tethered swimming, the tether line is attached to some form of resistance (e.g., weight stack) while allowing the swimmer to progress down the pool. The advantage of fully tethered swimming is that as the participant's swimming speed is zero, active drag is negligible and propulsive force is isolated. The advantage of semi-tethered swimming is that as the speed of the swimmer is greater than zero, the external power can be calculated as the product of the tether force and swimming speed (which is discussed later in Section 2.4).

In order to assess the test re-test reliability of tethered swimming, Kjendie and Thorsvald measured tether forces on separate days and different times during one week and then repeated this again on two more test sessions. Trials consisted of three repetitions of 10 s fully tethered swims. The authors presented a significant correlation (r = 0.98) between morning and afternoon testing. In addition, the average absolute coefficient of variation of morning and afternoon testing was just 3.4 ± 2.4%. The authors concluded that tethered swimming could be considered highly reliable. The validity of tethered swimming was investigated by Yeater, Martin, White and Gibson who presented a significant correlation (r = 0.86) between 500 yard swimming speed and mean tether force (191 ± 41 N). When comparing the five best swimmers with the five worst swimmers, the better swimmers produced significantly higher (p < 0.03) mean tether force values, however there was no significant difference in peak tether forces. The limitation of using peak tether force is that it represents the force at only one instant in the stroke, whereas mean tether force is recorded throughout the duration stroke and can be considered a better representation of the stroke as a whole. Morouço, Keskinen, Vilas-Boas and Fernandes (2011) presented a strong correlation (r = 0.92; p <

0.01) between mean tether force during a 30 s tethered swimming test and 50 m swimming speed. Both Morouço et al. (2011) and Yeater et al. (1981) found that normalising tether forces by body mass did not improve the relationship between tether forces and swimming speed. Morouço et al. (2011) concluded that the participant's technique (i.e., the individual's ability to apply a force to the water) played a far greater role in force production, than body mass.

In addition to the studies investigating the validity and reliability of tethered swimming, previous studies have compared the specificity of the movement performed during tethered swimming to free swimming (Bollens et al., 1988; Cabri, Annemans, Clarys, Bollens, & Publie, 1988). Bollens et al. compared the EMG recordings of the triceps (caput longus), pectoralis major (pars sternocostalis), latissimus dorsi, rectus femoris and gastrocnemius. Muscle activity was normalised as a percentage of the relative maximal voluntary contraction. With the exception of the latissimus dorsi, none of the tested muscles during tethered swimming induced a significantly higher muscle activity when compared to free swimming. Although there was no significant difference in muscle activity between free swimming and fully tethered swimming, muscle activity was higher during fully tethered swimming in all trials. Using the IDANCO system (described earlier) the authors concluded that the timing and amplitude of the selected muscles were at the least 'analogue' between fully tethered and free swimming. Clarys (1988) stated that muscle activity was similar between free swimming and semi-tethered (weight stack) swimming but only up to a resistive load of between 100 and 120 N, after which the muscle action was deemed non-specific. The non-specific muscle action at higher loads might have been due to the fluctuations in propulsive force throughout the stroke (Schleihauf, Gray, & DeRose, 1983). During points in the stroke where the propulsive force is relatively small, the swimmer can get '*jerked'* backwards causing the tether to slacken momentarily (Goldfuss & Nelson, 1971). Therefore, when measuring tether force using a semi-tethered weight stack system, it is vital that the resistive load is not too large as to elicit a difference muscle pattern to that of free swimming.

Although tethered swimming has been widely used within able-bodied research, only one study has measured tether forces in disabled swimmers (Souto et al., 2006). Using fully tethered swimming, Souto et al. (2006) measured the backstroke tether force in 60 disabled swimmers (IPC Class S2-S10). Tether force was recorded over 10 s and calculated as a mean. The highest tether force was produced by the S10 swimmers (144.6 ± 44.8 N) and the lowest tether force by the S2 swimmers (63.2 ± 16 N), respectively. IPC Class only explained 25% (r^2 = 0.25) of the variability in the tether force data. The small r^2 value may have been due to the range in the trained status and technical ability of the swimmers within each IPC Class. Unfortunately, the study did not provide any information on or make any provisions for the difference in the trained status or technical ability of the swimmers.

The limitation of fully tethered swimming is that unlike free swimming, the swimmer is restricted to a swimming speed of zero. At a swimming speed of zero the pulling arm encounters greater water resistance (Goldfuss & Nelson, 1971). Thus, the forces measured during fully tethered swimming are higher than the propulsive force produced during free swimming (Martin, Yeater, & White, 1981). Cautious interpretation of results is therefore required when relating tether forces to free swimming propulsive force (Sidney, Pelayo, & Robert, 1996). The limitation of fully tethered swimming was recognised in the early 1950's by Alley (1952) who stated that the propulsive force exerted at a swimming speed of zero is not the same as the propulsive force which can be exerted at a swimming speed greater than zero. To overcome the limitation of fully tethered swimming, Alley (1952) developed a device which released the tether at a constant speed whilst simultaneously measuring the force in the tether line. Alley (1952) concluded that as the speed of the tether increased, the tether force ('surplus' propulsive force or net propulsive force) decreased due to the increase in active drag. Using a theoretical approach, Martin et al. (1981) concluded that the best method to estimate propulsive force was during semi-tethered swimming using a tether speed equal to two thirds of the swimmers' maximum swimming speed.

Vorontsov, Popov, Binevsky and Dyrko (2006) manipulated water flow velocities in a flume whilst the swimmer was fully tethered. The authors concluded that tether force measured during water flow speeds of 0-1 $m \cdot s^{-1}$ provided an indication of the strength potential of the swimmer, whereas tether force measured during water flow velocities of 1.5-1.7 $m \cdot s^{-1}$ characterised the technical ability of the swimmer. As technical ability is a key determinant of performance, tether forces measured during water flows or tether speeds above 1 $m \cdot s^{-1}$ increase the ecological validity of the tether force data (Alley, 1952; Morouço et al., 2011; Vorontsov et al., 2006). However, Vorontsov et al. (2006) stated that measuring tether forces in a flume was limited by the formation of a large standing wave in front of the swimmer during water speeds above 1.7 $m \cdot s^{-1}$. For that reason the authors restricted the speed of the water flow to 1.7 $m \cdot s^{-1}$in their study. A further limitation was that the use of a flume was both costly and time consuming. In light of the previous research it appears that tethered swimming is the most reliable (Kjendlie & Thorsvald, 2006), valid (Yeater et al., 1981) and muscle specific (Bollens et al., 1988) method of directly accessing propulsive force. In addition, tether force should be recorded whilst the swimmer is progressing down the pool in order to increase the ecological validity of the measurements (Alley, 1952; Martin et al., 1981).

2.3 MECHANICAL POWER PRODUCTION IN SWIMMING

2.3.1 Definitions and Background Theory

Mechanical power can be defined as the rate at which work is done by a muscle or group of muscles, and is the product of force and velocity (Knudson, 2009; Van Praagh, & Dore, 2002). In the context of swimming, mechanical power is the rate at which energy is transferred from the swimmer to the aquatic environment (Toussaint & Truijens, 2005). The total mechanical power produced by the swimmer is used either to effectively overcome drag (i.e., propel the swimmer in a forwards direction) or is wasted by giving water kinetic energy in a non-propulsive direction (Toussaint & Truijens, 2005).

Toussaint highlighted that of the total mechanical power produced, faster swimmers expended a greater proportion to overcome drag, compared to their slower counterparts. Moreover, mechanical power losses to the water are highly dependent on technique, as skilled swimmers lose a lower proportion of mechanical power to the water, compare to unskilled swimmers (Toussaint & Truijens, 2005). The ratio between the power to overcome drag and the total mechanical power output is defined as propelling efficiency. Toussaint and Truijens (2005) reported that at a speed of 1.29 $m \cdot s^{-1}$ competitive swimmers have a higher propelling efficiency (63.5%) compared to lesser skilled triathletes (44%). The authors stated that the difference in propelling efficiency between skilled and lesser skilled swimmers, underlines the importance of technique (i.e., optimising propelling efficiency) as a performance determinant.

When assessing mechanical power as a determinant of performance and technical ability, identifying the effective power (power to overcome drag) and the wasted power (power lost to the water) is of greater importance than determining total mechanical power alone. While some swimming ergometers assess the total mechanical power against a fixed surface (Swain, 2000; Toussaint et al., 2006), others measure the external power against the ergometer (Costill, Rayfield, Kirwan, & Thomas, 1986). Surprisingly, researchers assessing mechanical power using swimming ergometers rarely specify which aspect of power is being calculated, so caution must be taken when making inter-study comparisons. Chapter 4 of this thesis will provide a detailed explanation regarding the differences in the power calculated by various swimming ergometers.

2.3.2 Swimming Ergometers

There are two main types of swimming ergometer; dry-land and water-based. One of the most well established dry-land ergometers is the swim bench. The swim bench requires the participant to lie in a prone position on a bench and mimic the swimming stroke by pulling on paddles, attached to a cable which is released at a pre-set maximum speed (Swaine, 2000). Scientific studies have stressed the importance of the swim bench in terms of increasing arm power (Sharp, Troup, & Costill, 1982), enhancement of physiological parameters, such as anaerobic capacity (Takahashi, Bone, Cappaert, Barzdukas, D'Acquisto, Hollander, & Troup, 2002) and determination of recovery time from injury (Swaine, 1997). Sharp et al. (1982) investigated the relationship between upper body power and performance in swimming, using a biokinetic swim bench. The study reported a significant correlation between power and 25 yard (r = 0.90), 100 yard (r = 0.86), 200 yard (r = 0.85) and 500 yard (r = 0.76) swim speeds. Conversely, Costill et al. (1986) concluded that the swim bench performance was a poor predictor of performance (r = 0.24). The discrepancy between these studies may be due to the difference between the participant sample groups.

Sharp et al. (1982) used a heterogeneous sample (training distance per day ranged between 2000-14,000 yards), while Costill et al. (1986) used a homogenous sample. As the swim bench is a dry-land method, no power is expended giving water kinetic energy. As no power is lost to the water the swim bench cannot account for the difference in technical ability between participants, which would explain why swim bench power is a poor predictor of performance in a homogenous sample.

Previous studies which have used the swim bench method have observed that the swimmers' movements do not directly replicate those exhibited during free swimming (Sharp et al., 1982; Swaine, 2000). Olbrecht and Clarys (1983) examined simulated front crawl arm movement on an isokinetic swim bench and concluded that specific swimming training could not be accomplished with dry-land devices because of mechanical and environmental differences. Olbrecht and Clarys (1985) further concluded that the lack of similarity in the EMG recordings between dry-land and water-based conditions was largely due to; i) the overall time differences between dry-land and water-based arm executions; ii) the tendency for muscles to show fewer EMG peaks on dry-land; and iii) that dry-land coordination creates a different pattern of movement. Based on the EMG evidence, Tanaka, Costill, Thomas, Fink and Widrick supported the work by Olbrecht and Clarys (1983) by concluding that the time course, amplitude and frequencies of muscles used during the swim bench movement were different to those of free swimming. Due to the limitations of the swim bench as a measure of power, previous researchers have emphasised the need for better devices with a higher ecological validity (Olbrecht & Clarys, 1983).

Toussaint and Vervoorn adapted the MAD system to examine the effect of a ten week training program on maximal force, swimming speed and power and to relate the changes in these variables to competitive front crawl performance. The participants within the study were well trained swimmers and were paired-off according to swimming performance and age. Paired participants were randomly assigned to either a MAD system training group or a control group. Both groups took part in the ten week training program with a total of eight 1.5 hours training sessions per week. Three times per week for 30 minutes the MAD system training group would perform sprints on the MAD system whilst the control group did regular normal sprints. The results of the study showed a 3% increase in force (91-94 N), 3% increase in swimming speed and 7% increase in power (160-172 W) for the MAD system training group, but no significant increase was seen within the control group. The authors concluded that the significant increase in force, swimming speed and power may have been a consequence of to the greater resistance encountered when pushing off a fixed pad rather than mobile water, during the ten week training intervention. Although it could be argued that the observed increases in force, swimming speed and power may have been due to a familiarisation effect on the MAD system. While being similar to free swimming (Toussaint et al., 2006), the main limitation of the MAD system is that although it is a water-based system, the swimmer pushes off fixed pads as opposed to the highly mobile water. This does not truly reflect free swimming.

As discussed in the Section 2.2.2.2, tethered swimming does not restrict the placement of the swimmer's hand during the underwater pull. Shionoya et al. (1999) developed a semi-tethered fixed loaded swimming ergometer by adapting a cycle ergometer (Figure 2.2). A rotating drum and a stepping magnetic motor were attached to the ergometer. A tether line was connected from the drum to the swimmer by means of a waist belt. As the swimmer progressed down the pool, the ergometer generated a voltage that was proportional to the swimmer's speed. Power was calculated as the product of the tether force and the swimming speed. In a later study, Shionoya, Shibukura, Ohba, Tachikawa and Miyake (2001) examined the power produced by swimmers during a 33 second maximal effort swim. Participants recorded a mean power of 26.9 ± 7.5 W over the duration of the test. A fixed resistive load of 7 kg was attached to the ergometer and a significant correlation ($r = 0.94$, $p < 0.01$) between the mean power over the test and 100 m swimming performance was reported.

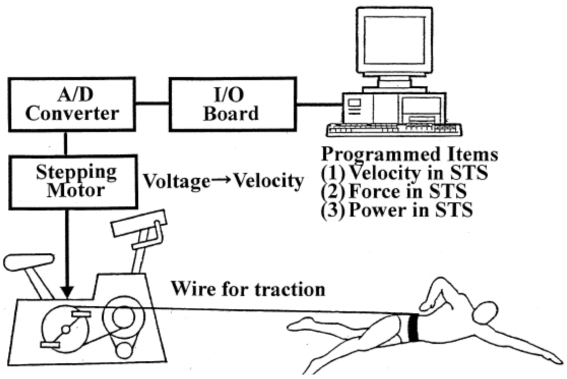


Figure 2.2: The adaptation of a cycle Ergometer to measure swimming specific power within the water (taken from Shionoya et al., 1999).

Instead of using a fixed loaded ergometer, some studies have used a tether ergometer which released the tether at a pre-set speed (Costill et al., 1986). Costill et al. (1986) adapted a biokinetic device adding a 20 m steel tether line to the system. As the swimmer progressed down the pool, the tether line restricted the speed of the swimmer. The tensional force in the tether line was measured by a force transducer in the biokinetic system and was converted to a proportional voltage output (0.5 volts, D.C.). The output from the biokinetic system was interfaced with a computer using an 8 bit A-D converter and timer. Costill et al. (1986) found that male swimmers (43.6 ± 3.3 W) produced significantly greater power during swimming than female swimmers (25.7 ± 1.8 W).

The main advantage of the system developed by Costill et al. (1986) was that it controlled the speed of the swimmer. During free swimming, the drag force acting on the swimmer increases with approximately the square of the swimming speed (Toussaint & Truijens, 2005). At a constant speed the drag force acting on the swimmer's body will remain constant. By restricting the swimmer to a constant speed any changes in power must be directly related to changes in the propulsive force. Although Alley (1952) did not calculate power, the device and methods used are relevant to this section of the chapter. The author realised that the measured tether force was only a proportion of the total propulsive force produced by the swimmer. The tether force was the propulsive force produced above and beyond that required to swim at the tether speed and was thus termed, the 'surplus' propulsive force (Alley, 1952). To gain a better understanding of the total propulsive force, Alley (1952) estimated the propulsive force required by swimmers to swim at each tether speed. This force was estimated by towing the swimmers passively towards the measurement apparatus. The total propulsive force was then calculated as the sum of the surplus propulsive force (tether force) and the estimated force required by the swimmer to swim at the tether speed (passive drag). The sum of these forces was referred to as the 'effective' propulsive force (Alley, 1952; Schleihauf et al., 1983). With recent technological advances, the study by Alley (1952) could be expanded by using current tether ergometers (e.g., Costill et al., 1986) to calculate the power measured by the ergometer, estimate the power to swim at the tether speed and to calculate the 'effective' power of the swimmer, at a range of speeds and under different conditions.

2.4 MUSCLE FATIGUE

2.4.1 Definitions and Background Theory

Muscle fatigue can be defined as any exercise-induced reduction in the maximal capacity to generate force or power (Vøllestad, 1997). By identifying the 'weak link in the fatigue chain' it is possible to delay the onset of fatigue and consequently, the associated decrease in performance (Williams & Ratel, 2009). Fatigue can be categorised into two main forms; these being central fatigue and/or peripheral fatigue. Central fatigue can be defined as failure in locations found in the brain, spinal cord and up to the point of the excitation site of the motoneuron (Williams & Ratel, 2009). Peripheral fatigue is related to the failure in the transmission of the neural signal or a failure of the muscle to respond to neural excitation (Williams & Ratel, 2009). However, the relative roles of peripheral and central factors in the development of muscle fatigue remain unclear (Vøllestad, 1997). Fatigue comprises of a spectrum of events for which there appears to be no single causative factor (Williams & Ratel, 2009). Due to the complexity of fatigue and the intricate swimming movement, very few studies have examined the effect of fatigue on biomechanical aspects of swimming performance.

2.4.2 Quantifying Fatigue in Swimming

Fatigue has a detrimental effect on swimming performance. For example, during a 100 m swimming race a swimmer's speed can reduce by ~12% due to fatigue (Toussaint et al., 2006). Fatigue can affect the body's ability to successfully reproduce a movement (Gates & Dingwell, 2008). During a swimming power test to exhaustion on the swim bench, Potts, Charlton and Smith (2002) found that towards the end of the test some swimmers appeared to lose 'fluidity' of the swimming stroke and adopted a 'lurching' stroke. During the test, participants (5 male, 5 female; age 20.5 ± 2.3 years; 400 m freestyle time 278 ± 20.5 s) were required to complete four incremental swims to exhaustion. Only the fourth trial was used for the final analysis. Potts et al. (2002) noted the power produced by each arm decrease over time, while the bi-lateral difference in power increased. By the final 30 s of the test, participants presented a broad imbalance of power between the left arm (54.0 ± 3.87% of peak power) and right arm 46.0 ± 3.87% of peak power).

Toussaint et al. (2006) examined the effect of fatigue on power output and efficiency during a 100 m front crawl swim and a 100 m front crawl swim on the MAD system (arms only). During the 100 m swim, the power produced by the swimmers decreased by 24%. The authors concluded that with the onset of fatigue, not only did power output decrease but stroke rate and swimming speed also decreased. Toussaint et al. (2006) emphasised that when swimming on the MAD system a decrease in propulsive force was directly related to stroke rate, with technique remaining constant (Toussaint et al., 2006). Conversely, during free swimming the authors observed a reduction in propelling efficiency (i.e., a greater proportion of total power lost to the water) towards the end of the race as the swimmer became fatigued, due to a reduction in stroke technique. Very few studies have examined the effect of fatigue on swimming technique.

One study which has examined the effect of fatigue on technique was performed by Aujouannet, Bonifazi, Hintzy, Vuillerme and Rouard (2006). The authors examined the spatial and temporal parameters of both the whole stroke and 3D finger tip pattern during a high intensity swimming test. This high intensity swimming test consisted of 4 × 50 m maximal effort front crawl sprints separated by 10 s rest. Aujouannet et al. (2006) found a significant difference in temporal stroke parameters with the onset of fatigue, whereas no significant difference was found between spatial or trajectory parameters. The authors concluded that with the onset of fatigue, stroke rate became the most important factor to determine swimming speed, supporting the work by Toussaint et al. (2006).

As previously discussed within this literature review (Section 2.2.2), tethered swimming is highly reliable and can be considered the most sports specific ergometer for swimmers (Filho & Denadai, 2008). Yet surprisingly very few studies have investigated or attempted to quantify the decline in force and power during tethered swimming. One study which has examined the effect of fatigue on tether force was performed by Morouço et al. (2011) who recorded maximum force (the highest value of force produced during the first 5 s), mean force and fatigue index during an all-out 30 s tethered swimming test. The fatigue index was expressed as the percentage decline in force from the peak force recorded during first 5 s and the peak force recorded in the final 5 s of the test. The authors reported a fatigue index of 37.59 ± 8.24%. In a separate study, Shionoya et al. (2001) examined the decline in power during a 33 s maximal effort swim on a fixed loaded ergometer. The authors reported a 79.1 ± 9.4% decline in power. To date this is the only study which has examined the decline in power using a tether ergometer.

2.4.3 Electromyography as a Measure of Fatigue

Surface EMG reflects both central and peripheral neuromuscular properties, since its main characteristics (amplitude and frequency) depend on the muscle fibre membrane properties and timing of motor unit action potentials (Farina, Fattorini, Felici, & Filligoi, 2002). As the muscle becomes fatigued, the number of active motor units decrease, muscle fibre conduction velocity decreases, motor units fire more slowly and the motor units become more synchronised (Farina et al., 2002; Gates & Dingwell, 2008). This can lead to a decrease in the mean and median frequencies of the EMG signal. The shift in the frequency of the EMG signal is usually analysed in the frequency domain (i.e., Fourier transform). Despite the frequent use of the Fourier transform within swimming research, there are limitations to this type of analysis which are outlined later in Chapter 8.

Aujouannet et al. (2006) examined EMG recordings of the biceps brachii and triceps brachii during isometric voluntary contractions before and after a 4 × 50 m high intensity swimming test. The authors used a Fourier transformation to evaluate the frequency content of the static recordings and found a decrease in the mean frequency in both muscles. Using the same exhaustive test, Caty, Rouard, Hintzy, Aujouannet, Molinari and Knaflitz (2006) examined neuromuscular fatigue in both the frequency and time domain. The shift in the instantaneous mean frequency of the extensor carpi ulnaris and the flexor carpi ulnaris was examined for each 25 m of the test. Between the first 25 m and the final 25 m, the instantaneous mean frequency of the extrensor carpi ulnaris and flexor carpi ulnaris decreased by 11.41% and 8.55%, respectively. They concluded that the magnitude of the decrease strongly reflected the involvement of the two muscles during swimming.

Stirn, Jarm, Kapus and Strojnik (2011) examined neuromuscular fatigue, using amplitude and frequency parameters, during a 100 m maximal effort front crawl swim. Stirn et al. (2011) recorded EMG activity in the pectoralis major (sternal and clavicular portions), latissimus dorsi and triceps brachii (long head and lateral head). Muscles were deemed ‘active’ at 30% of the local maximum energy envelope. The average duration of the active and non-active phases of the stroke was calculated for each of the five muscles at the beginning (from the second to sixth stroke of the first 25 m) and the end (five consecutive strokes without the last stroke in the final length) of the 100 m swim. The average duration of the active and non-active phases, for each muscle, were compared between strokes. The authors found that during the final part of the test, the duration of the underwater phase increased resulting in the latissimus dorsi remaining active for longer when the swimmer was in a fatigued state. In their study, Stirn et al.

(2011) also examined changes in the mean frequency of the muscle activity. The authors presented a decrease of 20.5 – 24.6% relative to the initial mean frequency at the beginning of the test. Stirn et al. (2011) concluded that the changes in the amplitude and frequency of EMG parameters mirrored the appearance of fatigue.

Rouard (2010) stressed that although EMG provides us with an insight into the fatigued state of the muscle, it does not account for the individual strategies used by swimmers to cope with fatigue. Therefore, when using EMG as a measure of muscle fatigue other biomechanical measures, such as propulsive force and external power, should be used. Few studies have examined the relationship between neuromuscular fatigue and the decline in propulsive force or external power; however, one such study was performed by Ganter, Witte, Edelmann-Nusser, Heller, Schwab and Witte (2007). The authors examined changes in the frequency of the EMG signal and changes in power calculated on the swim bench during different training periods. The selected muscles for the study were both portions of the triceps (long head and lateral head) and the latissimus dorsi. The authors found that the long head of the triceps was the most sensitive indicator of a decline in power output on the swim bench. Ganter et al. (2007) concluded that the sensitivity of the long head of the triceps was due to the important role the muscle plays in the development of propulsive force.

Only a few studies have examined neuromuscular fatigue during swimming, all of which have examined the frequency shift in different muscles (Aujouannet et al., 2006; Caty et al., 2006; Stirn et al., 2011). Despite the use of different muscles, each study concluded that the decline in the mean or median frequency confirmed the importance of each specific muscle during swimming. In a review of EMG literature, Clarys and Cabri (1993) stated that during swimming it can be assumed the majority of the muscles in the body are active (≈170 single muscles). Due to the limited number of studies examining neuromuscular fatigue in swimming, only a small number of muscles in the body have been examined. In addition, inter-study comparisons are quite difficult due to the different protocols and processing techniques employed in each study. The large number of muscles active during swimming, and the inconsistencies of the methods used, has resulted in the current knowledge base regarding the impact of neuromuscular fatigue on swimming to be quite limited.

CHAPTER 3

EXPERIMENTAL STUDY 1

FORCE PRODUCTION OF TRAINED ABLE-BODIED AND UNILATERAL ARM AMPUTEE SWIMMERS DURING A 30 S TETHERED FRONT CRAWL SWIM.

The aim of this study was to examine changes in the tether (propulsive) force produced by trained unilateral arm amputee swimmers during a 30 s maximal effort swim, and to compare the results to those of a group of well-matched able-bodied swimmers.

Chapter 3: Force Production of Trained Able-Bodied and Unilateral Arm Amputee Swimmers During a 30 s Tethered Front Crawl Swim.

3.1 INTRODUCTION

In competitive swimming, a key determinant of success is the magnitude of the propulsive forces generated by the swimmer. In the front crawl technique, the majority of the propulsive force is generated by the swimmer's arm action (Berger, De Groot, & Hollander, 1995; Arellano, 1999). Most studies that have attempted to estimate the amount of propulsion generated by the arms have focussed on the hand (Gourgoulis, Aggeloussis, Vezos, Kasimatis, Antoniou, & Mavromatis, 2008) or the hand together with the forearm (Berger et al., 1999; Bixler & Riewald, 2002; Roubou, Silva, Leal, Roacha, & Alves, 2006). The motion of the upper arm is not generally thought to contribute to propulsion in able-bodied front crawl swimming. This notion is supported by Hay and Thayer (1989) who demonstrated that when the arm is in the propulsive phase of the arm stroke cycle, the upper arm and shoulder are moving forwards relative to the water and therefore encounter resistive drag.

Competitive swimmers who have a partial or total amputation of the arm are at a disadvantage, when compared to their able-bodied counterparts, as they have been deprived of important propelling surfaces (Payton & Wilcox, 2006); this is reflected by the performances of elite amputee swimmers. At the end of 2010, the world best 100 m front crawl times for male and female unilateral arm amputees were 55.3 s and 64.9 s, respectively; approximately 15-20% slower than the corresponding able-bodied world records. While there is evidence to indicate that the upper arm segment does not contribute significantly to propulsion in able-bodied front crawl, this may not be the case for single arm amputee swimmers. Using computational fluid dynamics, Lecrivain et al. (2008) demonstrated that it is possible to generate propulsive forces with the upper arm alone, but the forces produced are considerably lower than those previously reported for hand and forearm propulsion (Berger et al., 1996; Rouboa et al., 2006). This finding may be important to competitive swimmers who have a partial or complete amputation of the arm but currently it has not been verified through direct measurement of forces.

A popular method of measuring a swimmer's propulsive force capability is tethered swimming. This involves attaching the swimmer to a cable, the other end of which is connected to a force measuring transducer. This method has been shown to have good test-retest reliability (Kjendlie & Thorsvald, 2006) and to involve muscle activity patterns that are very similar to those displayed in free swimming (Bollens et al., 1988). The validity of tethered swimming as a swimming specific mode of testing was further supported by Yeater et al. (1981) who presented a significant correlation (r = 0.86) between mean tether force and 100 yard swimming time.

In addition to being able to determine a swimmer's capacity to generate propulsive force and any bilateral asymmetry resulting from physical impairment, tethered swimming can also be used to measure the decline in force production over a give time period. This decline is commonly expressed as a 'fatigue index'. Several researchers have used a 30 s fully tethered swimming protocol to investigate fatigue in able-bodied swimmers (Rohrs & Stager, 1991; Morouço et al., 2009) but to date no such research has been conducted on swimmers with a disability. Swimmers, such as arm amputees, who have to rely predominantly on one arm for propulsion might be expected to fatigue more rapidly than those who can share the load evenly between two arms. Consequently, when attempting to facilitate fair competition for swimmers with a disability, consideration must be given not only to how their impairment limits their capacity to generate propulsion, but also to how it might affect their ability to sustain propulsion during a race.

In the IPC classification system, assigns swimmers to one of ten classes based on the level of their physical impairment (Chapter 2; Section 2.2.1). Swimmers with a single arm amputation at elbow level are considered to have a relatively low level of impairment and compete in the S9 class alongside swimmers who are deemed to have a similar level of impairment. The current classification system combines a dry-land musculoskeletal assessment and a water-based assessment. As there is little scientific literature available to underpin classification, the system relies on expert, but predominantly subjective opinion, rather than on empirical evidence. Some have questioned the fairness and subjectivity of the classification system (Keogh, 2011; Souto et al*.,* 2006). Therefore, there is a clear need for objective data to help develop a more objective, evidence-based classification system for disability swimming.

In order to contribute to the limited extant research literature providing objective classification data for swimmers with a disability, the aim of this study was to examine changes in the tether (propulsive) force produced by trained unilateral arm amputee swimmers during a 30 s maximal effort swim, and to compare the results to those of a group of well-matched able-bodied swimmers. The experimental hypotheses were: 1) that the arm amputee group will produce significantly lower mean tether forces than the able-bodied group, and 2) the arm amputee group will exhibit a significantly greater decline in force (fatigue index) than the able-bodied group.

3.2 METHOD

3.2.1 Participants

The study involved two groups of swimmers. Group 1 consisted of nine well trained IPC Class S9 female swimmers (age 16.1 ± 3.2 years; height 1.64 ± 0.04 m; body mass 57.7 ± 6.5 kg; 100 m front crawl time 74.5 ± 5.1 s). All were congenital unilateral arm amputees, at the level of the elbow. All swimmers competed at national level or above. Group 2 consisted of nine well trained female swimmers who had no physical impairment. This group were of a similar age (15.6 ± 0.5 years), height (1.66 ± 0.06 m) and body mass (56.2 ± 5.1 kg) to Group 1, but had a mean 100 m front crawl time of 62.7 ± 2.1 s. Data collection procedures were approved by MMU Cheshire's Department of Exercise and Sport Science Ethics Committee. All participants (or their parents in the case of minors) provided written informed consent before taking part in the study.

