Wearable Resistance Technology To Enhance Swimming Performance

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Abstract

Resistance training that replicates specific sport actions may optimise the transference of muscular adaptations to performance. In swimming, there are many different in-water training aids that are used by swimmers with this principle of specificity in mind. However, the majority of these have negative consequences on stroke mechanisms and technique. Wearable resistance technology (WRT) may provide a novel way to effectively overcome these challenges. It may also help improve performance when used to prime athletes. To date, physiological and performance effects of WRT use in swimming has not been reported in the literature. Therefore, the aim of this thesis was to determine: 1) the acute effects of WRT on physiological responses during submaximal freestyle swimming; and 2) whether WRT can improve 200m freestyle performance when incorporated as a post-activation potentiation (PAP) tool during a swim-specific priming strategy.

Study 1 investigated the physiological response to proximal upper arm loads of 0g-500g per arm utilising WRT during submaximal 200m freestyle swimming. 15 national level swimmers (age: 16-24y, 7 male & 8 female, 200m PB: 126.31 ± 10.46sec) completed a 7x200m incremental step test to determine submaximal swimming speed. 24 hours later six submaximal 200m freestyle swims were completed with varying wearable resistance (WR) loads (0g, 100g, 200g, 300g, 400g and 500g, randomly assigned). During the 400g & 500g trials the males showed an increase in blood lactate (BL) (400g: ↑0.74 ± 1.32 mmol^{-1}; ES: 0.41, 90%CI: (-0.13 – 0.96), 500g: ↑2.40 ± 3.06mmol^{-1}, 1.29, (-0.06-2.63)) while maintaining their submaximal speed. Conversely in females, BL was unaffected, and swimmers were unable to maintain their 200m submaximal speed (400g: ↑3.11 ± 2.56sec; ↑1.9%, (90% CI) = 0.8-3.1, 500g: ↑4.05 ± 2.35sec; ↑2.6%, (1.4-3.8)). Rate of perceived exertion (RPE) was also increased (400g: ↑1.1 ± 1.9RPE, 0.58, (-0.11 – 1.27), 500g: ↑1.1 ± 2.3RPE, 0.58, (-0.26 – 1.42). There was no substantial change in heart rate (HR) in either gender. In conclusion, WRT makes substantial changes on male BL at heavier loads which may have implications for WRT training design. However, the females decreased speed and no change in BL mean its effectiveness as a training tool is still unclear from a physiological perspective.

Study 2 investigated the benefits of utilising WRT during a swim-specific warm-up to improve 200m swimming performance. 10 national level female swimmers (age: 17.60 ± 2.46, 200m personal best: 133.13 ± 7.80) completed two performance trials 48 hours apart. Each trial consisted of a standard warm up (SWU) including 4x25m sprints either with or without WRT. Specific loads were determined for each participant with the intention of eliciting a PAP response. Following the SWU and 8-min recovery both groups commenced a 200m freestyle time trial (TT). BL, HR and RPE were collected prior to, and after, both the 4x25m sprints and 200m TT. Using WRT during the warm-up induced a PAP effect resulting in a possible increase of speed over the first 50m of -0.15 ± 0.40 sec (↓0.5%; (-0.3-1.2)). However, it also reduced the time to fatigue resulting in a possible harmful effect to back-half speed with an increase of 0.53 ± 1.18sec (↑0.6%; (-1.6-0.2)) in the second 100m split. Therefore, the addition of WRT to induce a PAP response using an 8-min recovery period had no substantial effect on 200m TT performance with a trivial difference of 0.34 ± 1.12sec (↑0.3%; 90% CI: (-0.2 – 0.7)). There was a small effect on BL and HR which could also indicate a PAP response to intervention. Our results showed that integrating a swim-specific PAP strategy, using WRT, to a SWU did not improve 200m swimming performance in elite female swimmers; however, did induce a PAP response and improved first 50m pace.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed

Ellen Quirke

Date: 07/10/18

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Ethical Approval

Ethics approval (17/280) from the AUT University Ethics Committee was gained prior to commencement of the study and written informed consent was obtained from each subject prior to commencing data collection (Appendix A).

Chapter One: Introduction

Rationale and significance of thesis

The aquatic environment of swimming places a unique demand on athletes. These demands must be considered to achieve the required sport specific adaptations to training. According to Wei, Mark, and Hutchison (2014) "nowhere in sport is performance so dependent on the interaction of the athlete with the surrounding medium than in competitive swimming." Most propulsive forces apparent in freestyle swimming are dependent on the upper body musculature of the athlete (Hollander, de Groot, van Ingen Schenau, Kahman, & Toussaint, 1988) with the relationship between stroke length and stroke frequency having the biggest impact on horizontal swimming velocity (Crowley, Harrison, & Lyons, 2017). Therefore, investigating the use impact of WRT in the sport of swimming would have a significant impact on current training practices.

The training principle of specificity is vital to improving performance. However, the aquatic environment of swimming poses difficulties in integrating this principle successfully into resistance training programming. Swimming is a very versatile sport, which is used for recreational fitness, triathlons, surf lifesaving, Ironman, water polo and competitive swimming. It has been suggested that "traditional" swimming training should include elements of high frequency, high intensity and long duration often resulting in a sizeable overall training volume (González-Boto, Salguero, Tuero, González-Gallego, & Márquez, 2008). It is also common practice for aquatic athletes to partake in traditional resistance training to supplement their training programs (Crowley et al., 2017). While, concurrent endurance and resistance training has been shown to be beneficial in other endurance sports (Hirofumi Tanaka & Thomas Swensen, 1998), research in swimming shows that traditional resistance training only translates into improvements in sprint swimming performance when administered through precise programming (Aspenes, Kjendlie, Hoff, & Helgerud, 2009; Sébastien Girold et al., 2012; Sebastien Girold et al., 2007; Strass, 1988; H. Tanaka & T. Swensen, 1998).

Accordingly, the principle of training specificity indicates that added resistance training in swimming will be more effective if applied through the exact stroke mechanics in an aquatic environment. It is common practice for swimming programs to utilise many in-water training modalities to enhance swimming performance for both endurance and sprint training. These in-water modalities can be commonly differentiated between resisted free swimming and tethered swimming. Resisted free swimming allows the swimmer to train with added resistance through uninterrupted swimming. While this is beneficial to training specificity, there are drawbacks including reduced oxygen uptake and loss of coordination between the upper and lower body during arms only swimming (Crowley et al., 2017), changes in stroke coordination during hand paddle and parachute swimming (Telles, Barbosa, Campos, & Júnior, 2011) and lack of translation to free swimming performance following training interventions (Dragunas et al., 2012; Konstantaki, Winter, & Swaine, 2008; Telles et al., 2011). While tethered swimming modalities are useful in applying increased resistance through sprint and power-based training, they affect the position of the swimmer by holding them in a fixed location or limiting their movement through the water, which is undesirable to maintain stroke technique and specificity of training adaptions.

The training principle of specificity can also be applied to priming for performance. Swimming is an increasingly demanding and challenging sport with the difference between medalling and non-medalling in the female 200m freestyle at the Rio Olympic Games being 0.26seconds (Olympics, 2018), showing small improvements can have a significant impact on the final position. Accordingly, effective interventions and optimisation of pre-competition routines that could be advantageous to performance are of interest. The proposed aim of a structured warm-up before the competition is to decrease the chance of injury and increase performance (Burnley, Doust, & Jones, 2005) by priming the musculoskeletal and physiological systems for exercise. Traditional middle-distance swimming warm-up involves an initial loosen up, an interval set to elevate heart rate and gain the feel for the water, a series of pacing swims to practice for the event ahead followed by a few sprints to achieve max speed. The mechanism of post-activation potentiation (PAP) has recently been used in swimming during warm up with the intention of increasing performance (A. Barbosa, Barroso, & Andries Jr, 2016; Cuenca-Fernández, López-Contreras, & Arellano, 2015; Eriksson, 2017; Hancock et al., 2015; Kilduff et al., 2011; Sarramian, Turner, & Greenhalgh, 2015). The rationale behind PAP lies in the performance potential of skeletal muscle and is defined by its contractile history, with PAP and fatigue being two contributing factors (Rassier & Macintosh, 2000). It is believed that fatigue dissipates at a faster rate than PAP under specific circumstances and can provide a "window of opportunity" where elevated contractile response can improve subsequent sporting performance (Figure 1) (MacIntosh, Robillard, & Tomaras, 2012). This period is most likely to occur between 8-12 minutes post PAP intervention (Gouvêa, Fernandes, César, Silva, & Gomes, 2013). The idea of utilising PAP as a way of improving performance mirrors the theory of complex training, which involves loading sport specific muscle groups through resistive movements before commencing a sport-specific activity (Hancock et al., 2015).

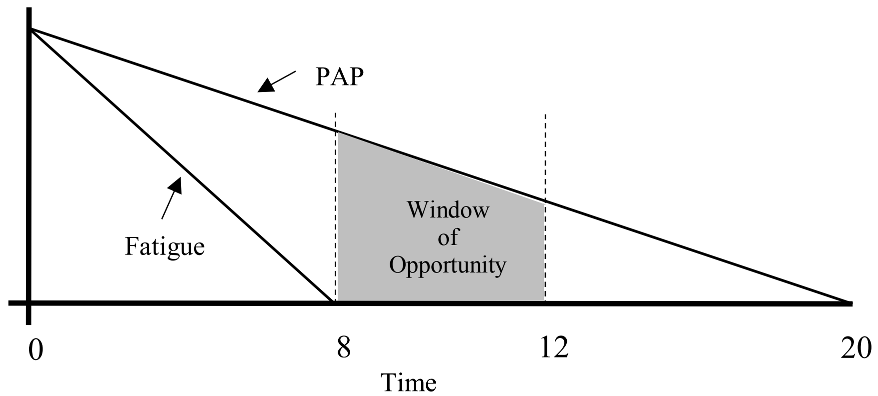

Figure 1. Diagram representing the “window of opportunity” adjusted from Hancock, Sparks, and Kullman (2015)

Several researchers have examined the effect of PAP on swimming performance (A. Barbosa et al., 2016; Cuenca-Fernández et al., 2015; Eriksson, 2017; Hancock et al., 2015; Kilduff et al., 2011; Sarramian et al., 2015) with mixed results. Hancock et al. (2015) were the only authors who showed positive results in swimming performance with a significant increase in 100m performance (0.54sec; p=0.029) following 4x7second maximal sprints on a weighted power rack. Cuenca-Fernández et al. (2015) showed improvement in swim dive start performance including horizontal velocity (CON= 3.63 ± 0.11, INT= 4.89 ±0.12 m/s; p<0.01), time to 5m (CON: 1.75 ± 0.057 sec, INT: 1.65 ± 0.052 sec; p<0.01) and time to 15m (CON: 7.54 ± 0.23 sec, INT: 7.36 ± 0.22 sec; p<0.05). Similarly, Kilduff et al. (2011) saw improvements in peak horizontal force (PHF) and peak vertical force (PVF) during a swim dive start after a PAP evoking stimulus (PHF 770 6 228 vs 814 6 263 N, p = 0.018; PVF: 1,462 6 280 vs 1,518 6 311 N, p = 0.038). However, this was not translated in swimming speed to 15m (7.1 6 0.8 vs. 7.1 6 0.8 secs, p = 0.447). Eriksson (2017) and Sarramian et al. (2015) both saw no improvements in both distance (400m freestyle; CON: 291.05 ± 16.07, INT: 290.96 ± 15.53; p =0.93) and sprint (50m freestyle; CON: 29.00±2.05, INT: 29.11±2.18; p<0.05) swimming performance following a warm-up designed to evoke a PAP stimulus. The improvements in swimming performance shown by Hancock et al. (2015) may be due to the specificity of intervention, as it was the only study to utilise an in-water intervention stimulus.

Accordingly, it appears that land-based interventions have a positive effect on land-based measures such as the dive start (Cuenca-Fernández et al., 2015; Kilduff et al., 2011). However, the lack of specificity to the swimming stroke did not provide benefits to increased swimming performance (Eriksson, 2017; Kilduff et al., 2011; Sarramian et al., 2015).

Wearable resistance (WR) is a relatively new field of study, with current research primarily investigating its effects on sprint running and jumping (Macadam, Cronin, & Simperingham, 2017; Macadam, Simperingham, & Cronin, 2017). Wearable resistance technology (WRT) provides an opportunity to apply an added resistance to athletes throughout a sport specific movement, without altering technique (Macadam, Cronin, et al., 2017). Exogen™ Exoskeleton technology by Lila™ (Sportboleh Sdh Bhd, Malaysia) is designed to allow site-specific loading on the athletes' body to incorporate the concept of progressive muscular overload while maintaining specificity to the sport being undertaken (Macadam, Cronin, et al., 2017). To date, this technology has not been used in an aquatic environment in the sport of competitive swimming. Specifically, research is needed to ascertain whether this technology could be used as a training tool and used to prime athletes for performance.

Study Aims

The specific aims of this thesis were:

1. To review current literature concerning the use of in-water resistance training modalities in the sport of swimming, as well as to review the current literature on the use of PAP for priming in swimming.
2. To determine the acute metabolic effects of variable proximal upper limb loading using WRT during submaximal swimming (Study 1).

3. To determine whether proximal upper limb loading using WRT induces a PAP response and has an effect on 200m swim performance (Study 2).

Thesis Outline and Structure

This thesis consists of five chapters which includes the review of current literature and original research. References are included for the entirety of review and research and at the end of this thesis. Chapter One is an introduction to the thesis highlighting the purpose and aims of this research project. The second chapter gives an overview of existing literature and is separated into three parts; part A: details the physiological demands of the sport of swimming, part B: reviews whether current in-water training modalities are effective training tools for endurance swimming and part 3: reviews the current literature within the use of post-activation potentiation (PAP) in swimming. Chapter three details the methods used in both studies included in this thesis. The fourth chapter shows the results found within the research. Finally, chapter five discusses the findings of the thesis and highlights the limitations, practical application and suggested areas for future research.

Chapter Two: Literature Review

This chapter discusses the existing literature that is relevant to the research aims of this thesis. It is divided into three parts with Part A: detailing the physiological demands of swimming, Part B: reviewing whether current in-water training modalities are useful training tools for endurance swimming and part 3: reviewing the current literature within the use of post-activation potentiation (PAP) in swimming.

Part A: The Demands of Swimming

Introduction

Swimming is unique compared to other individual sports due to the aquatic environment reduces the effects of gravity and the athlete predominately training and competing in a supine body position among many other effects. This distinctiveness introduces unique physiological and anthropometric training adaptations in swimming athletes that may not correlate with land-based measures. Holmér (1974) presented the first comprehensive review of the swimming athlete titled the "Physiology of Swimming Man" in 1974, which was followed by reviews and research on the physiological, biomechanical and anthropometric attributes of swimming athletes by Troup (1999), Wells, Schneiderman-Walker, and Plyley (2006), Reis et al. (2012) and Pyne and Sharp (2014). Since Holmér (1974) initial review the basic principles of swimming physiology have changed very little. Swimming requires elements of power, speed and endurance (Pyne & Sharp, 2014) where athletes rely heavily on both oxidative and glycolytic energy systems to keep up with the total energy expenditure required (Pyne & Sharp, 2014). Therefore a range of different training methods are utilised to promote physiological adaptations with the goal of improving a range of critical physiological attributes including VO_2 peak, lactate threshold, muscular strength and endurance and power production.

In any form of human locomotion, muscles generate the energy or power to create movement (Rodríguez & Mader, 2011). Specifically, in swimming, the upper body musculature (John A Hawley, Williams, Vickovic, & Handcock, 1992; Hollander et al., 1988) creates enough energy to overcome the hydrodynamic forces to propel the swimmer through the water (Rodríguez & Mader, 2011). Therefore, the success of a swimmer is mainly dependent on the following three factors:

1. Swimming economy: defined by the relationship of stroke length vs stroke rate. Each arm stroke needs to produce the highest impulse possible through efficient muscle contraction in the direction of propulsion (Aspenes et al., 2009)
2. Maximum Lactate Steady State (MLSS): the highest intensity at which lactate production and removal are at equilibrium (Oliveira, Caputo, Lucas, Denadai, & Greco, 2012)
3. VO_{2max}: the maximum rate at which oxygen can be utilised in the Krebs cycle to continually produce adenosine triphosphate (ATP) as energy for muscular contraction.

Energy Requirements in Swimming

Human skeletal muscle utilises (ATP) to create energy to function. There are three ways ATP is created and used during exercise (Figure 2).

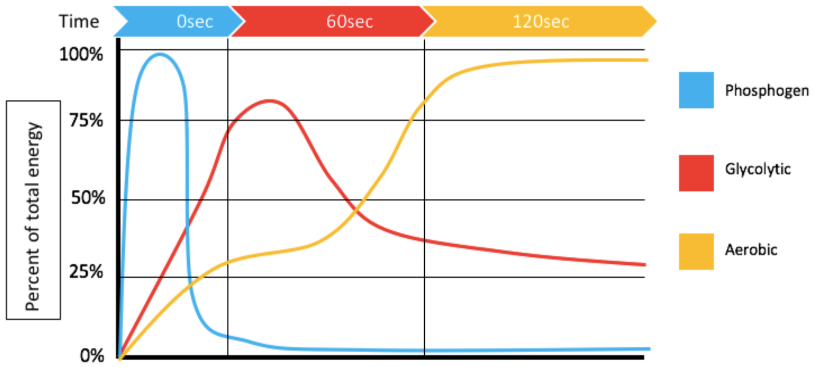

Figure 2. Image showing the relationship between the three energy

There is a small supply of stored ATP that is used in the ATP Phosphocreatine (ATP PCr) system for short bursts of high-intensity work. Glycolysis creates ATP from stored muscle glycogen in an anaerobic (lack of oxygen) environment and creates lactate as a by-product. Finally, the oxidative system creates ATP in an aerobic environment utilising oxygen to continually produce a low sustainable amount of energy (Gastin, 2001). All three of these pathways are used to maintain the levels of energy required for physical activity. The energetic demands during swimming performance are dependent on several factors including swimming event duration and stroke, and physiological characteristics.

