The Effects of Anaerobic Swim Ergometer Training on Sprint Performance in Adolescent Swimmers

by

Adam J. A. Pinos

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Examining Committee:

Chair of Examining Committee	Dr. Manon Lemonde
Research Supervisor	Dr. Heather M Logan-Sprenger
Examining Committee Member	Dr. David J Bentley
Thesis Examiner	Dr. Jared Fletcher, Mount Royal University, Calgary Alberta

The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

Abstract

The effects of anaerobic training using a swim ergometer on sprint swimming performance have not been investigated in competitive adolescent swimmers. The purpose of this study was to compare 4-weeks of sprint interval training (SIT) with a similar ergometer training intervention on associated anaerobic performances. Fourteen competitive adolescent swimmers performed two pre and post intervention tests: 1) a 6 & 30 second maximal swim ergometer test, and 2) a maximal anaerobic lactate test (MANLT), (4 x 50 m short-course maximal swims with 10 second rest intervals). The results of this study demonstrated there was a significant improvement in 1) speed of the 4th 50m sprint, 2) mean power in 6 & 30-second maximal ergometer tests, and 3) 50m freestyle performance for both intervention groups after 4 weeks of SIT training respectively. As such, sprint ability may be improved through multiple modalities (pool and dryland) to elicit a positive training response.

Keywords: Physiology; Intervention; Swimming; Power; Youth

CO-AUTHORSHIP STATEMENT

All manuscripts enclosed within this thesis were primarily written by Adam Pinos. Dr. Heather Logan-Sprenger, Dr. David Bentley, and Erica Gavel provided assistance with the writing and editing process. Elton Fernandes, Eric Viana, Joshua Goode, Abdul Safadie, and Adam Di Salvo provided assistance during the data collection portion of this thesis.

AUTHOR'S DECLARATION

I hereby declare that this thesis consists of original work of which I have authored. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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The research work in this thesis that was performed in compliance with the regulations of Ontario Tech's Research Ethics Board/Animal Care Committee under **REB Certificate 14715**.

____________________________________ Adam Pinos

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DEDICATION

This thesis is dedicated to Murray Drudge. Murray was the North York Aquatic Club (NYAC) head coach for 23 years, from 1996 to 2019. Over the course of his career, he was renown for developing some of the best athletes to come out of the province. It saddens me to say that in the final weeks of this thesis Murray passed away. He and I were really excited about the research we were doing and the importance of his athletes understanding the science behind swimming. I was fortunate to have had the time I had with him and know that without his and Eduardo Toro's support throughout this thesis, none of this would have been possible. From the bottom of my heart thank you both, and Murray, this is for you.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Arm Stroke
ATP-PCr	Phosphocreatine System
ADP	Adenosine Diphosphate
ATP	Adenosine Triphosphate
BLa	Blood Lactate
BE	Backwards Extrapolation
b_m	Body Mass
CSIO	Canadian Sport Institute Ontario
Cs	Energy Cost of Swimming
ERG	Swim-Ergometer Group
FINA	Federation Internationale de Natation de Amateur
HIT	High Intensity Training
HR	Heart Rate
HVT	High Volume Training
K	Leg Kicking
kg	Kilogram(s)
LT	Lactate Threshold
m	Metre(s)
MANLT	Maximal Anaerobic Lactate Test
MAOD	Maximal Accumulated Oxygen Deficit
min	Minute(s)
mL	Millilitre(s)
mmol/L	Millimole/litre
O_2	Oxygen
NYAC	North York Aquatic Club
p	Level of Significance (statistic)

PST	Pool-Based Sprint group
PFK	Phosphofructokinase
r	Pearson r Coefficient (correlation statistic)
R^2	R-Squared (statistical measure that represents the proportion of the variance)
s	Second(s)
S	Whole-Body Swimming
SB	Swim Bench
SD	Standard Deviation
SIT	Sprint Interval Training
t	Time (seconds)
TTL	Total Training Load
VO_2	Oxygen Uptake (ml/kg/min)
y	Year(s)
1RM	One-Repetition Max
3RM	Three-Repetition Max
Δ	Delta (change: $x_1 - x_2$)
*	Multiply