3.2.2 Data Collection

Propulsive force measurements were taken during fully tethered swimming. Participants wore a belt around their waist. Attached to the belt was a 2.5 m aluminium pole, which was then secured to a strain gauge force transducer (Tedea-Huntleigh S type, model 616) mounted on the end of the pool. The electrical output from the transducer was converted using a 12-bit analogue to digital converter (Picoscope ADC42) with a sampling frequency of 100 Hz. Force data were captured on a laptop computer using bespoke software.

After a 1000 m warm-up, participants were given sufficient time to familiarise themselves with tethered swimming. They then performed a maximal effort front crawl swim for 30 s. A 5 s period was given at the beginning of the test for the participants to reach maximal effort. In order to eliminate possible effects of the breathing action on the tether force measurements, participants wore a swimming snorkel (Finis®).

Trials were filmed from the side view underwater using an analogue video camera (Bowtech ROS DIVECAM) and recorded using a digital video cassette recorder (Sony GV-D1000E). Stroke cycle duration was obtained using SIMI Motion 7.2 (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). This software enabled individual video fields to be displayed so the analysis could be undertaken at a sampling frequency of 50 Hz. Force data was synchronised with the video sequences using a manual trigger which simultaneously activated an LED in the field of view of the camera and created a 'pulse' on the force data.

3.2.3 Data Analysis

Each 30 s trial was divided into six 5 s windows. The mean tether force (TF) produced by three consecutive stroke cycles within each window was calculated (one stroke cycle was defined as the period between two consecutive hand entries). TF_{0-5} represents the mean tether force produced by three stroke cycles within the first 5 s window; TF_{5-10} the mean tether force produced by three stroke cycles, within the second 5 s window, and so on. TF_{0-30} was the mean tether force produced during the 30 s trial. TF_{MAX} was the highest mean tether force recorded within one 5 s window and TF_{PEAK} was the mean of all the peaks produced by the dominant arm (able-bodied) or affected arm (arm amputee) over the 30 s test (Figure 3.1). The fatigue index (FI) was the percentage decline in the mean tether force between the first and final 5 s of the test, i.e., $([TF_{0\text{-}5} - TF_{25\text{-}30}] / TF_{0\text{-}5}) \times 100\%$.

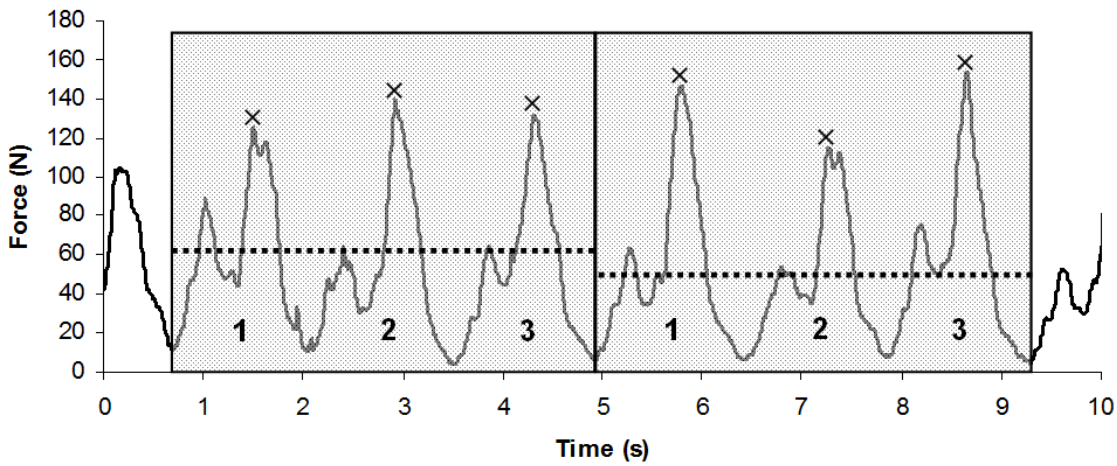


Figure 3.1: A typical force-time curve during the first 10 s of the tethered swimming test for an amputee swimmer. The shaded boxes highlight the three strokes identified within each 5 s window. The dashed lines (.....) signify the mean tether force; the crosses (×) signify the peak tether force.

Stroke rate (SR), expressed in strokes per minute, was calculated for each 5 s window from the time taken to complete three full stroke cycles (SR = 3 / three stroke time × 60). $SR_{0\text{-}5}$ represents the mean stroke rate between 0-5 seconds; $SR_{5\text{-}10}$ the mean stroke rate between 5-10 seconds, and so on. The decline in stroke rate (SRD) was calculated as the percentage decline in stroke rate between the first and final 5 s of the test, i.e., $SRD = ([SR_{0\text{-}5} - SR_{25\text{-}30}] / SR_{0\text{-}5}) \times 100\%$.

3.2.4 Statistical analysis

Homogeneity of variance was verified using Levene's test. The data were normally distributed which was assessed using the Shapiro-Wilks test. Independent *t*-tests were used to compare $TF_{0\text{-}30}$, TF_{PEAK}, SRD and the FI between the two groups. Multiple independent *t*-tests were used to compare the mean tether force and the SR within each 5 s window between the two groups. A Pearson's Product Moment correlation was performed to examine the relationship between TF_{MAX} and 100 m sprint performance (i.e., 100 m personal best time). In all comparisons, the level of significance was set at $p < 0.05$. Statistical analysis procedures were performed using SPSS 14.0 software.

3.3 RESULTS

The tethered forces produced by the two groups during the 30 s test are illustrated in Figure 3.2. There was a significant correlation between TF_{MAX} and 100 m time for the amputee group ($r = -0.71$; $p < 0.05$) and the able-bodied group ($r = -0.83$; $p < 0.01$). The mean tether force produced by the able-bodied group over the 30 s ($TF_{0\text{-}30} = 71.0 \pm 8.9$ N) was significantly higher than of the arm-amputee group ($TF_{0\text{-}30} = 55.7 \pm 3.5$ N). Both groups produced their highest tether forces in the first 5 s of the test, that is, $TF_{MAX} = TF_{0\text{-}5}$ (able-bodied $TF_{MAX} = 80.8 \pm 10.6$ N; arm-amputee $TF_{MAX} = 66.1 \pm 3.2$ N, $p < 0.05$) and the lowest tether forces in the last 5 s (able-bodied $TF_{25\text{-}30} = 63.6 \pm 7.8$ N; arm-amputee $TF_{25\text{-}30} = 48.9 \pm 3.5$ N, $p < 0.05$). There was no significant difference in TF_{PEAK} between the groups with the amputee group recording slightly higher values of TF_{PEAK} (157 ± 29 N) compared to the able-bodied group (155 ± 16 N).

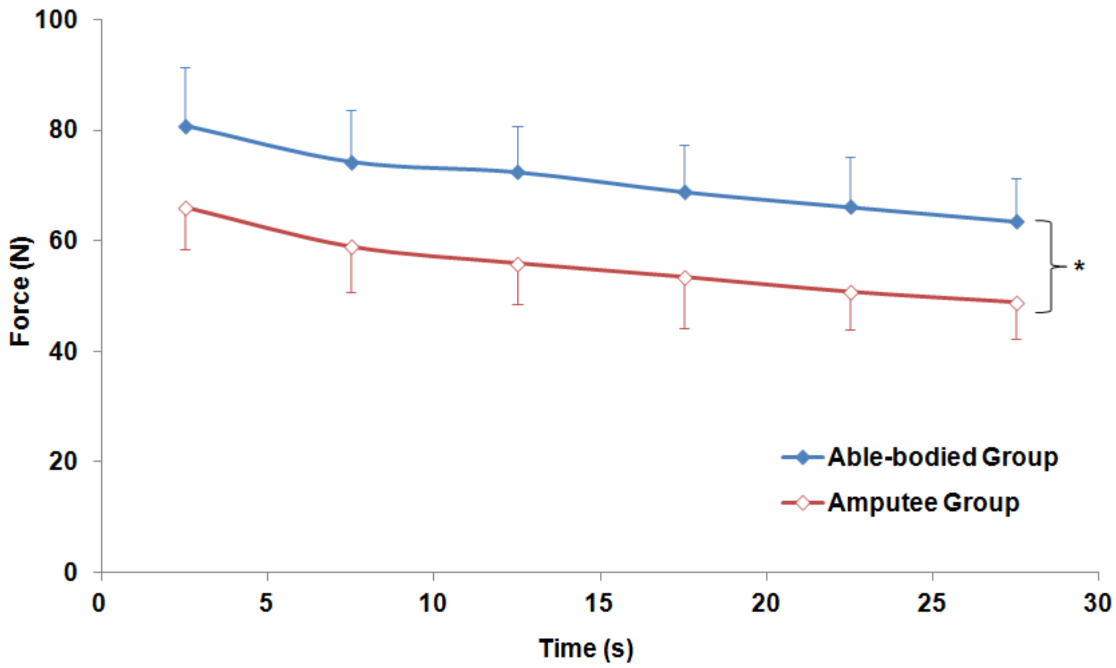


Figure 3.2: Tether force (mean ± SD) for each 5 s window of the 30 s tethered swimming test for the able-bodied (N = 9) and arm-amputee (N = 9) groups. * denotes a significant difference ($p < 0.05$)

There was no significant difference between the FI of the two groups. The able-bodied group exhibited a mean FI of 21.7 ± 7.4%, compared to 23.2 ± 5.1% for the arm-amputee group.

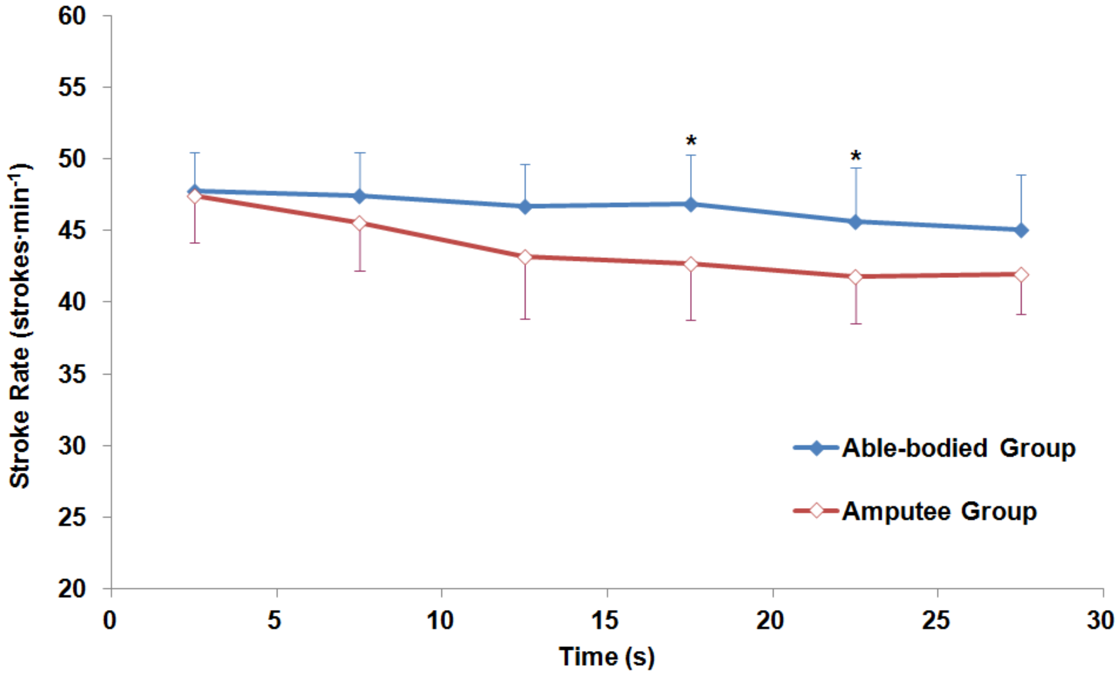


Figure 3.3: Stroke Rate (mean ± SD) for each 5 s window of the 30 s tethered swimming test for the able-bodied (N = 9) and arm-amputee (N = 9) groups. * denotes a significant difference between groups at *p* < 0.05 level.

The stroke rates used by the two groups are presented in Figure 3.3. During the first 15 seconds of the test there was no significant difference in the SR used by the two groups. However, between 15-25 s, the amputee group presented a significantly (p<0.05) lower SR than the able-bodied group. During the course of the test, the arm-amputee swimmers experienced a statistically greater SRD compared to the able-bodied group (able-bodied = 6.5 ± 5.5%; arm-amputee = 11.4 ± 4.1%).

3.4 DISCUSSION

The aim of this study was to quantify the decline in tether force exhibited by trained unilateral arm amputee swimmers during a 30 s maximal effort front crawl tethered swim and to compare the results to those of a matched group of able-bodied swimmers. The study showed that the arm amputee swimmers produced significantly lower mean tethered forces than the able-bodied group; the first hypothesis was therefore accepted. There was no significant difference in the decline in force over the 30 s swim (FI) between the arm amputee group and the able-bodied group; the second hypothesis was therefore rejected.

Both groups presented a strong relationship between TF_{MAX} and 100 m time, supporting the work by Yeater et al. (1981). Interestingly, Yeater et al. (1981) recorded mean tether forces that were approximately 2-3 times higher than those recorded in this current study. The disparity between the two studies may be attributed primarily to age and gender differences of the participants; Yeater et al. (1981) used a sample of male university swimmers; the current study used female swimmers with a mean age of 15.8 years. Previous studies have stressed that when comparing tether force between studies, test duration, gender, anthropometric characteristics and performance level must be taken into consideration (Magel, 1970; Morouço, Soares, Vilas-Boas, & Fernandes, 2008; Sidney et al., 1996; Vorontsov et al., 1999). Morouço et al. (2008) examined tethered forces over 30 s using a similar sample to the current study (age 14-17 years; height 1.71 ± 0.09 m; body mass 60.6 ± 6.2 kg). These authors however did not specify the gender of the participants. The study reported a mean tether force of 61.4 ± 22.8 N which is higher than the $TF_{0\text{-}30}$ for the amputee swimmers and slightly lower than the $TF_{0\text{-}30}$ for the able-bodied swimmers within this study.

Surprisingly, despite the significant difference in mean tether force and the comparatively large difference in 100 m performance time (able-bodied = 62.7 ±2.1 s; amputee swimmers = 74.5 ± 5.1 s), there was no significant difference in the peak tether force produced by the dominant arm. As the two groups were closely matched in terms of age, height and body mass, the similarity in peak tether forces between the amputee and able-bodied swimmers is a strong indication that the main discriminating factor between the two groups was the physical impairment of the amputee swimmers. Due to the overlapping of the propulsive phase of the two arms that occur during front crawl (Seifert, Chollet, & Allard, 2005) it was not possible to calculate the mean tether force for each arm independently.

If it were possible to measure the tether force produced solely by the short arm during fully tethered swimming, the findings from this study could not be directly related to free swimming. During able-bodied free swimming the upper arm and shoulder move forwards relative to the water (Hay & Thayer, 1989). In fully tethered swimming the forward motion of the swimmer is prevented, resulting in the hand, forearm and upper arm having a backward velocity component relative to the water. This results in a greater proportion of the arm producing propulsive force, compared to just predominantly the hand and forearm during free swimming (Berger et al., 1999). The propulsive force values measured during fully tethered swimming can be considered an exaggerated representation of those produced during free swimming (Goldfuss & Nelson, 1971). To date no study has directly measured the propulsive force produced solely by the affected arm. Through the use of CFD, Lecrivain et al. (2008) calculated the force produced by the upper arm of a unilateral arm amputee swimmer and estimated that the affected arm does produce propulsive force (mean 3.2 N) at speeds higher than 1 $m \cdot s^{-1}$.

The stroke rate exhibited by the swimmers within this study fell slightly below the suggested optimum stroke rate (48 – 54 strokes·min^{-1}) for the generation of tether force in able-bodied swimmers (Yeater et al., 1981). The SR used by the amputee swimmers in the first 5 s of the test was identical to the stroke rate reported for female unilateral arm amputee swimmers during maximal effort free swimming (Osborough et al., 2009). Osborough et al. (2009) examined the relationships between stroke rate, stroke length and swimming speed in the same group of arm amputee swimmers. The identical SR used during maximal free swimming (Osborough et al., 2009) and fully tethered swimming, combined with a significant relationship between TF_{MAX} and performance time, indicates that fully tethered swimming has a high ecological validity in the assessment of propulsive force generation in unilateral arm amputee swimmers. On the whole there was no significant difference in $SR_{0\text{-}30}$ between the two groups; however during the latter stages of the test (15-25 s) the amputee group began to exhibit a significantly lower stroke rate. As a consequence the amputee group experienced a significantly greater SRD during the 30 s test compared to their able-bodied counterparts. The greater SRD experienced by amputee swimmers may have a negative impact on performance as not only is a high stroke rate an important determinate for sprint swimming speed (Osborough et al., 2009). Interestingly, although the amputee swimmers were more susceptible to a SRD, the group FI was not significantly different to that of the able-bodied group.

The FI (amputee 23.2 ± 5.1%; able-bodied 21.7 ± 7.4%) within this study are slightly lower than 37.6 ± 8.2% reported by Morouço et al. (2011), although it should be noted that Morouço et al. (2011) calculated FI as the percentage decline of the highest peak in the first 10 s to the lowest peak in the final 5 s. The limitation to using the peak tether force is that it is a measure of the tether force at just one instant in the stroke, whereas the mean tether force is a representation of tether force throughout the stroke (Dopsaj, Matkovic, & Zdravkovic, 2000). In addition, peak force can be affected by factors such as, the type of tether line and the frequency response of the load cell.

There was no significant difference in the FI between the amputee group and able-bodied group. It was hypothesised that the amputee swimmers would exhibit a greater decline in propulsive force, due to their inability to share the load evenly between the arms. Due to the asymmetry between the arms it was thought that the swimmers may try and compensate for the lack of an important propelling surface on the affected side, by generating more propulsion with the unaffected arm. This was not the case as the peak force produced by the affected arm of the amputee swimmers, was not significantly different to the peak force produced by the dominant arm of the able-bodied group.

The main limitation to the present study was that the propulsive force was measured whilst the swimmer was stationary. The propulsive force a swimmer can exert during static swimming is very different to that they can generate at a swimming speed greater than zero (Alley, 1952). Due to the lack of forward progression during fully tethered swimming, a greater proportion of the arm produces propulsion than during free swimming (Goldfuss & Nelson, 1971; Martin et al., 1981). As the speed of the swimmer is zero during fully tethered swimming, the drag acting on the swimmer is minimal. As swimming speed is dependent upon the individual's ability to produce high propulsive forces, whilst keeping drag force to a minimum (Toussaint & Truijens, 2005), measuring the propulsive force generated by a swimmer as they progress down the pool (i.e., during semi-tethered swimming) would have a higher ecological validity than fully tethered swimming. During semi-tethered swimming, the measured propulsive force is, in fact, the net propulsive force (i.e., the propulsive force minus the drag force). If the drag force present during semi-tethered swimming is to be accounted for, the speed of the swimmer (tether) must be taken into consideration, since drag force is directly proportional to the square of the swimming speed (Toussaint & Truijens, 2005). Since mechanical power is the product of the propulsive force and the speed of the swimmer, this measure would be expected to provide a better representation of the performance potential of the swimmer, than fully tethered forces alone.

3.4.1 Conclusion

The findings of this study demonstrated that although the tether force exhibited by trained unilateral arm amputee swimmers significantly declined during the 30 s test, it did so as at a similar rate to that of able-bodied swimmers. During a 30 s maximal effort fully tethered swim, as a consequence of their physical impairment, arm amputee swimmers produced significantly lower mean tether forces than able-bodied swimmers. However, the peak tether force produced by the dominant arm of the amputees did not differ significantly to that of the able-bodied swimmers. It appeared that arm amputee swimmers did not compensate for the lack of an important propelling surface on the affected side, by generating more propulsion with the unaffected arm.

CHAPTER 4

THE DEVELOPMENT OF AN ISOKINETIC TETHERED SWIMMING (ITS) ERGOMETER

This chapter outlines the development of a swimming specific ergometer designed to measure the mechanical power produced by both able-bodied swimmers and swimmers with a physical impairment. The development of the ergometer was a pivotal part of the Ph.D as it was the main measurement tool used in the experimental studies 2-5. This chapter details the performance characteristics and construction of the device. In addition, this chapter explores the reliability and validity of the ergometer. Finally, the chapter discusses additional items of peripheral equipment which were developed and tested in conjunction with the ergometer.

4.1 INTRODUCTION

Mechanical power can be defined as the rate at which work is done (Knudson, 2009). It should be noted that for the remainder of this thesis mechanical power will be referred to as ‘power’. The power produced during cyclical movements is often assessed using ergometers, which measure the work done, from which external power is calculated. The Wingate Anaerobic Test (WAT) is one of the most well regarded tests of power. The WAT test requires the participant to pedal or arm crank at a maximal speed against a frictional resistance for 30 seconds. External power is then calculated as the product of the known resistance (force) and the velocity of the flywheel. The main limitation of the WAT is that the test is a poor predictor of performance in sports specific tasks (Bar-Or, 1987). When relating external power to sports performance, it is vital that the movement pattern elicited on the ergometer replicates the movement pattern observed within that sporting action . Within the context of swimming, power can be defined as the rate at which energy is transferred from the swimmer to the water (Toussaint & Truijens, 2005). However, as the generation of propulsion leads to a loss of mechanical energy (e.g., in the form of kinetic energy to the fluid), swimming ergometers are poorly developed in comparison to other sports ergometers (Shionoya et al., 1999; Swaine, 2000; Toussaint & Truijens, 2005).

The most well established swimming ergometer is the swim bench (Chapter 2; Section 2.3.2). Typically the swim bench was used to measure the external power produced solely by the upper body, however, Swaine (1997; 2000) adapted the swim bench to measure the external power produced by the legs as well as the arms. Interestingly, Swaine (2000) found the peak power output during leg kicking was higher than that of the arms. The author concluded that it might be necessary for swimmers to develop leg and arm power equally in dry-land training. While Sharp et al, (1982) presented a significant relationship (r = 0.90) between external power measured on the swim bench and performance, Costill et al. (1986) stated that this relationship (r = 0.24) was much lower in a homogenous sample (Chapter 2; Section 2.3.2). These findings are perhaps not surprising as the external power measured on the swim bench is the total power produced by the swimmer; as no power is lost to the water. As no power is lost to the water, the external power measured on the swim bench does not take into account inter-individual differences in technical ability (Chapter 2; Section 2.4.1). Excluding the effect of technique may have advantages from a physiological perspective (Swaine, 2000), from a biomechanical perspective technical ability is an important determinant of performance. In order to incorporate the effect of technical ability on external power production, measurements must be performed within the water.

The MAD system (Chapter 2; Section 2.2.2.2; Figure 2.1) was originally designed to measure active drag, but has been further used to examine power (Toussaint & Vervoorn, 1990), fatigue and propelling efficiency (Toussaint et al., 2006). Although the power measured on the MAD system appears ecologically valid, there are practical limitations to the device that preclude its use with many disabled swimmers. The MAD system requires the swimmer to push off fixed pads with the arms, while the legs are fixed together and supported by a standard pull buoy. Although the legs of the swimmer are restricted on the MAD system, Hollander et al. (1988) reported that the legs only make a small contribution to total power output (6-27%) of the swimming stroke as a whole and that power output from the arms is unaffected by the leg action. In contradiction to this, previous studies have emphasised the importance of the leg kick and its contribution to the propulsive force produced by arms and alteration of the underwater wrist trajectory (Deschodt, Arsax, & Rouard, 1999; Swaine, 2000). Nonetheless, even if the findings by Hollander et al. (1988) were true for able-bodied swimmers, this would not be applicable to disabled swimmers who have an impairment which affects part of, or both of the arms (e.g., cerebral palsy, amputation). Such swimmers may be more reliant on their legs to provide propulsion and power which would result in the legs playing a far greater role in the overall power output produced during swimming. Furthermore, swimmers with an impairment of the upper-limb may be unable to push off the fixed-pads on the system. Therefore, although power measured on the MAD system is similar to that of free swimming for able-bodied swimmers (Toussaint et al., 2006), due to the requirement of bi-lateral hand placement and by restricting the leg movement the system is unsuitable for some swimmers with a physical impairment.

Unlike the MAD system, tether ergometers do not limit the placement of the hands and the external power measured reflects the output from the whole body rather than just the upper body. There are two main forms of tether ergometer; fixed tension (Shionoya et al., 1999; 2001) and constant tether speed (Alley, 1952; Costill et al., 1986). Shionoya et al. (1999) developed an ergometer which used the fixed tension approach (described in detail in Chapter 2; Section 2.3.2). As the drag of the swimmer increases with the square of the swimming speed (Hollander et al., 1986), changes in the external power using a fixed ergometer can be related to changes in propulsive force or drag. Conversely, tether ergometers that release the tether at a constant speed ensure that any changes in external power are directly related to changes in propulsive force. For this reason, tether ergometers where the tether is released at a constant speed, are favoured over fixed tension ergometers.

Alley (1952) developed the first tethered swimming ergometer, although the author used the device to measure tether forces and made no attempt to calculate external power. The constructed device released a tether line at a pre-set speed. Swimmers were attached to the tether via a belt worn around their waist. The entire apparatus was suspended eight inches above the water during testing. During the study

Alley (1952) identified that the apparatus would swing excessively during testing, and that future studies should use a more stationary apparatus. In a much later study, aided by technological advances, Costill et al. (1986) developed a tethered swimming ergometer which released the tether at a constant speed whilst measuring the tether force produced by the swimmer. External power was computed as the product of the tether force and tether speed. Costill et al. (1986) reported a correlation of 0.84 between external power and swimming performance. Although Alley (1952) and Costill et al. (1986) developed tether ergometers that released the tether at a pre-set speed, the main limitations to the studies were that the devices allowed for a limited number of discrete speed settings and these settings were not truly isokinetic.

To date no study has examined external power in swimmers with a physical impairment. Fully tethered swimming has however, been used to measure tether forces in swimmers with a physical impairment, ranging from S2-S10 (Souto et al., 2006). The aim of this study was to develop a water-based swimming ergometer with the capability of measuring the external power of any swimmer with a physical impairment. The performance requirements of the ergometer were to: 1) measure tether force (ranging from 0 to 300 N, with a resolution < 1 N and a linearity < 3%) and, 2) control swimming speed (providing a tether speed between 0 $m \cdot s^{-1}$ to 2 $m \cdot s^{-1}$ with a resolution < 0.1 $m \cdot s^{-1}$ and a linearity < 1%). In addition, the ergometer should allow the swimmer to perform with minimal disruption of their normal swimming technique.

4.2 THE ISOKINETIC TETHERED SWIMMING (ITS) ERGOMETER

4.2.1 Construction of the ITS Ergometer

The ITS Ergometer (hardware and software) was developed in the Department of Exercise and Sports Science at Manchester Metropolitan University and was funded by British Disability Swimming. Peripheral equipment (pulley system and harness) was developed by technicians at the Loughborough Technology Institute and was funded by UK Sport.

4.2.2 The Constructed ITS Swimming Ergometer

The ITS Ergometer is a semi-tethered device which incorporates a motor-driven drum that feeds out the tether at a constant, user-selected speed (Figure 4.1). The tether is attached to the swimmer's waist via a belt and limits the swimmer to the preset speed, irrespective of the amount of propulsive force the swimmer produces. Embedded in the core of the ergometer is a strain gauge force transducer (Tedea-Huntleigh S type, model 616). As the swimmer progresses down the pool they apply a tensional force to the tether line. This force pulls on the ergometer causing it to slide fractionally along the base plate. The slight movement compresses the force transducer which is embedded in the core of the ergometer. The tether force recorded represents the surplus propulsive force produced (net propulsion) by the swimmer above and beyond that required to swim at the user-selected tether speed. For example, if the tether speed was set to 1 $m \cdot s^{-1}$ and the swimmer chose to swim at 1 $m \cdot s^{-1}$, no tether force (surplus propulsive force) would be recorded.

External power output is calculated using the following equation:

External Power (W) = Tether Force (N) × Tether Speed ($m \cdot s^{-1}$) (4.1)

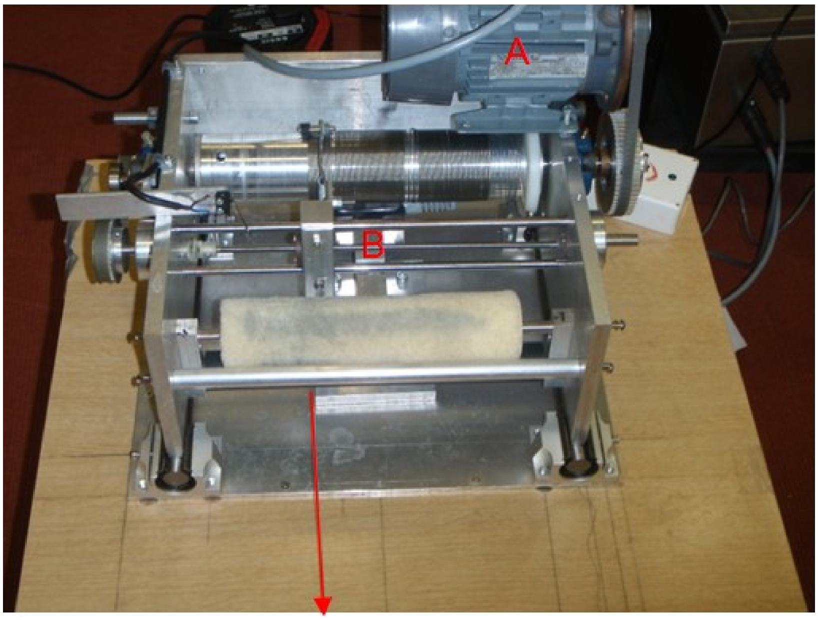


Figure 4.1: The ITS Ergometer. The area labelled A and B identify the motor and force transducer, respectively. The arrow indicates the direction in which the tether line is released.

4.3 TETHER SPEED MEASUREMENT AND CALIBRATION

4.3.1 Speed Measurement

A key performance requirement of the device was that it could provide a constant tether speed between 0 $m \cdot s^{-1}$ and 2 $m \cdot s^{-1}$ (with a resolution < 0.1 $m \cdot s^{-1}$ and a linearity < 1%). A range in tether speed of 0 – 2 $m \cdot s^{-1}$ would ensure that the device could cater for any swimmers regardless of their IPC classification.

4.3.2 Speed Calibration

Tether speed was calibrated in order to convert the motor frequency (Hz) into speed ($m \cdot s^{-1}$). This process was performed by displacing the tether belt a measured distance of 15.0 m through timing gates. A wide range of forces were manually applied during these trials, with the experimenter walking with a belt around their waist. Five trials were performed at nine different motor frequencies (range 10 – 50 Hz in increments of 5 Hz). The time to cover the set distance was used to obtain the tether speed ($m \cdot s^{-1}$). Motor frequency was then plotted against the mean tether speed (Figure 4.2). Linearity was calculated as 0.24%.