Spencer and Gastin (2001) showed that the crossover to predominant reliance on the aerobic system occurs between 15-30sec in a long sprint and middle-distance running events (duration between 50sec – 4min). At an elite level the 100m, 200m and 400m freestyle events and 100m, 200m stroke events fall into this time window. It is believed the ability to maintain a higher percentage of VO_2 (Wells et al., 2006) and utilise the glycolytic system for more extended periods of time in these events will result in higher performance (Troup, 1999). Therefore, VO_2 peak is no longer viewed as a limiting factor to maximal performance (Wells et al., 2006).

An added variable in swimming compared to other individual sports is the hydrodynamic forces acting upon the athlete. The energy expenditure rate increases exponentially with velocity due to the exponential increase in hydrodynamic drag (Holmér, 1974). The hydrodynamic drag is different depending on the anthropometric characteristics of the athlete and the stroke that is being performed. Freestyle is the most economical stroke with the lowest total energy expenditure over a range of given velocities followed by backstroke, butterfly and breaststroke (T. M. Barbosa et al., 2006). Additionally, females are more economical than males across all four strokes showing lower levels of total energy expenditure at a range of velocities due to their ability to hold a higher body position in the water and reduce drag (Seifert, Barbosa, & Kjendlie, 2010). The skill level of the swimmer is also a determining factor of energetic demands with skilled swimmers showing much lower energy expenditure compared to recreational swimmers when swimming the same stroke at the same speed (Holmér, 1974)).

Cardiovascular and Ventilatory Effects of Swimming

Steady state and interval training are both used in a majority of swim training programs with the intention of developing and increasing VO_2 peak, high lactate threshold, high oxidative muscle capacity (mitochondrial density) and high muscle fuel stores (glycogen) (Pyne & Sharp, 2014). The VO_2 peak is defined as the maximal rate at which oxygen is delivered and utilised by working muscle during exercise. The delivery of oxygen is dependent on the cardiovascular capabilities of the athlete. Endurance training elicits a range of chronic cardiovascular adaptations including increased cardiac output, increased stroke volume, increased contractility, cardiac hypertrophy, decreased resting HR, increased VO_2 peak, vasodilation, increased venous return, increased end-diastolic volume, decreased afterload, increased capillarization and a higher lactate threshold (Schaible & Scheuer, 1985).

While all these adaptations hold true, being in an aquatic environment and maintaining a horizontal body position places unique demands on the cardiovascular system of a swimmer (Lazar, Khanna, Chesler, & Salciccioli, 2013). The supine position of a swimmer allows for greater venous return (Lazar et al., 2013), higher preload of the left and right ventricles (Lazar et al., 2013) and increased end-diastolic volume (Troup, 1999), stroke volume (Reilly, Secher, Snell, Williams, & Williams, 2005), systolic blood pressure (BP) (Schaible & Scheuer, 1985). While diastolic BP remains unchanged (Schaible & Scheuer, 1985) water submersion places compressive forces on the body which further increases overall BP (Lazar et al., 2013). This increase in BP activates baroreceptors which reduces heart rate (Lazar et al., 2013). The combined effect of increased stroke volume and decreased heart rate explains why increases in cardiac output of swimmers are comparable to other endurance-based sports.

Ventilation and the delivery of oxygen are also affected by the body position and the aquatic environment that is specific to the sport of swimming. The delivery of oxygen to muscles for oxidative energy production is utilised in all swimming disciplines and training sessions but is of particular importance to distance swimmers. Reilly et al. (2005) and Holmér (1974) both reported some unique characteristic in swimming ventilation, notably; the frequency of breathing in swimming is determined by stroke rate (particularly in freestyle and butterfly). There is a forced inspiration phase that must overcome increased pressure on the thoracic cavity, and the expiration phase must overcome an increased pressure difference (breathing into water). Another discovery by Holmér (1974) was that unlike maximal effort in other sports (and backstroke), swimmers are unable to hyperventilate due to the controlled nature of breathing frequency. These characteristics lead to chronic adaptations including a lowered vital capacity, with tidal volume increasing to a higher percentage of total lung capacity, reducing the expiratory reserve volume and shifting the breathing position towards the residual volume (Holmér, 1974). Additionally, swimmers as a population have larger lung capacity when compared to expected values and control groups (Mickleborough, Stager, Chatham, Lindley, & Ionescu, 2008).

Muscle Metabolism

Elite swimmers have been shown to be tall, have a long trunk and arms, broad-shouldered and have more musculature in the upper body and trunk compared to other athletes (Reilly et al., 2005; Reis et al., 2012; Troup, 1999). This increase in length and upper body dominance is due to the majority of propulsive forces in swimming being generated by the upper body with the legs being used to maintain body position in the water (T. Barbosa, Costa, & Marinho, 2013; Seifert et al., 2010). Troup (1999) summarised the importance of muscular demands in swimming, stating that swimming is a power-limited sport. A swimmer who can maintain a higher percentage of peak power and maximise propelling efficiency per stroke will be faster. Swimmers partake in both endurance and resistance training concurrently and utilise all three energy systems, therefore exhibit a full range of fibre types. Motor units are recruited in a ramp-like fashion, and the energy demands of the length of the event determine which fibre types are preferentially recruited (Feiereisen, Duchateau, & Hainaut, 1997).

Motor units can be divided into slow twitch (type I) and fast twitch (type IIa & IIb). Slow twitch fibres are differentiated by having greater oxidative properties, while fast twitch fibres demonstrate a higher glycolytic potential (Holmér, 1974). For distance swimmers type I fibres are preferentially recruited as low muscle force is required for each stroke and they are the most resistant fibres to fatigue (Troup, 1999). It is believed that oxygen utilisation rather than delivery has more of an impact on the ability of an athlete to maintain higher levels of VO_2 peak over a more extended period (Holloszy & Coyle, 1984). Endurance training increases mitochondrial density in slow-twitch fibres, increasing oxygen utilisation in muscle (Holloszy & Coyle, 1984). Middle distance events (200m freestyle, approx. 2min) recruit both type I and IIa fibres (Troup, 1999). This is in agreement with research showing these events rely more on the anaerobic systems peak energy production (Holmér, 1974). Finally, sprint events utilise all three fibre types (Troup, 1999) with glycogen depletion starting in type IIb fibres and following in IIa and I fibres (Holmér, 1974). Type IIb fibres are preferentially recruited due to the explosive forces required in sprint events. However, their glycogen stores are rapidly depleted, which leads to recruitment of type IIa and type I (Troup, 1999). Having knowledge of how muscle fibres and how they are recruited, will have a direct impact on the specificity of training methods applied to athletes.

Training Methods

High intensity, short duration training and low intensity, high volume training are both essential components within the training structure for athletes that are successful in intense exercise events such as swimming (Laursen, 2010; Seiler, 2010). Coaches often prescribe a combination of three training methods; long bouts of submaximal exercise, periods of internal training at speed correlating at around onset of blood lactate (OBLA) intensity and maximal sprint training (J. A Hawley, Myburgh, Noakes, & Dennis, 1997). Specifically for swimming land-based resistance training is also incorporated into the training plan with the goal of increasing muscular strength and power production (Aspenes et al., 2009); however, this has been questioned by coaches with concerns over increased muscle mass and decreased flexibility (Crowley et al., 2017).

In-water training modalities are often implemented by swimming programs to enhance muscular performance through swimming specific movements for both sprint and endurance training. In chapter three we go into greater detail about these in-water training tools including pull buoys, hand paddles, parachutes, power racks and bungee cords. Crowley et al. (2017) reviewed the use of different in-water training modalities; however, a majority of it was focused on the effects on sprint performance. Applying resistance through the exact stroke pattern of a swimmer without affecting body position or stroke mechanism could provide a novel way to influence swimming performance in the future.

WRT allows resistance to be applied to an athlete through a sport specific movement without effecting technique (Macadam, Cronin, et al., 2017) and could be a training tool that allows swimmers to apply stroke specific resistance in the aquatic environment that they train and race in. Exogen™ Exoskeleton technology by Lila™ (Sportboleh Sdh Bhd, Malaysia) is designed to allow site-specific loading on the athletes' body to incorporate the concept of progressive muscular overload while maintaining specificity to the sport being undertaken (Macadam, Cronin, et al., 2017). To our knowledge, this technology has never been utilised in more extended exercise efforts or in an aquatic environment.

Summary

The sport of swimming is exceptionally unique compared to other on-land competitive and recreational sports, with the supine body position and aquatic environment affecting the efficiency of the cardiac and ventilatory systems. Therefore, coaches need to be aware of the specific physiological and biomechanical considerations when programming training. Swimming economy, OBLA and VO_{2max} have all been identified as limiting factors to swimming performance (Aspenes et al., 2009). Specifically, this requires coaches to program for the integration of all three energy systems and enhance the ability to utilise the glycolytic system for longer. Additionally, muscular overload is required to improve muscular strength, endurance and power. However, performing resistance exercise in a swim specific manner is difficult and solving this could result in enhancements in swimming performance.

Part B: Are In-Water Training Modalities Effective in Improving Endurance Swimming Performance?

Introduction

Swimming is popular worldwide, as both a competitive sport and recreational activity. In competitive swimming the margins between placings are closer than ever with only a 1.26sec (men) and 2.56sec (women) difference between 1st and 8th place in the 200m freestyle at the 2016 Rio Olympic Games (Olympics, 2018). Many training approaches and strategies are adopted in swimming to optimise conditioning of swimmers for competition including high volume training, interval training and dryland-based resistance training. However, the aquatic environment of swimming poses difficulties to integrating the principle of specificity successfully into programming, which is an essential principal of training that determines the adaptive response to exercise and its impact on performance (McCafferty & Horvath, 1977). Therefore, finding ways to get a competitive edge would be advantageous.

The upper body accounts for 90% of propulsive forces in freestyle swimming (Hollander et al., 1988), with the efficiency of freestyle swimming coming from muscle contractile qualities and the muscular strength of the upper limbs (John A Hawley et al., 1992). Traditional resistance training in the weight room is often used to supplement in-water swimming training by numerous coaches around the world (Aspenes et al., 2009). While research has shown improvements in sprint swimming performance following a traditional resistance training intervention utilizing high velocity concentric phases with low repetitions (Aspenes et al., 2009; Sébastien Girold et al., 2012; Sebastien Girold et al., 2007; Strass, 1988), coaches have concerns around the increases of muscle mass and lack of flexibility due to this type of training (Crowley et al., 2017). Additionally, there is no research linking these benefits to endurance swimming performance, which may be due to the lack of specificity to the freestyle stroke.

The importance of specificity in swimming gives rise to the use of in-water training modalities to enhance muscular performance through swimming specific movements, especially for endurance swimming events. Several different modalities are commonly integrated into swim training programs, however there is limited research showing their efficacy. These modalities include arms only swimming (Konstantaki et al., 2008; Morris, Osborne, Shephard, Skinner, & Jenkins, 2016), hand paddles (Telles et al., 2011), parachutes (Schnitzler, Brazier, Button, Seifert, & Chollet, 2011; Telles et al., 2011; Telles et al., 2017), drag suits (Dragunas et al., 2012), power racks` (Hancock et al., 2015; Johnson, Sharp, & Hedrick, 1993), bungees (S Girold, Calmels, Maurin, Milhau, & Chatard, 2006; Juárez Santos-García et al., 2013) and "push off pad" devices (Toussaint & Vervoorn, 1990). The purpose of this review is to investigate the advantages and disadvantages of these different modalities and determine if they are an effective tool to enhance endurance swimming performance.

Free Swimming

Arms Only Swimming

Arms only swimming is designed to increase upper body resistance in a swimming specific manner by increasing the contribution of the arms and decreasing the contribution of the legs and is commonly used by elite swimmers (Crowley et al., 2017). It is widely used in training programs because of its simplicity and cost effectiveness either needing no equipment, a band to place around the ankles and/or a pull buoy (Figure 3A). Arms only swimming results in a 4-16% reduction of $\dot{V}O_2$ compared to that observed in whole body swimming (Holmér 1974a; Ogita et al. 1996, 2003; Ogita and Tabata 1992; Ribeiro et al. 2015; Rodriguez et al. 2015), which results in a decrease in training load while maintaining volume (Crowley et al., 2017).

Konstantaki et al. (2008) examined the effectiveness of arms-only swimming as a training modality by measuring swimming performance and $\dot{V}O_2$ kinetics following a six-week training intervention period, which required swimmers to include 20% of their training volume as arms only swimming with a pull buoy and band around the ankles. Submaximal oxygen intake (INT: ↓22.50 ± 2.3%, p=0.04, CON: ↑1.02 ± 0.8%, p=0.09) and peak exercise intensity (INT: ↑17.80 ± 4.2%, p=0.03, CON: ↑0.97 ± 0.23%, p=0.06) during arms only simulated swimming on the Biokinetic swim bench significantly improved only for the intervention group following the training period. The intervention period also resulted in a substantial increase in arms only swimming performance (INT: ↓14.02 ± 13.6% vs. CON: ↑1.6 ± 0.5%). However, these improvements did not translate into whole body swimming performance, which could be due to the lack of coordination between the upper and lower body (Crowley et al., 2017). The isolation of the arms could also affect body position, body roll and stability in the water which may take an extended period of time to adapt or require an increase in core muscle strength. Morris et al. (2016) examined the effect of stroke rate on stroke aerobic power ($\dot{V}O_2$), velocity and metabolic cost during arms only swimming and whole-body swimming. The subjects performed six 200 m freestyle efforts under two

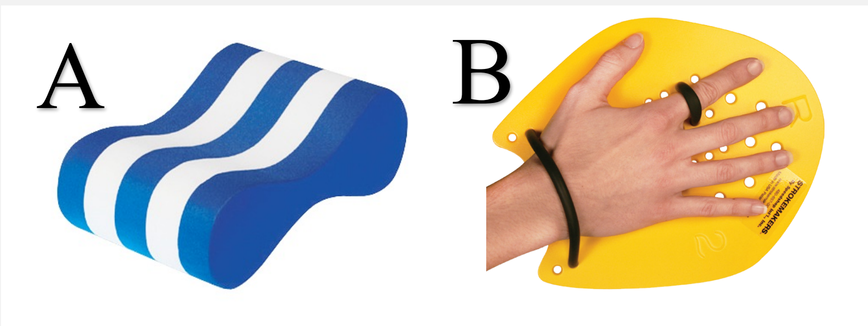

Figure 3. A. Pull Buoy, B. Hand Paddles

different conditions: (a) arms only and (b) whole body swimming at six different stroke rates (22, 26, 30, 34, 38 and 42 stroke-cycles min^{-1}). They found that regardless of stroke rate, velocity was decreased by 11% ($p<0.01$) when only the arms were used. $\dot{V}O_2$ was lower in arms only swimming compared to whole body swimming in all stroke rate conditions for females ($p< 0.01$). However, this was only shown in the "high stroke rates" for males ($p>0.01$). Accordingly, stroke rate influenced $\dot{V}O_2$ with high stroke rates producing higher $\dot{V}O_2$ values ($p = 0.006$). Metabolic cost was not affected by the intervention. However, metabolic cost did significantly increase as stroke rate increased ($p = 0.005$) and was higher in males than females. When metabolic cost was expressed as a function of velocity, males had a lower metabolic cost during whole body swimming compared to arms only. In conclusion, arms only swimming has a higher metabolic demand for males, while there is no difference for females when compared to whole body swimming.

Hand Paddles

Hand paddles (Figure 3B) are often worn during arms only swimming sets with the aim of overloading the upper body musculature. The oxygen uptake associated with hand paddle swimming is currently unknown. However, the increased surface area through the pull phase would indicate more demand is placed on the upper body musculature compared to normal free swimming. While no studies were found that investigate these concepts, Telles et al. (2011) showed that swimming with hand paddles significantly decreased stroke rate (Free Swim (FS): 59.21 ± 3.54 st/min vs Hand Paddles (HDP): 54.65 ± 7.74 st/min; $p < 0.05$) and increased stroke length (FS: 1.86 ± 0.13 m/st vs. HDP: 2.08 ± 0.26 m/st; $p< 0.05$). While the increase in velocity (FS: 1.83 ± 0.10 m/s vs. HDP: 1.87 ± 0.09 m/s) was not statistically significant it would be seen as worthwhile in the swimming community. Telles et al. (2011) also investigated the effect on stroke coordination mode, which is defined by the value of the index of coordination being 0%

(catch-up), negative% (opposition) or positive% (superposition) (Chollet, Chalies, & Chatard, 2000). Expert sprinters adopt an opposition coordination mode (Chollet et al., 2000), reducing the contribution of the non-propulsive phase (Chollet et al., 2000; Potdevin, Bril, Sidney, & Pelayo, 2006). The preferred coordination mode at speeds slower than 1.80m/s is catch-up (Seifert, Chollet, & Rouard, 2007), however, the addition of hand paddles changed the mode to opposition (Telles et al., 2011), likewise to sprint swimming. There is no indication if these changes while wearing paddles lead to a learning effect and translate into non-paddle swimming (Telles et al., 2011).