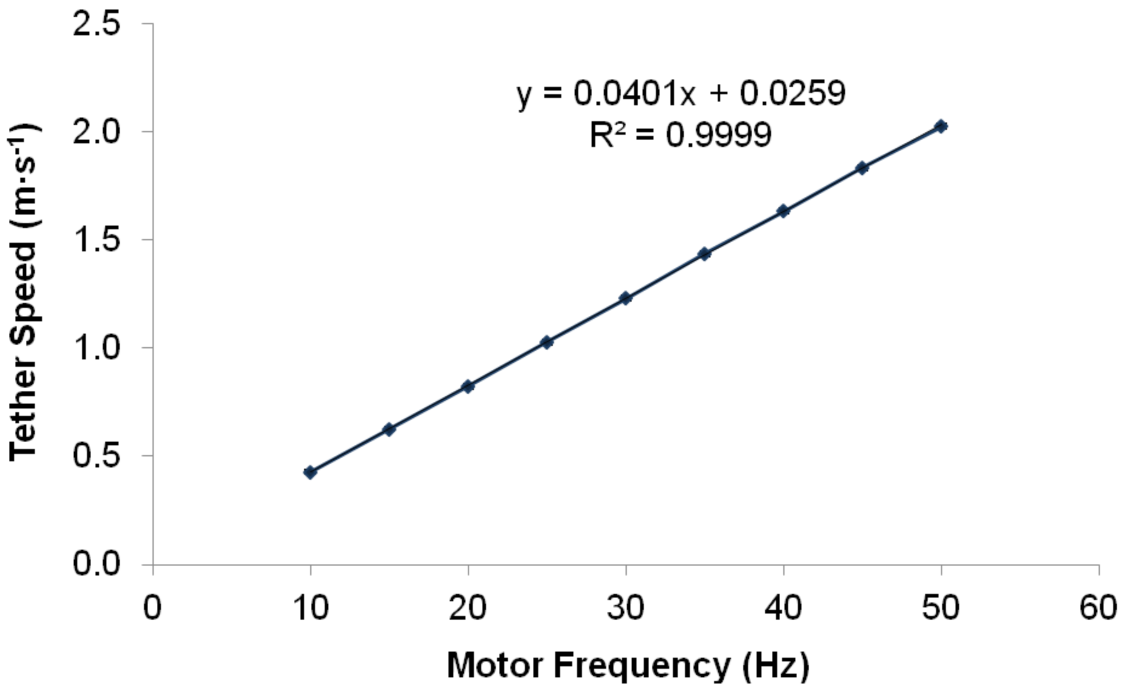


Figure 4.2: The relationship between motor frequency (Hz) and tether speed ($m \cdot s^{1}$). Each data point represents the mean value. Standard deviations were calculated but were too low (± 0.008) to display graphically. Linearity was 0.24%.

A linear trend was plotted against the data in MS Office Excel (2007), the equation for which is as follows:

$$y = m \cdot x + b \quad (4.2)$$

Where y is the tether speed ($m \cdot s^{-1}$), m is the gradient of the trend line, x is the motor frequency (Hz) and b is the intercept of the trend line. The gradient and intercept (Figure 4.2) of the trend line was substituted into the equation (4.2).

$$y = 0.0401 \cdot x + 0.026 \quad (4.3)$$

The speed control box allowed for the motor frequency to be set using a digital display on the inverter. Based on the required tether speed (y), equation 4.3 was rearranged in order to calculate motor frequency (x) based on the desired speed:

$$\text{Motor Frequency (Hz)} = (\text{Tether Speed } [m \cdot s^{-1}] - 0.026) / 0.0401 \quad (4.4)$$

4.3.3 Speed Measurement and Calibration Summary

From the speed calibration and laboratory-based testing it was evident that the criteria for the speed component of the ITS Ergometer (tether speed between 0 $m \cdot s^{-1}$ to 2 $m \cdot s^{-1}$ with a resolution < 0.1 $m \cdot s^{-1}$ and a linearity < 1%) had been met. Tether speed can be set in increments of 0.1 Hz which equates to a resolution of 0.04 $m \cdot s^{-1}$ and linearity was just 0.24%. During the trials the investigator applied varying forces to the tether line, yet no matter how much force the investigator applied the tether line would remain at the pre-set speed. A further advantage of the system was that if no force was applied to the tether line, the tether would stop being released. This feature ensured that if the speed of the swimmer dropped below the preset tether speed momentarily, the cable would remain taught.

From the five trials, at each of the nine different motor frequencies, the largest reported standard deviation was ± 0.008 $m \cdot s^{-1}$. It should be highlighted that the largest standard deviation occurred at a motor frequency of 50 Hz, which corresponded to a tether speed of 2 $m \cdot s^{-1}$. At such a high tether speed it was difficult to keep up with the speed of the tether, and ensure the tether line was under enough tension.

4.4 FORCE MEASUREMENT AND CALIBRATION OF THE ITS ERGOMETER

4.4.1 Force Measurement

Tether force is measured using a strain gauge force transducer (Tedea-Huntleigh S type, model 616) embedded in the core of the ITS ergometer. The electrical output from the transducer is converted using a 12-bit analogue to digital converter (picoscope ADC42) with a sampling frequency of 100 Hz. The electrical output from the load cell is displayed in real time and then recorded on a laptop computer using a Windows-based software developed 'in-house' at MMU.

4.4.2 Static Force Calibration

When the force transducer experiences compressive or tensional force, it produces an electrical output proportional to the force applied. Through the calibration process, a calibration equation was derived to convert the electrical output into force (N). A static calibration was performed by attaching known weights to the tether line which was horizontally aligned to the transducer and run over a pulley wheel. The electrical output of the load cell was recorded for 10 s for each given weight. Loads of between 2 – 20 kg were attached to the ergometer in increments of 2 kg. A calibration curve (Figure 4.3) was then plotted with load (N) as the independent variable and electrical output as the dependent variable.

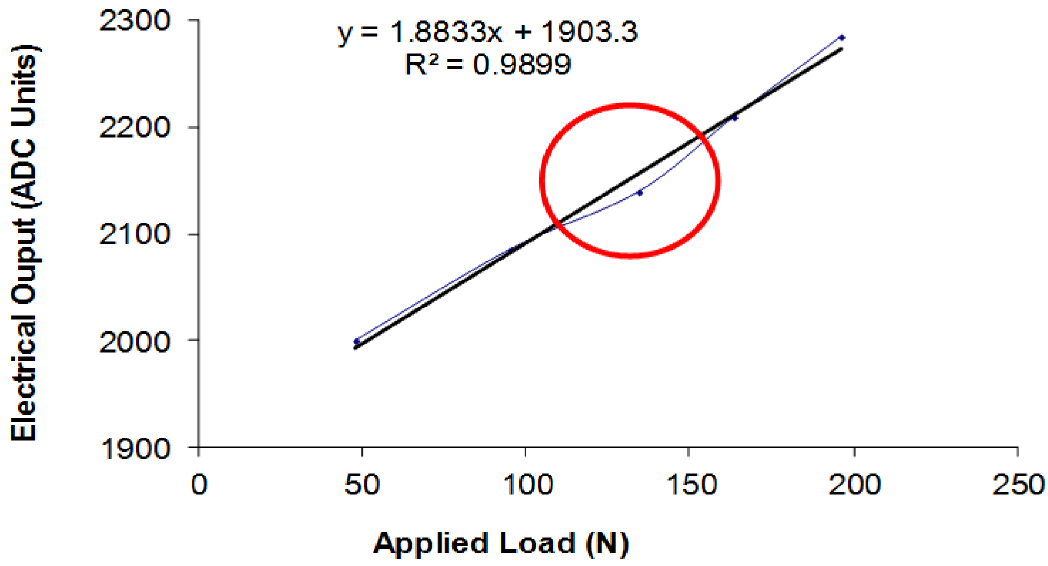


Figure 4.3: The electrical output (ADC Units) produced at each of the applied loads (N). Calibration trend line and equation are displayed within the figure. The point where the data deviated most from the trend line is highlighted.

A linear trend line was fitted to the data in MS Office Excel (2007), using the following equation:

$$y = m \cdot x + b \tag{4.5}$$

Where y is the electrical output (ADC units), m is the gradient of the trend line, x is the weight (N) and b is the intercept of the trend line.

Although the curve presents a high r^2 value the linearity was greater than 5% which was deemed unsatisfactory. It was believed that the main cause for the unacceptable linearity was due to the base-plate of the ergometer flexing as the load was applied. To combat this problem a thicker base-plate was manufactured and attached to the ergometer. The calibration process was repeated (Figure 4.4).

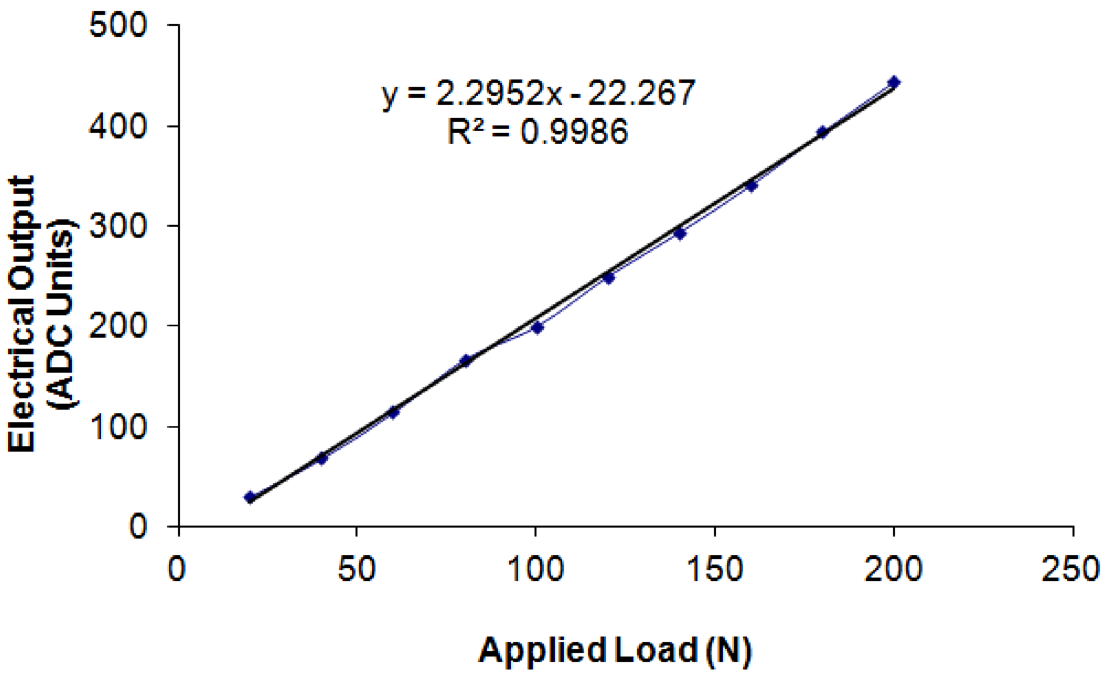


Figure 4.4: The electrical output (ADC Units) produced above the baseline value at each of the applied loads (N). Calibration trend line and equation are displayed within the figure.

As is evident from Figure 4.4, the thicker base plate improved the linearity of 0.96% ($r^2 = 0.99$) of the calibration curve. Although the data from the static calibration were valid, the ITS Ergometer is designed to measure force production under dynamic conditions, rather than static conditions. Therefore, as well as a static calibration a dynamic calibration was performed.

4.4.3 Dynamic Force Calibration

The load cell embedded within the ergometer creates two potential problems. First, the continual refinement of the ergometer around the load cell, combined with repeated testing could affect the accuracy of the measured force (e.g., linearity, frequency response). Second, at times the distance between the swimmer on the tether line and the force transducer within the ITS Ergometer may be around 30-40 metres. With such a large distance between the swimmer and ITS Ergometer any elastic properties in the tether line could have a dampening effect on the measured tether force. In order to examine these potential problems two dynamic calibration were performed; one land-based and one water-based.

4.4.3.1 Land-Based Dynamic Force Calibration

The land-based dynamic calibration was performed by simultaneously measuring the force recorded by the ITS Ergometer and the force recorded by an external ‘criterion’ load cell (Tedea-Huntleigh S type, model 616). The criterion load was attached to the end of the tether line and secured to a moveable trolley. The trolley was pulled away from the ergometer, at a range of tether speeds, in a manner similar to the way in which a swimmer would apply tension to the cable (i.e., steady fluctuations in force). Tether speeds ranged between 0.4 – 1.6 $m \cdot s^{-1}$, in increments of 0.4 $m \cdot s^{-1}$.

The electrical output from the two load cells were converted to force values using each load cell’s calibration curve (Figure 4.5).

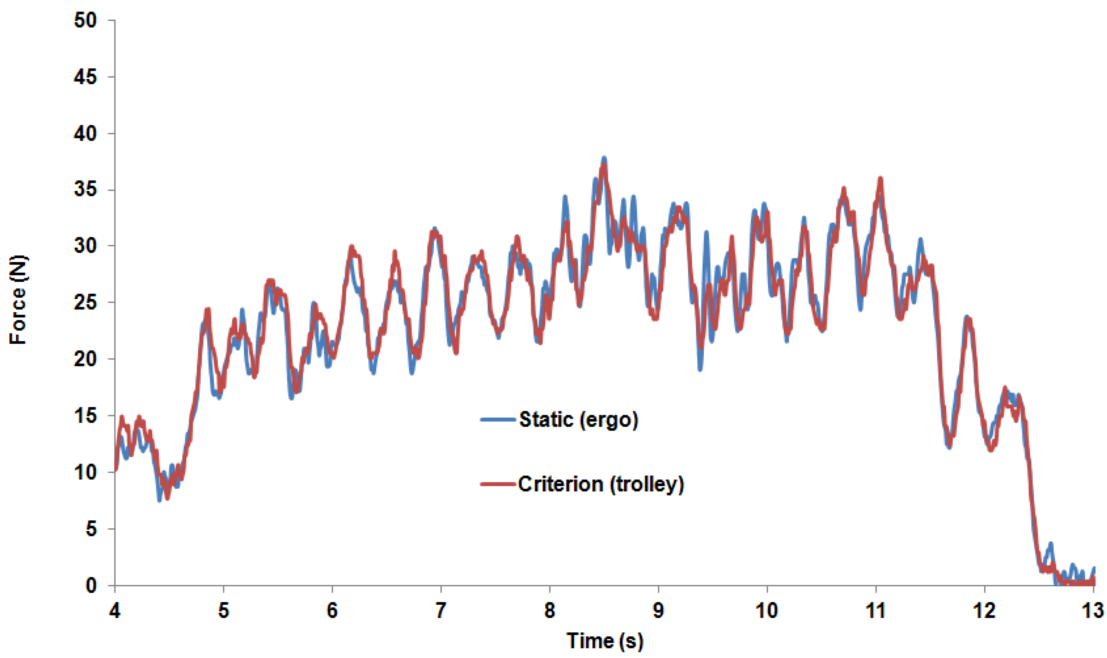


Figure 4.5: Forces measured by the load cell in the ITS Ergometer (static) and the criterion load cell attached to the trolley during the land-based dynamic calibration.

4.4.3.2 Water-Based Dynamic Force Calibration

A water-based dynamic calibration was performed using a similar protocol to that of the land-based dynamic calibration. Prior to testing, the same criterion load cell used for the land-based dynamic calibration was sealed in a neutrally buoyant enclosed case, referred to as the 'torpedo'. The torpedo was attached behind the swimmer, at a distance of 1.5 m from the waist belt. As the participant swam away from the device, tether force was measured simultaneously by the torpedo and the ITS Ergometer. The electrical output from the two load cells were converted to force values using each load cell's calibration curve. Figure 4.6 shows the over-laid signals recorded on the ITS Ergometer and the torpedo, respectively. These signals were filtered using a 2nd order, Butterworth filter with a cut-off frequency of 10 Hz.

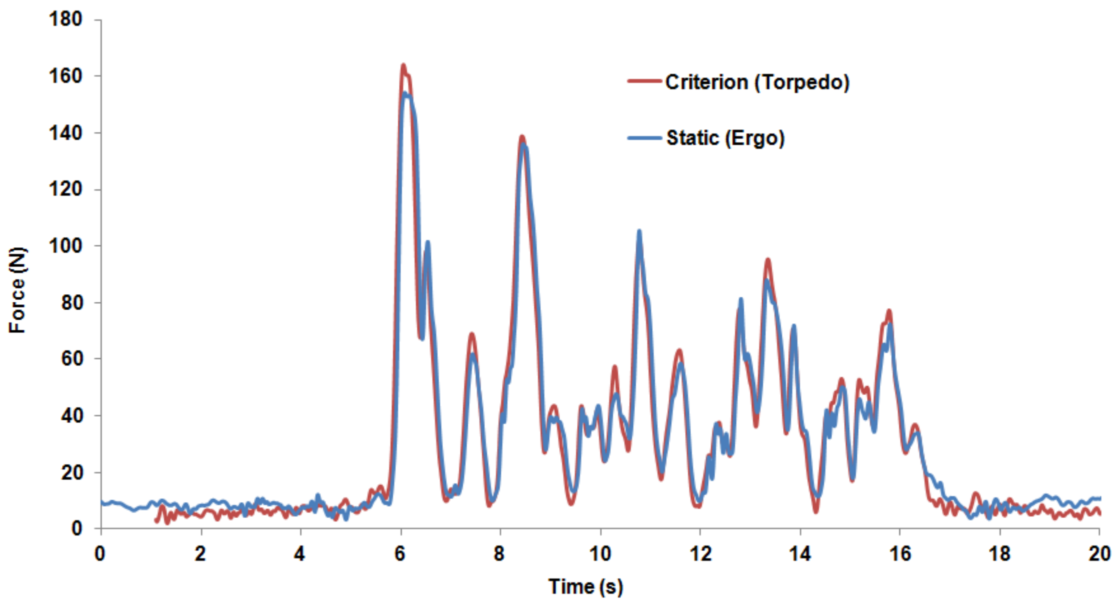


Figure 4.6: Forces measured by the load cell in the ITS Ergometer (static) and the torpedo (criterion) load cell attached to the swimmer during the water-based dynamic calibration.

4.5 TEST RE-TEST RELIABILITY

The test-retest reliability of a tether force and external power was examined. Two male (IPC Class S5 and S7) and one female (IPC Class S9) performed two trials on the ITS Ergometer at six different tether speeds, with 2 min rest between trials. The tether speeds were set as a percentage (30, 40, 50, 60, 70 and 80%) of their maximal clean swimming speed (SS_{MAX}). Figure 4.7 presents two force-time curves for an S5 swimmer at 50% of their maximal clean swimming speed (tether speed of 0.7 m·s^{-1}). During each trial the mean tether force was calculated over three consecutive stroke cycles (right arm entry to right arm entry). External power was calculated as the product of the mean tether force and the speed of the tether (Table 4.1).

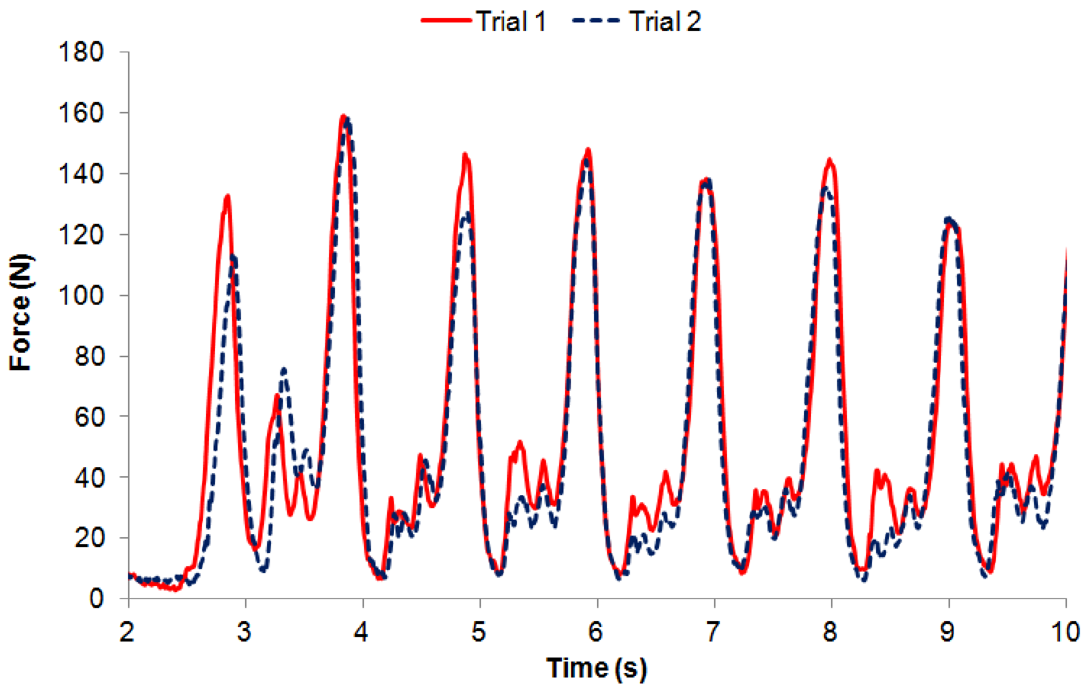


Figure 4.7: The tether force produced, during two separate consecutive trials, by an S5 swimmer at a tether speed of 0.7 m·s^{-1}.

Table 4.1: External power produced by an S5 (male), S7 (male) and S9 (female) swimmer at six different tether speeds, with two trials performed at each speed.

Participant IPC Class	Tether Setting (% of SS_{MAX})	Tether Speed (m·s^{-1})	Power (W) Trial 1	Power (W) Trial 2
S5 (Male)	30	0.39	17.8	16.9
	40	0.52	26.9	27.2
	50	0.66	32.2	35.0
	60	0.79	35.4	36.3

	70	**0.92**	**25.6**	**28.6**
	80	**1.05**	**22.9**	**19.6**
S7 (Male)	**30**	**0.51**	**36.2**	**38.1**
	40	**0.68**	**44.5**	**43.8**
	50	**0.85**	**47.3**	**45.8**
	60	**1.02**	**42.1**	**41.8**
	70	**1.19**	**30.5**	**35.5**
	80	**1.36**	**28.3**	**29.3**
S9 (Female)	**30**	**0.48**	**28.5**	**30.1**
	40	**0.64**	**32.9**	**33.6**
	50	**0.80**	**29.4**	**33.8**
	60	**0.96**	**28.6**	**28.5**
	70	**1.12**	**19.3**	**21.6**
	80	**1.28**	**10.0**	**13.9**

The repeatability of the external power scores between trial 1 and trial 2 was quantified using a coefficient of variation (CV). The CV for the S5, S7 and S9 participants was 5.2 ± 3.9%, 3.5 ± 3.7%, and 7.8 ± 8.4%, respectively. For the S5 and S9 participants these values were slightly higher than those (< 5%) reported for fully tethered swimming (Kjendlie & Thorsvald 2006); however, when excluding the 80% SS_{MAX} trial, the CV for all participants was below 5% (S5 = 4.0%; S7 = 3.5%; S9 = 4.7%). When examining the repeatability of the power scores within each tether speed setting, the CV was higher during the faster tether speeds (70% SS_{MAX} = 8.8 ± 1.6%; 80% SS_{MAX} = 12.2 ± 10.4%) than during the slow to medium tether speeds (30% SS_{MAX} = 3.7 ± 0.1%; 40% SS_{MAX} = 1.1 ± 0.4%; 50% SS_{MAX} = 6.0 ± 3.8%; 60% SS_{MAX} = 0.8 ± 0.8%). The higher CV at the faster tether speeds is most likely due to the swimmer being unable to produce any tether force at some points in the stroke. Although it should be noted that during faster tether speeds, the mean external power is closer to zero which will inflate the CV.

The repeatability of the external power scores for both the within trial and within participant analysis, are similar to those (6.9 – 8.3%) reported for the swim bench ergometer (Swaine, 1997). In conclusion, external power measured on the ITS Ergometer is highly repeatable, especially at tether speeds settings of below 60% SS_{MAX}.

4.6 ERGOMETER REFINEMENT

As the ITS Ergometer was a prototype, throughout the programme of work the system has undergone various refinements in order to ensure that the validity and reliability of the data collected was at its highest. This section of the chapter outlines pilot work and additional pieces of equipment which have been explored.

4.6.1 Tether Line Attachment

For the ITS Ergometer to measure tether force, the swimmer must be attached to the tether line. This attachment point must not restrict the technique of the swimmer and should remain as fixed as possible, whilst being comfortable for the swimmer. The majority of tethered swimming studies have attached the tether line to the swimmer via a waist belt (Costill et al., 1986; Goldfuss & Nelson, 1971; Shionoya et al., 1999; Sidney et al., 1996), although some studies have used a shoulder harness (Thanopoulos, Rozi, & Platanou, 2010). Based on the differing attachment points used within the literature, pilot work was undertaken to compare the use of a tether waist belt with a shoulder harness (Figure 4.8).

Figure 4.8: Tether attachment via a shoulder harness. Taken from Thanopoulos et al. (2010).

One participant, was video-taped performing six trials on the ITS Ergometer, alternating between the waist belt and shoulder harness attachment. Qualitative analysis of the video recordings indicated that neither the shoulder harness nor the waist belt restricted swimming technique. However, the participant felt that the shoulder harness added extra pressure on the shoulders and, unlike the waist belt, the shoulder harness felt uncomfortable. Furthermore, when using the shoulder harness, the tether line swung laterally in the air with each arm pull. The lateral movement of the tether above the surface of the water could potentially produce noise and irregularities within the force data. When wearing the waist belt the participant noted how comfortable and secure the belt felt, as the belt rested securely on the hips. Another advantage of the belt over the shoulder harness was that it measured the force produced at the hips. As the hips are closer to the participants centre of mass the recorded force would have 1) been a closer representation of the forces acting through the swimmer's centre of mass, and 2) would have resulted in a smaller leg sinking torque than that produced by the shoulder harness.

Based on observations and the feedback from the participant, it was concluded that the waist belt was the optimal attachment point for the tether line.

4.6.2 Tether Guide System

The ITS Ergometer was positioned on the poolside, roughly 0.5 m above the surface of the water, depending on the pool. So that the gradient of the tether line relative to the water was not too steep, swimmers started at the 5 m mark. At this distance the angle of the tether line would have been the Arc Tangent of 0.1 which equates to an angle of 5°. To ensure that the measurements on the ITS Ergometer were reliable between different swimming pools (e.g., deck level vs. sunken pool), a 'tether guide system' was designed and constructed. This ensured that the tether was released along the surface of the water eliminating the angle of the tether line relative to the water.

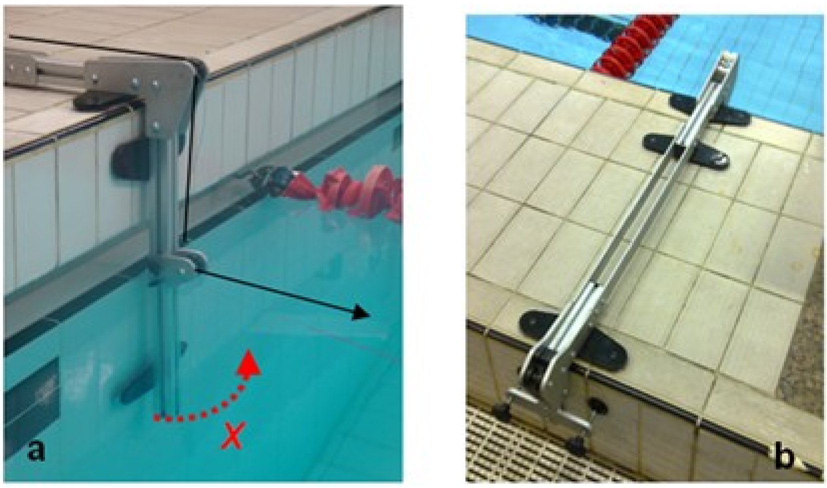


Figure 4.9a and Figure 4.9b: The Tether Guide System. Figure 4.9a, highlights the direction in which the vertical section of the section moved under the

application of large tether forces (X). Figure 4.8b, displays the horizontal section of the tether guide system secured the side of the pool.

The tether guide system consists of three pulleys which guide the tether line along the 'boom' and along the surface of the water. Figure 4.9a, is a side view of the tether guide system, the solid black line indicates the path and direction of the tether line as it is released. The horizontal and vertical components of the tether guide system can be adjusted to fit any pool, irrespective of pool dimensions.

During testing the tether guide system proved very successful and was quickly and easily secured to the side of the pool. The limitation of the system was that under the application of large tether forces, the vertical section of the tether guide system moved approximately 5 mm, away from the wall in the direction show by 'X' (Figure 4.9a). This problem was overcome by attaching clamps within the pool gutter (Figure 4.10b). The clamps can be adjusted so that they fit tightly within the gutter.

The tether guide system allows the tether to be released on the surface of the water, thus eliminating any effects that a change in tether gradient line could have on force measurements between different pools. The system is easy to put in place, and can withstand any force produced by an able-bodied or disabled swimmer.

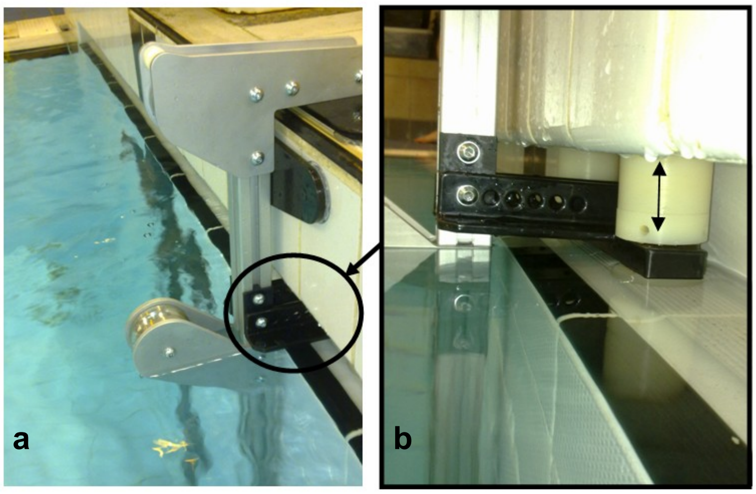


Figure 4.10a and Figure 4.10b: The addition of a gutter clamp to the tether guide system.

4.6.3 Tether Harness

Although the waist belt proved the optimal attachment point (Section 4.6.1) some swimmers found that during trials they would occasionally kick the tether line. Not only would kicking the tether line create a peak in the force data but more importantly it could injure the swimmer. With this in mind, a tether harness was developed (Figure 4.11) by Dr. Gavin Williams from the Loughborough Technology Institute. The tether harness comprised of an aluminium bar (B), from which ran two tether lines, which were secured on either side of the original tether belt (A). Velcro pads at the side of the belt allowed for the attachment point to be altered for each individual swimmer. The tether line ran from the ITS Ergometer and was attached to the middle of an aluminium bar (C).

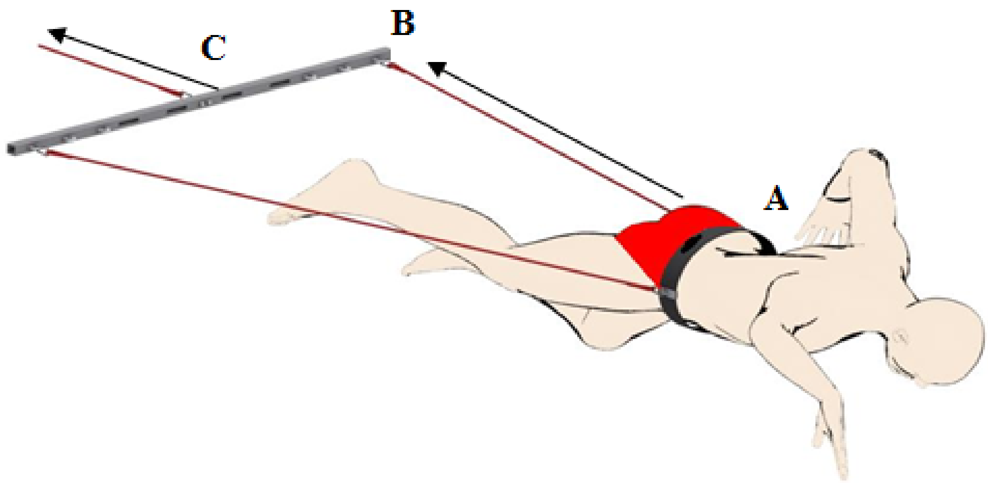


Figure 4.11: Version #1 of the tether harness design. The swimmer is attached to the harness via a waist belt (A) which rests on the swimmer's hips. The harness guides the tether away from the legs and connects to a rigid aluminium bar (B). A tether then runs from the centre of the bar (C) to the ergometer.

Although the harness prevented the swimmer from kicking the tether line, the harness created an unexpected amount of drag, making swimming on the ITS Ergometer noticeably harder for the swimmer. Therefore, as the tether line was only kicked occasionally and by just a handful of the least physically impaired swimmers (S7-S10), the original tether attachment point was reinstated. However, the first 1.5 m of the tether line (from the belt) was replaced with thicker cable to ensure that the swimmer would not get injured if the tether was accidently kicked. On the rare occasion that the participant kicked the tether line, an obvious spike was created on the force data and subsequently excluded from further analysis.

4.7 Key Findings

The force and speed components of the ITS Ergometer are both valid and reliable. The ecological validity of the external power produced by the swimmer on the ITS Ergometer will be addressed in Chapter 5 and Chapter 7 of this thesis. To date there are no standardised protocols to assess power in swimmers. The WAT is the most well known test for assessing power on land. The WAT requires the participant to arm crank or cycle against a fixed load. This fixed load ideally should be set at an optimal value for the individual being tested, such that it allows them to achieve peak power. The next chapter will examine what setting is optimal on the ITS Ergometer to enable the swimmer to achieve peak power.

CHAPTER 5

EXPERIMENTAL STUDY 2

THE EFFECT OF TETHER SPEED ON EXTERNAL POWER OUTPUT

The aim of this study was twofold: Firstly, to measure the external power produced by swimmers with a physical impairment over a range of ergometer tether speed setting, in order to identify the setting in which peak power occurs. Secondly, the study aimed to establish the relationship between peak power and IPC Class.

5.1 INTRODUCTION

Swimming fast is highly dependent upon a swimmer's ability to produce high mechanical power output, enabling the production of high propulsive force (Toussaint & Truijens, 2005). A swimmer generates propulsion by pushing against masses of water that acquire a backward momentum (Berger et al., 1997). It is the backward water momentum that makes the measurement of propulsive force, and the further calculation of power, incredibly difficult during swimming. Yet despite the difficulties imposed by the water, several systems (ergometers) have been developed to calculate swimming power (Costill et al., 1986; Shionoya et al., 1999, 2001; Toussaint et al., 2006).

Although originally designed to measure active drag, the MAD system has been used to calculate power (Toussaint et al., 2006) and develop power (Toussaint & Vervoorn, during swimming. When swimming on the MAD system, the swimmer pushes-off from fixed pads under the surface of the water. A force transducer measures the push-off force produced by the swimmer on the system. Power is calculated as the product of the average force produced on the pads and the average speed of the swimmer (Toussaint et al., 2006). The power measured on the MAD system represents the power produced by the swimmer to overcome drag. However, as the swimmer pushes against a fixed surface no power is lost to the water, thus the power to overcome drag is considered to be equal to the total power output of the swimmer. This is not synonymous with free swimming during which some of the total power produced by the swimmer is always lost through giving the water kinetic energy in a non propulsive direction (Toussaint et al., 2006). As power losses to the water are highly dependent upon the skill level of the swimmer, the MAD system cannot account for inter-individual differences in technical ability.

Tethered swimming devices are one of the most sports-specific ergometers for swimmers (Filho & Denadain, 2008) as, unlike the MAD system, the pulling pattern and placement of the hand is not restricted by a fixed surface. Tether ergometers can be categorised as either having a fixed tension (load) or a constant speed (Alley, 1952; Costill et al., 1986; Shionoya et al., 1999). The power measured is the external power produced by the swimmer on the ergometer and is the product of the tether force and the swimming speed. Shionoya et al. (1999) developed a swimming ergometer using the fixed tension approach. Conversely, Costill et al. (1986) developed an ergometer which released the tether at a relatively constant speed, whilst simultaneously measuring tether force.

Peak power is the highest external power calculated up to an exercise duration of 30 s (Van Praagh & Doré, 2002). Both Shionoya et al. (1999) and Costill et al. (1986) examined the external power produced by swimmers at various settings in order to identify the setting at which peak power occurred. Shionoya et al. (1999) examined the external power produced by 71 (31 male and 40 female) junior and senior high school swimmers at different wire tension settings and found that the optimal setting for the production of peak power was 94.4 ± 10.6 N. Similarly, Costill et al. (1986) calculated external power using a range of tether speeds (0.323, 0.641, 0.954, 1.263 and 1.605 $m{\cdot}s^{-1}$). By fitting a curve to the external power data and interpolating this, the authors found that peak power occurred at 0.93 $m{\cdot}s^{-1}$ for the male participants (*n* = 46) and 0.62 $m{\cdot}s^{-1}$ for the female participants (*n* = 30). Interestingly, although the studies used different types of tether ergometer (i.e., fixed tension or constant tether speed) both studies found an inverted 'U' trend in the external power data with an increase in the ergometer setting (load or speed). The main limitation to the device developed by Costill et al. (1986) was that it only had a limited number of discrete speed settings and these were not truly constant. Consequently, Costill et al. (1986) highlighted that, at faster tether speeds, the weaker swimmers were unable to produce any force in the tether and therefore no external power was registered. Shionoya et al. (1999) and Costill et al. (1986) used a generic range of settings to identify the setting at which peak power is produced in a group of able-bodied swimmers. Competitive disability swimmers are a heterogeneous population, as the swimmers vary greatly in their level and type of physical impairment (IPC Class) and swimming speed (Pelayo, Sidney, Moretto, Willie, & Chollet, 1999). Within a heterogeneous group, such as swimmers with a physical impairment, the range in settings used to identify peak power will inevitably be specific to each individual swimmer. Thus, in order to calculate the peak power produced by swimmers with a physical impairment, an appropriate range of tether settings must be used in which to find the optimal condition for peak power production.

To date no reported study has measured the power produced by swimmers with a physical impairment, however, one study has recorded the tether force produced by swimmers from a range of IPC Classes. Souto et al. (2006) examined the tether force produced by 60 Brazilian swimmers, ranging in an IPC Class of S2 to S10. The study found that those swimmers who were the least physically impaired (S10) produced higher tether forces than those with a more severe physical impairment (S2). Based on the recent criticism of IPC classification system (Chapter 2; Section 2.2.1), it appears that tether force may be a possible tool to improve the objectivity of the classification system (Souto et al., 2006).

The aims of the study were: 1) to calculate the external power produced by competitive swimmers with a physical impairment at a range of tether speeds in order to identify the setting at which peak power occurred, and 2) to examine the relationship between peak power and IPC Class. The experimental hypotheses were: 1) there will be an optimum tether speed setting in which peak power would occur, and 2) there will be a significant positive relationship between IPC Class and peak power.

5.2 PILOT WORK

5.2.1 Introduction

To date only one reported study has examined power output using a tether ergometer which releases the tether at a constant speed (Costill et al., 1986). Costill et al. (1986) observed that as tether speed increased some of the participants were unable to produce any external power on the ergometer (Chapter 5; Section 5.1). This problem could potentially be exacerbated within the main experimental study as the participants vary greatly in IPC Class and consequently swimming speed (Daly et al., 2003; Pelayo et al., 1999). Pelayo et al. (1999) reported that male and female S3 swimmers (male = 0.73 ± 0.07 $m \cdot s^{-1}$; female = 0.53 ± 0.13 $m \cdot s^{-1}$) have a significantly lower swimming speed compared to S10 swimmers (male = 1.59 ± 0.04 $m \cdot s^{-1}$; female = 1.35 ± 0.12 $m \cdot s^{-1}$). To overcome the potential problem of some swimmers being unable to register any tether force, the tether speed settings will be set below the maximal clean swimming speed of the swimmer (SS_{MAX}). The aim of this pilot study was to examine external power at a range of tether speeds, set to a percentage of the individuals' SS_{MAX}. From these tether settings the study aimed to identify where peak power occurred.

5.2.2 Method

A total of sixteen able-bodied competitive swimmers (twelve male and four female) took part in the pilot study. Participants ranged from county to national swimming standard. The SS_{MAX} for the participant group ranged from 1.39 $m \cdot s^{-1}$ to 1.82 $m \cdot s^{-1}$ and was computed using the swimmer's personal best time for 50m front crawl. Tether force was measured and external power calculated using the ITS Ergometer (described in Chapter 4). Tether speeds were set to 20%, 40%, 60% and 80% of the individual's SS_{MAX}. Tether speeds were randomised and two 10 s trials were performed at each tether speed setting. A two minute rest period was allocated between each trial. Prior to testing swimmers were familiarised with each tether setting on the ITS Ergometer. Before each trial swimmers were instructed to swim maximally while maintaining a good technique.

5.2.3 Results

As tether speed increased, the tether force decreased. The highest tether force was recorded at a tether speed of 20% of SS_{MAX} (105.1 ± 32.3 N) and the lowest recorded tether force was at a tether speed of 80% of SS_{MAX} (34.3 ± 14.5 N). During each tether speed setting, the highest tether force and external power was produced within the first 5-7 s of the trial. The external power data produced an 'inverted U trend' (Figure 5.1) with the lowest external power produced at tether speed settings of 20% and 80% of SS_{MAX} and the highest external power (peak power) occurring between 40% and 60% of $SS_{MAX.}$

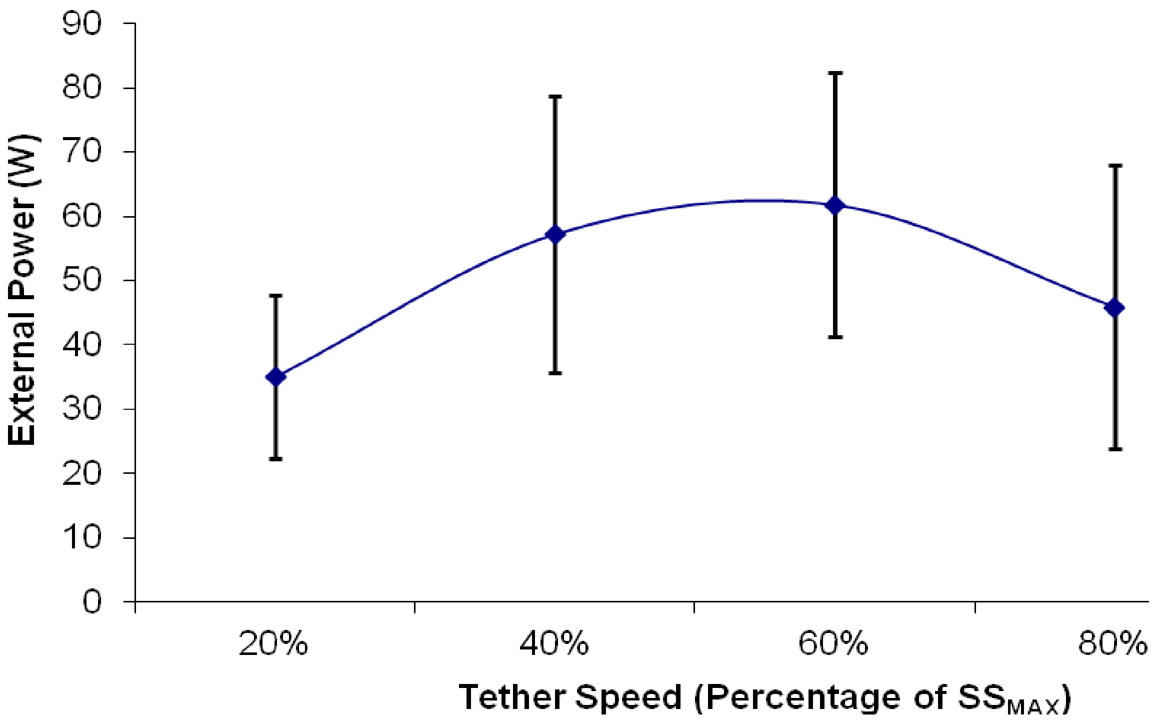


Figure 5.1: The calculated external power on the ITS Ergometer at each of the tether speed settings (20, 40, 60 and 80% SS_{MAX}). Data points represent the group means and error bars represent the standard deviations.

5.2.4 Key Findings

Peak power was produced by the swimmers at tether speeds of between 40% and 60% of their SS_{MAX}. The highest tether force and external power was produced within the first 5-7 s of the test, confirming that 10 s of duration for each trial was adequate. From the data it was evident that peak external power occurred at a tether speed setting of between 40% and 60% of SS_{MAX}. To identify each individual's optimal speed setting more precisely, it was decided in the main study to increase the tether speeds in increments of 10%, rather than the 20% used in this pilot study. The results from the pilot study highlighted that the lowest external power was recorded at 20% SS_{MAX}. As the main aim of the experimental study was to identify the setting at which peak power occurs, it was decided to remove this speed setting.

5.3 METHOD

5.3.1 Participants

A total of 19 female (age 20.1 ± 4.5 years; height 1.59 ± 0.18 m; mass 59.2 ± 8.7 kg) and 13 male (age 22.5 ± 7.3 years; height 1.65 ± 0.30 m; mass 70.1 ± 13.4 kg) well trained swimmers with a physical impairment took part in the study. All swimmers were part of the 'World Class Development' or 'World Class Podium' programme. Swimmers ranged from well-trained to an international level of performance. Swimmers ranged in IPC Class (level of physical impairment) from S3 – S10 for the female participant group and S5 – S10 for the male participant group. The median IPC Class for the male and female participants was S7 and S9, respectively. Data collection procedures were approved by MMU Cheshire's Department of Exercise and Sport Science Ethics Committee.

5.3.2 Data Collection

Prior to testing, swimmers performed their own individual warm-up. A standardised warm-up was not imposed as the swimmers varied in trained status and IPC Class. Following the warm up, swimmers were given time to familiarise themselves with the ITS Ergometer (detailed in Chapter 4). Only when the swimmer felt comfortable with swimming on the ITS Ergometer would testing begin. The SS_{MAX} for each participant was calculated using their 50 m freestyle long course season best time. Based on the findings from the pilot study, tether speeds were set to 30, 40, 50, 60, 70 and 80% of the individual's SS_{MAX}. Two 10 s trials were performed at each tether speed. Tether speeds were randomised and a minimum of two minutes rest was allocated between trials. Before each trial swimmers were asked to swim maximally whilst maintaining good technique.

5.3.3 Data Analysis

External power was calculated on the ITS Ergometer as the product of tether force (N) and tether speed ($m \cdot s^{-1}$). Force was measured using a strain gauge force transducer (Tedea-Huntleigh S type, model 616) which was embedded in the core of the ITS Ergometer. The electrical output from the transducer was converted using a 12-bit analogue to digital converter (Picoscope ADC42) with a sampling frequency of 100 Hz. Force data were captured on a laptop computer using bespoke software.

Tether force was calculated as the mean tether force produced over three consecutive stroke cycles (right arm entry to right arm entry). Data processing was carried out in MS Office Excel (2007). The stroke cycles selected for analysis were the three strokes that produced the highest tether force once the swimmer had commenced a regular stroking pattern. Thus, the external power output represented the external power produced over three consecutive stroke cycles. Peak power was identified as the highest external power calculated from all trials.

5.3.4 Statistical Analysis

Means and standard deviations were computed for tether force, external power, peak power and SS_{MAX}. Normal distribution of the data was verified using the Shapiro-Wilks test. Pearson's correlation coefficient was performed to examine the relationship between SS_{MAX} and the following variables; tether force and peak power. Levene's test revealed that the assumption of homogeneity of variance between the male and female participant groups had been violated deeming the data non-parametric. Therefore, a Mann-Whitney U test was used to compare the peak power between the male and female participant groups. As IPC Class is an ordinal level of measurement and due to the small number of participants within each IPC Class, a Kendall's Tau test was used to examine the relationship between IPC Class and peak power. In all comparisons, the level of significance was set at $p < 0.05$. Statistical analysis procedures were performed using SPSS 14.0 software.

5.4 RESULTS

Tether force declined linearly ($r^2 = 0.99$) with an increase in the tether speed setting for both the male and female participants (Figure 5.2). A significant correlation was observed between the tether force at a tether setting of 30% SS_{MAX} (highest recorded tether force) and SS_{MAX} for both the male ($r = 0.92$; $p < 0.01$) and female ($r = 0.85$; $p < 0.05$) participant groups.

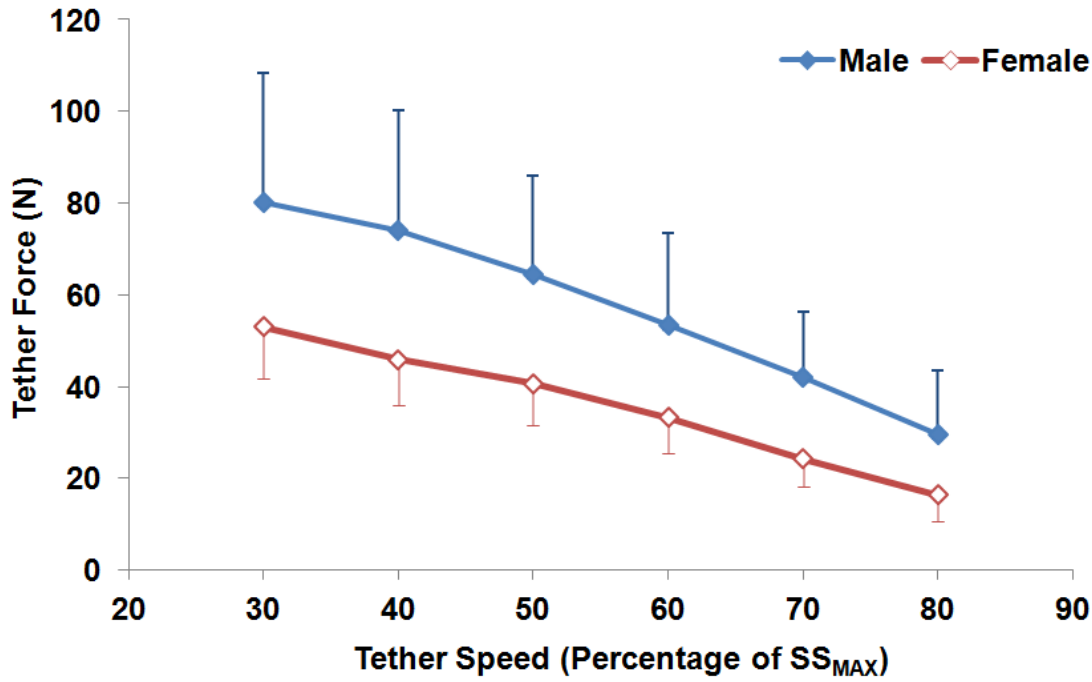


Figure 5.2: The measured tether force at tether speed settings ranging from 30-80% of SS_{MAX} for the male (n = 13) and female (n = 19) swimmers. Data points represent group means and error bars represent the standard deviations.

The calculated external power output presents an 'inverted U trend' (Figure 5.3). Peak power was produced at a tether speed setting of either 50 or 60% of SS_{MAX} for all participants. For the male and female swimmer who produced the highest peak power score, peak power was produced at a tether speed setting of 1.0 $m{\cdot}s^{-1}$ for the male swimmer, and 0.8 $m{\cdot}s^{-1}$ for the female swimmer. There was a significant difference in peak power between the male and female participants (p = 0.015). There was a strong relationship between peak power and SS_{MAX} for both the male (r = 0.94; $p < 0.01$) and female (r = 0.87; $p < 0.01$) swimmers. The computed standard deviations for external power output were much larger for the male participant group than the female participant group.

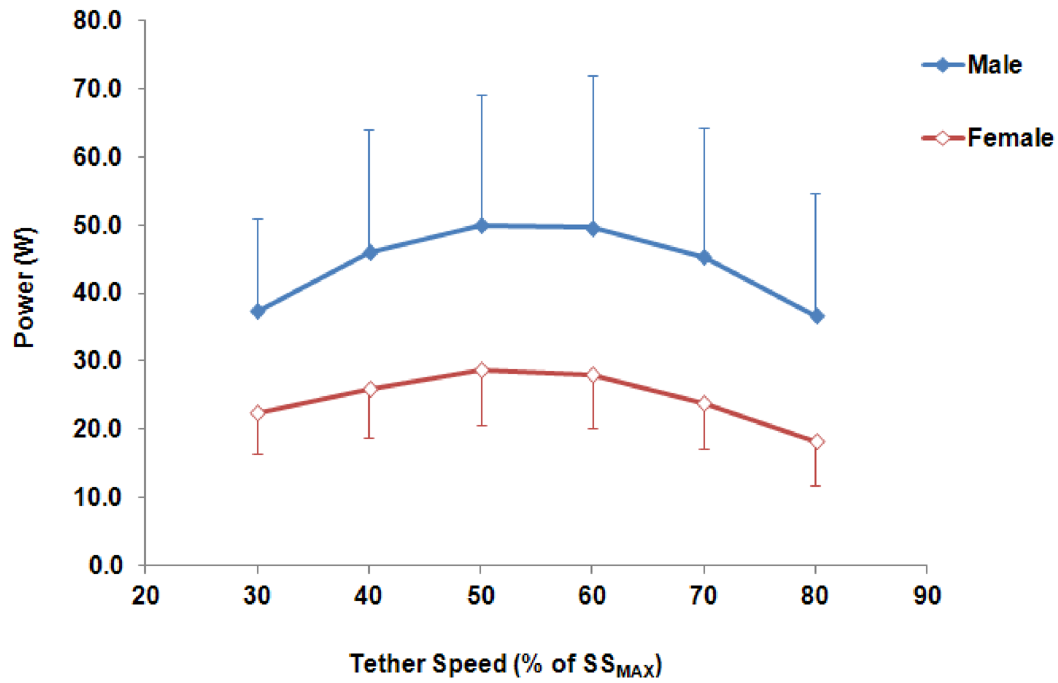


Figure 5.3: The maximal power output at each tether speed for the male (*n* = 13) and female (*n* = 19) participants at each of the tether settings. Data points and error bars represent mean and standard deviations, respectively.

Within the male participant group the highest peak power (96.9 W) was produced by an S10 swimmer and the lowest peak power was produced by an S5 swimmer (3.8 W). Within the female participant group the highest peak power (42.3 W) was produced by an S9 swimmer and the lowest peak power was produced by an S4 swimmer (1.7 W). Due to the limited number of participants within each IPC Class no statistical inter- or intra-IPC Class comparisons were made. There was a significant relationship between peak power and IPC Class in both the male (r = 0.73; p < 0.01) and female (r = 0.69; p < 0.01) participant groups. Within each IPC Class the male swimmers produced higher values of peak power than their female counterparts (Figure 5.4).

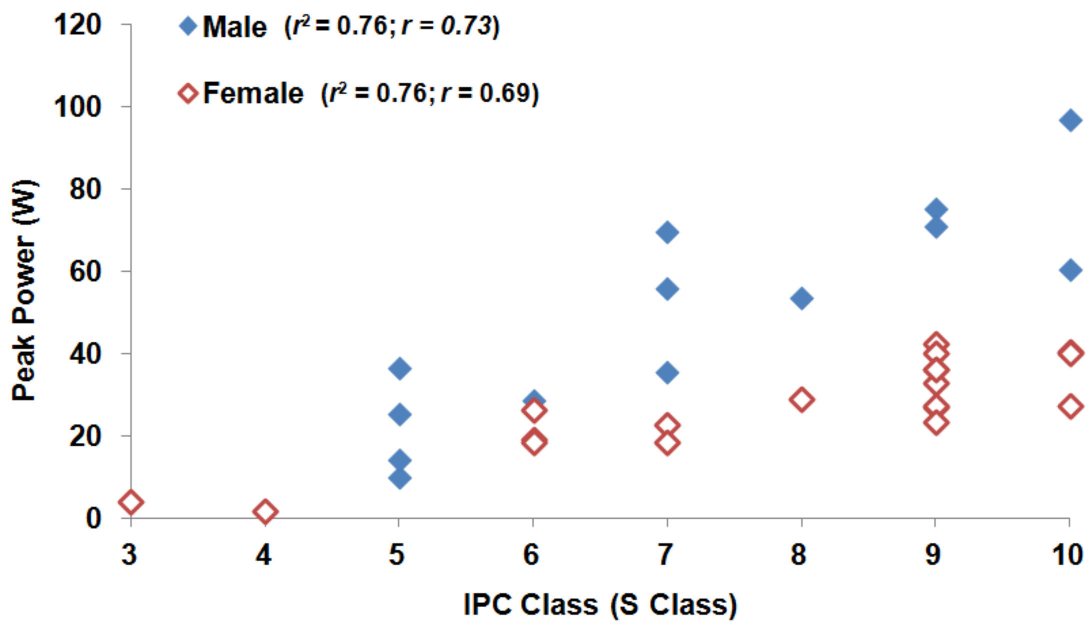


Figure 5.4: The peak power produced by the male (n = 13) and female (n = 19) participants in their respective IPC Class.

5.5 DISCUSSION

The aims of this study were: 1) to calculate the external power produced by competitive swimmers with a physical impairment at a range of tether speeds in order to identify the setting at which peak power occurred; and 2) to examine the relationship between peak power and IPC Class. The study found that external power followed an 'inverted U trend' when viewed as a function of tether speed setting. The lowest external power was recorded at a tether speed setting of 30% and 80% SS_{MAX} and the highest external power (peak power) occurred at a tether speed setting of either 50 or 60% SS_{MAX}; the first hypothesis was therefore accepted. There was a significant relationship between peak power and IPC Class in both the male and female participants; the second hypothesis was therefore also accepted.

During each tether speed setting, prior to the calculation of external power, tether force was recorded (Figure 5.2). An increase in tether speed was directly related (r^2 = 0.99) to a decline in tether force, supporting the findings by Alley (1952), Counsilman (1955) and Costill et al. (1986). It is important to emphasise that the measured tether force is not synonymous with the total propulsive force produced by the swimmer. The measured tether force is the 'surplus' propulsive force produced by the swimmer, that is, the net propulsive force produced at the preset tether speed (Alley, 1952). As drag force increases approximately with the square of the swimming speed (Toussaint & Truijens, 2005), the higher the tether speed, the greater the amount of propulsive force required to overcome drag and consequently, the smaller the measured tether force (surplus propulsive force) on the ITS Ergometer. Although the ITS Ergometer does not measure the total propulsive force, the external power calculated on the ITS Ergometer not only takes into consideration the tether force, but also the speed at which that force was produced.

As the tether speed setting (% of SS_{MAX}) increased, the external power peaked at a mid setting (50 – 60% of SS_{MAX}) and then decreased during the final settings, supporting the work by Costill et al. (1986) and Shionoya et al. (1999). Peak power occurred at a tether speed setting of either 50 or 60% SS_{MAX} for all swimmers. The inter-individual difference in the peak power setting may have been due to the way in which SS_{MAX} was determined. The SS_{MAX} for each swimmer was calculated using their seasonal best time for 50 m freestyle (long course). At a tether speed setting of 80% of SS_{MAX} some of the swimmers registered very little force indicating this tether speed setting was closer to their maximal swimming speed than predicted. In addition, for some swimmers their 50 m time was relatively recent, while for other swimmer (who rarely competed in 50 m freestyle events), their time was not a current time and thus, not an exact measure of their SS_{MAX}. Nonetheless, this is not seen as a limitation to the study as the computed SS_{MAX} was simply used to gauge the appropriate range of tether settings for that individual, in order to find the setting in which peak power occurred.

Peak power was a strong predictor of SS_{MAX} for both the male ($r = 0.94$; $p < 0.01$) and female ($r = 0.87$; $p < 0.01$) swimmers. These values are above that ($r = 0.84$) reported by Costill et al. (1986). The higher values within this study may be due to the use of a heterogeneous sample, as opposed to the homogenous sample used by Costill et al. (1986). For the male and female swimmer who produced the highest external power, the setting in which peak power occurred corresponded to a tether speed of 1.0 $m \cdot s^{-1}$ and 0.8 $m \cdot s^{-1}$, respectively. These tether speeds are slightly higher than those reported by Costill et al. (1986) who calculated peak power at a tether speed of 0.93 $m \cdot s^{-1}$ for male and 0.62 $m \cdot s^{-1}$ for female able-bodied swimmers. In the present study, the peak power calculated for the male swimmers was significantly greater than that calculated for the female participants ($p = 0.015$). Similarly, Costill et al. (1986) reported a significant difference ($p < 0.05$) in peak power between male (43.6 ± 3.3 W) and female (25.7 ± 1.8 W) swimmers. Costill et al. (1986) used a homogenous group of collegiate able-bodied swimmers; unfortunately the authors did not provide information regarding the trained status of the swimmers. The peak power calculated by Costill et al. (1986) for male and female able-bodied swimmers was lower than the peak power reported for the male and female S8-S10 swimmers within this current study. The comparatively higher values in peak power reported within this study for S8-S10 swimmers suggest that these swimmers were of a higher calibre than those in Costill et al. (1986) study. Within this study, the male swimmer who produced the highest peak power (S10 swimmer) is the current British Recorder holder for 50 m freestyle and has won relay gold medals at the last two Paralympic Games. The female swimmer (S9) who produced the highest peak power was an ex-international able-bodied swimmer, and is currently the World Record holder in one event, European Recorder holder in four events and British Record holder in two events.