Parachutes

A swimming parachute is designed to increase the load placed on a swimmer by using the water as an opposing resistance (Figure 4). Parachutes are often used by swimming programs because they are relatively inexpensive and easy to incorporate into programming. Telles et al. (2011) examined the effects of parachutes on speed and stroke kinematics during maximal swimming. They found that the additional drag added by the parachute significantly decreased the velocity (CON: 1.83 ± 0.10 m/s vs. INT: 1.25 ± 0.11 m/s), stroke rate (CON: 59.21 ± 3.54 st/min vs INT: 54.94 ± 4.02 st/min; $p < 0.05$) and stroke length (CON: 1.86 ± 0.13 m/st vs. INT: 1.37 ± 0.09 m/st; $p < 0.05$) compared to free swimming. Additionally, as it was shown with the addition of hand paddles, the coordination mode was changed from catch-up in free swimming to opposition in swimming with a parachute (0.1+3.1%). Schnitzler et al. (2011) investigated the effects

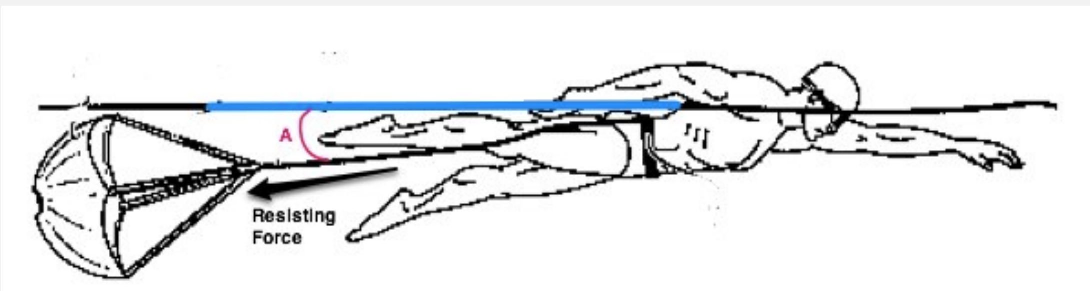

Figure 4. Swimming parachute showing the direction of force applied

of swimming with a parachute at different velocities. Seven national level swimmers took part in the study which involved swimming at five different velocities for 20seconds (60%, 70%, 80%, 90% (*15sec) & 100% (*10sec)) in a swimming flume under three different conditions. These were free swimming (FS), low resistance (P1) and high resistance (P2) using a parachute. It was found that the addition of the parachute resulted in decreased swimming velocity and stroke rate and increased stroke length by minimizing the catch phase and prolonging the pull phase. Schnitzler et al. (2011) also found a change in stroke coordination with a change to superposition. Both studies utilized parachutes to examine the effects over very short distances and up to maximal speeds. While parachutes are used for this purpose in many swimming programs, they are also used during submaximal training for aerobic training purposes. Unfortunately, the effectiveness of this endurance training technique could not be found in the literature. As mentioned, a drawback of this technology is the change in body position and coordination of stroke. As shown in Figure 4 the parachutes pulls the swimmers body back and down, thus forces the hips to sit in a lower position in the water. Additionally, the cord attaching the parachute to the swimmers hips pushes down on the feet often interfering with the kick coordination, which could affect the specificity of the training aid and impact on overall swimming performance.

Drag Suits

Drag suits offer a constant resistive force on a swimmer without effecting the natural movement of the arms of legs or holding the swimmer in a fixed location. Often, they are a brief type garment made out of mesh that has additional pockets (Figure 5), which is worn over the top of the swim suit. This increases the resistance placed on a swimmer. Mechanically, wearing a drag suits results in a decrease in velocity and stroke length (Taguchi, Shibayama, & Miyashita, 1988).

Figure 5. Picture showing the TYR 2.0 drag suit with four pockets (Dragunas, Dickey, & Nolte, 2012)

There appears to be only one study that has examined the training effect of drag suits on endurance swimming performance. Dragunas et al. (2012) implemented a five-week training intervention protocol which followed a matched pair study design. Both groups were prescribed three anaerobic focused training sets a week which constituted 2% of total weekly training volume. The intervention group was required to wear the drag suit. Stroke rate, stroke distance and 50m TT performance were collected pre and post intervention in both drag suit and regular swimming conditions. They found that in regular swimming conditions following intervention the control group had a significant increase in stroke rate of 1.93 strokes per minute ($p < 0.05$, ES: 0.39) and decrease in stroke length of 0.8m ($p < 0.05$, ES: 0.40) with non-significant changes in swimming time. The intervention group showed no change in stroke rate, stroke distance or swimming time. In drag suit conditions both free swimming and drag suit groups showed a significant decrease in stroke length of 0.11m and 0.06m per stroke respectively ($p < 0.001$, ES: 0.13; $p < 0.05$, ES: 0.33) with no change in swimming time. Only the control group showed a significant increase in stroke rating of 2.88 strokes per minute ($p < 0.05$, ES: 0.226). This suggests that drag suits are ineffective as a training aid for sprint performance measures. However, it is unknown as to whether this training method could have effected performances of longer distances.

Tethered Swimming

Power Racks

Power racks are a common and recently popularised in-water modality used by numerous swim programs worldwide. They involve swimmers being tethered around the waist to a weight stack over land that can then be adjusted to your choice of resistance (Figure 6). The cables are generally 10-15m long so restrict the time the stimulus can be applied for. To our knowledge, there is currently no literature regarding the use of the power rack as an effective training modality, although the power rack has been used in two acute studies.

Figure 6. Swimming power rack. Reprinted from *TPIswim,* n.d., Retrieved 29th June, 2018, from www.tpiswim.com/power-rack

Specifically, Johnson et al. (1993) correlated power output and swimming velocity using the power rack, and Hancock et al. (2015) utilized it to illicit a PAP response during warm up to improve 100m swimming performance (INT: 62.91sec vs CON: 63.45sec; $p>0.029$) (Hancock et al., 2015). However, neither of these studies reported any changes in body position, stroke kinematics or physiological variables. At this stage it is unknown as to whether power racks would be an effective training tool for endurance swimming performance.

Bungee Cords

Resisted and assisted bungee swimming is another in-water training modality that is widely used in the swimming community (Figure 7). Practically it provides variable resistance, which changes based on the distance from the anchor point of the swimmer or can produce over-speed when the swimmer is assisted by the bungee. It has been shown that compared to free swimming, swimming resisted by the bungee leads to a decrease in stroke rate and stroke length, whereas assisted swimming increases stroke rate and has no effect on stroke length (E. Maglischo, Maglischo, Zier, & Santos, 1985). To our

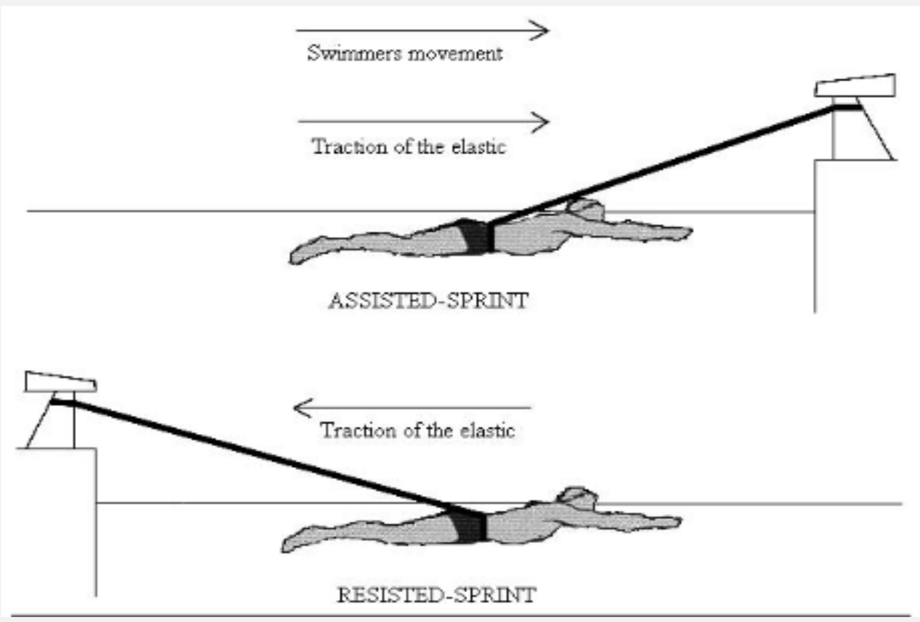

Figure 7. Example of the swimmers position when swimming assisted and resisted with a bungee cord (Sebastien Girold, Maurin, Dugue, Chatard, & Millet, 2007).

knowledge there are no training intervention studies isolating either resisted or assisted bungee swimming. However, Sebastien Girold et al. (2007) investigated the effects of combined assisted and resisted bungee swimming (RAS) on sprint performance.

They found that following 12 weeks of a RAS integrated training program there was a significant increase in 50m performance compared to control (INT: 2.3 ± 1.3%, CON: 0.9 ± 1.2%, $p < 0.05$). However, the improvement was only realized over the last 6-weeks of the intervention. Stroke depth was significantly decreased in RAS but not CON (INT: 0.82 ± 0.06m to 0.80 ± 0.05m vs. CON: 0.85 ± 0.06m to 0.83 ± 0.07m; $p<0.05$) but there was significant improvements in stroke rating in both groups (INT: 48.2 ± 3.5cycle.min^{-1} to 49.5 ± 3.45cycle.min^{-1} vs. CON: 47.8 ± 3.75cycle.min^{-1} to 48.7 ± 3.75cycle.min^{-1}; $p<0.05$). Finally, after 12 weeks of RAS training muscle strength in the upper body was significantly improved compared to control (32% increase in the concentric strength of elbow extensors at $60 \cdot s^{-1}$; $p < 0.05$). Interestingly, the decrease in stroke depth and increase in stroke rate had an additive effective and were the most influential factor in improving 50m sprint performance at the end of the training intervention. While not specific to endurance swimming, it is worthwhile noting that swimming resisted on bungees does not have to be done at maximal speeds and can be used for technique focused swimming.

Push Off Pad Device

Toussaint and Vervoorn (1990) investigated the effect of utilising a push off pad (POP) (Figure 8A) training system on competitive swimming performance. The idea came from the MAD system (system to Measure Active Drag) which is an in-water device used to measure active drag on swimmers in their specific environment. The MAD system (Figure 8B) provides submerged fix points from which a swimmer places each hand on during each stroke, from which the force applied can be calculated. This allows power to be calculated when velocity is known.

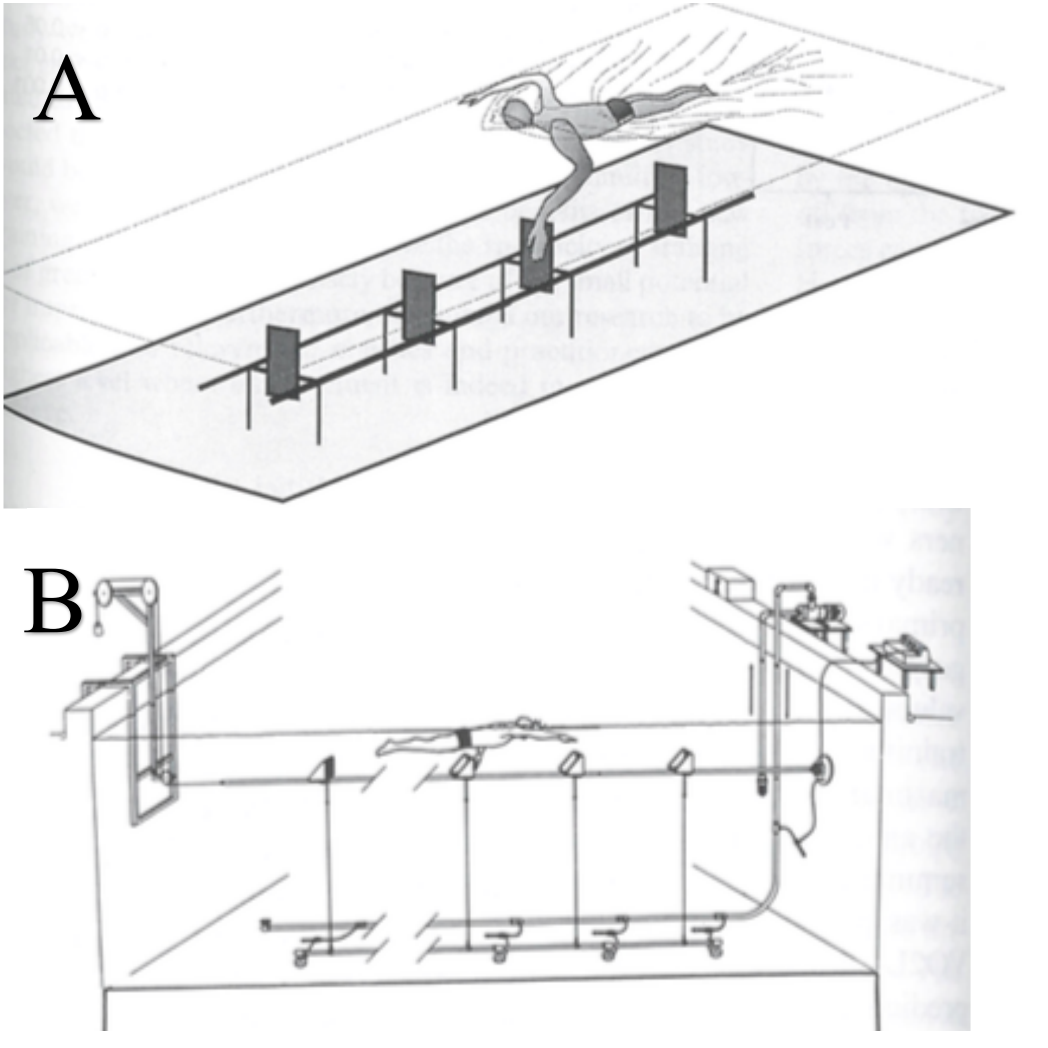

Figure 8. A Picture the push off pad (POP) device; **B**. Picture the MAD apparatus (Toussaint & Vervoorn, 1990)

Both devices consist of 16 push off pads mounted 1.35m apart, 0.8m below the surface of the water (Toussaint & Vervoorn, 1990). Twenty-two subjects were divided into an intervention (POP) and control (CON) group through matched pair design for a ten-week training period. All subjects were required to swim eight 1.5-hour training sessions a week including three 30min sprint sets. However, during the sprint sets where completed on the POP device for the intervention group. Toussaint and Vervoorn (1990) found that following the 10-week intervention the POP group had significant improvements in power output (CON: ↓0.9 ± 0.4W vs. POP: ↑11.2 ± 8.3W, $p<0.01$), maximum velocity (CON: 0.02 ± 0.01m/s vs. POP: ↑0.06 ± 0.02 m/s, $p<0.05$) and force (CON: ↓1.9 ± 1.2N vs. POP: ↑3.0 ± 3.0), with the control group having no significant changes, when measured on the MAD device. However, neither group showed any significant improvement in 25m or 50m free swimming performance. Therefore, the training period may have just provided a familiarization of the equipment for the POP group, which resulted in the improvements when swimming using the MAD system. Interestingly, the number of strokes during 25m and 50m sprints significantly decreased following the POP intervention (19.0 ± 2.3 vs. 18.6 ± 2.0 and 46.4 ± 3.7 vs. 44.9 ± 3.9, $p<0.01$). While seemingly promising technology, the POP device restricts the swimmer's stroke to a fixed length and depth and could be the reason that stroke count was decreased in the intervention group as they were having to train their sprints with a longer stroke length. Additionally, since the POP and MAD device are identical in design, the POP group may have been influenced by a learning effect which enabled them to swim more efficiently on the MAD device during post testing. Finally, this device may change the coordination between the upper and lower body as the resistance stimulus is specific to the freestyle arm stroke.

Table 1. Summary of training modalities and ratings of effectiveness

Training Aid	Study	Intervention	Stoke / Distance	Results	Ratings (1 worst – 7 best) Practicality	Cost (per 10 swimmers)	Specificity
Pull Buoys	Konstantaki et al. (2008)	**Chronic**; 6 weeks, 20% of volume	Freestyle	↑ Oxygen Intake ↑ Peak exercise intensity Only during simulated arms only swimming ↑ Arms only swimming speed	6	5	1
	Morris et al. (2016)	**Acute;** Arms only with varying stroke rate	Freestyle 200m	↓ VO_2 (arms only) ↓ Velocity (arms only) Higher SR = metabolic cost & higher VO_2, regardless of intervention			
Hand Paddles	Telles et al. (2011)	**Acute;** Addition of hand paddles	Freestyle	↓ Stroke rate ↑ Stroke length ↑ Velocity	7	5	6
Parachutes	Telles et al. (2011)	**Acute,** Addition of parachute	Freestyle	↓ Stroke rate ↓ Stroke length ↓Velocity	2	4	5
	Schnitzler et al. (2011)	**Acute,** different resistance and velocity	Freestyle (10-20sec)	↓ Stroke rate ↓ Velocity ↑ Stroke length			
Drag Suits	Dragunas et al. (2012)	**Chronic,** 5 weeks, 2% of volume	Freestyle 50m time trial	FS: control ↑ Stroke rate, ↓ Stroke length; int: no change INT: control: ↓ Stroke length, ↑ Stroke rate; int: ↓ Stroke length	5	5	7
Bungees	Sebastien Girold et al. (2007)	**Chronic**, 12 weeks resisted and assisted	Freestyle, 50m time trial	↑ 50m performance ↓ Stroke depth ↑ Stroke rate (both groups) ↑ Upper body strength	4	3	3
POP	Toussaint and Vervoorn (1990)	**Chronic,** 10 week, 3x30min int per week	Freestyle, 25m & 50m time trial	↑ Power output ↑Velocity ↑ Force	1	1	4

Summary and Conclusion

The principle of training specificity indicates that added resistance training in swimming will be more effective if applied through the exact stroke mechanism in an aquatic environment. It is common practice for swimming programs to utilise many in-water training modalities to enhance swimming performance for both endurance and sprint training. The existing literature showed that in-water training modalities all have the same goal in providing an overload stimulus to swimmers in a highly specific manner. However, most impact the biomechanical and physiological variables of a swimmer differently and have different limitations regarding their effectiveness as a training tool (Table 1). Additionally, most research is focused on using these modalities as power or sprint-based training tool. While it seems that power racks and push-off pad devices are limited purely to sprint based training, all other modalities mentioned in this review have the potential to be used to supplement more aerobically based swimming distances. Accordingly, the majority of these modalities are already in use throughout the swimming community with that focus. However, the effectiveness as a training modality to improve swimming performance is unclear. Future research should focus on stroke patterns during submaximal swimming speeds and the training effects on aerobic physiological parameters to investigate the effectiveness of in-water modalities improving endurance performance.