Within this study it appeared IPC Class could account for 76% of the variability in peak power scores ($r = 0.76$), while Souto et al. (2006) found that IPC Class could explain just 25% of the variability in tether forces (Souto et al., 2006). In light of the findings within this study, it appeared that peak power calculated using the ITS Ergometer, may be a better tool to aid the IPC classification process, than just tether force alone. The relationship between peak power and IPC Class was stronger for the male swimmers ($r = 0.73$; $p < 0.01$) than for the female swimmers ($r = 0.69$; $p < 0.01$). The stronger relationship observed for the male participant group can be attributed to an even distribution of male participants within each IPC Class (one to four swimmers in each IPC Class), as opposed to the uneven distribution of female swimmers within each IPC Class. Despite the female participant group having the greater range in IPC Class than the males (female = S3-S10; male = S5 – S10), of the nineteen swimmers; eleven swimmers were in either the S9 or S10 IPC Class. Thus, the weaker relationship between peak power and IPC Class within the female participant group was due largely to the inter-individual differences in technical ability and trained status of the swimmers within each IPC Class. As the peak power produced by the swimmer is a reflection of their ability to generate propulsion and (or) reduce drag, any change in these parameters would lead to a change in peak power. In order to strengthen the current study a greater number of participants, distributed evenly across the full range of IPC Classes, would be required. However, it should be highlighted that although the numbers within each IPC Class are relatively small for statistical comparisons only one reported study (Souto et al., 2006), with the exception of race analysis, have used participants from such a wide range of IPC Classes. To put the study further into perspective, it is quite common within Paralympic finals for there to be no S1 or S2 finals due to limited numbers of swimmers within those IPC Classes worldwide. Due to limited pool time, further limitations to the study were that some swimmers only performed one trial at each tether speed setting and that participants were tested at different times of the day and at different points within their training cycle.

Despite the strong relationship between peak power and SS_{MAX}, it is important to highlight that during a swimming race it is not just the swimmer's ability to attain high propulsive force and power that is important, their ability to maintain these values for as long as possible is equally important. To date there has been no standardised protocol to assess the decline in a swimmer's external power using a swimming specific ergometer. The commonly used WAT requires the participant to pedal or arm crank for 30 s from which the participants peak power and fatigue index (decline in external power) is calculated. The main reason a duration of 30 s was chosen for WAT, was that during a duration of greater than 30 s, participants began to pace themselves (Bar-Or, 1987). Based on the WAT the following chapter will examine the decline in external power during a maximal effort 30 s swim on the ITS Ergometer.

5.5.1 Conclusion

Tether force (net propulsive force) declined with an increase in tether speed setting. Swimmers produced peak power at a tether speed setting of either 50 or 60% of SS_{MAX}. The peak power measured on the ITS Ergometer was a strong predictor of performance in disabled swimmers. There was a significant relationship between IPC Class and peak power, suggesting the possible application of this measure as a tool to aid the IPC classification process.

CHAPTER 6

EXPERIMENTAL STUDY 3

DECLINE IN EXTERNAL POWER DURING A 30 S MAXIMAL EFFORT SWIMMING TEST

The aims of the study were to: 1) examine changes in external power during a 30 s maximal effort swim on the ITS Ergometer; and 2) establish the relationship between the decline in external power and IPC Class.

6.1 INTRODUCTION

Fatigue is a major limiting factor of competitive swimming performance (Toussaint et al., 2006). During a Paralympic 100 m final, across all IPC Classes, swimmers exhibit a ~12% decline in swimming speed (Daly et al., 2003). These values are typical of those reported within able-bodied research (Seifert, Boulesteix, Carter, & Chollet, 2004; Toussaint et al., 2006). Furthermore, the decline in swimming speed is mirrored by decreases in stroke rate in both able-bodied (Toussaint et al., 2006) and disabled swimmers (Daly et al., 2003; Osborough et al., 2009). Seifert et al. (2004) reported a decline in stroke rate of 8.9% over a 100 m swim, in national to international standard male able-bodied swimmers. While Daly et al. (2003) reported a similar decline in stroke rate of 8.4% in male Paralympic swimmers during a 100 m front crawl swim.

Swimming fast is highly dependent upon the swimmers' ability to produce high power output, enabling the generation of high propulsive forces (Toussaint & Truijens, 2005). Thus, during a race swimmers must not only attain a high power output, but must further maintain this power output in order to sustain swimming speed and consequently, performance. To date, the decline in power output exhibited by a swimmer has only been examined in able-bodied swimmers (Toussaint et al., 2006) and not in swimmers with a physical impairment. Toussaint et al. (2006) reported that during a 100 m front crawl swim (57.8 ± 1.0 s) on the MAD system, senior male swimmers exhibit a decline of 24% in total power output. Conversely, Shionoya et al. (2001) presented a far greater decline in external power output of 79.1 ± 9.4% in male junior swimmers during a 33 s maximal effort swim using a tether ergometer. The difference in the decline in external power values reported by Shionoya et al. (2001) and Toussaint et al. (2006) was that they defined and measured power differently. Shionoya et al. (2001) used a tether ergometer to measure the external power output which was the product of the fixed tension on the tether line and the swimming speed of the participant. Toussaint et al. (2006) used the MAD system to measure the total power output, which equalled the power to overcome drag (as no power is lost to water).

The advantage of tether ergometers over the MAD system is that the power measured on tether ergometers is dependent upon technical ability (Chapter 5; Section 5.1). The main limitation to the tether ergometer developed by Shionoya et al. (1999; 2001) was that it did not control the speed of the swimmer. Consequently, it was not possible to identify which component (i.e., propulsion or drag) resulted in the decline in external power. By restricting the swimmer to a constant speed and assuming the swimmer's technique does not change significantly, drag force is held constant. As a consequence, any decrease in external power must be directly related to a decline in propulsive force. Previous studies have measured external power using tether ergometers which release the tether at a constant speed, thus controlling the speed of the swimmer (Costill et al., 1986). However, to date no studies have examined the effect of fatigue on external power using this type of ergometer. Chapter 3 demonstrated that during a 30 s maximal effort fully tethered swimming test, unilateral arm amputee swimmers exhibited the same decline in propulsive force as able-bodied swimmers of a similar age, height and mass. Yet there are no reports in the literature examining the decline in propulsive force or power of swimmers with various disabilities from a range of IPC Classes.

The aims of the study were to: 1) examine changes in external power during a 30 s maximal effort swim on the ITS Ergometer; and 2) establish the relationship between the decline in external power and IPC Class. The experimental hypotheses were: 1) there will be a decline in external power during the 30 s test; and 2) there will be no relationship between the decline in external power and IPC Class.

6.2 METHOD

6.2.1 Participants

A total of 10 female (age 19.3 ± 5.1 years; height 1.52 ± 0.21 m; mass 55.1 ± 6.4 kg) and 12 male (age 18.8 ± 4.0 years; height 1.58 ± 0.30 m; mass 66.8 ± 13.8 kg) well trained swimmers with a physical impairment took part in the study. All swimmers were part of the 'World Class Development' or 'World Class Podium' programme. Female swimmers ranged in IPC Class from S3 – S10 and male swimmers ranged in IPC Class from S5 – S10. All the swimmers within this study had participated in the previous experimental study (Chapter 5). Data collection procedures were approved by MMU Cheshire's Department of Exercise and Sport Science Ethics Committee.

6.2.2 Data Collection

Prior to testing, swimmers were given time to warm up and re-familiarise themselves with the ITS Ergometer. Swimmers were then asked to swim maximally for 30 s on the ITS Ergometer. The tether speed was set to the tether speed setting at which that individual produced their peak power output (Chapter 5). Before the trial, swimmers were instructed to ensure they swim maximally (i.e., no pacing), maintain good technique and limit breathing. When ready, each swimmer was asked to take up the 'slack' in the tether line and tread water 5 m away from the end of the pool. The swimmer was then instructed to begin swimming. Tether force was measured and captured using the same procedures as detailed in Chapter 5 (Section 5.3.3).

6.2.3 Data Analysis

Tether force was measured on the ITS Ergometer (Chapter 4) and external power was calculated as the product of the tether force and tether speed (as detailed in Chapter 5; Section 5.2.3). Each 30 s trial was divided into six 5 s windows in which external power and SR was calculated (as described in Chapter 3; Section 3.2.3). The decline in SR and external power (FI) was calculated as the percentage decline between the first 5 s and the final 5 s of the test.

6.2.4 Statistical Analysis

Means and standard deviations were computed for tether force, external power and stroke rate during each 5 s window throughout the test. Normal distribution of the data was verified using the Shapiro-Wilks test. Pearson's correlation coefficient tests were performed to examine the relationship between SS_{MAX} and the following variables; FI, external power during the first 5 s and external power during the final 5 s of the test. The relationship between FI and the decline in SR was also examined using a Pearson's correlation coefficient test. Levene's test revealed that the assumption of homogeneity of variance between the male and female participant groups had been violated deeming the data non-parametric. The Mann-Whitney U test was performed to examine the statistical difference in: i) FI; ii) external power during first 5 s; and iii) external power during the final 5 s of the test, between the male and female participants. As IPC Class was measured at ordinal level, the relationship between IPC Class and FI was quantified using a Kendall's Tau test. In all comparisons, the level of significance was set at $p < 0.05$. Statistical analysis procedures were performed using SPSS 18.0 software.

6.3 RESULTS

All swimmers experienced a decline in external power throughout the test (Figure 6.1) with the highest external power values observed during the first 5 s (41.9 ± 19.5 W) and the lowest power calculated during the final 5 s of the test (29.8 ± 12.8 W).

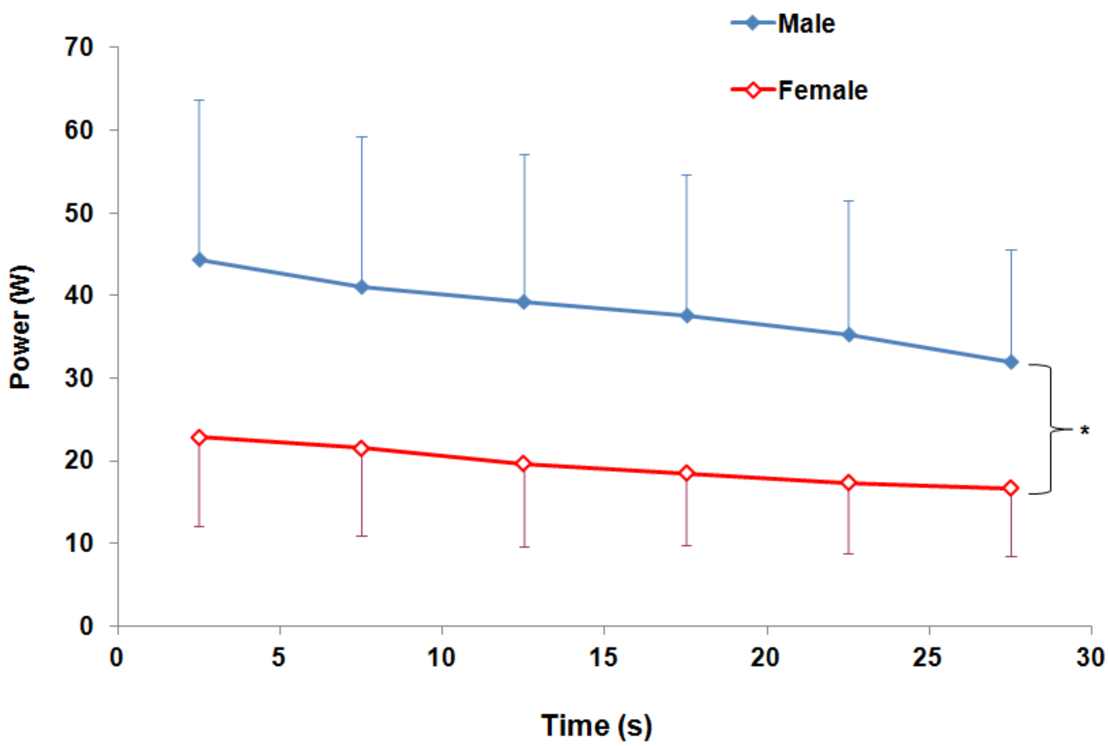


Figure 6.1: External power for each 5 s window during the 30 s maximal effort swim on the ITS Ergometer for the male (*n* = 12) and female (*n* = 10) participants. * denotes a significant difference in external power between the male and females.

There was a significant relationship between SS_{MAX} and external power produced during the first 5 s ($r = 0.81$, $p < 0.01$) and between SS_{MAX} and the external power recorded in the final 5 s ($r = 0.81$, $p < 0.01$). Male swimmers produced significantly higher ($p < 0.05$) external power throughout the test compared to the female swimmers. Stroke rate declined throughout the test by 11.1 ± 5.3%. The largest decline in stroke rate was 19.5% (female S3 swimmer) and the smallest decline in stroke rate was 1.3% (female S4 swimmer). There was no statistical relationship between FI and the decline in stroke rate (r = 0.10).

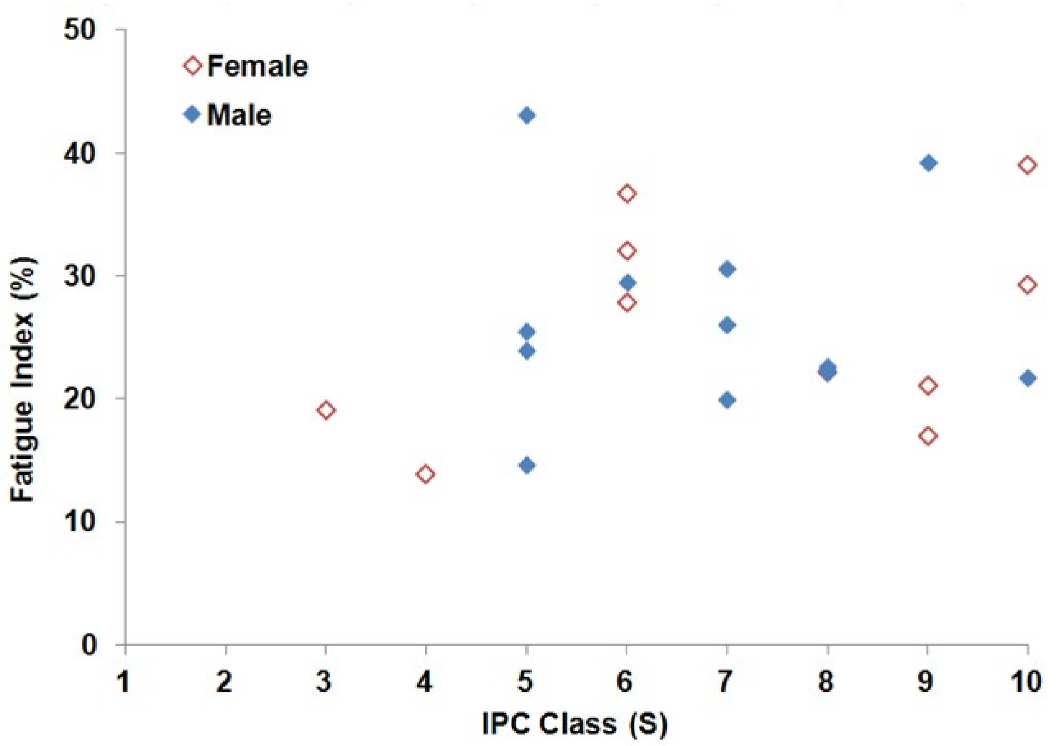


Figure 6.2: The Fatigue Index (%) for the male (n = 12) and female (n =10) participants in their respective IPC Class (S).

There was no significant difference in the FI between the male (26.6 ± 8.0%) and female (25.8 ± 8.5%) participants. The highest FI was 42.0% (male S5 swimmer) and the lowest was 13.9% (female S4 swimmer). There was no relationship between FI and IPC Class for either the male (r = -0.07) or female (r = 0.24) participant groups (Figure 6.2).

6.4 DISCUSSION

The aims of the study were to: 1) examine changes in external power during a 30 s maximal effort swim on the ITS Ergometer; and 2) establish the relationship between the decline in external power and IPC Class. The study found that the decline in external power (FI) during the 30 s test was 26.6 ± 8.0% for the female and 25.8 ± 8.5% for the male participants; the first hypothesis was therefore accepted. The study also found no relationship between IPC Class and the decline in external power; therefore the second hypothesis was also accepted.

The FI reported within this study for the male and female swimmers, was much lower than that the 79.1 ± 9.4% reported by Shionoya et al. (2001) for able-bodied swimmers. This discrepancy between the studies may be due to a number of factors. First, the fixed load on the ergometer used by Shionoya et al. (2001) may have been too high for the calibre of some of the swimmers used in their study. Second, during the final 10 s of the Shionoya et al. (2001) test protocol, the speed of the swimmers decreased greatly, resulting in low values of external power (9.5 ± 5.5 W). This could have affected the motivation of the swimmers as they began to feel their speed diminish. A third explanation for the relatively high FI values of Shionoya et al. (2001), compared to the current study, could be due to differences in the trained status of the participants in the respective studies; however the authors provided no detail regarding the competitive level or trained status of their participants, they merely reported that their participants were all 'junior' swimmers. Given that previous studies have demonstrated that young swimmers fatigue more than older swimmers (Soares et al., 2010) this may also help explain the high FI reported by Shionoya et al. (2001).

Toussaint et al. (2006) reported a similar decline in power (25%) to the current study, during a 100 m swim on the MAD system, despite the duration of the swim (57.8

± 1.0 s) being nearly double that used in the current study. A direct comparison between studies is difficult because, when performing on the MAD system the forward progression of the swimmer is assisted by fixed pads and there is no power lost to the water. In contrast, during semi-tethered swimming, power is lost to the water and, as fatigue increases, there is likely to be an increase in this power loss due to a deterioration in technique (Tella, Toca-Herrera, Gallach, Benavant, Gonzalez, & Arellano, 2008; Toussaint et al., 2006). Therefore swimmers are likely to fatigue at a greater rate during semi-tethered swimming, compared to swimming on the MAD system, due an increasing power loss to the water as the test progresses.

The FI exhibited by the male (26.6 ± 8.0%) and female (25.8 ± 8.5%) swimmers within this study was slightly higher than that reported (23.2 ± 5.1%) during fully tethered swimming (Chapter 3). This was an unexpected finding as it was anticipated that swimming on the ITS Ergometer in semi-tethered mode would elicit a lower FI scores than during fully tethered swimming. In fully tethered swimming the arm encounters greater water resistance, and the propelling muscles will work harder, than in semi-tethered swimming (Goldfuss & Nelson, 1971). A direct comparison between the fully tethered test results from Study 1, with those of the current study, should be done with caution. Participants within this study were from a wide range of IPC Classes (S3-S10), whereas in Study 1 all participants were female S9 unilateral arm amputees.

This study found no relationship between the level of physical impairment (IPC Class) of the participants and the FI. This finding is perhaps not surprising given that, under race conditions, disabled swimmers across IPC Classes S3-S10 experience no greater decline in swimming speed or stroke rate than able-bodied swimmers (Daly et al., 2004; Seifert et al., 2004). Swimmers produced a wide range of values for the FI in this study (13.9 – 42.0%). As this range could not be explained by the IPC Class of the participants, other factors will have had a greater influence on the FI. Possible reasons for the inter-swimmer differences in FI include: 1) type of physical impairment; 2) age (Soares et al., 2010); 3) gender (Williams & Ratel, 2009; Seifert, Chollet, & Chatard, 2007); 4) physiological characteristics (e.g., fibre type composition); and 5) stroke and distance specialism (Williams & Ratel, 2009). A further explanation for the wide range in FI could be due to some participants swimming sub-maximally during the test, despite being encouraged to swim maximally. Motivational stimuli based on cognitive information, has been reported to have little to no effect on performance in the WAT (Bar-Or, 1987). An indication that the swimmers may not have performed maximally, was that their external power produced within the first 5 s of the current test was lower than their peak power recorded during the six speed test in Study 2 (Chapter 5). It must be noted however that some swimmers performed the six speed test and the 30 s test at a different time of the day and at a different phase in their training cycle.

During testing it was observed how one of the swimmers was able to walk onto poolside before the test but required the use of a wheelchair post test. This is indicative of her condition, as some medical conditions (e.g., cerebral palsy, multiple sclerosis) leave swimmers more susceptible to fatigue and are more debilitating than other conditions (e.g., an amputation). During the current IPC classification process swimmers are assessed in a non-fatigued state. Given the detrimental effect fatigue has on performance and the way in which certain conditions leave some athletes more susceptible to fatigue, future work is needed to assist the IPC classification process and develop an understanding into fatigue and different types of physical impairments.

One of the limitations to the study was that due to restricted pool time, no provision could be made to ensure that each swimmer was tested at the same time of day and during the same phase in their training cycle. A further limitation to the study was that fatigue was only assessed in terms of the decline in external power. A previous study by Hautier, Belli and Lacour (1998) highlighted that fatigue can be underestimated if only force and power measurements are examined. Moreover, fatigue is a complex phenomenon for which there is no single causative factor (Williams & Ratel, 2009) and thus should be evaluated using multiple measurement techniques (Rouard, 2010). With this in mind, Chapter 8 will examine the relationship between neuromuscular fatigue (using EMG) and the decline in external power.

6.4.1 Conclusion

Highly trained swimmers with a physical impairment exhibited a decline in external power during a 30 s maximal effort swim on a semi-tethered ergometer. This decline in external power was not related to the level of physical impairment (IPC Class) of the swimmer.

CHAPTER 7

EXPERIMENTAL STUDY 4

EFFECT OF TETHER SPEED ON MUSCLE ACTIVATION AND RECRUITMENT PATTERNS

The primary aims of this study were to establish whether: 1) the level of muscle activity and, 2) the muscle recruitment patterns, exhibited when swimming maximally on the ITS Ergometer, at various tether speeds, differ from those during free swimming. A secondary aim was to gain a better understanding of the relationship between muscle activity and the external power produced by the swimmer. In order to achieve this, the power to overcome drag was estimated and combined with the measures of external power.

7.1 INTRODUCTION

Measuring propulsive force and power during front crawl is difficult due to the continual displacement of water and the lack of any suitable transducer to record propulsive force (Swaine, 2000). These difficulties have led to the development of swimming ergometers (Costill et al., 1986; Shionoya et al., 1999; Swaine, 2000), the specificity of which has been the focus of previous research (Clarys et al., 1988; Olbrechy & Clarys, 1983; Takashahi et al., 1992; Shionoya et al., 1999). Swimming ergometers are typically separated into two main categories; dry-land and water-based.

The most popular swimming specific dry-land ergometer is the swim bench. Within the scientific literature the importance of the swim bench has been stressed, as training studies have shown it to increase arm power and endurance (Swaine, 1994) and enhance anaerobic capacity (Takahashi et al., 1992). The specificity of movement on the device has, however, been questioned as the replication of the front crawl arm action on the swim bench does not elicit the same muscle activation levels and coordination patterns as free swimming (Olbrecht & Clarys, 1988).

Muscle function and coordination is predominantly examined using EMG which records the electrical signals generated by the muscles. Previous research has demonstrated that the repeatability of EMG recordings from skilled swimmers is exceptionally high (Clarys et al., 1988), yet there appears to be little electromyographic similarity between mimicking the swimming action on dry-land and free swimming. Olbrecht and Clarys (1983) concluded that the lack of similarity between dry-land devices and free swimming was due in part to the overall time differences in arm cycle executions and the different patterns of movement created by dry-land conditions.

Although originally designed to measure active drag, the MAD system has been adapted to calculate swimming power (Toussaint & Vervoorn, 1990). In order to explore the muscle specificity of swimming on this system, Clarys et al. (1988) compared the amplitude and timings of EMG recordings when swimming on the MAD system to free swimming. The authors concluded that when swimming on the MAD system, the amplitude and timing of the triceps brachii, pectoralis major and latissimus dorsi were similar to free swimming. However, the flexor digitorum superficialis presented different EMG patterns between swimming on the MAD system and free swimming. In addition, EMG recordings from the flexor digitorum superficialis presented considerable inter-individual variability. Therefore, although the majority of muscles tested elicited a similar pattern of movement to free swimming, it appeared that when swimming on the MAD system some adaptation of the hand and forearm movement was present. This could be explained by the differing ways in which the swimmers pushed off the fixed pads (for a more detailed description of the MAD system, refer to Chapter 2).

Other than the MAD system the majority of water-based ergometers have evolved around semi-tethered swimming (Costill et al., 1986; Hopper et al., 1982; Shionoya et al., 1999) due to the high reliability (Kjendlie & Throsvald, 2006), strong ecological validity (Yeater et al., 1981) and high muscle specificity (Bollens et al., 1988) of this form of swimming. The muscle specificity of fully tethered and a form of semi-tethered swimming (weight stack) was examined by Clarys et al. (1988) and Bollens et al. (1988). The authors concluded that the muscle patterns during fully tethered swimming were similar to that of free swimming. During semi-tethered swimming, whilst the specificity of the muscular patterns were similar to free swimming, this was only the case up to a resistive load of between 100 and 120 N, after which the muscle action was deemed to be non-specific (Clarys et al., 1988). In light of the findings by Bollens et al. (1988) it is surprising that the muscle specificity of tether ergometers has not been reported within the scientific literature.

The primary aims of this study were to establish whether: 1) the level of muscle activity and, 2) the muscle recruitment patterns, exhibited when swimming maximally on the ITS Ergometer, at various tether speeds, differ from those during free swimming. A secondary aim was to gain a better understanding of the relationship between muscle activity and the external power produced by the swimmer. In order to achieve this, the power to overcome drag was estimated and combined with the measures of external power. The primary hypotheses were, as tethered swimming speed increases: 1) the level of muscle activity and, 2) muscle recruitment patterns will match more closely to those found during free swimming. The secondary hypothesis was: an increase in tether speed setting would affect the level of muscle activity but would not affect the power output of the swimmer, when drag is accounted for.

7.2 PILOT STUDY

7.2.1 Introduction

Due the complexity of the front crawl movement and the difficulties posed by the aquatic environment, the use of EMG in swimming is considered problematic. In order to preserve the EMG recordings during swimming, a waterproof layer is generally applied to the electrodes (Silver & Dolny, 2011). Rainoldi, Cescon, Bottin, Casale and Caruso (2004) stressed the importance of waterproof taping over the electrodes, stating that the tape maintains the frequency and amplitude of information while in a wet environment. Yet despite the importance of waterproofing the electrodes during swimming, very few studies have provided a detailed account of the taping methods and materials used (Silvers & Dolny, 2011). Therefore, the following pilot study was carried out to compare different taping materials, and assess which material was the best at protecting the electrodes from water.

7.2.2 Method

One male county level swimmer (age 21 years; body mass 71.5 kg; height 1.73 m) consented to take part in the study. The participant performed three maximal effort trials; with two trials performed on the ITS Ergometer, at a tether speed of 0 $m \cdot s^{-1}$ (fully tethered) and 1 $m \cdot s^{-1}$, and one trial performed during free swimming. The muscles selected for this study were the pectoralis major (clavicular and sternal portions), anterior deltoid, biceps brachii, triceps brachii, posterior deltoid, trapezius and latissimus dorsi. The rationale for muscle selection and complete EMG methodology is detailed in Section 7.3 of this chapter.

7.2.3 Electrode Waterproofing and Protection

To protect the electrodes from water impedance, four of the electrodes (Figure 7.1a) were covered by an 8 × 8 cm layer fabric tape (Strappal® Hypoallergenic Zinc Oxide Tape, BSN Medical, Charlotte NC) while the remaining electrodes were covered with an 8 × 8 cm layer adhesive film (Opsite™, Smith and Nephew, Largo, FL), the edges of which were sealed with the fabric tape (Figure 7.1b). Once the waterproof tape was in place the swimmer put on a body suit to limit the movement of the leads during the swimming action. Leads connecting the electrodes to the junction box ran out from the top of the suit, behind the head of the swimmer and were gathered through a plastic tube (Figure 7.1b). The plastic tube prevented the leads from being caught up in the front crawl arm action.

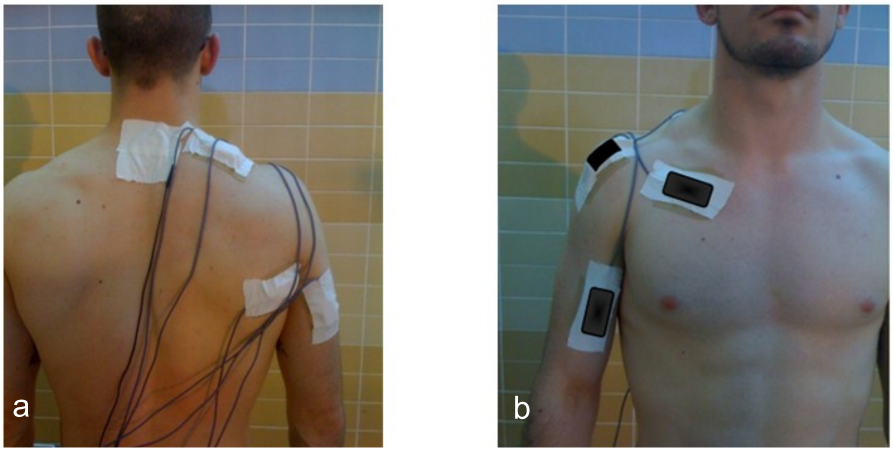


Figure 7.1a: Electrode arrangement with fabric waterproof taping. Figure 7.1b: Electrode arrangement with adhesive film and fabric waterproof taping.

7.2.4 Key Findings

Although the EMG recordings from all muscles were visually free from noise, by the end of the final trial both the fabric taping and adhesive film had begun to pull away from the skin, irrespective of the taping method used. By observing the trials it was evident that the fabric tape, in both taping arrangements, was the primary reason the waterproof layers over the electrodes had begun to fail. The fabric tape was highly adhesive, thick and lacked elasticity; so as the skin stretched during the front crawl movement, it resisted movement and gradually pulled away from the skin. Once the fabric tape began to separate from the skin, it then pulled the waterproof plasters or adhesive film away as well. Another area of concern was the gap created between the adhesive film and the skin at the point where the lead exited the sensor. This allowed water to gradually build up under the adhesive film and seep towards the electrodes. Based on these findings it was decided that, during future testing the fabric tape which bordered the adhesive film would be replaced by a tape with greater elasticity. Furthermore, during future testing sessions a small incision would be made in the adhesive film at the point where the lead runs from the sensor to ensure that the adhesive film is in contact with the skin rather than the lead.