Part C: The Effect of Post-Activation Potentiation on Swimming Performance

Introduction

In any form of human locomotion, muscles generate the energy and/or power to create movement (Rodríguez & Mader, 2011). Specifically, in swimming, the upper body musculature (John A Hawley et al., 1992; Hollander et al., 1988) creates enough power to overcome hydrodynamic forces to propel the swimmer through the water (Rodríguez & Mader, 2011). The performance potential of skeletal muscle is dependent on its contractile history and its activation patterns through sport specific movements. Two components of this muscle contractile history are fatigue and PAP. While the effects of fatigue and PAP have polar opposite consequences, with fatigue diminishing performance and PAP potentially enhancing it, they can coexist. Moreover, their relationship is a growing area of human performance research (MacIntosh et al., 2012). PAP is grounded in the theory of complex training, which involves loading sport-specific muscle groups through resistive movements before commencing a sport-specific activity (Hancock et al., 2015). This method of training is already used in a variety of sports and has been shown to be equally valid if not superior to other forms of combined weight and plyometric training (Ebben, 2002). The maximal contractions used during prior loading results in both fatigue and PAP; however fatigue dissipates at a faster rate than PAP which allows for a "window of opportunity" where the potentiated state of the muscle groups used during activation allows for possible increased performance (MacIntosh et al., 2012) (Figure 1).

There are a growing number of studies that have investigated the effects of PAP on athletic performance showing mixed results. With studies showing increases (Cuenca-Fernández et al., 2015; Feros, Young, Rice, & Talpey, 2012; Hancock et al., 2015; Kilduff et al., 2008), decreases (A. Barbosa et al., 2016; Sarramian et al., 2015) and no change

(Eriksson, 2017; Kilduff et al., 2011; Sarramian et al., 2015) in performance. Only seven studies have examined the effect of PAP on swimming performance (A. Barbosa et al., 2016; Cuenca-Fernández et al., 2015; Eriksson, 2017; Hancock et al., 2015; Juárez Santos-García et al., 2013; Kilduff et al., 2011; Sarramian et al., 2015). While the benefit of PAP on swimming performance measures is still not conclusive, the physiology behind PAP is much better understood. The purpose of this review is to 1) identify the physiology of PAP 2) analyse the current literature concerning to best practice around eliciting a PAP response to increase performance measures and 3) how this has been implemented in the sport of swimming.

Physiology of Post-Activation Potentiation

PAP is defined as an increase in muscle twitch and low-frequency tetanic force after a conditioning contractile activity (Sale, 2002). The primary mechanism for PAP is the phosphorylation of myosin light chain kinase (MLCK) (Sale, 2002), which has two significant effects that may contribute to eliciting a PAP response. Firstly, phosphorylation of MLCK stimulates mobility of the myosin heads which increases the rate at which cross-bridges form during skeletal muscle activation and therefore increases the rate of force development (RFD) (MacIntosh et al., 2012). Additionally, it results in actin-myosin interactions being more sensitive to Ca^{2+} released from the sarcoplasmic reticulum (Rassier & Macintosh, 2000). This sensitivity has the most significant effects at low myoplasmic levels of Ca^{2+}. Early research showed that PAP has a substantial impact on fast twitch Type 2 fibres because of the increased rate of MLCK phosphorylation during activity (Rassier & Macintosh, 2000). Therefore, muscles that have an increased percentage of Type 2 fibres will possibly have an elevated response to PAP though limited research exists to confirm this. Although the ratio of muscle fibres is genetically determined, it can shift depending on age and training history including the type of training, the intensity of training and how long an athlete has been training for

(Hamada, Sale, MacDougall, & Tarnopolsky, 2000). Additionally, males tend to have a higher percentage of type 2 fibres compared to females due to their increased percentage of fat-free mass (Rixon, Lamont, & Bemben, 2007). However, since PAP occurs in twitch and low-frequency tetanic contractions (Sale, 2002), it indicates that the greatest benefits of PAP may be realised during submaximal contractions seen during endurance activities. Endurance athletes typically have a larger percentage of type 1 fibres (Hamada, Sale, & Macdougall, 2000) and it is suggested that endurance training can increase the amount of "fast" MCLK in type 1 fibres (Hamada, Sale, & Macdougall, 2000). Consequently, this would allow a greater response to a PAP stimulus in endurance-trained athletes, as they also have a superior resistance to fatigue compared to power based athletes (Hamada, Sale, & Macdougall, 2000). The 200m freestyle event in swimming takes between 1-min 45sec – 1-min 55sec for national level males and 1-min 55sec – 2-min 05sec for national level females and utilises all three energy systems, depending on the contribution of type 1 and type 2 fibres (Stager & Tanner, 2008). This would suggest that including a PAP stimulus during the warm-up for elite athletes would likely have a positive effect on an event that has the physiological demands of a 200m freestyle in swimming.

Eliciting a PAP Response

When implementing a PAP evoking stimulus into a warm-up with the goal of increasing swimming performance, two main factors need to be considered: 1) what conditioning exercise should be used to optimally promote a PAP response in swimming? And 2) what duration of recovery time is needed to receive the most benefit to swimming performance?

Conditioning Exercise

The conditioning exercise used to illicit a PAP response has a significant impact on whether it is going to positively influence performance. Several different methods have been used including maximal voluntary contractions (Hamada, Sale, & Macdougall, 2000), isometric contractions (Feros et al., 2012), 1 rep max and 3 rep max concentric movements (Kilduff et al., 2011; Sarramian et al., 2015) and sprinting with added resistance (Hancock et al., 2015). It has been shown that ~ 10 seconds of contraction is optimal at eliciting a PAP response (Vandervoort & McComas, 1983). However, repeating short maximal contractions 10 times has a cumulative PAP response that will develop without increasing levels of fatigue (Batista, Ugrinowitsch, Roschel, & Lotufo, 2007). These two methods contradict one another so finding a balance between the two may lead to even more increases in performance. Hancock et al. (2015) did this by having his subjects complete four maximal effort tethered swimming sprints approximately 7 seconds in duration, with positive effects on performance. However, in swimming it takes 5-7 seconds to reach maximal power output during a freestyle sprint (Stager & Tanner, 2008) therefore an effort that takes 12-15 seconds may result in a more performance specific conditioning exercise.

Recovery Period

Kilduff et al. (2008) examined the effect of recovery time following a PAP evoking stimulus on performance in professional rugby players. In this study, participants were instructed to perform a counter-movement jump (CMJ) immediately following a maximum effort squat protocol and every 4-min after (e.g. 4-min, 8-min, 12-min, 16-min, 20-min and 24-min) up to 24-min. They found that the first CMJ within 15sec of exercise cessation had a significant decrease in power output, the RFD and jump height when compared to baseline values and all these variables returned to baseline values after 4min of recovery. The highest power output, RFD (6,290 N/s, s=810 vs. 12,358 N/s, s=673; $P > 0.05$) and jump height (34.3 cm, s=1.2 vs. 36.0 cm, s=1.2; $P > 0.01$) was found after 8 min of recovery compared to baseline and all other recovery times. Kilduff et al. (2008) findings are in agreement with a recent meta-analysis on PAP and jump performance reporting a medium effect size (ES = 0.24, CI: 0.02 to 0.49) for increased jump height performance following a recovery period of 8-12 min and decreased performance (ES= -0.25, CI: -0.51 to 0.01) when only allowing 0-3 min of recovery (Gouvêa et al., 2013). Information on optimal recovery periods for endurance-based performance measures is not currently available.

PAP in Swimming

Research in the field of PAP and swimming is very new with the oldest piece of literature dating back only seven years (Kilduff et al., 2011). To date, a majority of studies have focused on dive start and sprint event (up to 100m) performance which only constitutes 38% of swimming events on the Olympic program. Similarly, a majority of existing research use land-based interventions which lacks the specificity to the stroke-specific movements and aquatic environment unique to the sport of swimming.

Dive Start Performance

Two studies examined the effect of a PAP stimulus on dive start performance and time to 15m, which represents 30% of a 50m sprint in swimming (Cuenca-Fernández et al., 2015; Kilduff et al., 2011). Kilduff et al. (2011) were the first try translate the success of CMJ performance following a PAP intervention (Kilduff et al., 2008) into a more sport specific movement, like the swim dive start. Swimmers time to 15m was measured under 50m race conditions, which was preceded by either an individualized warm up in the control

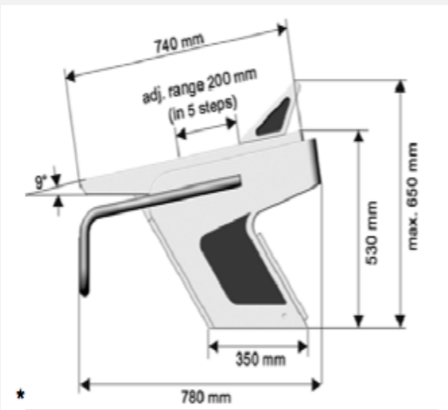

Figure 9. OMEGA OSB11 Dive Block

trial or 3RM squat during the intervention trial. The authors found that following an 8-min recovery period the athletes peak vertical force (CON: 1,462 6 280 vs INT: 1,518 6 311 N, $p = 0.038$) and peak horizontal force (CON: 770 6 228 vs INT: 814 6 263 N, $p = 0.018$) off the block was significantly higher during the PAP trial compared to control; however, time to 15m was unaffected by intervention (Kilduff et al., 2011). These results were confirmed by Cuenca-Fernández et al. (2015) who also examined the ability of a PAP stimulus to improve the swim dive start and time to 15m. They recognised since the development of the new starting block by OMEGA (OBS11, Corgémont, Switzerland) (Figure 9) a squat no longer replicated the position of the lower limbs on the starting block as the legs were now split between the front of the block and the rear kickstand. Therefore, they trialled a split lunge (1x3 maximal effort) and the Yoyo squat fly-wheel device (1x4 maximal effort) to illicit a PAP response. They found that dive distance increased (INT: 304.28 ± 9.066 cm vs CON: 294.2 ± 8.679 cm; $p < 0.01$), flight time decreased (INT: 0.28 ± 0.13sec vs CON: 0.33 ± 0.14sec; $p < 0.001$), horizontal hip velocity increased (INT: 4.89 ± 0.12 m/sec vs CON: 3.63 ± 0.11 m/sec; $p < 0.001$) and time to 5m (INT: 1.65 ± 0.052 sec vs CON: 1.75 ± 0.057 sec; $p < 0.001$) and 15m (INT: 7.36 ± 0.22 sec vs. CON: 7.54 ± 0.23 sec; $p < 0.05$) decreased following the Yoyo squat fly-wheel protocol compared to control (Cuenca-Fernández et al., 2015). The split lunge also had positive results; however, not to the same extent as the Yoyo. Both of these studies show that a land-based PAP stimulus is effective in improving the power produced on the block and the velocity leaving the blocking and entering the water. However, this increased performance on the block did not translate into underwater undulations or the first few breakout swimming strokes. This could be explained by two different things. The first being swimmers in the study were not able to handle the increased speed off the block and carry it through into their underwater undulations, with the second demonstrating the PAP stimulus was only specific to the dive itself and not the other movements required through the first 15m of swimming.

Sprint Swimming Performance

Three studies examined the effect of a PAP evoking stimulus on sprint swimming performance (A. Barbosa et al., 2016; Hancock et al., 2015; Sarramian et al., 2015). In the first study three different PAP interventions; upper body (weighted pull-ups, UB), lower body (weighted squat jumps, LB) and combined (both interventions concurrently, CB), were implemented with the intention to improve 50m sprint performance (Sarramian et al., 2015). Recovery time was individualised for each subject with pre-testing identifying if 4-min, 8-min or 12-min resulted in the best medicine ball throw (upper body) and CMJ (lower body) following a PAP stimulus. When analysing all 18 participants together, the upper body PAP resulted in a significantly slower 50m freestyle time than a traditional warm-up (CON: 29.00 ± 2.05 vs. UB: 29.36 ± 1.88s, p= 0.046), with a non-significant difference between the lower body and combined trials. Within-trial gender differences showed that only males had significant changes in 50m performance, with females remaining unchanged. For the males, both the traditional (CON: 27.51 ±1.06 vs UB: 28.01 ± 1.17s; p=0.047) and combined trials (CON: 27.49 ± 1.12s vs UB: 28.01 ± 1.17s; p=0.02) resulted in significant improvements to 50m performance compared to the upper body trial. This study reiterates previous research indicating that dryland based resistance fails to evoke a PAP response that improves sprint swimming performance beyond what a traditional warm-up would. Investigating individualised optimal recovery times was an interesting addition to the study design. However, this study did not randomise the order of intervention which could lead to an order effect in the results. Additionally, they completed testing in a 25m pool which results in increased velocity due to the extra turns and does not correlate to Olympic Pool (50m) swimming (Keskinen, Keskinen, & Mero, 2007).

Hancock et al. (2015) were the first authors to successfully show the benefit of a water-based PAP evoking stimulus on sprint swimming performance. In this study, all swimmers were measured in their 100m freestyle performance which was proceeded by either a 900m race warm up (CON) or 900m race warm-up followed by a PAP stimulus (INT). Participants were given 6-min of recovery following the completion of either warm-up schedule. The PAP stimulus utilised in this study design was four maximally loaded power racks sprints (Figure 6), individually determined to ensure that each participant all-out effort lasted approximately 7 seconds. This method allowed for the staircase effect enhancing the PAP response to the intervention (Batista et al., 2007). They found that the mean time of the PAP trial was significantly faster than control (INT: 62.91 sec vs CON: 63.45 sec; $p>0.029$) with no significant difference between males and females swimmers. There was also no significant difference for either the first or second 50m splits (INT: 0.26sec vs. CON: 0.27sec). However, this would be substantial to the swimming community (Pyne, Trewin, & Hopkins, 2004). Additionally, although blood lactate levels were higher following the PAP trial (INT: 12.3mmol vs CON: 11.5mmol; $p = 0.099$), it was not statistically significant. The power rack used in this study may have limited the effectiveness of the PAP evoking stimulus as it may have changed the athletes hip position and therefore their technique through freestyle swimming. Additionally, it takes swimmers 5-7seconds to reach maximal power output during freestyle sprint swimming (Stager & Tanner, 2008). Accordingly, an intervention of only 7 seconds may not have been long enough to maximise the PAP response of the muscles fibres. Therefore, a more significant effect may be possible with these slight changes in methodology. The authors of this research indicated the possibility of in water swim specific PAP enhancing performance measures of longer than 100m.

A. Barbosa et al. (2016) recognised the lack of swimming specificity in previous studies (Cuenca-Fernández et al., 2015; Kilduff et al., 2011; Sarramian et al., 2015) and set out to investigate the effects of water-based resistance exercises to illicit a PAP response. Eight competitive swimmers performed two pre-intervention (8min and 4min) 10m maximal tethered swims, followed by 8x12.5m maximal effort sprint with hand paddles and parachutes on a 2.5-min interval. Swimmers then completed two post-intervention (2.5-min and 6.5-min) 10m maximal tethered swims to examine the effects of the resistance swimming on peak force, impulse and rate of force development. They found that the intervention negatively affected peak force and impulse and additionally did not affect the rate of force development. These results are not surprising for a multitude of reasons. As previously mentioned, an 8-12 min recovery period allows for the effects of fatigue to dissipate allowing the "window of opportunity" where PAP effects will be greatest (Gouvêa et al., 2013). Therefore, only allowing a 2.5 min and 6.5 min window would result in a high level of fatigue remaining. The intervention in this study was also excessively long compared other studies, with the 8x12.5m taking 20-min to complete. Subsequently, by the time the athletes completed their first post-test it had been 24-min since the beginning of the intervention protocol. Kilduff et al. (2008) showed that 24-min following intervention performance measures were back down to baseline measures. While, it has been shown that intermittent voluntary contractions have a "staircase effect", evoking consequential PAP responses without the increase of fatigue. For this to occur it has been suggested that successive contractions occur on 20-30 sec intervals (Batista et al., 2007). Finally, adding hand paddles and parachutes to a swimmer increases the hydrodynamic forces acting upon that athlete. While this increased resistance and therefore muscular force, it also changes the positioning of the swimmer in the water, which can have a negative kinematic response on stroke technique (Telles et al., 2011).

Distance Swimming Performance

The lack of research focused on PAP and longer swimming distances was addressed by Eriksson (2017) who investigated the effect of a resistance band PAP intervention on submaximal 400m freestyle swimming. Specifically, the velocity associated with a BL concentration of 4 $mmol^{-1}$ (E. W. Maglischo, 2003) (V4) was chosen as the submaximal intensity, to isolate the aerobic energy system. Two sets of 10 rep upper body resistance band exercises were used as a PAP stimulus to utilise the triceps and latissimus dorsi muscles (Stager & Tanner, 2008). The intervention trial was initiated 72 hours after the completion of the control trial, where 6-min of passive recovery was allowed following the PAP stimulus. The author found that while PAP resulted in an elevated BL levels during the submaximal 400m freestyle time trials compared to control (INT: 4.37 ± 0.89 $mmol^{-1}$ vs. CON: 3.64 ± 0.80 $mmol^{-1}$; $p < 0.02$), it did not have a significant impact on total time (INT: 290.96 ± 15.53sec vs. CON: 291.05 ± 16.07; $p < 0.93$). This lack of improvement is likely due to restricting athletes to a submaximal speed and utilizing a PAP stimulus that was not specific enough to the swimming pull pattern and aquatic environment used during the performance measure.