7.3 METHOD

7.3.1 Participants

A total of five highly trained male swimmers (age 25.4 ± 6.7 years; height 1.58 ± 0.28 m; mass 69.0 ± 14.7 kg) with a physical impairment consented to take part in the study. All swimmers were part of the ‘World Class Development’ or ‘World Class Podium’ programme. Each swimmer represented a different IPC Class (S5, S6, S8, S9 and S10). All participants were familiar with the ITS Ergometer and had participated in the last two experimental studies (reported in Chapters 5 and 6). Data collection procedures were approved by MMU Cheshire’s Department of Exercise and Sport Science Ethics Committee.

7.3.2 Testing Procedure

Each participant completed a total of five maximal effort trials; with four trials performed on the ITS Ergometer and one trial performed as free swimming. During each trial, the muscle activity of eight upper-body muscles was recorded using EMG. When swimming on the ITS Ergometer tether speed was set to 0% (fully tethered swimming), 30%, 50% and 70% of SS_{MAX}. Prior to testing, swimmers were allocated a five minute dry-land warm up, and a five minute warm up in the water at a tether speed setting of 0% SS_{MAX}. A tether speed setting of 0% SS_{MAX} was selected in order to re-familiarise the swimmers with the ITS Ergometer. Furthermore, at 0% SS_{MAX} the swimmer remained stationary allowing the experimenter to check that none of the electrodes had been displaced during the land based warm up or as the swimmer entered the water.

7.3.3 Calculating Force and External Power

Tether force was measured using the ITS Ergometer and external power was calculated as outlined in Chapter 5 (Section 5.3.3).

7.3.3.1 Estimating the Power to Overcome Drag and Effective Power

External power (PO_{EXT}) is a measure of the power produced by the swimmer against the ITS Ergometer (Chapter 4) and does not account for the power required from the swimmer to overcome drag, and swim at the preset tether speed (PO_D). To provide an estimate of PO_D, passive drag measurements were taken for each swimmer. The sum of the estimated power to overcome drag (PO_D) and the external power (PO_{EXT}) is referred to as the 'effective power' (PO_{EFF}), the equation (7.1) for which is as follows:

$$PO_{EFF} = PO_D + PO_{EXT} \tag{7.1}$$

The PO_{EXT} was calculated as a product of the tether force and tether speed (Chapter 5). The PO_D was estimated using the following equation:

$$PO_D = F_D \cdot v \tag{7.2}$$

Where F_D is the estimated drag force (N) during the semi-tethered trial and v is the speed of the swimmer during the trial (the tether speed) in m·s^{-1}.

F_D was calculated by towing the swimmers on the surface of the water in a streamlined position at 1.5 m·s^{-1}, using the ITS Ergometer. Three towing trials were performed by each swimmer. The lowest drag force recorded (F_{Dm}) was then used to estimate F_D as follows. Assuming that the measured drag force is proportional to the square of the towing speed (1.5 m·s^{-1}), then:

$$F_{Dm} = k \cdot 1.5^2$$

Thus, $k = F_{Dm} / 2.25$

The constant, k, was then used to estimate the drag force acting during the semi-tethered trials (Equation 7.3).

$$F_D = k \cdot v^2 \tag{7.3}$$

Where F_D is the estimated drag force (N), k (kg·m^{-1}) is the drag constant and v is the swimming speed (m·s^{-1}) in the trial (tether speed).

Once F_D was calculated for each swimmer, the power required to overcome drag, PO_D, was estimated for each tether speed setting (equation 7.2). Finally, the effective power, PO_{EFF}, was calculated (equation 7.1).

7.3.4 Video Data

All trials were recorded from the side view above water using a digital camcorder (Sony HDR-HC7) using a shutter speed of 1/350 s. Stroke cycle durations were obtained using SIMI Motion 7.2 software (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany) which displayed individual fields at a sampling frequency of 50 Hz.

7.3.5 Synchronisation of Video, EMG and Tether Force Data

Tether force, EMG recordings and video data were synchronised using a manual trigger at the beginning of each trial. The manual trigger simultaneously activated an LED in the field of view of the camera and created a ‘pulse’ on the force data and EMG data.

7.3.6 Electrode Placement and Preparation

The muscles selected for this study were; pectoralis major (clavicular and sternal portions), anterior deltoid, biceps brachii, triceps brachii (long head), posterior deltoid, trapezius (upper) and latissimus dorsi. The eight muscles were selected based on their importance during front crawl (Clarys et al., 1993; Pink, Perry, Browne, Scovazzo, & Kerrogan, 1991; Stirn et al., 2011) and their relatively large size and superficial nature, in an attempt to reduce the risk of cross-talk. To lower skin impedance the locations of the electrodes were shaved and then cleaned using disposable alcohol wipes (70% alcohol). The electrode placement for the trapezius, anterior deltoid, posterior deltoid, triceps brachii and biceps brachii were located in accordance with SENIAM procedures (Freriks, Hermens, Disselhorst-Klug, & Rau, 1999). The remaining electrodes were positioned on the 'belly' of the contracted muscle, the locations of which were identified by asking the participant to perform a range of movements against manual resistance. A reference electrode was placed on the spinous process of C5.

7.3.7 Electrode Waterproofing

The taping technique and materials used to waterproof the electrodes were used in accordance with the key findings from the pilot study (Section 7.1). Two layers of waterproof, transparent, adhesive film (Opsite™, Smith and Nephew, Largo, FL) were applied to each electrode; the first layer was placed along the edge sealing the contact area between the electrode and the skin, while second layer (8 × 8 cm strip) was applied over the electrode. A small incision was made in the second layer at the point where the lead ran from the electrode. The incision ensured that the adhesive film was in contact with the skin rather than the lead. Finally a thin border of tape (Kinesio® Tex) sealed the second adhesive layer (Figure 7.2a and 7.2b).

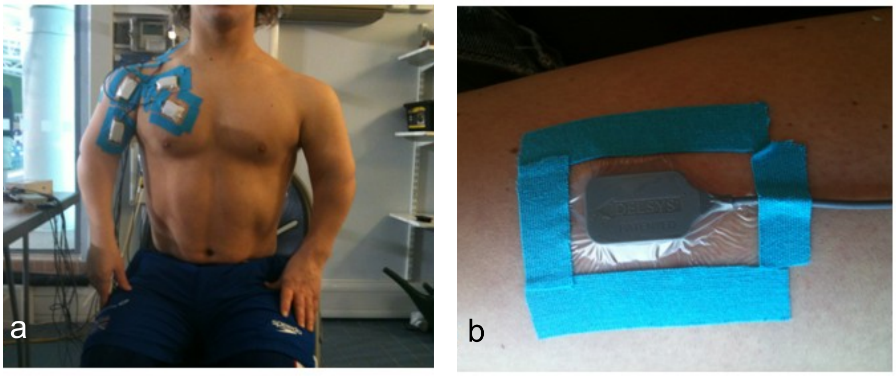


Figure 7.2a and 7.2b: The appearance of the electrodes once waterproofing was complete.

7.3.8 EMG Data Acquisition

Muscle activity was recorded at sampling frequency of 1000 Hz using an eight channel wireless Delsys system (Myomonitor® IV Wireless Transmission & Datalogging system, Boston, MA). Electrodes were encased in a pre-amplifier with an input impedance of $10^{15}\Omega$ //0.2pF and a common mode rejection ratio (60/10 Hz) of 92 dB. Each sensor (including electrodes and differential amplifier) was inserted into a connection box which connected to the main unit (protected by a water resistant layer) and secured to a pole which was held above the swimmer. Leads running from the electrodes to the amplifier were gathered using plastic tubing to prevent the swimmer's arm from catching the leads during the front crawl movement (Figure 7.3). Signals were transmitted wirelessly to a laptop computer (Toshiba Tecra M3) and displayed in EMGworks acquisition software

(Delsys, Boston, MA). Unfortunately, due to water impeding the EMG recordings, some of the muscles had to be excluded from further analysis (Table 7.1).

Table 7.1: The eight muscles available for analysis. Muscles represented by green boxes were able to be used, while those represented by red boxes were not.

Participant	IPC Class	Pec (cl)	Pec (st)	Delt (Ant)	Biceps	Triceps	Delt (Post)	Traps	Lats
1	S5								
2	S6								
3	S8								
4	S9								
5	S10								

Figure 7.3: The gathered leads running from the bodysuit and through the plastic tubing to prevent the arms from catching them during the swimming movement.

7.3.9 EMG Data Processing

Using the synchronisation system (Chapter 7; Section 7.3.5) the three strokes used to calculate external power were also used for EMG analysis. Raw data were processed using EMGworks analysis software (Delsys, Boston, MA). From the raw EMG the root mean square (RMS) of the amplitude was obtained by using a window length of 100 ms and window overlap of 50 ms (Figure 7.4). Data were normalised as a percentage of the average peak activity of three stroke cycles recorded during the swimmer's fully tethered swimming trial. Muscle recruitment patterns were examined using threshold analysis in which the muscle was deemed 'active' at 20% of the peak processed EMG. Stirn et al. (2011) used a higher threshold of 30%, however they were only interested in the muscle activity during the propulsive phase; in the current study both the propulsive and recovery phases were of interest. Furthermore, during the analysis varying threshold values were explored (5, 10, 15, 20 and 25%), and from visual inspection of the data a threshold of 20% best reflected when the muscle was active.

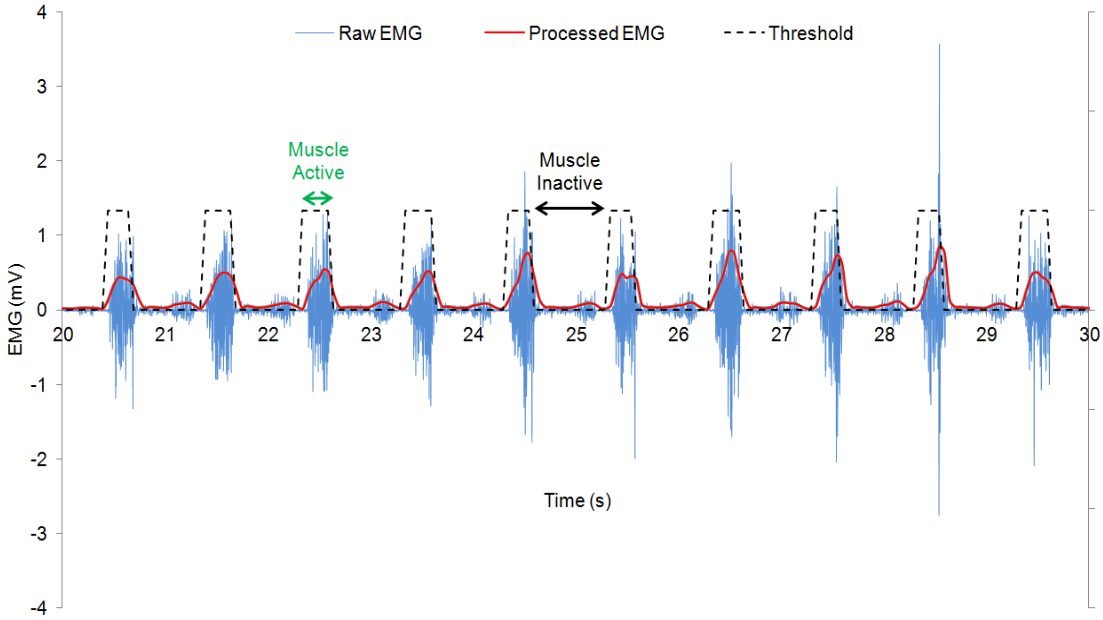


Figure 7.4: The raw EMG recordings, the processed RMS and the threshold EMG from the pectoralis major (clavicular portion) of an S5 swimmer performing a maximal effort front crawl trial at a tether speed of 50% SS_{MAX}.

Once the threshold analysis was complete, the point at which the muscle becomes active, and the duration of activation was calculated as a percentage of the total stroke time. The absolute percentage difference in the point of activation and activation duration was calculated between free swimming and each tether speed setting. Based on this percentage difference, the point and durations of muscle activation for each tether setting was categorised as, 'identical' (0-5%), 'similar' (5-10%) or 'different' (>10%) to free swimming (see Figure 7.5 for examples).

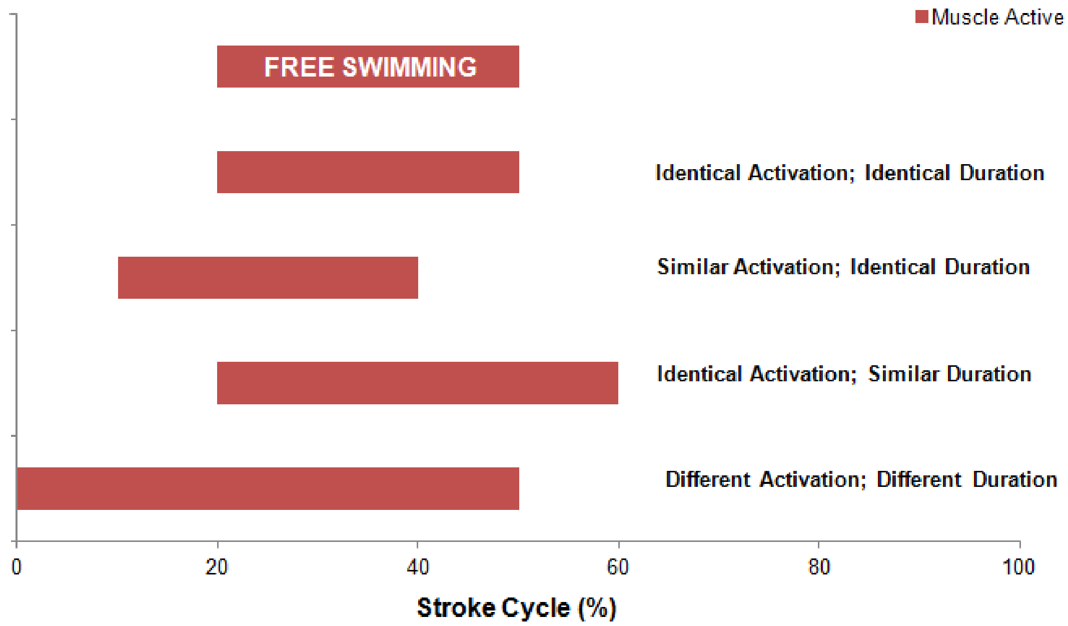


Figure 7.5: The point of activation and duration of muscle activation. Muscle patterns are compared to free swimming and identified as identical (no difference in activation/ duration 0-5%), Similar (difference in activation/duration 5-10%) or different (different in activation/ duration > 10%).

7.3.10 Statistical Analysis

Means and standard deviations were computed for the following variables; tether force, passive drag, external power, effective power and muscle activity for each tether speed setting and free swimming, where necessary. Due to the small number of participants, a Friedman's Analysis of Variance was used to examine the difference in the amplitude of the muscle activity during the various tether speed settings. The variability between participants in the point of activation and activation duration of the muscle (with the exception of the anterior deltoid) during free swimming was expressed as a coefficient of variation (CV%). A Friedman's Analysis of Variance, followed by a Wilcoxon Signed Rank Test, was used to examine the difference in external power and effective power between the different tether speeds. The difference between external power and effective power within each tether speed setting was examined using a Wilcoxon Signed Rank Test. In all comparisons, the level of significance was set at $p <$ 0.05. Statistical analysis procedures were performed using SPSS 18.0 software.

7.4 RESULTS

7.4.1 Tether Force and External Power

Tether force declined linearly with an increase in tether speed (Figure 7.6), with the highest tether force recorded during fully tethered swimming (115.0 ± 30.7 N) and the lowest tether force recorded at a tether setting of 70% SS_{MAX} (41.4 ± 17.8 N). The estimated drag force (F_D) was considered negligible during fully tethered swimming, and increased in a curvilinear fashion with the increase in tether speed (Figure 7.6). The drag force (F_D) was estimated to be 4.6 ± 1.2 N at a tether speed of 30% SS_{MAX}, 12.9 ± 3.3 N at a tether speed of 50% SS_{MAX} and 25.2 ± 6.7 N at a tether speed of 70% SS_{MAX}.

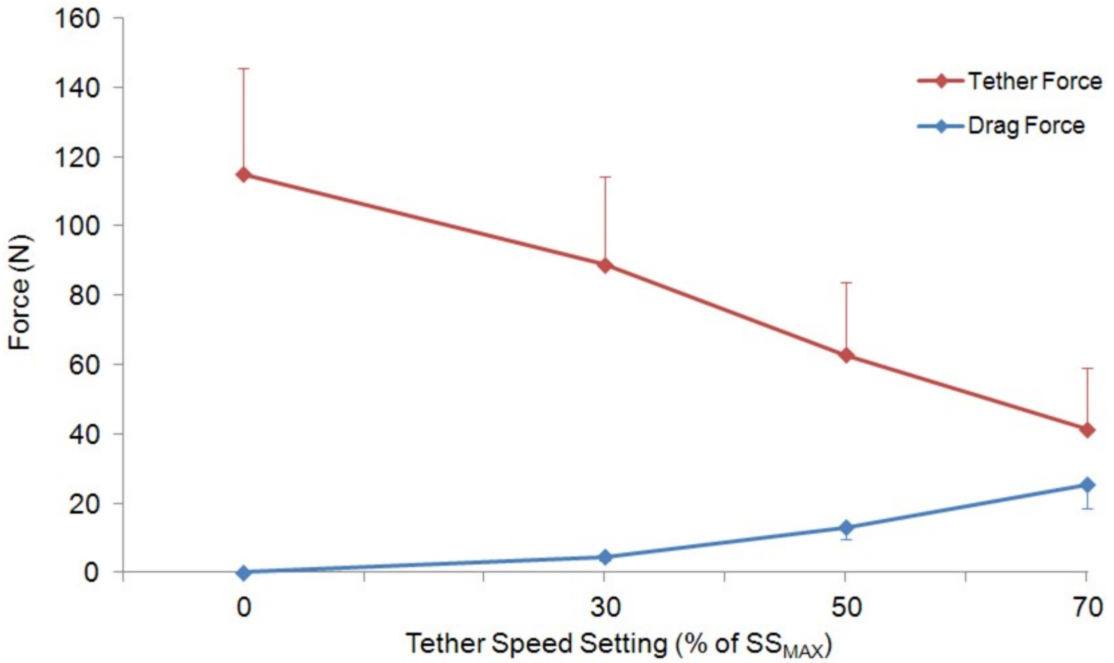


Figure 7.6: Tether force and estimated drag at 0 (fully tethered), 30, 50 and 70% of SS_{MAX}. Data points and error bars represent means and standard deviations, respectively.

External power (P_{EXT}) peaked at a tether speed of 50% SS_{MAX} (49.9 ± 21.1 W). Lower values were observed during the tether speeds of 30% SS_{MAX} (42.2 ± 16.7 W) and 70% SS_{MAX} (45.9 ± 23.6 W), as shown in Figure 7.7. There was no significant difference in the external power produced at the different tether speeds ($p > 0.05$). The power required to overcome drag increased with an increase in tether speed (30% SS_{MAX} = 2.2 ± 0.8 W; 50% SS_{MAX} = 10.3 ± 3.7 W and 70% SS_{MAX} = 28.1 ± 10.3 W). The effective power produced by the swimmers (PO_{EFF}) was 44.1 ± 17.4 W at a tether speed of 30% SS_{MAX}; 60.2 ± 24.3 W at a tether speed of 50% SS_{MAX} and 73.9 ± 31.9 W at a tether speed of 70% SS_{MAX} (Figure 7.7). There was a significant difference ($p < 0.05$) in the effective power between tether speeds of 30% and 50% SS_{MAX}, and between 50%

SS_{MAX} and 70% SS_{MAX}. There was a significant difference ($p < 0.05$) between effective power and external power at tether speed settings of 50% SS_{MAX} and 70% SS_{MAX}.

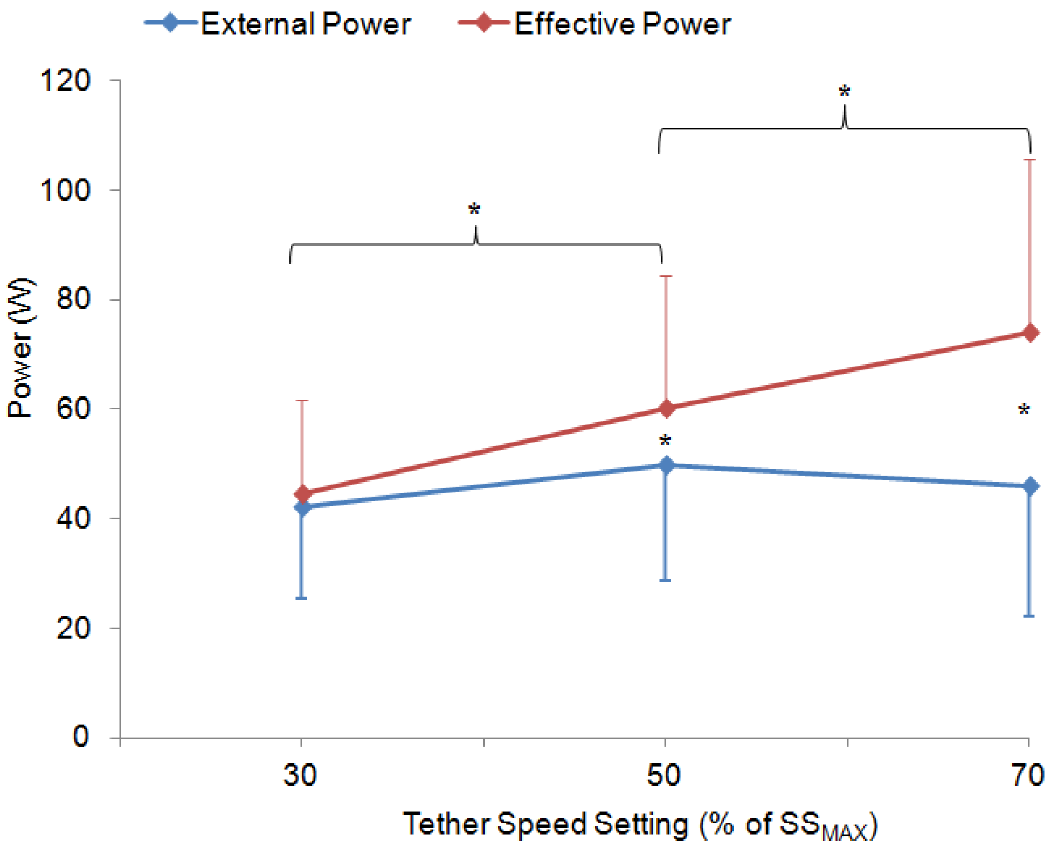
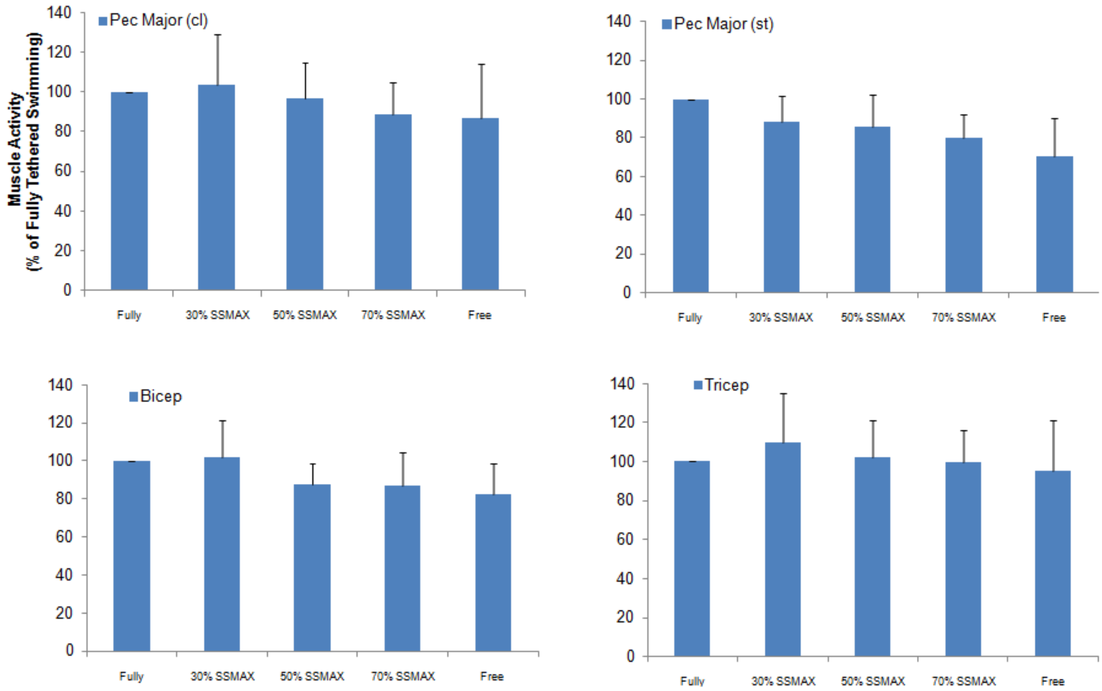
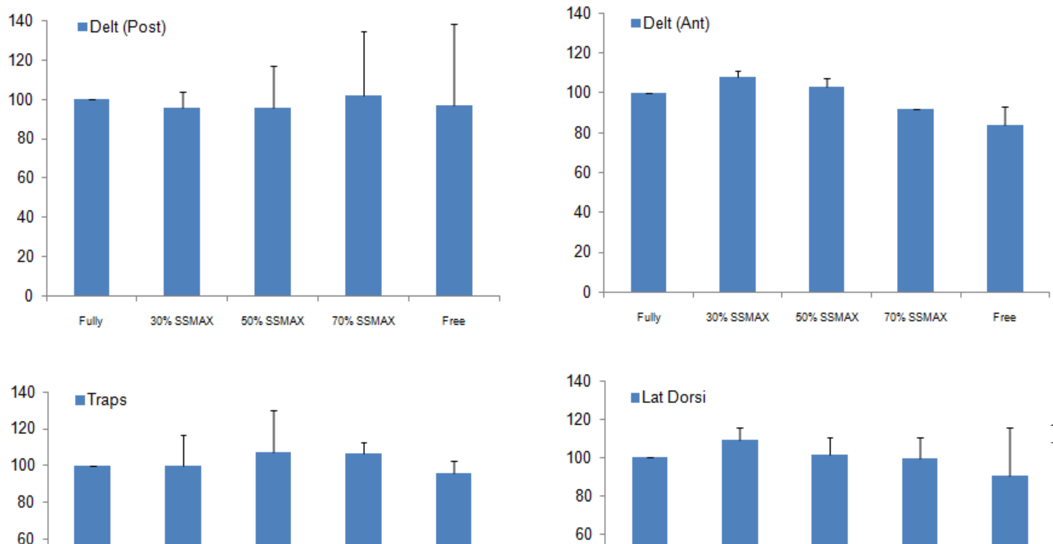


Figure 7.7: The external power and effective power at tether speed settings of 30, 50 and 70% SS_{MAX}. Data points and error bars represent means and standard deviations, respectively. * denotes a significant difference ($p < 0.05$).

7.4.2 EMG Data

There was no significant difference ($p > 0.05$) in the amplitude of the muscle activity between the trials performed on the ITS Ergometer and free swimming. The highest muscle activity (Figure 7.8) was recorded during fully tethered swimming (pectoralis major [sternal portion] and posterior deltoid) or at a tether speed setting of 30% SS_{MAX} (pectoralis major [clavicular portion], biceps brachii, triceps brachii long head, trapezius, latissimus dorsi and deltoid anterior). With the exception of the posterior deltoid and trapezius, after a tether speed setting of 30% SS_{MAX} amplitude of muscle activity decreased with an increase in tether speed. The lowest muscle activity was recorded during free swimming. From the threshold analysis, the point at which the muscle became active and the duration of activation was found to be either 'identical' or 'similar' to that of free swimming (Table 7.2a and 7.2b). The percentage difference in the point of activation and activation duration was between 3.0 and 4.5% for each tether speed setting. The tether speed setting which presented the closest values to free swimming, in terms of the point of activation and duration of activation was 70% SS_{MAX}. The inter-individual differences in the point in which the muscle became active was 50.2 ± 19.7% and 32.6 ± 26.1% (Appendix, Table A2.3).


Pec Major (cl)
Muscle Activity
(% of Fully Tethered Swimming)
Pec Major (st)
Bicep
Tricep
0
20
40
60
80
100
120
140
Fully
30% SSMAX
50% SSMAX
70% SSMAX
Free


Delt (Post)
Delt (Ant)
Traps
Lat Dorsi
0
20
40
60
80
100
120
140
Fully
30% SSMAX
50% SSMAX
70% SSMAX
Free

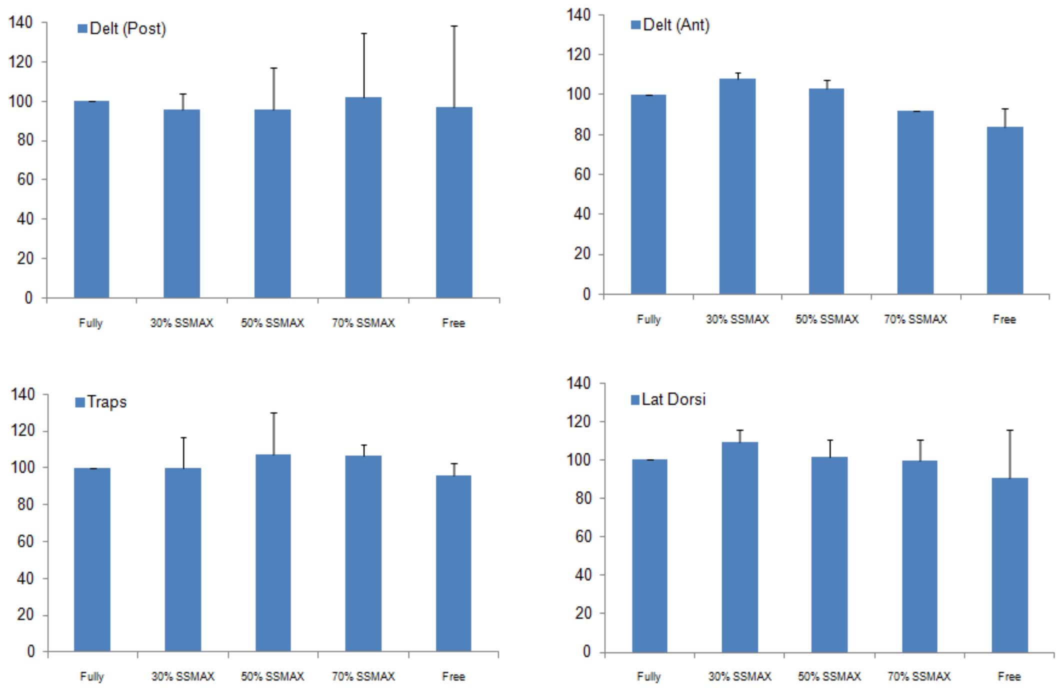


Figure 7.8: The normalised muscle activity (expressed as a percentage of the muscle amplitude recorded during fully tethered swimming) for each muscle, during each condition on the ITS Ergometer (0, 30, 50 and 70% of SS_{MAX}) and free swimming. The columns represent the group means and the error bars represent standard deviations.