Summary and Conclusion

The existing literature shows that eliciting a PAP response is physiologically possible in endurance-trained athletes and through careful design can result in increased swimming performance. However, there is currently no best practice to administer a PAP intervention in swimming athletes. This review shows that multiple contractions of 10 seconds in length will efficiently evoke a PAP response and 8-12 min of recovery will allow fatigue to dissipate without losing the cumulative effect on contraction. Existing swimming specific research shows that land-based stimuli effectively improve dive start performance. However, this does not translate into swimming performance. Therefore, in-water stimuli are more effective in eliciting a PAP response for swimming performance. Current in water training modalities effect body position in the water and swimming technique. Research in other sports has shown that WRT allows the load to be applied through sport specific movements without compromising technique (Macadam, Simperingham, et al., 2017). Therefore, WRT may provide a suitable alternative for future research to administer loading through a totally sport specific movement in an aquatic environment.

Chapter Three: Research Methodologies

Methods: Study 1

Experimental Approach

A randomised repeated measures design was used to investigate the cardiovascular and metabolic effects of proximal upper limb loading using WRT during 200m submaximal freestyle swimming. Two sessions were completed by each participant with 24 hours between sessions allowed for recovery. Both sessions began with the same standardised race warm-up (Figure 10) and were completed in a 50m indoor swimming pool. The first session involved determination of the subjects lactate threshold using a 7x200m incremental step test (Pyne, Lee, & Swanwick, 2001). The second session required each subject to complete 6x200m freestyle swims at individualised submaximal speeds with variable loads ranging from 0g-500g proximally loaded to each arm using WRT.

Standard Warm Up (SWU)

3x200 Swim/Kick/Drill @ 4.00
4x100 descend 1-4 @ 1.40
50 easy swim @ 1.10
2x50 freestyle 200m race pace @ 1.00
50 easy swim @1.10

Figure 10. Standard Warm Up (SWU)

Subjects

Fifteen (male = 7; female = 8) national level swimmers volunteered to participate in this study (Table 2). Prior to the commencement of testing, subjects were asked to follow their normal training schedules and pre-race preparations including having adequate sleep, hydration and nutrition. Subjects were provided with information on the study (Appendix B) and informed written consent (Appendix B) was obtained prior to any data collection occurring. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study (17/280) (Appendix A).

Table 2. Table showing participant characteristics		
Variables	**Males (n=7)**	**Females (n=8)**
Age (years)	18.4 ± 2.4	18.1 ± 2.6
Height (cm)	183.4 ± 4.3	166.5 ± 10.9
Wingspan (cm)	184.2 ± 6.6	167.8 ± 11.7
Weight (kg)	79.4 ± 7.3	60.7 ± 8.8
Lean Body Weight (kg)	74.4 ± 6.6	51.3 ± 8.2
Body Fat (%)	6.2 ± 1.9	15.5 ± 1.6
200m PB (sec)	119.70 ± 6.37	132.49 ± 8.59
200m PB compared to National winner (%)	+8.47%	+10.16%

Equipment and Measurements

All warm-up and testing took place in a 50m indoor pool at a water temperature of 27°C to replicate the regulated international competition environment. All 200m times and 50m splits were measured manually by the squad's head coach who has 20 years of combined swimming and coaching experience, using digital chronometers (Seiko S141; Seiko Holdings Corporation, Tokyo, Japan).

Following each 200m effort during both testing sessions acute response variables were collected. Ear lobe capillary BL was measured using the Lactate Pro 2 analyser (Arkray KDK, Japan). HR was collected manually by the swimmers themselves through palpation of the carotid artery counting beats for 10seconds then multiplying by 6 to get beats per minute (bpm). RPE was also collected after each 200m to see if the subjects identified a difference in difficulty between the different WR loads (Borg, 1982).

During all experimental submaximal 200m freestyle efforts, subjects wore Lila^{TM} Exogen^{TM} compression upper arm sleeves (Sportboleh Sdh Bhd, Malaysia) positioned right above the elbow joint (Figure 11). This acted as a control across all trials and allowed lachrymiform shaped 100g loads with a Velcro backing to be proximally loaded during five of the six trials. The loads were placed horizontally on the arm bands, interweaving

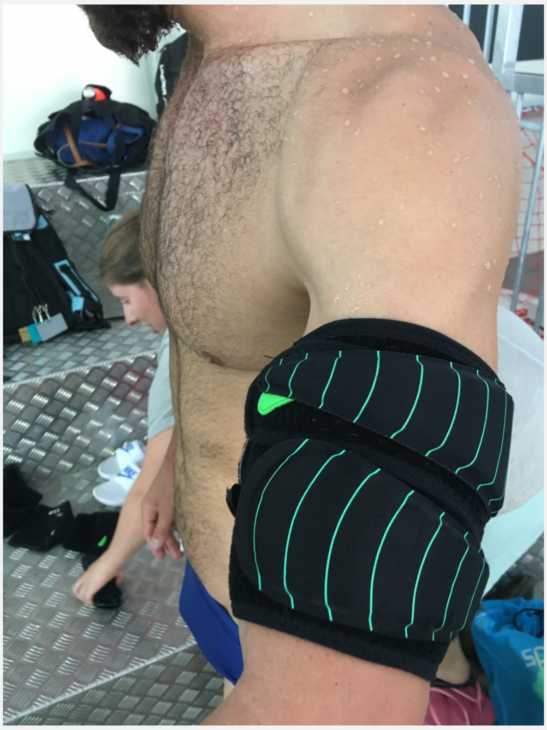

Figure 11. Lila™ Exogen™ compression upper arm sleeves (Sportboleh Sdh Bhd, Malaysia) with lachrymiform load attached

with one another.

Procedures

7x200 Incremental Step Test

To establish baseline measures of HR, BL and submaximal 200m swimming speed, a 7x200m incremental step test was used as detailed by Pyne et al. (2001). Briefly, this involved a graded incremental protocol where HR, BL and RPE responses to increasing swim speed were determined. Seven even paced 200m freestyle swims were completed on a 5min cycle, where subjects 200m freestyle personal best time from the previous 12 months was used to determine their goal time for each effort (Table 3). The subjects were instructed that each effort should increase in speed by five seconds until maximal effort is reached on number seven. All swims started from a push start, and the subjects were given their goal pace (100m split times) and total 200m goal time prior to the start of each effort.

Table 3. Example of how goal times were set for the incremental step test

Subject	PB (min:sec)	Goal Time (min:sec)						
		#1	#2	#3	#4	#5	#6	#7
1001	1:50	2:25	2:20	2:15	2:10	2:05	2:00	1:55

Submaximal Speed Calculation

The BL results for each trial were plotted against swimming velocity (average 200m velocity expressed as ms^{-1}) (Figure 12). The BL curve involved the determination of the

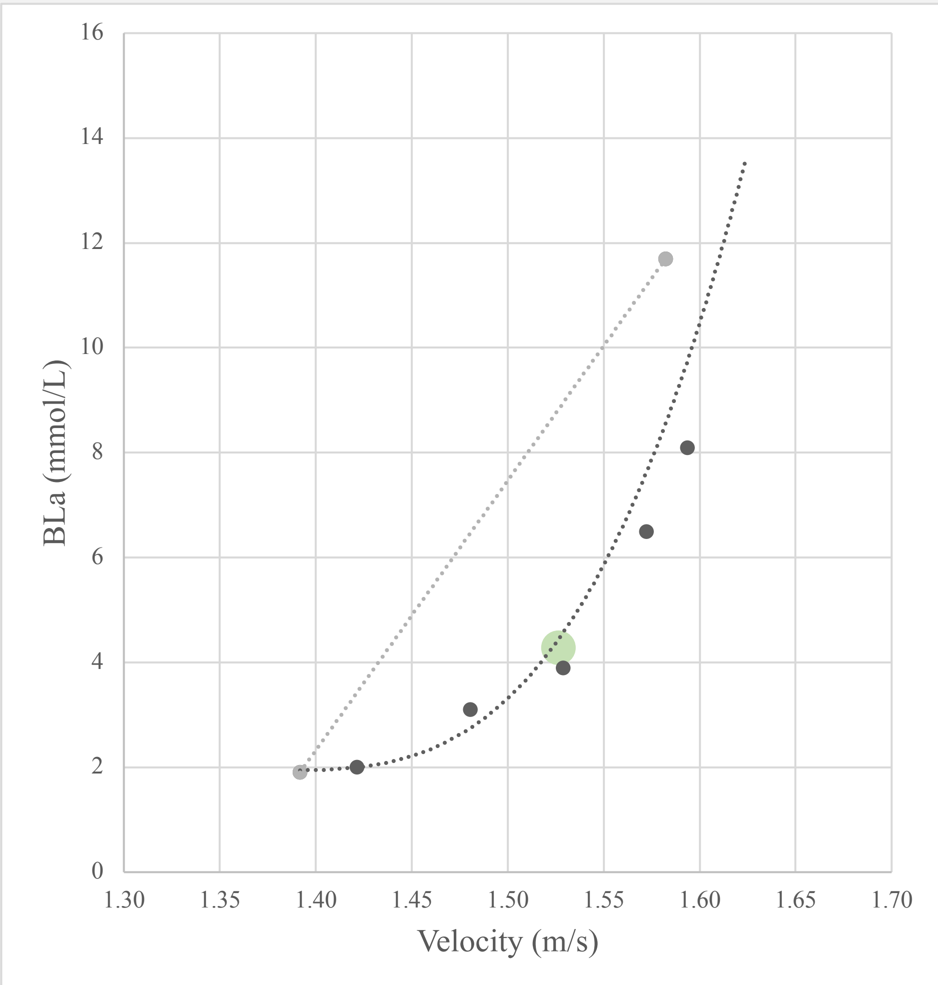

Figure 12. Example of the plot using the D_{max} method to calculate submax speed and blood lactate following the incremental step test. Most distant point between the curve and straight line represented D_{max},

upper lactate threshold (LT) using the D_{max} method which has shown to present high test-retest reliability (Oliveira et al., 2012). A straight line connected the two end points of a third order curvilinear regression calculated from the blood lactate vs speed curve. The most distant point between the curve and straight line represented D_{max}, with the x and y axes representing submaximal speed and blood lactate threshold (Figure 12).

Variable Load Testing

Twenty-four hours later subjects completed the 6x200m submaximal freestyle swims with variable load. During each swim the subjects were randomly assigned one of six WR loads [0g (control), 100g, 200g, 300g, 400g, 500g] to be proximally loaded to each upper arm compression sleeve (Exogen™ Exoskeleton by Lila™) (Figure 11). We chose fixed loads instead of percentage of body weight because the loads were small relevant to the body weight of the participants. Each 200m effort commenced on a 12-min cycle to ensure no carry over effect from the previous WR load. Following each effort swimmers were instructed to exit the pool and have their HR, BL and RPE collected immediately. The WR load was then removed, and subjects had the remaining rest cycle as seated passive recovery. The new WR load was applied 1-min prior to the next 200m effort.

Statistical Analysis

Descriptive statistics were used to calculate means and standard deviations (SD) and 90% confidence intervals (CI) for all measures collected throughout the study. All variables representing performance were log transformed to reduce non-uniformity of error and to express effects as percentages (W. G. Hopkins, 2002). The coefficient of variation (CV) of international level swimmers between competitions is 0.7% (95% CI: 0.6% - 0.9%) for 200m freestyle (Pyne et al., 2004), therefore a custom effect (%) beyond this threshold would represent the smallest worthwhile change between efforts. Quantitative chances of a real change (beneficial/greater, trivial/similar or harmful/lesser) in performance measures between the loaded and control trials were practically assessed as follows:

<1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99%, very likely; >99%, almost certain. If chance of benefit and harm were both >5%, true effect was assessed as unclear (W. Hopkins, Marshall, Batterham, & Hanin, 2009). Changes in physiological variables were expressed in effect size (ES) using Cohens d to standardise the difference between the loaded and control trials (<0.1 (trivial), >0.2 (small), >0.6 (moderate), >1.2 (large) and >2.0 (very large)) with an ES > 0.2 representing the smallest worthwhile change (W. Hopkins et al., 2009). In order to analyse gender differences in the response to the intervention ES were adjusted using sex (male/female) as a covariate. Accordingly, males were marked as "0" and females as "1" in the same "post-only" spreadsheet (http://www.sportsci.org)

Methods: Study 2

Subjects

Ten national level female swimmers volunteered to participate in this study (Table 4). The subjects were primarily sprint/middle distance freestylers with a few other stroke or distance specialists (Sprint/Middle: 7, Long Distance: 3; Freestyle: 7, Backstroke: 2, Breaststroke: 0, Butterfly: 0, IM: 1). Before commencement of the study, subjects followed their normal training routine. This included ensuring adequate sleep, hydration and nutrition. Subjects were provided with information on the study (Appendix B) and informed written consent (Appendix B) was obtained prior to any data collection occurring. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study (17/280) (Appendix A).

Table 4. Information of participants

	n=10 (mean ± SD)
Age (years)	17.60 ± 2.46
Height (cm)	166.47 ± 10.43
Wingspan (cm)	167.13 ± 10.55
Weight (kg)	61.47 ± 9.32
Lean Body Weight (kg)	51.07 ± 8.05
Body Fat (%)	16.94 ± 1.99
Personal Best (PB) from past 12months (sec)	133.13 ± 7.80
PB compared to NZ National Champion (%)	+10.7%

Procedures

Testing Sequence

Upon arrival to the testing area, subjects were asked to conduct their normal dryland-based warm-up routine. On completion, swimmers were match-paired based on their 200m freestyle personal best time from the past 12months. Participants from each matched pair were then randomly assigned to either the experimental or control condition.

Participants performed two trials on separate days, with 48 hrs of recovery. Both trials began with a standardised 1300m race warm up (SWU) (Figure 13) followed by 8min of passive recovery after which, the 200m time trial was initiated. During the intervention trial upper arm band sleeves and individually assigned WR load (Exogen™ Exoskeleton by Lila™) was added to the participants during the 4x25m sprints.

Standard Warm Up (SWU)

3x200 Swim/Kick/Drill @ 4:00min
4x100 descend 1 to 4 @ 1:40min
50 easy swim @ 1:10min
2x50 freestyle 200m race pace @ 1:00min
50 easy swim @1:10min

4x25 Max Effort!! @1:00min

Figure 13. Standard Warm Up with addition of PAP sprints

Proximal Arm Load Prescription

Upper arm loading was prescribed individually for the subjects. This was done by the following calculation: Upper Arm Load = (LBW/PB)*100.

Where LBW is the subjects lean body weight (LBW) and PB is their personal best 200m time in seconds over the last 12months.

Table 5. **Example of how load was prescribed and reflected participant characteristics**

Subject	Gender	Age	Experience	Variables	Values
1025	Female	16	Age Group National Finalist	LBW	51.10 kg
				PB Time	138.74 sec
				Ratio	0.331
				Load per arm	**300g**
1015	Female	24	International	LBW	61.50 kg
				PB Time	120.09 sec
				Ratio	0.461
				Load per arm	**400g**
1011	Female	16	Age Group Nationals	LBW	37.25 kg
				PB Time	143.45 sec
				Ratio	0.231
				Load per arm	**200g**

The LBW was calculated using the sum of 7-site skin folds collected using skin-fold callipers (Jackson & Pollock, 1978; Jackson, Pollock, & Ward, 1980). LBW was used to consider the muscle mass of each subject. PB time was selected because it gives an indication into the athletic ability of each subject. This ratio represented a WR load that was realistically able to be applied to each subject (Table 5).

Equipment and Measurements

All testing took place in a 50m indoor pool at a water temperature of 27°C to replicate the regulated international competition environment. Times were measured manually by an experienced coach using digital chronometers (Seiko S141; Seiko Holdings Corporation, Tokyo, Japan). Times for the 4x25m sprints during the warm up and 50m split segments as well as total 200m time trials were recorded.

BL, HR and RPE were taken four times for both control and interventions trials. All measures were collected 60sec prior to and within 60 seconds of completing both the 4 x 25 m maximal efforts (post warm up), and post 200 m TT. Ear lobe capillary BL was measured in all subjects using the Lactate Pro 2 analyser (Arkray KDK, Japan). HR was collected electronically using the Polar HR monitor (F11 Polar Electro, Finland). The Borg (1982) RPE scale was used to quantify any differences in difficulty during the 200m TT between the two trials.

During the intervention trial subjects wore Lila™ Exogen™ compression upper arm sleeves (Sportboleh Sdh Bhd, Malaysia), which allowed lachrymiform shaped 100g WR loads with a Velcro backing to be proximally loaded (Figure 11). The loadin

Chapter Four: Results

Results: Study 1

7x200 Incremental Step Test

The peak speed reached in the incremental step test was 1.47 ± 0.09m/s and 1.40 ± 0.08m/s for males and females respectively. Utilising the D_{max} method this resulted in a submaximal swimming speed of 1.43 ± 0.07ms^{-1} for males and 1.32 ± 0.07ms^{-1} for females. D_{max} speed was 95.95% of the participants peak swimming speed during the step test. The incremental step test resulted in a peak BL of 10.87 ± 1.48mmol^{-1} for males and 8.60 ± 3.06mmol^{-1} for females. The BL at Dmax was 3.71 ± 1.50mmol^{-1} for males and 2.44 ± 0.81mmol^{-1} for females, which was 31.4% of peak blood lactate.

Response to Load

We found no substantial difference between the goal time and the control trial time (0g load). However, there was a *large* increase from predicted submaximal BL of 1.97 ± 0.43mmolL^{-1} (1.42, (0.63 – 2.21) (Figure 14.C). Gender had a large effect on the response to variable proximal upper arm loading when analysing the variables of speed, BL, HR and RPE (Table 6).

Speed

For males, there was no substantial difference in swim times between any of the WR loaded trials and the control trial (0g). Though no substantial differences in swim time between control and lighter (<300g) loads was evident for females, *very likely* slower swim speeds for the 400g (↑3.11 ± 2.56sec, 1.9%, (0.8-3.1)) and 500g (↑4.05 ± 2.35sec, 2.6%, (1.4-3.8)) trials were observed.

Blood Lactate

The males showed a *likely small* increase during the 400g trial (↑0.74 ± 1.32 $mmol^{-1}$; 0.41, (-0.13 – 0.96)) and a *likely large* increase (↑2.40 ± 3.06$mmol^{-1}$, 1.29, (-0.06-2.63)) in the 500g trial compared to control (0g). The 100g trial also showed a *likely moderate* increase in BL (↑1.73 ± 2.19$mmol^{-1}$, 0.96, (0.07 – 1.86)). However, the results of the other trials were *unclear*. All the BL results for the females were *unclear*; however, a trend showed only *trivial* increases in BL across all five loaded trials.

Heart Rate

There was a *likely* increase in HR in the 100g trial for the males compared to control (↑8.6 ± 15.0bpm, 0.76, (-0.22 – 1.74)) (Figure 14.B). The results for all other trials for both genders were *unclear*. However, there was a trend towards only *trivial* decreases in HR for the females and *small* increases in the males.

Rate of Perceived Exertion

The males showed consistent RPE across all trials compared to control with an average of 15.4 ± 2.1RPE. The females showed a *likely small* increase in RPE in both the 300g (↑1.2 ± 1.9RPE, 0.53, (-0.19 – 1.25)) and 400g (↑1.1 ± 1.9RPE, 0.58, (-0.11 – 1.27)) trials and also a *possible small* increase in the 500g trial (↑1.1 ± 2.3RPE, 0.58, (-0.26 – 1.42)) compared to control (0g). The remainder of the trials only showed a trend towards *trivial* increases in RPE.

Table 6. Change in time, blood lactate, heart rate and RPE in variable loads compared to control (0g)																	
Load	Gender	**Time**				**Blood Lactate**				**Heart Rate**				**RPE**			
		Mean Change (sec)	Percent Change (%)	Inference	±90% Confidence Limits	Mean Change (mmol/L)	Effect Size	Inference	±90% Confidence Limits	Mean Change (bpm)	Effect Size	Inference	±90% Confidence Limits	Mean Change (RPE)	Effect Size	Inference	±90% Confidence Limits
100	Male	+2.21 ± 2.41	1.6	Unclear	0.3 – 2.8	+1.73 ± 2.19	0.96	Likely	0.07 – 1.86	8.6 ± 15.0	0.76	Likely	-0.22 - 1.74	1.3 ± 2.7	0.54	Unclear	-0.29 - 1.37
	Female	+0.68 ± 2.19	0.4	Unclear	-0.5 – 1.4	-0.59 ± 1.46	0.43	Unclear	-0.29 – 1.15	-4.7 ± 14.0	0.35	Unclear	0.35 - 1.05	0.6 ± 1.5	0.29	Unclear	-0.27 - 0.85
200	Male	+0.03 ± 2.42	0	Unclear	-1.2 – 1.3	+1.10 ± 2.57	0.57	Unclear	-0.49 – 1.62	2.3 ± 16.9	0.20	Unclear	-0.90 - 1.30	-0.6 ± 2.7	0.24	Unclear	-1.07 – 0.59
	Female	+2.38 ± 1.96	1.5	Unclear	0.7 – 2.4	+0.30 ± 1.79	0.15	Unclear	-0.45 – 0.75	-0.2 ± 8.9	0.01	Unclear	-0.23 - 0.25	0.3 ± 2.2	0.14	Unclear	-0.68 – 0.97
300	Male	+0.20 ± 1.67	0.1	Unclear	-0.7 – 1.0	+1.39 ± 2.54	0.77	Unclear	0.27 – 1.81	5.7 ± 12.7	0.51	Unclear	-0.32 - 1.33	0.3 ± 2.3	0.12	Unclear	-0.59 – 0.83
	Female	+2.09 ± 3.75	1.3	Unclear	-0.4 – 3.0	0.01 ± 1.00	0.01	Unclear	-0.33 – 0.34	-1.1 ± 14.3	0.08	Unclear	-0.68 - 0.85	1.2 ± 1.9	0.53	Likely	-0.19 – 1.25
400	Male	-0.21 ± 3.27	-0.1	Unclear	-1.4 – 1.1	+0.74 ± 1.32	0.41	Likely	-0.13 – 0.96	4.0 ± 12.3	0.35	Unclear	-0.45 - 1.16	0.4 ± 3.4	0.18	Unclear	-0.86 – 1.22
	Female	+ 3.11 ± 3.04	1.9	Very likely	0.7 – 3.2	+0.33 ± 1.21	0.16	Unclear	-0.24 – 0.57	-1.2 ± 2.4	0.06	Unclear	-0.33 - 0.45	1.1 ± 1.9	0.58	Likely	-0.11 – 1.27
500	Male	+1.29 ± 1.46	0.9	Unclear	0.1 – 1.7	+2.40 ± 3.06	1.29	Likely	0.06 – 2.63	4.9 ± 10.1	0.43	Unclear	-0.22 - 1.09	0.7 ± 2.5	0.30	Unclear	-0.47 – 1.07
	Female	+4.05 ± 3.82	2.6	Almost certain	1.0 – 4.2	+0.20 ± 1.16	0.10	Unclear	-0.29 – 0.49	-2.5 ± 13.7	0.14	Unclear	-0.66 - 0.38	1.1 ± 2.3	0.58	Possible	-0.26 – 1.42

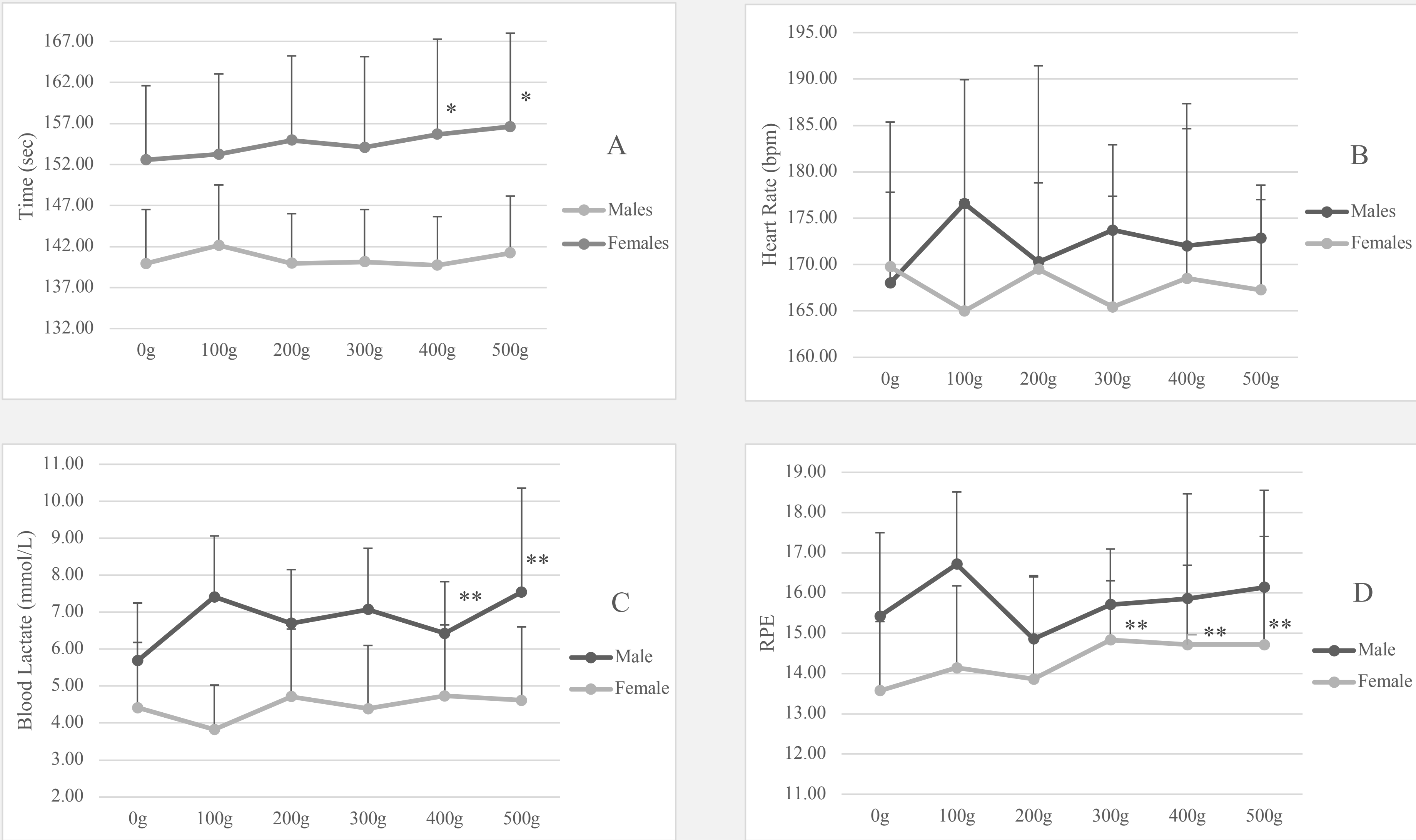

Figure 14. (A) Time (B) heart rate, (C) blood lactate and (D) RPE response to variable loading; * denotes a substantial change >0.7%, ** represents an effect size >0.2

Results: Study 2

Effects on 200 Time Trial

200m Freestyle Time

The WRT intervention had a *likely trivial* effect on 200 m swimming with a between-trial difference of 0.3% (↑0.34 ± 1.12sec, (-0.2-0.7)). There was a *possible trivial* between-trial difference of 0.5% (↓0.15±0.40sec, (-0.3-1.2)) in the first 50m split and *almost certain trivial* between-trial difference in the second 50m split of 0.1% (↓0.04 ± 0.20sec, (-0.2-0.4)) (Table 7). Consequently, this resulted in a *likely trivial* change in swimming time for the first 100m split of 0.3% (↑0.19 ± 0.46sec, (-0.3-0.7)). For the time taken to complete the second 100 m, there was a *possible increase* of 0.7% (↑0.53 ± 1.18sec, (-1.6-0.2)) (Figure 15). Accordingly, within the 200 m time trial there was a greater *likely small* change in the difference between the 1st and 2nd 100 m time for the intervention with an increase of 8.7% (↑5.76 ± 2.01sec) compared to 7.6% (↑5.04 ± 1.30sec) in the control trial.

Table 7. Effect of PAP intervention on performance measures when compared to control.

Performance Measures	Difference (mean ± SD sec)	Custom Effect (%)	± 90% Confidence Limits	Chances that the true effect has a substantial ...		
				Benefit (%)	Harm (%)	Practical Assessment
1st 50m Split	-0.15 ± 0.40	0.5	-0.3 – 1.2	30	1	Benefit possible
2nd 50m Split	-0.04 ± 0.20	0.1	-0.2 – 0.4	0	0	Almost certain no effect
3rd 50m Split	0.20 ± 0.40	-0.6	-1.2 – 0.1	0	34	Harm possible
4th 50m Split	0.33 ± 0.92	-0.9	-2.3 – 0.5	4	61	Harm possible
1st 100m Split	-0.19 ± 0.46	0.3	-0.3 – 0.7	4	0	Very likely no effect
2nd 100m Split	0.53 ± 1.18	0.6	-1.6 – 0.2	1	53	Harm possible
200m Time	0.34 ± 1.12	0.3	-0.2 – 0.7	5	0	Likely no effect

[a] Substantial is an absolute change in performance of >0.7% (see methods)
[b] If chance of benefit and harm both >5%, true effect was assessed as unclear (could be beneficial or harmful). Otherwise, chances of benefit or harm were assessed as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99%, very likely; >99%, almost certain.

Blood Lactate During 200m Trials

There were *unclear* between-trial difference in pre TT BL (0.52, (-0.25 – 1.29)). However, there was a *possible small* increase in post TT BL of 1.64 ± 4.47 mmol^{-1} (0.35,

(-0.21 – 0.92)) after the intervention trial compared to control. There was a *likely small* increase of 1.90 ± 4.23mmol^{-1} (0.40, (-0.12 – 0.92)) in BL from pre to post TT following intervention compared to control (Table 8).

Heart Rate and RPE During 200m Trials

The intervention resulted in a *likely moderate* increase in pre-TT HR of 11.40 ± 20.79bpm (0.83, (-0.05-1.71)). Post TT HR, and the change in HR pre to post TT were statistically *unclear*. There was a *small* but unclear increase in post TT RPE (↑0.70 ± 2.16) following the intervention trial compared to control (Table 8).

Table 8. Change in physiological measures following intervention compared to control.

Physiological Measures	Mean Change	Effect Size	± 90% Confidence Limits	Chances that the true effect is substantial[a]...		
				Benefit (%)	Harm (%)	Practical Assessment[b]
Pre TT BL	-0.26 ± 0.67 mmol^{-1}	0.52	-0.25 – 1.29	77	6	Unclear
Pre TT HR	+11.4 ± 20.8 bpm	0.83	-0.05 – 1.71	89	3	Benefit Likely
Post TT BL	+1.64 ± 4.47 mmol^{-1}	0.35	-0.21 – 0.92	69	5	Benefit Possible
Post TT HR	-0.9 ± 23.3 bpm	0.04	-0.53 – 0.60	31	23	Unclear
Post TT RPE	+0.70 ± 2.16	0.36	-0.29 – 1.01	67	7	Unclear
Change in BL	+1.90 ± 4.23 mmol^{-1}	0.40	-0.12 – 0.92	75	3	Benefit Likely
Change in HR	-5.8 ± 24.6bpm	0.26	-0.43 – 0.96	56	13	Unclear

[a] Substantial is an absolute change in physiological measure of >0.2 (see methods) representing a small ES

[b] If chance of benefit and harm both >5%, true effect was assessed as unclear (could be beneficial or harmful). Otherwise, chances of benefit or harm were assessed as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99%, very likely; >99%, almost certain.

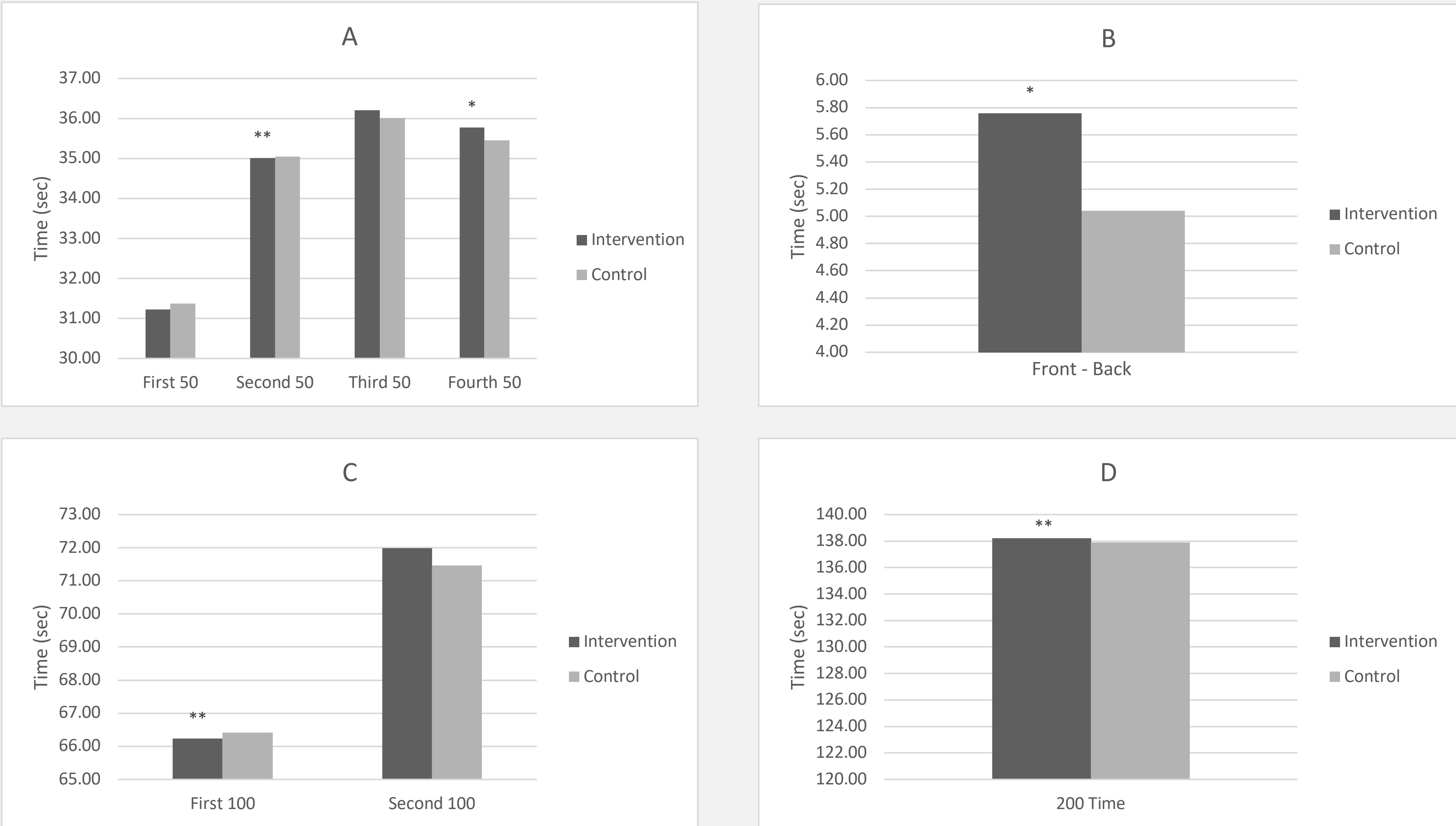

Figure 15. Comparison of (A) 50m splits (B) front/back half times, (C) 100m splits and (D) 200m time trial between intervention and control; * denotes a substantial change >0.7%, ** represent a non-effect with probability >25%

4x25m Maximal Effort Warm Up Sprints

4x25m Sprint Times

The added resistance resulted in an *almost certain* substantial increase of average time for the 25m of 0.49 ± 0.17sec (3.3% (2.6-4.1%)) (Figure 16).