Table 7.2a (Top) and 7.2b (Bottom): The absolute percentage difference in the point at which the muscle becomes active and the duration of muscle activation, between each tether speed setting (0, 30, 50 and 70% of SS_{MAX}) and free swimming. The values with the green background represent an 'identical' difference and the values with the blue background represent values with a 'similar' difference.

The absolute percentage difference in the point at which the muscle becomes 'active' between each trial on the ITS Ergometer and free swimming.

	PM (cl)	PM (st)	Delt Ant	Lat Dorsi	Biceps*		Triceps*		Traps*		Delt Post*		
					i	ii	i	ii	i	ii	i	ii	iii
Fully	5.04	6.34	1.41	2.04	2.21	3.79	5.78	1.58	7.12	5.12	1.55	2.51	1.08
30%	2.93	1.27	0.92	4.25	2.67	6.17	4.28	8.09	6.09	5.85	3.34	2.51	3.68
50%	5.18	3.46	3.57	4.13	4.71	6.79	2.82	3.72	6.74	7.72	3.66	3.11	1.06
70%	4.53	2.94	1.37	3.65	3.25	3.84	1.81	4.33	6.91	3.93	1.27	3.92	1.67

The absolute percentage difference in the duration of the muscle activation between each trial on the ITS Ergometer and free swimming.

	PM (cl)	PM (st)	Delt Ant	Lat Dorsi	Biceps*		Triceps*		Traps*		Delt Post*		
					i	ii	i	ii	i	ii	i	ii	iii
Fully	3.84	7.57	5.34	2.70	1.61	4.81	4.38	0.96	3.14	0.91	4.45	7.42	1.13
30%	3.87	2.19	4.54	2.23	0.44	3.08	3.60	2.62	2.98	1.50	6.54	7.55	1.72
50%	2.40	6.43	3.52	2.08	2.29	5.52	6.18	1.90	2.68	4.31	5.76	8.09	0.60
70%	2.88	5.36	1.75	1.74	3.25	4.73	2.45	2.90	5.14	0.70	4.94	2.12	0.05

* denotes the muscles which were 'active' more than once in the stoke cycle.

7.5 DISCUSSION

The primary aims of this study were to establish whether: 1) the level of muscle activity and, 2) the muscle recruitment patterns exhibited when swimming maximally on the ITS ergometer, at various tether speeds, differ from those during free swimming. The amplitude of the muscle activity was not significantly different during any of the tether speed settings (0, 30, 50 and 70% SS_{MAX}) to free swimming. From closer inspection of the data it was evident that muscle activity was higher during either fully tethered swimming or at a tether speed of 30% SS_{MAX}, after which (with the exception of the posterior deltoid and trapezius) muscle activity decreased with an increase in tether speed setting. The lowest muscle activity was recorded during free swimming. Although the statistical analysis does not support the hypothesis, due to the small number of participants and limited statistical power, the first primary hypothesis was accepted based on the trend of the data. Muscle recruitment patterns (point of activation and duration of activation) were deemed either 'identical' or 'similar' to free swimming. Moreover, these recruitment patterns were not affected by a change in the tether speed setting; therefore the second primary hypothesis was rejected. A secondary aim was to gain a better understanding of the relationship between muscle activity and the external power produced by the swimmer. In order to achieve this, the power to overcome drag was estimated and combined with the measures of external power. The study found that an increase in tether speed setting resulted in a decrease in the level of muscle activity, and a significant increase in the power when accounting for drag (E_{FF}). The secondary hypothesis was therefore rejected.

External power peaked at a tether speed of 50% SS_{MAX}, supporting the findings from Study 2 of this thesis (Chapter 5). Power to overcome drag was based on measures of passive drag obtained through towing. The limitation of the passive drag measurements within this study were that the three towing trials were performed at only one tether speed, due to restrictions in pool time. The limitation of using passive drag measurements are that, apart from the initial glide phase of the dive and push off from the wall, the swimmer is never in a stable prone position while swimming (Toussaint et al., 2004). It must be emphasised that due to these limitations in measuring passive drag, the power to overcome drag and the effective power were only estimates. Effective power increased significantly with an increase in tether speed setting. Therefore, by taking into account the power to overcome drag at the tether speed setting (effective power = external power + power to overcome drag), the effective power data presents a very different trend to that of external power. Furthermore, at tether speed settings of 50% and 70% SS_{MAX}, the effective power was significantly greater than the external power produced on the ITS Ergometer.

While the effective power produced by the swimmer increased with tether speed setting, the amplitude of the muscle activity decreased. This apparent discrepancy between the muscle amplitude and effective power may be due to a component of power which could not be accounted for in this study; the power lost to the water (P_K). Assuming that the total power output (P_{TOT}) of the swimmers was the sum of the external power, the power to overcome drag and the power lost to the water ($P_{TOT} = P_{EXT} + P_D + P_K$) and that this total remained constant between trials, it appears that the slower the tether speed, the greater the power lost to the water. One explanation for this observation is that during slower tether speeds, the hand and arm repeatedly pulls through the same fast flowing water, which was accelerated during the previous stroke. This is quite unlike free swimming, where handfuls of slowly moving water are used to propel the swimmer forwards (Counsilman, 1968).

Despite no statistical difference ($p > 0.05$) in the amplitude of the muscle activity between free swimming and the trials performed on the ITS Ergometer, the highest amplitudes were recorded during fully tethered swimming or at a tether speed of 30% SS_{MAX}. These findings support the work by Bollens et al. (1988) who found that although there was no statistical difference ($p > 0.05$) in the muscle amplitude between free swimming and fully tethered swimming, muscle activity was higher during fully tethered swimming. In the current study, the increased muscle activity observed in the fully tethered and the lowest tether speed conditions was due to a greater volume of the arm having a backward velocity relative to the water, during the propulsive phase, when compared to free swimming (Study 1; Section 3.4). This increases the drag force acting on the hand and arm (Goldfuss & Nelson, 1971), resulting in an increase in muscle activity.

The amplitude of the muscle activity presented a non-significant decrease with an increase in tether speed setting, with the exception of the posterior deltoid and trapezius, for which the amplitude of the EMG signal remained relatively constant between the trials. The reason for this may be due to the relative roles the muscles play within the stroke. The posterior deltoid is responsible for the transition between the end of the propulsive phase (i.e., shoulder extension) and the beginning of the recovery phase (Pink et al., 1991). The trapezius is predominantly responsible for upwardly rotating the scapula as the hand begins to exit the water (Pink et al., 1991). Since the posterior deltoid and trapezius are responsible for the beginning of the recovery phase, rather than the beginning of the propulsive phase, a change in tether speed is less likely to have an effect on the activity of these muscles, compared to those that are active in the propulsive phase.

Muscle recruitment patterns presented a high level of inter-individual differences in the point of activation (CV = 50.2 ± 19.7%), and activation duration (CV = 32.6 ± 26.1%). These inter-individual differences are attributed to the different physical impairments of the swimmers (i.e., amputation, cerebral palsy). The participant with the most severe physical impairment (S5) had no legs, an affected arm and a sound arm, while the swimmer who was the least physically impaired (S10) had 'fixed' ankles and was unable to plantar flex the foot. Understanding the affect different physical impairments have on muscle recruitment patterns is beyond the scope of this thesis. However, future EMG studies could provide a greater insight into how disabled swimmers adapt their swimming stroke due to their physical impairment. These studies would add to the current limited body of knowledge.

The point of activation and activation duration were found to be either 'identical' or 'similar' to free swimming. Although no direct comparisons could be made to the scientific literature, Bollens et al. (1988) examined muscle recruitment patterns in terms of the timing and amplitude of the linear envelope using the 'IDANCO' system (detailed in Chapter 2; Section 2.3.2.2). The authors compared the recordings of three upper body muscles during fully tethered and free swimming, and found the similarity in timing and amplitude was, at the least, 'analogue' (i.e., a difference of between 11-20%). Within the current study, the tether speed setting which appeared to be most similar to free swimming, in terms of muscle specificity was 70% SS_{MAX}. In this condition all muscles were deemed 'identical' to free swimming, with the exception of the first point of activation of the trapezius and the activation duration of the pectoralis major (sternal portion). These findings highlight that although the swimmers presented individual muscle recruitment patterns, when swimming on the ITS Ergometer, they reproduced 'identical' or 'similar' muscle recruitment patterns to that of free swimming.

The main limitations to the study were that despite pilot work, some of the muscles recordings were impeded by water and had to be excluded from further analysis. From observing the trials, it appeared that the bordering layer of tape (Kinesio

Tex) pulled the adhesive film away from the skin. During the final testing session, the decision was made to apply just the adhesive film to the electrodes. This proved successful, with muscle activity recorded for all eight muscles. Therefore, increasing the number of layers of tape over the electrodes during EMG testing in the water can have a negative impact of the durability of the waterproof layers. Another limitation to the study was the small number of participants, which was due to restrictions on pool time. With regards to EMG, it was unfortunate that due to the lack of any standardised methodologies to examine muscle activity and recruitment patterns during swimming, few inter-study comparisons were made. Electromyography provides a valuable insight into the muscle patterns performed during swimming, information which cannot be obtained by other measurement techniques (Clarys, 1983). It is surprising that, despite the increasing use of EMG in the water, there are currently no reports in the scientific literature that have attempted to validate and standardise methodologies (Rainoldi et al., 2004).

7.5.1 Conclusion

When swimming on the ITS Ergometer there was no significant difference in the amplitude of the EMG signal or the muscle recruitment patterns. Based on the general trend of the data, the higher the tether speed setting, the closer the amplitude of the muscle activity is to free swimming. Furthermore, during a tether speed setting of 70% SS_{MAX}, more of the muscles were deemed to have recruitment patterns that were ‘identical’ to free swimming. These findings emphasise that despite there being no statistical difference between free swimming and swimming on the ITS Ergometer (at tether speed settings of 30, 50 and 70% SS_{MAX}), a tether speed setting of 70% SS_{MAX}

appears to elicit the closest muscle amplitude and recruitment patterns to free swimming. Effective power increased with an increase in tether speed setting. Assuming the total power remained constant between trials, during slower tether speeds a greater proportion of power was lost to the water.

CHAPTER 8

EXPERIMENTAL STUDY 5

NEUROMUSCULAR FATIGUE AND THE DECLINE IN EXTERNAL POWER

The aims of this study were twofold: First, to examine the effect of neuromuscular fatigue on the frequency content of the EMG signal during a 30 s maximal effort swim on the ITS Ergometer. Second, to establish whether there was a relationship between changes in the frequency content of the EMG signal and the decline in external power during a 30 s test.

8.1 INTRODUCTION

Locating fatigue is often conceptualised as finding the 'weak link' in the chain (William & Ratel, 2009). Once this 'weak link' has been identified, training can be altered to delay fatigue and ultimately improve swimming performance. Although this idea of identifying the cause and consequently delaying fatigue appears quite simple, in practice this notion is difficult due to the confounding variables (e.g., type of task, trained status of the individual, location of fatigue) which impact it (William & Ratel, 2009). During swimming fatigue leads to a decline in propulsive force (Chapter 3) and external power (Chapter 6), which can be related to central (neural) and/or peripheral (muscle) fatigue (Rouard, 2010).

Central fatigue can be defined as failure in locations found within the brain, spinal cord and up to the point of the excitation site of the motoneuron (William & Ratel, 2009). Peripheral fatigue is the failure in the transmission of the neural signal or a failure of the muscle to respond to neural excitation (William & Ratel, 2009). Surface EMG reflects both central and peripheral alterations, and is a measure of neuromuscular fatigue. Neuromuscular fatigue is typically analysed in the frequency domain, i.e., by using a Fourier transform. The Fourier transform separates the raw EMG into the different frequencies found within that signal. From the decomposition of the signal, central parameters such as the mean and median frequencies can be calculated (Ganter et al., 2007).

With the onset of fatigue the mean and medium frequencies shift to lower frequencies (Ganter et al., 2007; Rouard, 2010) when compared to non-fatigued states. Aujouannet et al. (2006) and Caty et al. (2006) examined changes in the mean frequency content before and after a 4 × 50 m exhaustive test. Before and after the test, Aujouannet et al. (2006) found a decrease in the mean frequency of the biceps brachii and triceps brachii during a dry-land isometric voluntary contraction. Caty et al. (2006) examined the time-frequency of two wrist muscles (flexor carpi ulnaris and the extensor carpi ulnaris) and found a significant decrease in the instantaneous mean frequency between the first 25 m on the initial 50 m sprint and the final 25 m on the fourth 50 m.

In a recent study, Stirn et al. (2011) compared the mean frequency and performance measures (i.e., swimming speed, stroke rate and stroke length) between the beginning and the end of a maximal effort 100 m swim, and found that by the end of the test the mean frequency was significantly lower, than at the beginning in all muscles (pectorialis major, triceps brachii and latissimus dorsi). They concluded that the changes in frequency parameters mirrored the appearance of fatigue during swimming. Ganter et al. (2007) presented a significant relationship between external power measured on the swim bench and median frequency of the long head of the triceps brachii. However, this relationship was weaker for the lateral head, and no such relationship was found for the latissimus dorsi. Combining EMG frequency analysis with biomechanical measures (e.g., external power), would provide a greater insight into how neuromuscular fatigue impacts the decline in power and ultimately swimming performance.

The aims of this study were twofold: First, to examine the effect of neuromuscular fatigue on the frequency content of the EMG signal during a 30 s maximal effort swim on the ITS Ergometer. Second, to establish whether there was a relationship between changes in the frequency content of the EMG signal and the decline in external power during a 30 s test. The experimental hypotheses were: 1) that the frequency of the EMG signal would decrease significantly between the beginning and the end of the test; and 2) that there would be a significant relationship between the decline in the frequency of the EMG signal and the decline in external power.

8.2 METHOD

8.2.1 Participants

Five highly trained, physically impaired, male swimmers (age 25.4 ± 6.7 years; height 1.58 ± 0.28 m; mass 69.0 ± 14.7 kg) consented to participate in the study. All swimmers were part of the 'World Class Development' or 'World Class Podium' programme. One participant was selected from each of the following IPC Classes, S5, S6, S8, S9 and S10. All participants were familiar with the ITS Ergometer and had participated in the previous three experimental studies (Studies 2-4). Data collection procedures were approved by MMU Cheshire's Department of Exercise and Sport Science Ethics Committee.

8.2.2 Calculating External Power

External power was calculated as outlined in Chapter 5 (Section 5.3.3) and the percentage decline in external power (FI) was quantified in accordance with the methods outlined in Chapter 6 (Section 6.2.3).

8.2.3 Testing Procedure

Participants performed a 30 s maximal effort swim on the ITS Ergometer. Based on the results of Chapter 7, an individual's tether speed setting was set to that at which they produced their highest external power. Electromyograms were recorded for eight upper body muscles. The testing procedure within this study directly followed that of the previous study (Chapter 7) with no warm up imposed on the swimmer.

8.2.4 Electrode Placement, Preparation and Waterproofing

The selected muscles for analysis and the procedures for electrode placement are as detailed in Chapter 7 (Section 7.3.4). Prior to the 30 s test, all the electrodes and waterproof taping were checked and in some cases replaced with a new electrode and taping. Unfortunately, due to water impedance some muscles had to be excluded from the study, as shown in Table 8.1.

Table 8.1: The eight muscles available for analysis. Muscles represented by green boxes were able to be used, while those represented by red boxes were not.

Participant	IPC Class	Pec (cl)	Pec (st)	Delt (ant)	Biceps	Triceps	Delt (post)	Traps	Lats
1	S5								
2	S6								
3	S8								
4	S9								
5	S10								

8.2.5 EMG Data Acquisition and Processing

Information regarding data acquisition is detailed in Chapter 7 (Section 7.3.6). The median (MDN) frequency of the EMG signal was calculated for three strokes at the beginning, and three strokes at the end of the test by applying a fast Fourier transform to the data in MS Office Excel (2007). The MDN frequency was used, as opposed to the mean, as the MDN is less sensitive to noise (De Luca, 1997). The mean of the three strokes was calculated at the beginning and the end of the test for each muscle (mean MDN frequency). The percentage decline in mean MDN frequency between the beginning (MDN_{0-5}) and the end (MDN_{25-30}) of the test was calculated, i.e., decline in mean MDN frequency = $((MDN_{0-5} - MDN_{25-30})/ MDN_{0-5}) \times 100$.

8.2.6 Statistical Analysis

Means and standard deviations were computed for external power during each 5 s window of the test and the FI. The repeatability of the three MDN frequency values used to calculate each mean MDN frequency (Section 8.2.5) was examined using an intra-class correlation coefficient (ICC). Within each muscle the difference in the mean MDN frequency between the beginning and the end of the test was determined using a Wilcoxon Signed Rank Test. The biceps brachii was the only muscle in which signals were recorded for all participants, therefore the relationship between the decline in the mean MDN frequency and the FI was only examined for this muscle. This relationship was quantified using a Spearman's Rank test. In all comparisons, the level of significance was set at $p < 0.05$. Statistical analysis procedures were performed using SPSS 18.0 software.

8.3 RESULTS

8.3.1 External Power

The highest external power was recorded during the first 5 s (54.5 ± 19.6 W) and the lowest recorded during the final 5 s (37.4 ± 12.5 W) of the test (Figure 8.1). During the first 5 s, the highest (82.3 W) and lowest (37.0 W) external power was produced by the highest IPC Class (S10) and lowest IPC Class (S5) swimmer, respectively. The mean FI was 37.4 ± 12.5%, with the highest FI recorded by the S10 swimmer (39.1%) and the lowest FI was recorded by the S8 swimmer (22.2%).

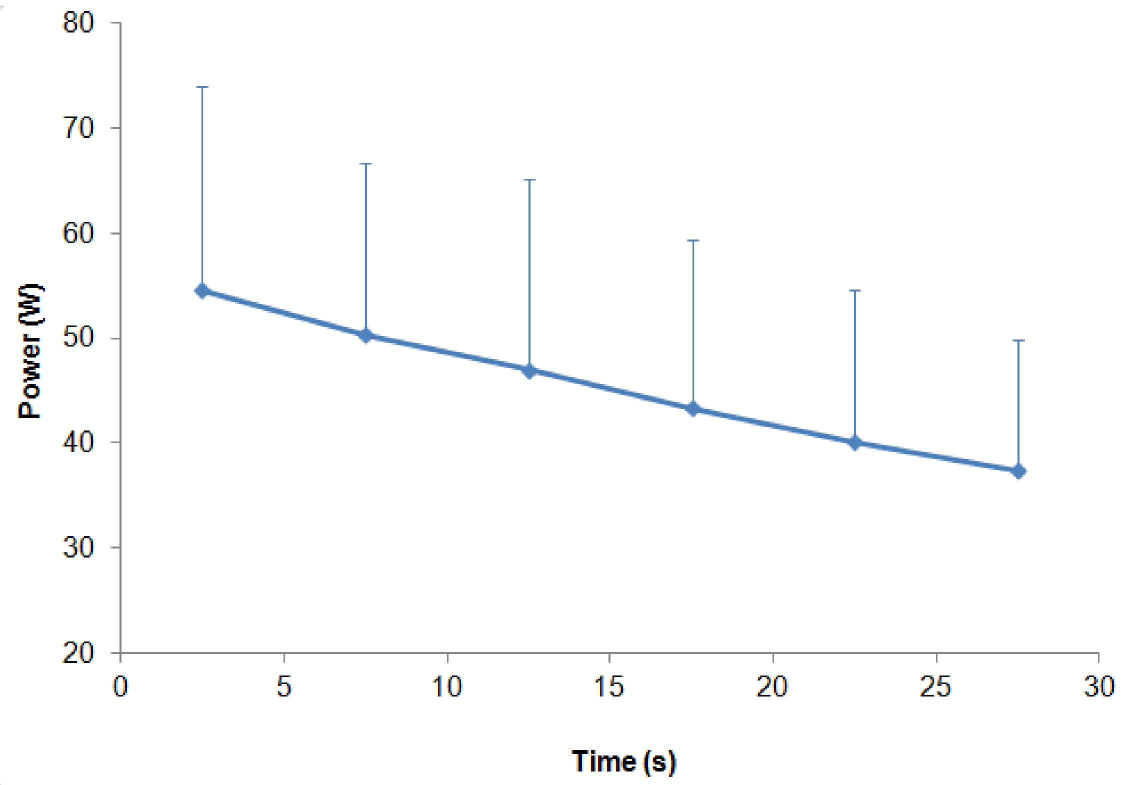


Figure 8.1: External power for each 5 s window of the 30 s maximal effort swim on the ITS Ergometer for the participant group (*n* = 5). Data points represent means and error bars represent the standard deviations.

8.3.2 Frequency of the EMG Signal

The ICC of the MDN frequency within the first 5 s was 0.96 between stroke one and two, and 0.97 between stroke two and three. Within the final 5 s the repeatability of the MDN frequency was 0.96 between stroke one and two, and 0.98 between stroke two and three. The mean MDN frequency was higher during the first 5 s compared to the final 5 s of the test (Figure 8.2), with the exception of the one muscles from the S9 swimmer (pectoralis major, sternal portion) and one muscle from the S10 swimmer (pectoralis major, clavicular portion). The biceps brachii were the only muscle to present a significant decrease ($p < 0.05$) in the mean MDF frequency between the beginning and the end of the test. The muscle which presented the greatest percentage decline in the mean MDN frequency (Appendix, Table A2.4) varied with each participant (S5 swimmer = biceps brachii, 29.1%; S6 swimmer = latissimus dorsi, 12.3%; S8 swimmer = triceps brachii, 20.3%; S9 swimmer = anterior deltoid, 13.2%; S10 swimmer = biceps brachii, 19.1%). There was a strong significant relationship ($r = 0.8$; $p < 0.05$) between the decline in the MDN frequency of the biceps brachii and the FI.

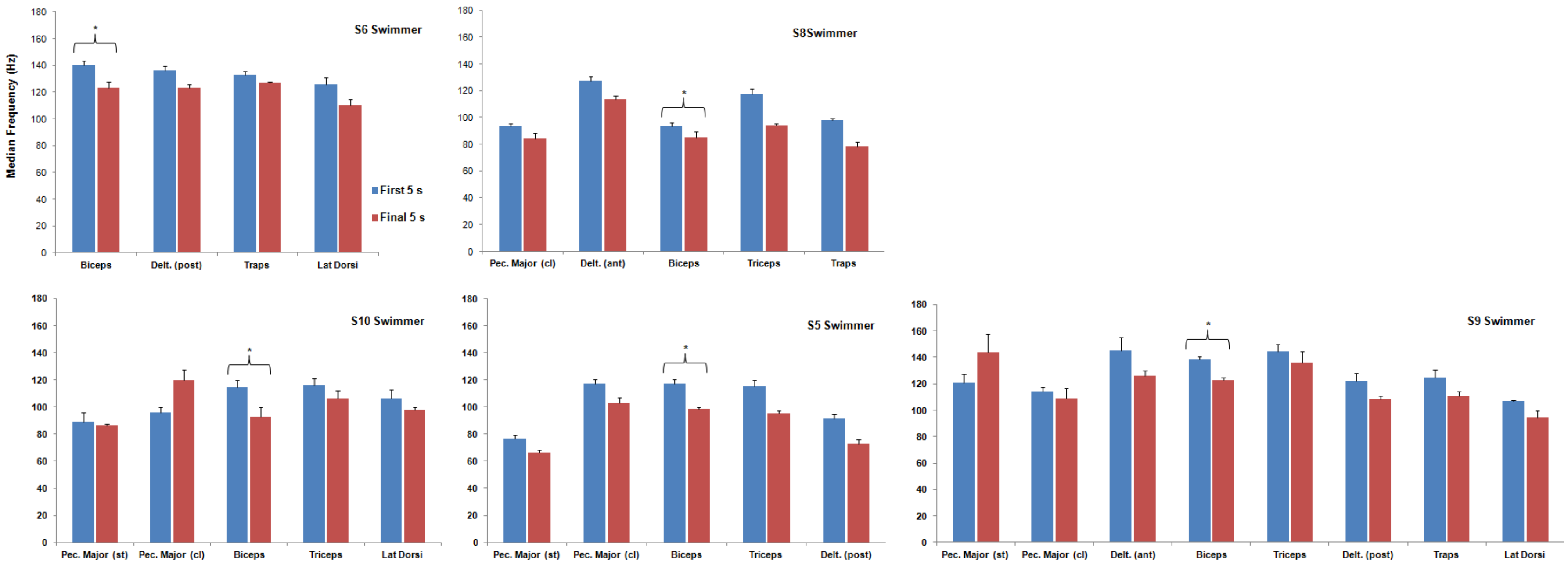


Figure 8.2: The mean median frequency (Hz) of the EMG during the first 5 s and final 5 s of the 30 s maximal effort swim on the ITS Ergometer for each participants.

8.4 DISCUSSION

The aims of this study were twofold. Firstly, to examine the effect of neuromuscular fatigue on the frequency content of the EMG signal during a 30 s maximal effort swim on the ITS Ergometer. The mean MDN frequency was higher in the first 5 s compared to the final 5 s of the test, with the exception of the pectoralis major (clavicular portion) of one participant, and the pectoralis major (sterna portion) of another. Only the biceps brachii presented a significant decline in mean MDN frequency. This is most likely due to the biceps brachii being the only muscle which was analysed in all participants. Based on the main trend of the data, the studies first hypothesis was accepted. The secondary aim was to establish whether there is a relationship between changes in the frequency content of the EMG signal and the decline in external power during the 30 s test. Due to water impeding some of the recordings from the muscles, this relationship was only examined for biceps brachii. For this muscle there was a strong positive significant relationship between the decline in the frequency of the EMG signal and the decline in external power. Therefore the secondary hypothesis was accepted.

The highest external power was recorded during the first 5 s and the lowest external power recorded during the final 5 s of the test, supporting the findings from Chapter 6. The FI within this study (37.4 ± 12.5%) was higher than that presented in Chapter 6 (26.6 ± 8.0%). This is most likely due to the additional resistance and restricted movement imposed by the taping and leads attached to the swimmer. A similar observation was made by Aujouannet et al. (2006) who stated that the use of EMG equipment increased drag and reduced the performance of the participants. Based on these observations, caution must be taken during inter-study comparisons regarding the effect of fatigue on biomechanical measures (i.e., stroke rate, stroke length, external power), as the additional use EMG equipment within some studies must be taken into consideration.

Neuromuscular fatigue was assessed by examining the shift in the MDN frequency of the EMG signal. The repeatability of the MDN frequency (ICC = 0.96-0.98) was excellent during both the first 5 s, and final 5 s of the test, for all muscles. Within the majority of muscles, the mean MDN frequency shifted to lower frequencies indicating the onset of fatigue. The shift to lower frequencies was due to the recruitment of slower motor units and/or a decrease in conduction velocity (Rouard, 2010). The only muscle to show a significant decrease in mean MDN frequency was the biceps brachii. This was due to the biceps brachii being the only muscle where a clear signal was recorded for all participants, increasing the statistical power in comparison to the other muscles. This was in agreement with Aujouannet et al. (2006), who reported a significant decline in the biceps brachii between the beginning and end of an exhaustive test.

There was increase in the mean MDN frequency of the pectoralis major sternal portion for the S9 swimmer, and the pectoralis major clavicular portion for the S10 swimmer. This may be due to the swimmers pacing the 30 s swim and not truly swimming maximally, however this would be surprising as the S10 recorded the highest FI. In addition, any sub-maximal effort would have been reflected in a smaller MDN frequency shift in the other muscles, than was observed. Alternatively, it may be that these swimmers were less reliant on the pectoralis major muscles and more reliant on others. Indeed, the muscle which presented the greatest decline in the mean MDN frequency was different for each individual swimmer. These results were not surprising as muscle fatigability is highly specific to the individual swimmer (Rouard, 2010). The difference in the way in which fatigue affects individuals makes inter-individual and inter-study comparisons quite limited. Yet the main advantage of EMG frequency analysis is that this non-invasion procedure provides useful information regarding alterations within the muscle for each individual swimmer. This information can be used to adapt muscle training programs specific to each swimmer (Caty et al., 2006).

There was a significant relationship between the decline in the MDN frequency of the biceps brachii and the FI. This finding highlights the importance of the biceps brachii in the production of power during swimming. It was unfortunate that the relationship between the decline in MDN frequency and the FI could not be further explored in the other muscles. Further work is needed to examine the relationship between neuromuscular fatigue and the decline in external power, to gain a better understanding of the roles of the muscles during front crawl swimming and possible alterations in motor recruitment patterns with the onset of fatigue (Ganter et al., 2007).

The major limitation to this study was that neuromuscular fatigue was examined in just the frequency domain. When examining the frequency content of the signal the time window over which the signal was analysed was fixed and spread over a wide time interval (Tscharner, 2000). Although examining the shift in the frequency of the EMG is highly reliable during static conditions, during dynamic conditions such as swimming (e.g., where fatigue effects alterations in motor recruitment patterns) signal properties should be examined in both the frequency and time domain (Caty et al., 2006; Stirn et al., 2011). The use of time-frequency analysis within the swimming literature is quite sparse, however, researchers are currently developing and validating methods (e.g., continuous wavelet analysis) to analyse the muscle fatigue during dynamic movements (Karlssson, Yu, & Akay, 2000).

8.4.1 Conclusion

During a 30 s test on the ITS Ergometer, external power and the MDN frequency of the EMG signal decreased over time due to fatigue. With fatigue, the biceps brachii presented a significant decrease in the MDN frequency content of the EMG signal. Neuromuscular fatigue within this muscle correlated strongly with FI, emphasising the importance of the biceps brachii in the production of propulsive force. It was unfortunate that due to the small number of participants and the muscle recordings lost to water impedance, few statistical comparisons could be made. It is hoped that this work will be continued with further data collection and by applying a time-frequency analysis to the current data.