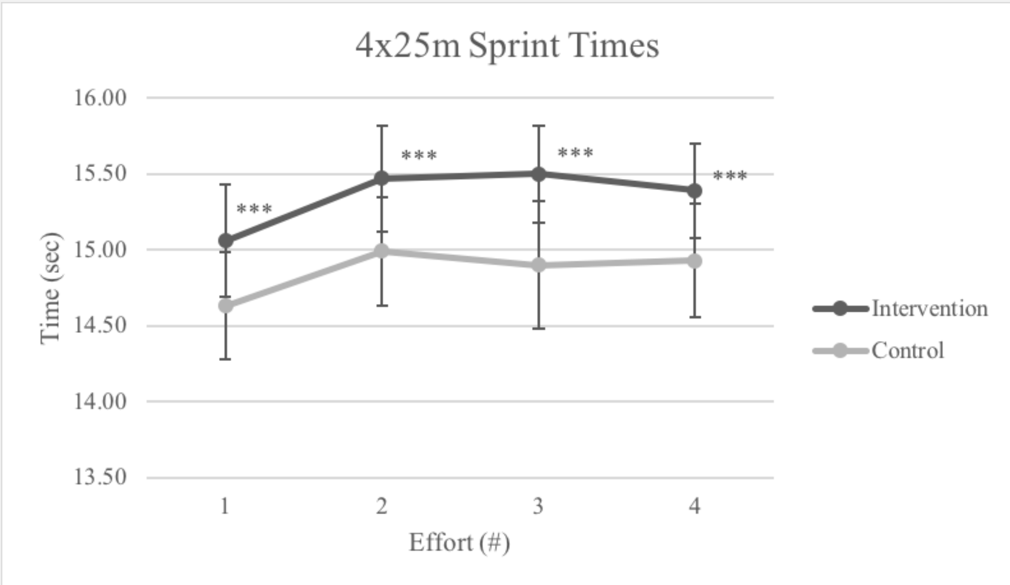

Figure 16. Graph showing the difference in time between intervention and control trials; *** denotes a substantial change (>0.7%) in time

Blood Lactate

The differences of BL post initial warm for intervention and control trials was unclear with a trend towards there being no substantial difference. However, adding WRT during the subsequent 4x25m sprints resulted in a *likely small* decrease of post intervention BL of 0.47 ± 0.98mmol^{-1} (0.40, (-0.05 – 0.86)). This was also shown as a *very likely small* substantial decrease of 0.34 ± 0.40mmol^{-1} (0.34, (0.05 – 0.63)) in the change of BL pre to post sprints during the intervention trial (Table 9).

Heart Rate and RPE

The differences between the two trials in relation to HR and RPE were unclear (Table 9).

Table 9. Physiological measures shown during the 4x25m sprint intervention compared to control

Physiological Measures	Mean Change	Effect Size	± 90% Confidence Limits	Chances that the true effect is substantial[a]...		
				Benefit (%)	Harm (%)	Practical Assessment[b]
Pre 4x25m BL	+0.07 ± 0.78 $mmol^{-1}$	0.17	-1.21 – 1.55	49	31	Unclear
Pre 4x25m HR	+2.43 ± 9.22 bpm	0.21	-0.37 – 0.78	58	11	Unclear
Post 4x25m BL	-0.47 ± 0.98 $mmol^{-1}$	0.40	-0.05 – 0.86	78	2	Benefit Likely
Post 4x25m HR	+5.20 ± 17.22 bpm	0.24	-0.22 – 1.71	57	6	Unclear
Post 4x25m RPE	+0.44 ± 1.59	0.29	-0.36 – 0.95	60	10	Unclear
Change in BL	-0.34 ± 0.40 $mmol^{-1}$	0.34	0.05 – 0.63	81	1	Benefit Likely
Change in HR	-1.43 ± 21.56 bpm	0.08	-0.85 – 1.02	41	29	Unclear

[a] Substantial is an absolute change in physiological measure of >0.2 (see methods) representing a small ES
[b] If chance of benefit and harm both >5%, true effect was assessed as unclear (could be beneficial or harmful). Otherwise, chances of benefit or harm were assessed as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99%, very likely; >99%, almost certain.

Chapter Five: Discussion of Thesis Findings

This thesis aimed to investigate two uses of WRT. The first aim was to determine the physiological effects (BL, HR, RPE) of variable loading through WRT during submaximal swimming in national level swimmers and the second aim was to investigate the use of WRT as a stimulus to elicit a PAP response in female swimmers and its impact on 200m freestyle performance. In study one our main findings were realized during the heavier trials (400g & 500g). The males showed increased BL levels (400g: ↑0.74 ± 1.32 $mmol^{-1}$, 0.41, (-0.13 – 0.96), 500g: ↑2.40 ± 3.06$mmol^{-1}$, 1.29, (-0.06-2.63)) to maintain their submaximal goal time throughout all five loaded weights. Conversely, the females failed to hold their time with the increased load (400g: ↑1.9% (0.8-3.1); 500g: ↑2.6% (1.4-3.8)) which was reflected in an increased RPE (Figure 13). In study two, we found *trivial* differences between 200m TTs following either a loaded or non-loaded warm-up protocol (0.3% (-0.2 – 0.7)), with a possible improvement in the first 50m split (0.5%; (-0.3-1.2)) and impairment in the second 100m split (0.6%; (-1.6-0.2)). Overall, we found that WRT provides a novel way to increase the intensity during freestyle swimming in national level male athletes. However, females were unable to cope with the increased load. Additionally, WRT is not a useful tool in eliciting a PAP response to improve 200m TT performance in female swimmers.

Acute Response to Variable Load at Submaximal Speed (Study 1)

In study 1, a key observation was that males and females responded differently to added WR loads applied. Importantly the two loaded trials that showed the most substantial effect were the 400g and 500g loads. While the males were able to maintain their prescribed submaximal goal time in both trials, their corresponding BL was substantially higher than the 0g control trial (400g: ↑0.74 ± 1.32 $mmol^{-1}$, 0.41, (-0.13 – 0.96), 500g: ↑2.40 ± 3.06$mmol^{-1}$, 1.29, (-0.06-2.63)) (Figure 14). Conversely, the females BL was *unclear*. However, a trend showed only *trivial* increases in BL across all five loaded trials. The differences observed in the observed lactate levels between males and females may be due to the fact females were unable to maintain their submaximal goal time with a substantial increase in time in both trials (400g: ↑3.11 ± 2.56sec, 1.9%, (0.8-3.1); 500g: ↑4.05 ± 2.35sec; 2.6%, (1.4-3.8)). The difficulty in maintaining goal time for the females was also reflected in a substantial possible *small* increase in RPE for both the 400g and 500g trials compared to control (0g) (400g: ↑1.1 ± 1.9RPE, 0.58, (-0.11 – 1.27), 500g: ↑1.1 ± 2.3RPE, 0.58, (-0.26 – 1.42). This increase could be due to the WR load being too high, making it too difficult for the females to maintain an optimal stroke distance and rating, which are two determining factors in swimming economy affecting overall speed (Aspenes et al., 2009). Therefore, this slow-down in speed inhibited the females from increasing physiological demand during the heavier trials reflected in the BL results. The results for HR response at the heavier load was unclear for both males and females. The observed differences between males and females could be due to their morphological and physiological differences. For example, Miller, MacDougall, Tarnopolsky, and Sale (1993) showed males to be 152% stronger than females with significant ($p < 0.01$) increases in type I fibre area (4597 vs 3483 um^2), mean fibre area (6632 vs 3963 um^2) and type II fibre size (8207 vs 4306 um^2) in the biceps brachii with no difference in motor unit characteristics. Accordingly we can postulate that by increasing motor unit recruitment, the males were strong enough to withstand that increased load to maintain their swimming speed, which showed in their increased BL levels. Conversely, the females may not have had the strength to withstand the higher loaded trials which was reflected in the increased RPE following each of the trials and inability to maintain their swimming speed.

Prediction of Submaximal Variables compared to Control (0g) (Study 1)

It was important for the reliability of this study to identify a specific submaximal goal time for each subject. MLSS has been reported to be the "gold standard" by many for determining aerobic capacity (Beneke, 1996). However, the method described by Heck et al. (1985) involving several submaximal swims over multiple days is not practical for swimmers undergoing regular training regimes (Oliveira et al., 2012). Oliveira et al. (2012) identified the D_{max} method as a valid and reliable measure of BL characteristics in response to incremental exercise, with a significant correlation ($r=0.91$, $p<0.05$) between the speed at MLSS and the D_{max} point for BL (Oliveira et al., 2012). Utilising the D_{max} method, we found *trivial* difference between the calculated submaximal speed, and the speed swum during the control trial for both males (-0.3%) or females (0.5%). However, BL during the 0g trial substantially increased 1.97 ± 2.39 $mmol^{-1}$ (1.42, (-0.63 – 2.21)) from the predicted D_{max} BL point for all subjects. During the 0g trial participants were wearing the upper arm compression sleeves. A review authored by Born, Sperlich, and Holmberg (2013) identified no significant change in BL during endurance performance when wearing compression garments. However, the garments soaked in water may inadvertently add compressive load to the participant. Therefore, it is important to note that during the 0g trial and subsequent loaded trials, the submaximal time assigned to the participants may have been an overestimate of true submaximal speed and therefore affected the BL responses to loading.

Changes in 200m Time Trial Performance post WRT warm-up intervention (Study 2)

Our results showed utilising WRT to illicit a PAP response does not improve 200m freestyle time trial performance in national level female swimmers. We observed a *trivial* improvement in time during the intervention trial of 0.3% (-0.2 – 0.7). However, due to in-between event variability of 0.7% (0.6 - 0.9) in 200m freestyle performance (Pyne et al., 2004) this was not enough to show a substantial improvement. We were able to show the effect on first half (first 100m) and last half (second 100m) speed. Utilising the PAP intervention protocol resulted in a *very likely non-effect* on first half speed. However, there was a trend towards *possible* improvement in first 50m speed with a decrease of 0.5% (-0.3 – 1.2). Additionally, we saw a possible impairment of last half speed with a substantial increase of 0.7% in the last 100m split. These findings are in agreement with existing research on 1000m rowing performance (Feros et al., 2012), indicating first half speed is the most affected by a PAP stimulus. Feros et al. (2012) found that time (INT: 84.4 ± 2.9sec vs. CON: 86.1 ± 3.1sec, 0.62, p=0.009), power (INT: 590 ± 59.6W vs. CON: 554.1 ± 55.7W, 0.64, p=0.007) and stroke rate (INT: 42.3 ± 4.2 st/min vs. CON: 40.2 ± 3.5 st/min, 0.54, p=0.003) all improved over the first 500m, even though they only allowed 4-min of recovery time following the PAP intervention which is shorter in duration than the "window of opportunity" (Figure 1). As such, both time and power measures worsened in the second half of the 1000m effort. The decrement of last 100m split time is typical among elite female swimmers in the 200m freestyle with an average increase of 6.1% shown in the 200m freestyle final at the Rio Olympics (Olympics, 2018). However, the increase of 8.7% shown in our study indicates that the 8-min recovery may not have given the subjects was not long enough to allow the athletes to be prepared for the 200m TT (Figure 15). Individualised recovery period for each subject may have allowed for specific recovery for each participants and resulted in more positive outcomes.

PAP Intervention Protocol Methodology (Study 2)

The optimal length/duration of maximal effort during the PAP procedure was difficult to determine due to the conflicting existing literature. Previous research using concentric contractions only used 1RM or 3RM (Cuenca-Fernández et al., 2015) in quick succession, or short duration irregular voluntary contractions with 20-30sec of rest in-between to facilitate a “staircase effect” (Batista et al., 2007). Hancock et al. (2015) employed four repetitions of a 10m (approx. 7secs) tethered swimming sprint, this resulted in a significant improvement of 0.54 secs in 100m freestyle performance. During a freestyle sprint effort, it takes 5 - 7sec for a swimmer to reach maximal power output (Stager & Tanner, 2008). Therefore, a 7sec effort may have only just begun to evoke a PAP response. Increasing the effort to 15 - 17sec may allow the swimmer to perform at maximal power output for ~ 10secs therefore, maximising the PAP response to intervention. A 25m effort in this study resulted in an average maximal effort time of 15.36 ± 0.63sec, which falls into this window (Figure 16). One concern with the increased duration of the intervention is the metabolic implications of the repeated effort design, as duration increases there in a great reliance on the athlete’s glycolytic system. Burnley et al. (2005) showed that two different warm-ups which resulted in no effect on BL and elevated BL to approx. 3.0mmol^{-1} still improved performance in well-trained cyclists. Therefore, we are confident that the BL levels produced in both the control and intervention trials (1.50 ± 0.63mmol^{-1} vs 1.24 ± 0.46mmol^{-1}) would not be detrimental to performance.

PAP Intervention Loading Design (Study 2)

It has been suggested that site specific loading during training and warm-ups through sport specific movements will illicit the most beneficial PAP response (Hodgson, Docherty, & Robbins, 2005; Sale, 2002). While previous studies in swimming have attempted to measure the effect of a PAP stimulus on performance measures, (A. Barbosa et al., 2016; Cuenca-Fernández et al., 2015; Hancock et al., 2015; Sarramian et al., 2015) none have applied load through a sport-specific movement pattern. WR is a relatively new field of study, and to our knowledge, has never been used in the sport of swimming. Despite the specificity to sport specific movements no performance gains were observed in this study. We also saw that the addition of load during the 4x25m sprints affected the physiological outcome of the swimmers. Unfortunately, the results for RPE were unclear only indicating a trend towards a perception of increased difficulty (↑0.44 ± 1.59, 0.29, (-0.36 – 0.95)). Therefore, our observation would suggest that this form of resistance may not alter the swimmer's body position or stroke technique unlike other forms of in-water resistance. However, further research into the kinematics of WRT in swimmers needs to be investigated as this information would be especially important to coaches and swimmers alike before integrating this technology into programming.

Post PAP Intervention Recovery (Study 2)

Prior research showing an effective recovery period is in its infancy for both endurance based performance measures (4-mins) (Feros et al., 2012) and swimming performance measures (2-12min) (A. Barbosa et al., 2016; Cuenca-Fernández et al., 2015; Hancock et al., 2015; Sarramian et al., 2015). The most consistent data available is from a meta-analysis on jump performance following a PAP stimulus. The meta-analysis determined an 8-12min recovery period provides the optimal window to allow muscles recovery and optimal PAP retention (Gouvêa et al., 2013). The 4x25m sprints resulted in a *likely small* decrease in BL of 0.47 ± 0.98mmol^{-1} (0.40, (-0.05 – 0.86)) in the intervention trial compared to control (Table 9). Following the 8-min recovery window, we saw a *likely moderate* elevation in HR during the intervention trial of 11.4 ± 20.8 bpm (0.83, (-0.05 – 1.71)) with the result on BL being *unclear*. Accordingly, these increases in both HR and BL may suggest that an 8-min period of recovery may not have allowed enough time for the subjects to be ready for their 200m TT (Figure 15).

Wearable Resistance

WRT is a relatively new approach to training incorporating advancements in technology. Indeed, to our knowledge it has never been used in the sport of swimming. In other sports; however, WRT has been used during jumping and sprinting without effecting technique

(Macadam, Simperingham, et al., 2017). The feedback of the subjects in this study shows that the addition of WR load to the proximal arms utilising WRT (Lila™ Exogen™; Sportboleh Sdh Bhd, Malaysia) required them to be more aware of their stroke technique through the recovery phase and high elbow position during the catch phase of their stroke. Although changes in technique were not measured in this study, these reports would be of great interest to swimming coaches looking to implement WRT in their athletes' training program. Further research into the effects of WRT swimming technique would be a logical next step in this research space.

Limitations

It is recognised that there are some limitations in the studies undertaken as part of this thesis. First, the process of manually measuring swim times by an experienced coach may have limited the accuracy of the splits collected. However, the consistency in the person manually timing would minimise error was implemented to reduce the effect. Further studies should aim to use timing touchpads to increase the reliability of data collection. Unfortunately, electronic heart rate monitors were not available for use during Study 1 which introduces some limitations to the results. Manual HR measurements under report HR by 14bpm compared to electronic recordings (F11 Polar Electro, Finland) (Peart, Shaw, & Rowley, 2015). However, since all HRs in Study 1 were collected manually we felt they could still be used to report the response to intervention. We were able to use Polar HR monitors in Study 2. The Lila™ Exogen™ compression upper arm sleeves (Sportboleh Sdh Bhd, Malaysia) provided a novel way to load through a sport specific manner. There were some issues with the armbands slipping down to the wrists and the Velcro weights falling off in the water during heavier loads which only occurred in less than 5% of the trials within all participants and only in the concluding 25% of that specific trials. When removed from the results they had no impact on our overall findings. These issues are likely due to the increased inertia around the shoulder joint during the recovery phase and the increased hydrodynamic forces acting on the weights during the pull phase. Further product development may need to be focused on the needs of elite swimmers to ensure the technology can be successfully implemented into their training programs without disruptions. In Study 2, the limited subjected number (n=10), may have reduced the number of substantial results found. However, maintaining the high standard of swimmers included within the study meant the findings are more applicable to a more elite range of athletes. Additionally, in study 2 the results assume that the intervention evoked a PAP response in the specific muscle groups. However, the physiological measurements taken cannot verify this. More invasive techniques would need to be employed to measure twitch frequency, the RFD and muscle temperature to determine whether a true PAP response has occurred following use of WRT. Finally, further investigation into stroke kinematics and technique and the difference in upper body strength of subjects may lead to a better prescription of loads.