CHAPTER 9

SUMMARY AND PRACTICAL APPLICATIONS

9.1 SUMMARY

The academic aims of the Ph.D were twofold: First, to develop and validate tests of propulsive force and mechanical power that can be used to monitor swimmers on British Disability Swimming World Class Programmes. Second, to contribute to the development of an objective, evidence-based international classification system for swimmers with a physical impairment. To achieve these aims, a preliminary experimental study, an equipment development study and four experimental studies were undertaken.

Study 1 quantified and compared the decline in propulsive force exhibited by unilateral arm amputee swimmers during a 30 s fully tethered swim, to that of a closely matched group of able-bodied swimmers. During the maximal effort test, the amputee swimmers produced less mean tether force, compared to the able-bodied swimmers. However, the peak tether force produced by the dominant arm of the amputees did not differ significantly to that of the able-bodied swimmers. As the groups were closely matched in terms of age, height and body mass, the similarity in the peak tether force strongly indicated the main discriminating factor between the two groups was the physical impairment of the amputee swimmers. Due to their asymmetrical upper-limb impairment, it was hypothesised that the amputees would have compensated for the lack of hand and forearm, and thus presented a greater decline in tether force when compared to able-bodied swimmers. However this was not the case, as both groups experienced a similar decline in propulsive force (FI).

The main limitation to Study 1 was that propulsive force was assessed whilst the swimmer was stationary, during fully tethered swimming. This differs to free swimming where the swimmer progresses down the pool. Since power is the product of propulsive force and swimming speed, the study emphasised that the measurement of power would provide a better representation of the performance potential of the swimmer, than fully tethered forces alone. To do this, a device to measure external power was developed.

Chapter 4 outlined the development of the ITS Ergometer, which was designed to measure power in both able-bodied swimmers and swimmers with a physical impairment. The development of this device was a pivotal part of the Ph.D thesis and was the main measurement tool for experimental studies 2-5.

The ITS Ergometer was attached to the swimmer via a tether line and waist belt. The device released the tether at a predetermined speed whilst measuring the tension in the tether line. External power was calculated as the product of tether force and tether speed. Through laboratory- and pool-based testing, the speed and force components of the ITS Ergometer were found to be highly reliable and ecologically valid. The repeatability of external power scores within participants, between two consecutive trials, was extremely high.

Study 2 was the first in which the ITS Ergometer was used to measure the external power produced by swimmers with a physical impairment. In the study the participants ranged, in IPC Class, from S3-S10. All swimmers were able to perform their normal swimming technique on the ITS Ergometer. Peak power occurred at a tether speed setting of either 50 or 60% SS_{MAX}. Peak power was found to be a strong predictor of performance, with 76% of the variability in peak power scores being accounted for by IPC Class. The relationship between IPC Class and peak power was much higher than previously reported for IPC Class and tether force (Souto et al., 2006). It was concluded that external power measured on the ITS Ergometer had high ecological validity and that the device could have future applications in improving the objectivity of the IPC classification process.

In Study 3, during a 30 s maximal effort swim on the ITS Ergometer all swimmers exhibited a decline in external power (FI). This decline was not related to the level of their physical impairment (IPC Class), supporting the findings from Study 1. During testing for Study 3, one participant was able to walk onto poolside before the test but required the use of a wheelchair post test. Due to the participant's medical condition, it was clear that fatigue had a greater debilitating effect on the swimmer than was observed in other swimmers with a different condition. As the IPC classification procedure is performed when the swimmer is in a non-fatigued state, the effect of fatigue on a swimmer's physical impairment is not taken into consideration. Despite the detrimental effect fatigue has on swimming performance and the way in which certain conditions leave some athletes more susceptible to fatigue, it is clear that future work is needed to assist the IPC classification process and develop an understanding into fatigue and different types of physical impairments.

Study 4 combined the use of EMG and the ITS Ergometer during semi-tethered and free swimming. It was concluded that during semi-tethered swimming, the level of muscle activation and muscle recruitment patterns were similar to free swimming. However, the highest tether speed setting (70% SS_{MAX}) resulted in the level of muscle activation and the muscle recruitment patterns to be the closest to free swimming. It was concluded that the swimming movement performed on the ITS Ergometer is highly specific to free swimming.

Using passive drag measurements, Study 4 estimated the effective power produced by the swimmer (i.e., external power + power to overcome drag). The effective power increased with an increase in tether speed setting, despite the level of muscle activity remaining constant. The discrepancy between the level of muscle activity and effective power was accounted for by increased power loses to the water during fully tethered and slower semi-tether speeds.

Study 5 quantified neuromuscular fatigue by examining the shift in the median frequency of the EMG signal during a 30 s maximal effort swim of the ITS Ergometer. All muscles (with the exception of two of the pectoralis muscles, in two of the participants) presented a decrease in the median frequency content of the signal. Due to some of the muscle signals being lost to water impedance, statistical analysis could only be performed on signal from the biceps brachii muscle. This showed a significant decline in the median frequency between the beginning and end of the maximal effort test. Furthermore, there was a strong significant relationship between the decline in the median signal frequency of the biceps brachii and the decline in mechanical power. This relationship emphasised the importance of the biceps brachii in the production of propulsive force, in swimmers with a physical impairment.

9.2 PRACTICAL APPLICATIONS

9.2.1 Monitoring British Disability Swimmers on World Class Programmes.

The development of the ITS Ergometer was a pivotal part of this Ph.D thesis. The device is easily transportable and can be used in any swimming pool, irrespective of the pool's dimensions. The swimmer is attached to the ITS Ergometer's tether line, via a waist belt. Consequently, swimming technique is not restricted in anyway. As swimming technique is not restricted, the device is suitable for any swimmer with a physical impairment. It can accommodate those who swim on their back or front, or those who have adapted movement patterns as a consequence of their physical impairment.

During the Ph.D thesis, two main protocols were used for assessment of external power: 1) the six speed test (Study 2 and 4); and 2) the 30 s test (Study 3 and 5). The six speed test identified the tether setting at which a particular individual produced their peak power. In total, including rest periods, this test lasted 30 minutes and did not exhaust the swimmer. Thus, this test could be used in future to continuously monitor any improvements in the production of power for swimmer with a physical impairment; such as those on British Disability Swimming's 'World Class Development' and 'World Class Podium' programmes. If a swimmer's peak power was observed to increase during his or her training cycle, this could be attributed to one of two things: 1) the increased production of propulsive force; or 2) a reduction in active drag (e.g., improvement in technique), which would result in an increase in tether force (i.e., net propulsive force). An increase in peak power would result in an increase in performance. The 30 s test quantified decline in power during maximal effort swimming, similar to that during the WAT (Bar-Or, 1997). This test could be used in future to continuously monitor whether a swimmer's training has improved his or her ability to maintain power output when sprinting. An improved ability would result in a reduced FI. Since power is related to swimming speed, a swimmer's ability to maintain power during a race would be beneficial for performance.

The six speed test and the 30 s test were the only two protocols explored in this Ph.D thesis. Further protocols could be developed. These might include: a test to examine the duration for which a swimmer can maintain a desired power output (e.g., 80% of peak power); and a test to monitor a swimmer's ability to recover from injury. In this latter test, the tether force recorded using the ITS Ergometer could be combined with synchronised video data to examine any bi-lateral changes in propulsive force following a shoulder injury. However, due swimmers being classified into different IPC Classes, as well as specialising for different swimming strokes and event distances, it would be likely that any adopted protocols would need to be adapted to meet the specific of an individual swimmer and their coach.

9.2.2 Contribution to the development of an objective, evidence-based international classification system for swimmers with a physical impairment.

The current IPC classification system has come under much scrutiny due to the subjectivity of the process (Keogh, 2011; Souto et al., 2006). In order to improve the objectivity of the classification process, a greater scientific evidence base regarding the way in which different types and levels of physical impairment impact on performance, is needed. Due to the wide range in physical impairments and the complexity of certain medical conditions, improvements in objectivity cannot be achieved by one method alone. However, measurement tools such as the ITS Ergometer need to be utilised so that key performance determinants (e.g., propulsive force, mechanical power and fatigue) for swimmers with a physical impairment can be quantified. However, a detailed examination as to how these determinants change with different types and levels of physical impairments is required. Entirety

9.2.3 Conclusion

This thesis has contributed to the scientific body of knowledge regarding the propulsive force and external power produced by swimmers with a physical impairment. Initially, the propulsive force produced by uni-lateral arm amputee swimmers was compared with that of a closely matched group of able-bodied swimmers. It was concluded that, as a consequence of their physical impairment, uni-lateral arm-amputee swimmers produce significantly lower values of propulsive force than their able-bodied counterparts. The peak power produced by swimmers from a range of IPC Classes was then examined. The results demonstrated that peak power was strongly related to a swimmer's IPC Class, with those swimmers who were the least physically impaired producing higher values of peak power than those swimmers with a more severe physical impairment. The decline in propulsive force and external power with the onset of fatigue were also quantified within the thesis. The key findings were that arm-amputee swimmers exhibited a similar decline in propulsive force to able-bodied swimmers and that the rate at which external power declined was not related to a swimmer's IPC Class. Therefore, the level of a swimmer's physical impairment affects their ability to produce propulsive force and external power, but it does not affect the rate at which propulsive force and external power decline with fatigue.

There are two main areas in which this work will have an impact: 1) to monitor British Disability Swimmers on the World Class Programmes; and 2) to contribute to the development of an objective, evidence-based international classification system for swimmers with a physical impairment. When on a British Disability World Class Programme, the swimmer's ability to produce external power (six speed test) and to sustain this (30 s test) is now monitored throughout the year. The results from these tests provide the coach, swimmer and sports science support team with an indication of the effectiveness of training (e.g., whether strength and power gains on land, have been mirrored by power and performance gains in the water). This work has also contributed to the development of an objective, evidence-based classification system, by creating a database of power scores produced by well-trained swimmers with a physical impairment. This database has the potential to aid classifiers, by providing objective data regarding the effect that the type and severity of a physical impairment has on a swimmer's ability to produce power during swimming. However, before this data can aid the classification process, a greater number of participants are required in order to ensure that the inter-IPC Class variation in power scores is related to the level of physical impairment, and not due to other confounding variables (e.g., technical ability, trained status).

CHAPTER 10

REFERENCES

APPENDIX 1

The data shown in the following appendix relates to the development of the ITS Ergometer detailed in Chapter 4.

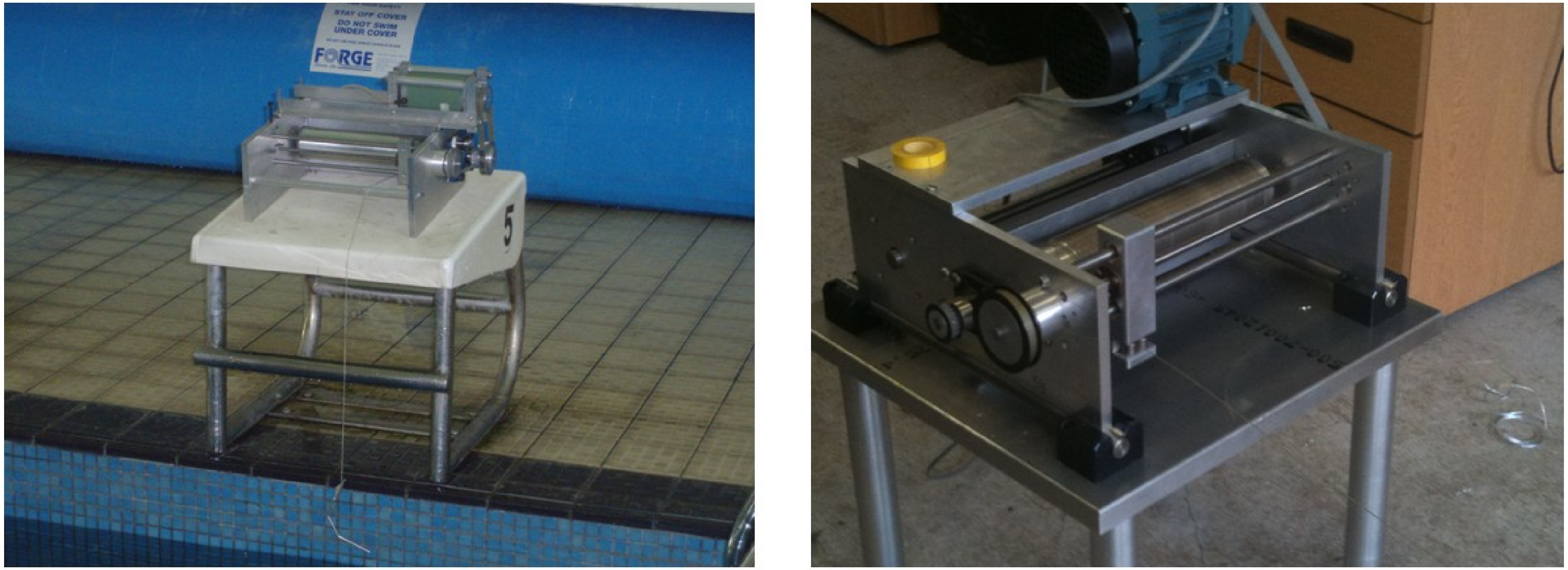


Figure A1.1a (left) and A1.1b (right): The ITS Ergometer at the beginning (a) and end of the PhD (b).

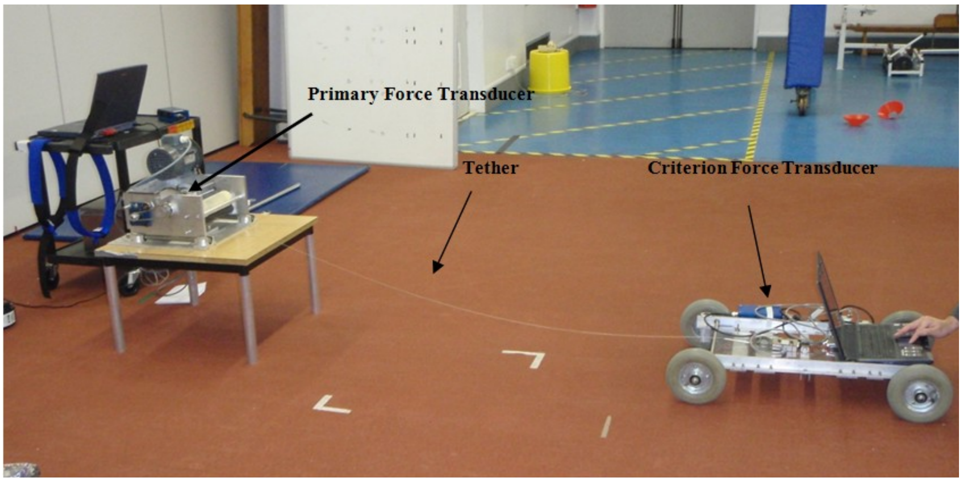
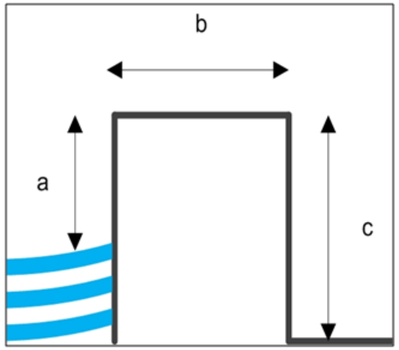
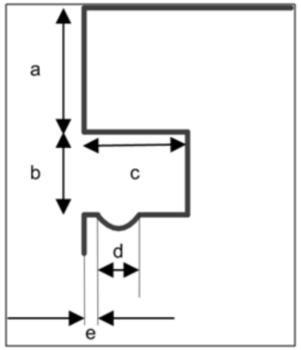


Figure A1. 2: The experimental set-up for the lab based dynamic calibration. Located within the figure is the force transducer embedded within the ITS Ergometer (primary force transducer), the tether line and the criterion force transducer secured to a trolley.

Pool	Pool Depth	Bulkhead Dimensions (mm)			Gutter Dimensions (mm)					Start Block Dimensions (mm)			
		Height - water surface (a)	Width (b)	Height - floor (c)	Pool edge to gutter (a)	Gutter height (b)	Gutter depth (c)	Indent width (d)	Indent from edge (e)	Width (at top)	Width (at base)	Height front/back	Base type
Loughborough	2 metres	320	610	320	200	120	115	30	40	500	330	400/?	Solid
Swansea	2 metres	300	996	290	185	130	120	25	40	570	400	360/320	Solid
Manchester	1.8 metres	290	1000	290	214	105	120	23	32	500	320	356/411	Solid
Bath	2 metres	320	524	335	No gutter at pool ends (side only)					500	320	370/430	Solid
Stockport - SCM	2 metres	300	510	300	230	70	100	25	30	500	330	315	Solid
LCM		300	1760	300	140	160	100	70	30	500	-----	-----	
Stirling	2 metres	280 *(315 to ledge)*	600	330	200	120	115	30	40	500	330	420	Solid





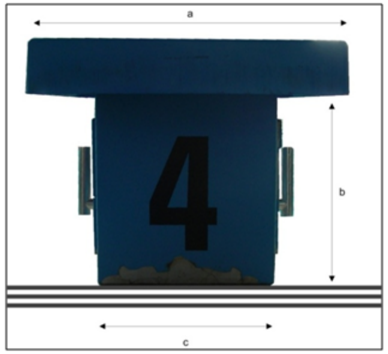


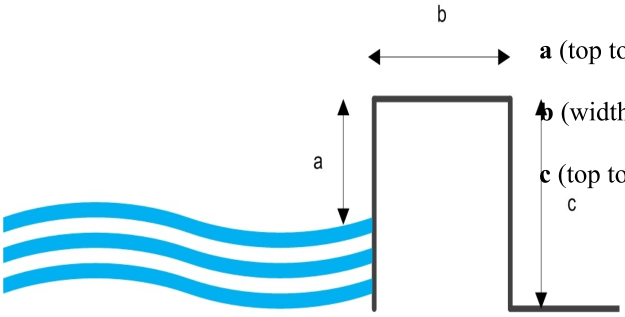
Figure A1.3: The dimensions of various pools around England and Wales. These dimensions were used to aid the construction of the feeder system.

Swimming pool dimensions document

(Please replace information in blue for your centre)

Pool : Swansea ITC Pool depth : 2m

Bulk head dimensions (if the pool has one)



Measurement:

a (top to waterline) = 300mm

b (width/depth of bulkhead) = 996mm

c (top to floor level) = 290mm

Gutter type/dimensions

Measurement:

a (top to start of gutter) = 185mm

b (height of gutter) = 130mm

c (depth of gutter) = 120mm

d (width of depression) = 25mm

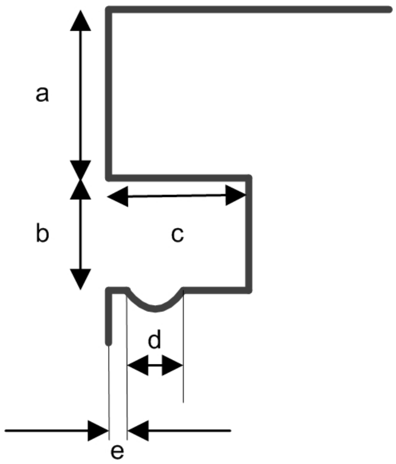


Figure A1.4: An example of how the dimensions from each pool were used to develop the feeder system.

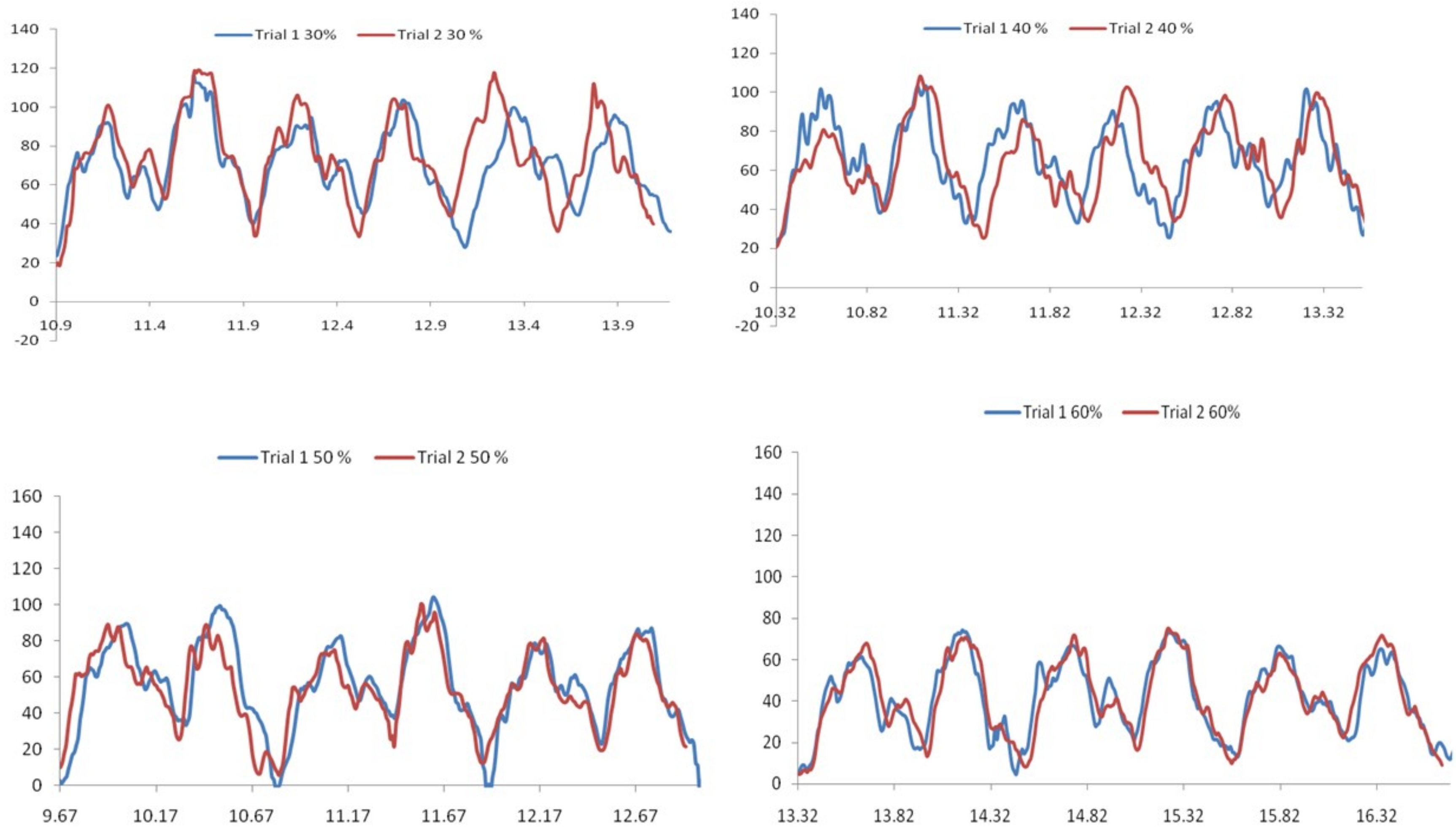


Figure A1.4: The repeatability of the tether force measured by the ITS Ergometer at tether speeds of 30, 40, 50 and 60% SSMAX. Two trials were performed at each tether speed. The Y axis is the 'Tether Force (N)' and the X axis is 'Time (s)'

APPENDIX 2

The data shown in the following appendix relates to EMG data from Chapter 7 and 8.

Table A2.1: The difference in the point in which the muscle becomes ‘active’ between free swimming and each trial on the ITS Ergometer, for each participant (Chapter 7).

The difference in the point at which the muscle is 'activate' (%) between each trial and free swimming

Trial	IPC Class	PM (cl)	PM (st)	Delt Ant	Lat Dorsi	Biceps i	ii	Triceps i	ii	Traps i	ii	Delt Post i	ii	iii
Fully	S5	3.97	3.99		1.39	1.11	3.03	6.41	1.08	12.94	6.93		3.68	1.08
	S6				1.62	0.93	4.17		2.08		3.31	3.03	1.33	
	S8	8.83		0.28		0.19								
	S10	5.52	5.24		3.37	8.07	4.59	6.28						
	S9	1.85	9.78	2.54	1.79	0.77	3.36	4.64		1.30		0.07		
30 % SSMAX	S5	6.04	0.25		4.26	0.71	3.03	4.02	3.68	10.42	11.69		3.68	3.68
	S6				5.31	2.31	12.50		12.50		0.00	6.55	1.33	
	S8	3.03		0.90		1.41								
	S10	1.52	3.17		4.62	6.20	4.59	6.28						
	S9	1.12	0.39	0.94	2.80	2.71	4.55	2.55		1.75		0.13		
50 % SSMAX	S5	5.17	0.20		3.89	1.22	0.65	2.24	3.68	3.31	11.69		2.51	1.06
	S6				4.60	10.80	12.50		3.75		3.75	6.69	3.70	
	S8	2.68		0.00		0.08								
	S10	2.25	2.60		1.98	0.74	3.40	4.35						
	S9	10.61	7.58	7.14	6.06	10.68	10.61	1.86		10.17		0.63		
70 % SSMAX	S5	4.98	1.73		3.50	1.09	0.48	0.78	1.67	6.02	4.55		6.94	1.67
	S6				2.73	7.03	8.09		6.99		3.31	2.38	0.89	
	S8	5.61		0.28		0.81								
	S10	1.02	5.64		2.12	1.21	0.94	1.86						
	S9	6.49	1.44	2.45	6.24	6.13	5.84	2.78		7.79		0.16		

identical'
similar'
different'

Table A2.2: The difference in the duration of muscle activation between free swimming and each trial on the ITS Ergometer, for each participant (Chapter 7).

		The difference in the duration of muscle activation (%) between each trial and free swimming												
Trial	IPC Class	PM (cl)	PM (st)	Delt Ant	Lat Dorsi	Biceps i	Biceps ii	Triceps i	Triceps ii	Traps i	Traps ii	Delt Post i	Delt Post ii	Delt Post iii
Fully	S5	0.44	11.46		2.68	0.42	4.39	12.93	0.21	5.67	0.80	0.58	3.78	1.13
	S6				0.24	4.37	11.99	2.46	1.72	2.45	1.02	3.03		
	S8	5.75		3.14		0.83	0.42					7.72	11.06	
	S10	6.76	2.48		5.92	1.18		1.19						
	S9	2.43	8.77	7.55	1.96	1.26	2.42	0.94		1.30		6.46		
30 % SSMAX	S5	0.99	2.91		1.00	0.50	0.74	2.34	0.68	3.79	0.34	2.06	2.56	1.72
	S6				1.27	-1.23	5.02	6.28	4.57	3.38	2.65	6.55		
	S8	3.03		4.74		0.13	2.19					11.24	12.54	
	S10	4.69	1.66		4.34	1.52		4.69						
	S9	6.76	1.99	4.33	2.32	1.26	4.38	1.09		1.75		6.32		
50 % SSMAX	S5	0.99	15.57		2.85	0.28	0.21	4.08	3.45	1.26	2.64	1.69	1.06	0.60
	S6				2.36	5.71	13.21	6.61	0.36	2.67	5.98	6.69		
	S8	1.49		2.27		1.30	2.73					10.42	15.12	
	S10	2.43	1.70		0.73	2.92		8.23						
	S9	4.69	2.02	4.76	2.38	1.23	5.92	5.81		4.11		4.22		
70 % SSMAX	S5	0.23	13.40		0.09	2.77	1.24	1.63	3.81	4.51	0.13	1.70	2.76	0.05
	S6				0.78	3.61	9.49	1.31	2.00	3.11	1.27	2.38		
	S8	4.61		3.14		3.08	3.63					10.42	1.49	
	S10	3.34	1.10		5.58	2.01		5.51						
	S9	3.34	1.59	0.36	0.52	4.76	4.55	1.33		7.79		5.24		

identical'
similar'
different'

Table A2.3: The between participant variability (CV%) in the point of activation and activation duration of each muscle (with the exception of the anterior deltiod) during free swimming.

	Variation in the point of activation and activation duration of the muscle during free swimming (CV%)						
	Pec (st)	Pec (st)	Biceps	Triceps	Delt (post)	Traps	Lats
Point of activation	18.6	43.9	39.0	71.0	72.0	64.2	42.5
Activation duration	25.7	17.4	12.1	42.9	87.6	19.4	23.3

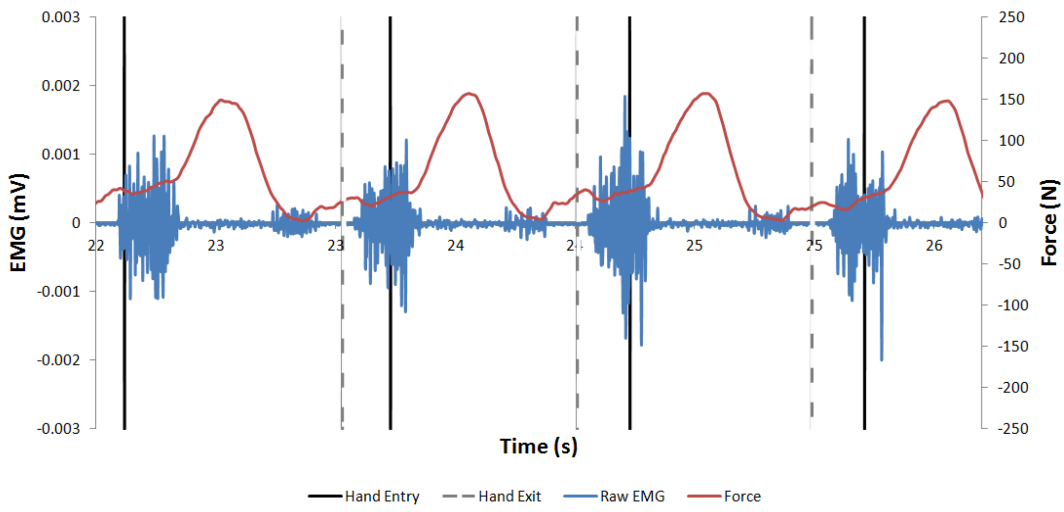


Figure A2.1: The synchronised tether force from the ITS Ergometer, hand entry and exit and raw EMG from an S5 swimmer (Chapter 7).

Table A2.4: The percentage decline in the mean median frequency and the percentage decline in power (FI) for each participant in their respective IPC Class (Chapter 8).

		Percentage (%) Decline in the Mean Median Frequency								Decline in External Power
Participant	IPC Class	Pec. Major (st)	Pec. Major (cl)	Delt. (ant)	Biceps	Triceps	Delt. (post)	Traps	Lat Dorsi	FI (%)
1	S5	13.5	12.3		29.1	17.4	20.2			35.9
2	S6				11.9		9.5	4.2	12.3	29.5
3	S8		10.0	10.7	9.3	20.3		19.5		22.2
4	S9	-19.1	4.7	13.2	11.6	5.8	11.4	11.4	11.7	29.3
5	S10	2.9	-24.5		19.1	8.2			8.0	39.1