Practical Applications

This thesis is unique as it provides the first insights into the use of WRT in swimming. The findings in this study show that WRT provides a novel way to increase resistance on swimming athletes through sports-specific movements. This technology provides a very stroke specific in-water training and priming tool which is affordable and easily accessible. We have shown that males and females respond differently to load using WRT, which highlights the importance of specific loading and consequently the desired training manipulation. The results in this study showed that the addition of load could have an impact on the swimmers "training zone" (Figure 17). In this context, Buchheit and Laursen (2013) identified five different responses to high-intensity interval training ranging from purely aerobic to aerobic, anaerobic and neuromuscular strain. These zones could also be an effective way to describe the strain on the subject through variable WR loads, therefore influencing the "training zone." As described in Figure 17 the addition of load took the males subjects from zone 2 (0g) through to zone 3 (loads 100-300g) and potentially zone 4 (400 & 500g). In contrast, the females were unable to manage the increase in load at 400g & 500g. As shown by the lack of increase in BL the female

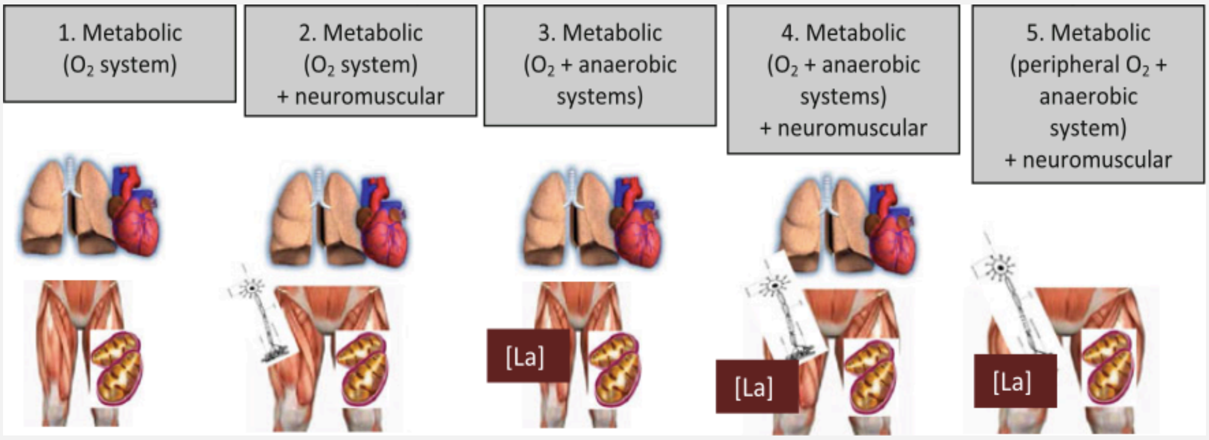

Figure 17. Image depicting "training zones" recreated from (Buchheit & Laursen, 2013)

subjects never entered into zone 3, rather reducing their swimming speed and staying purely in an aerobic zone.

The males in this study showed that WRT (especially at 500g) was able to influence BL at a prescribed speed, increasing the interaction of the anaerobic system suggested by substantial increases in BL (Buchheit & Laursen, 2013). This information could be used by coaches to increase the stress on athletes at a specific race pace to influence muscular and metabolic response. Conversely, females may need more emphasis on holding goal times regardless of the RPE. The data in study 1 also suggests that loads over 300g may be too high for female athletes. Unfortunately, we found no added benefit to 200m freestyle performance for female athletes following using WRT during warm up and therefore cannot suggest it as a viable tool for coaches and swimmers to use.

Future Research

The next logical step for research into WRT and swimming athletes would be investigating the kinematic and kinetic effects of using this technology in the water. We currently don't know of any stroke changes that may occur as a result of being proximally loaded using WRT and if any of these effects may change with variable load. This will certainly be a key coaching question in need of answering. Investigating the effects of using WRT as a priming tool to illicit a PAP response in male swimming athletes would also be of interest. The findings in study 1 indicate that males may have an enhanced response to WRT which may also result in enhanced 200m TT performance. We focused our research on freestyle 200m swimming, therefore investigating other strokes and distances will give a more comprehensive understanding of the effect of this technology. Finally, a training intervention study to examine the long-term effect of WRT as a training modality would be of interest.

Conclusion

In summary, there was a significant gender interaction when using variable upper arm loading through the use of WRT in swimming. Our results showed that males were able to hold D_{max} time but increased their BL in doing so. Conversely, females held submaximal BL but decreased their swim time to accommodate the demands of swimming with loads, especially heavier loads (400g and 500g) which were reflected in an increase in RPE. Neither gender showed changes in HR. Practically, this technology could be used to influence the "training zone" of the athlete. The use of WRT likely changes the input of each energy system and applying overload to the upper body musculature. Additionally, utilising WRT alongside a SWU did not improve 200m TT performance in national level female swimmers. WRT had a potential positive effect on the first 50m split. However, it also resulted in a possible increased impairment of 8.7% to back half (second 100m) speed, which is greater than the expected 6.1% normally seen in elite level female swimmers. This impairment to second 100m speed is likely due to the recovery period of 8 min being too short inducing higher levels of fatigue earlier in the 200m event. Finally, study 1 provides precedence to investigate the use of WRT to induce a PAP response in male national level swimmers and should be investigated.

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Appendices

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Appendix A: Ethics Approval

13 September 2017

Daniel Plews
Faculty of Health and Environmental Sciences

Dear Daniel

Re Ethics Application: **17/280 Acute metabolic effects of proximal upper limb loading using functional resistance training during submaximal swimming and its priming effect on maximal 200m freestyle performance**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 13 September 2020.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: ellenquirkenz@gmail.com; Andrew Kilding

Appendix B: Participation Information and Informed Consent

Participation Information Sheet

Date Produced: 27th July 2017

Project Title: Acute metabolic effects of proximal upper limb loading using functional resistance training during submaximal swimming and its priming effect on maximal 200m freestyle performance.

Invitation: My name is Ellen Quirke and I am a Masters student enrolled at SPRINZ (Sports Performance Research Institute New Zealand) at the AUT Millennium Campus of the Auckland University of Technology (AUT). We are currently conducting a study on the effects of functional resistance training (Exogen™ Exoskeleton by Lila™; photos below) on physiological markers and swimming performance in elite swimmers. We would like to invite you to volunteer to join this study as a participant with the understanding that you are free to withdraw from the study at any time.

Figure 1. Exogen™ Exoskeleton

What is the purpose of this research?

The purpose of this research is to investigate how utilizing functional resistance training (FRT) using the Exogen™ Exoskeleton technology by Lila™ impacts on acute metabolic markers (HR, blood lactate) in "elite" swimmers. Variable loads (0g-500g) will be proximally loaded to the upper limbs during testing to examine the physiological effects during submaximal freestyle swimming. This primary study will help identify which load is the most advantageous to swimming performance and will guide the load applied when analysing the ability of this technology to prime a swimmer during a warm-up. This could have a direct impact on warm up procedures of elite endurance swimmers. Various measures will be taken throughout the study to quantify the outcomes of this technology including; blood lactate levels, heart rate, pre-activation proprioception (PAP), stroke rate, stroke count and swimming speed. Practically, this research will give coaches and practitioners more insight into the physiological effects of this technology, which will indicate what loads may be applicable to safely incorporate into training and if it can be used effectively as a primer for increased swimming performance.

How was I identified for this research?

To be eligible for this research you need to have been training regularly for at least three months prior to participation, be 16 years of age or older, be considered "elite" by reaching finals at New Zealand Nationals in the previous 12 months or represented NZ, and have no current or previous illness or injury that could affect performance.

Your coach was approached by the primary researcher (Ellen Quirke) after you were identified from your swimming results over the past 12 months. Access was granted by your coach to allow me to hold an informational sessions with all identified in your club to present this study and participation information sheet to you.

What are the benefits of this research?

The research findings will be used to provide insight into the effectiveness of functional resistance training for any endurance athlete that competes in an aquatic environment at a competitive level (swimming, ocean swimming, triathlon, iron man etc.). As a participant you will receive a report of the research outcomes including your individual results compared to the mean averages of the study. Additionally, these results can be shared with your coaches and practitioners (if indicated on the attached consent form) and can help guide your future programming.

This research does have a commercial interest for Lila™ as any positive results of this study may be used in marketing to increase sales of their product.

Finally, this research is an integral part in my Master's degree and without your involvement this research would not be possible. So thank you in advance for your consideration!!

What compensation is available for injury or negligence?

In the unlikely event of a physical injury because of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

What does this research involve?

This research is divided into two studies. You can choose to participate in just one of the studies or in both. Prior to the commencement of either study I will be available to provide the equipment involved so you can familiarize yourself (contact me either through your coach or directly via the contact information provided)

Study One: Acute Study

You will be required to attended two, 2 hour testing sessions separated by 24 hours at the Sir Owen Glenn National Aquatic Center, Auckland. The first session includes a standardized race warm up (Figure 2.) and an incremental step test (7x200m Fr descending @5.00min). During the incremental step test heart rate and blood lactate levels will be measured and recorded. The second session includes the same standardized warm up (Figure 2.) followed by 6x200m Fr at submaximal speeds with variable load added to the upper arm via the Exogen™ upper arm sleeve (pictured above). All the same data will be collected after each 200m Fr and you will be allowed 9min of active recovery between each effort.

Warm Up
Block A 400m choice swim 200m free kick 200m free drill 200m pull
Block B 4x100 free desc @1.30 100 recovery 4x50 free 200m race pace @60sec
Block C 200 recovery

Figure 2. Warm up procedure

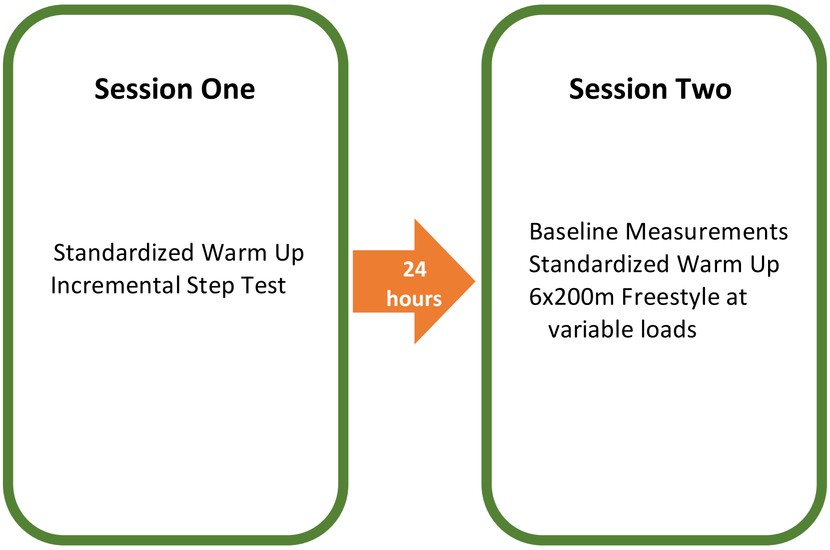

Figure 3. Study One Procedure

Study Two: Priming Study

You will be required to attended two 1-hour testing sessions separated by 48 hours at the Sir Owen

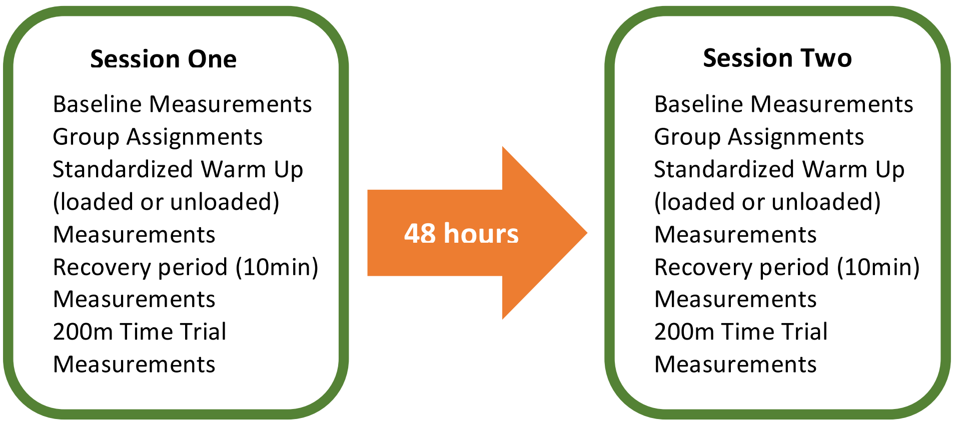

Figure 4. Study two procedure

Glenn National Aquatic Center, Auckland. Both sessions will follow the same procedure; however, all participants will be randomly assigned to one of two groups, through a matched pair crossover design. During session one group one will receive the intervention (Exogen™ upper arm sleeve with added load, pictured above) with group two acting as the control, and in session two visa-versa. Each session will include a standardised race warm-up (Figure 2.) (either intervention or control) followed by a 200m Fr at maximal effort.

What are the discomforts and risks and how will they be alleviated?

You should experience no discomfort or risk above what you already experience in your current training and testing program. Shortness of breath and muscle fatigue will likely be involved as maximal efforts are required. The study has been designed to include warm-up procedures and adequate recovery periods both between individual bouts of effort and between sessions. Being in the water does entail a drowning risk and adding weight to an individual who is in the water adds to that risk; however, your experience as an elite level swimmer decreases the likelihood of drowning. The blood lactate measurements require a blood sample via finger prick which may involve a small amount of discomfort. You will be asked to ensure you are well rested, fuelled and hydrated when showing up to all testing sessions just as you would to regular training.

Full disclosure of all testing protocols and measures will be discussed with you before each testing session, all measures will be taken by a qualified team of researchers and every effort made to make you as safe and comfortable as possible.

How will my privacy be protected?

- We will take several measures to protect your privacy as much as possible and to ensure your personal details remain confidential.
- The data from the project will be coded and held confidentially in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (1993).
- All reference to participants will be by code number only in terms of the research publications. Identification information will be stored on a separate file and computer from that containing the actual data.
- De-identified test results (i.e. without your associated name and personal details) may be stored indefinitely in the SPRINZ research database and may be used for similar research studies in the future.
- The findings of this project will be published in scientific journals, at a conference presentation(s) and in a master's thesis, but at no stage will you be identifiable. The results will be presented as averages and not individual responses. Your identifiable test results will only be made available to yourself and your sports coach and practitioners (if you agree to this option on the consent form).

Are there any costs involved with this research?

There are no financial costs involved in participating in this research. All equipment required will be provided by the research team. The only cost to you is your time; however, this will be designed around your current training schedule. In total, the acute study requires approximately four hours split over two sessions and the priming study requires two one hour sessions. All up if you participate in both studies approximately six hours of your time is required.

What opportunity do I have to consider this invitation?

- Please take the necessary time (up to 2 weeks) you need to consider the invitation to participate in this research.
- It is reiterated that your participation in this research is completely voluntary.
- If you require further information about the research topic please feel free to contact Dr Daniel Plews (details are at the bottom of this information sheet).
- You may withdraw from the study at any time without there being any adverse consequences of any kind.

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

- You may ask for a copy of your results at any time and you have the option of requesting a report of the research outcomes at the completion of the study.

How do I agree to participate in this research?

If you agree to participate in this study, please sign and date the consent form at the bottom of this information sheet and return to Ellen. I will then contact you to arrange and set up the first familiarisation session which will give you an opportunity ask further questions about the project to ensure it is something that you want to be a part of. Your participation in this research is voluntary and whether or not you choose to participate will neither advantage or disadvantage you. You are able to withdraw from this study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal or your data may not be possible.

Will I receive feedback on the results of this research?

We will provide a summary via email of your results from the testing and the averages of all participants. If you wish to receive your results, please provide your email on the attached consent form where indicated.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Daniel Plews, plews@plewsandprof.com

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, ethics@aut.ac.nz, 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:
Ellen Quirke
Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland 0632
ellenquirkenz@gmail.com
0273832107

Project Supervisor Contact Details:
Dr Daniel Plews
Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland 0632.
plews@plewsandprof.com

Consent Form

Project title:	Acute metabolic effects of proximal upper limb loading using functional resistance training during submaximal swimming and its priming effect on maximal 200m freestyle performance.
Project Supervisor:	Dr Daniel Plews
Researcher:	Ellen Quirke

☐ I have read and understood the information provided about this research project in the Information Sheet dated 27/07/2017

☐ I have had an opportunity to ask questions and to have them answered.

☐ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

☐ I understand that if I withdraw from the study then I will be offered the choice between having any data or tissue that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

☐ I understand that the data collected from my test will be used in a master's thesis and will be stored indefinitely on the SPRINZ database and may be used for future studies by SPRINZ approved researchers.

☐ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection

☐ I agree to provide blood samples by way of finger prick, to measure blood lactate levels

☐ I agree to take part in this research.

I wish to receive a summary of the research findings (please tick one)

Yes ☐ No ☐

I wish to receive my individual results at the completion of data collection and made available to my coach / manager / doctor (please tick one and highlight who these can be shared with)

Yes ☐ No ☐

I wish to have any material that contains my blood samples returned to me in accordance with right 7 (9) of the *Code of Health and Disability Services Consumers' Rights* (please tick one):

Yes ☐ No ☐

Participant's name:

....

Participant's signature:

....

Date :

....

Approved by the Auckland University of Technology Ethics Committee on 13/09/2017
AUTEC Reference number 17/280
Note: The Participant should retain a copy of this form.