Chapter 1. Introduction

1.1 Introduction

Swimming is one of the world's oldest competitive sports. Swimming was included as a sport in the first modern Olympic Games in 1896 as a men's sport; the first women's Olympic swimming was contested in 1912. The Federation Internationale de Natation de Amateur (FINA), the sport's governing body, was founded in 1908. The global popularity of swimming is illustrated by the fact that over 200 national swimming associations comprise the FINA membership. Swimming is the most popular of the sports directed by FINA; there are state, regional, intercollegiate, national, and international swimming competitions, in a number of different formats and age groups, available in every region of the world in a given calendar year. The sport competes in four competitive pool lengths: 25-yard, 25-metre (m), 50-yard, and 50-m. 25-m or yard races are referred to as short-course and 50-m or yard pools are referred to as long-course races. The Olympic standard for competitive meets is 50 metres. Swimming races range in length from the 50-m sprint (one length of the pool in Olympic competition) to 10,000-m events. The physiological demands of swimming are similar to those of running, in the sense that a 50-m sprint specialist will not likely succeed in a long-distance race, and the various distances and specialized strokes demand specialized training approaches. There are four general types of swimming strokes: freestyle, breaststroke, backstroke, and butterfly. The most commonly used stroke in research is the freestyle stroke (Crowley, Harrison, & Lyons, 2017).

Sprint swimming is short in duration but is highly explosive and requires a greater contribution of energy (adenosine triphosphate) production from anaerobic means (Ferran A Rodriguez & Mader, 2011). Having an effective anaerobic energy system improves sprint performances, and this is very important to competitive swimmers (Bangsbo, Michalsik, & Petersen, 1993; Hautier et al., 1994; Ogita, Hara, & Tabata, 1996). Understanding the difference in energy system utilization for each classification of swimmer can be useful for both training prescription and event specialization (Rodriguez 2011). Metabolic analysis during exercise has been performed in the past using incremental exercise testing and oxygen uptake (VO_2) or lactate measurements (Keskinen, Komi, & Rusko, 1989; Konstantaki, Trowbridge, & Swaine, 1998; Lätt et al., 2010; Pyne, Lee, & Swanwick, 2001; Reis, Alves, Bruno, Vleck, & Millet, 2012; F A Rodriguez, Keskinen, Keskinen, & Malvela, 2003). Although the metabolic demands of swimming are measured with the most validity in the pool, it is not always logically feasible. As such, dryland testing using equipment that simulates swim-specific movement and energy demands would prove valuable and practical. Although existing literature reports controversial evidence of the transferability of dryland strength and power training for in-pool sprint performance with swimmers (Guilherme, Guglielmo, & Denadai, 2000; Hawley, Williams, Vickovic, & Handcock, 1992; Morouço et al., 2011; Pérez-Olea, Valenzuela, Aponte, & Izquierdo, 2018; Swaine, 1997; Zamparo, Turri, Peterson Silveira, & Poli, 2014).

The physiological demands and characteristics of sprint and middle-distance swimming events (and swimmers) have been quantified in the past (Cooke, 2009; Costill et al., 1985; Mader, Heck, & Hollmann, 1978; Reis et al., 2012). There is minimal literature on the difference between sprint (50-100m) and middle-distance (200-400m) 'young' developmental age group swimmers (Balasekaran, Vilas-boas, & Barbosa, 2015; Chatard, Lavoie, & Lacour, 1990; Keskinen et al., 1989; P. Pelayo, Mujika, Sidney, & Chatard, 1996; Patrick Pelayo et al., 1995; Sousa et al., 2011). No studies have directly examined the relationship between dryland exercise metabolic demands in accordance with dryland power testing. One method for observing these demands is with the use of a maximal test on a swimming ergometer (Roberts, Termin, Reilly, & Pendergast, 1991). If both physiological and power output measures are obtained, we hypothesize that we will observe a relationship between anaerobic dryland power and in-pool sprint performance.

Characterizing the physiological outcomes of pool-based training compared to swim ergometer sprint training and their respective effects on sprint performance have strong implications for future research. The objective of this work is to compare pool-based and swim ergometer-based sprint training effects on anaerobic swimming performance in a trained adolescent group.

Chapter 2. Review of Literature

This review of literature will summarize published articles relating to the physiological demands of sprint swimming. Additionally, the literature review will also examine physiological factors that contribute to swim performance with a focus on sprint swimming. Finally, studies concerning the effects of 'dryland' swimming training and testing will be reviewed.

2.1 Physical and Biomechanical Characteristics of Swimmers

Swimming speed is a product of arm pulling and leg kicking propulsion to produce forward movement of the body through water. There is some debate amongst coaches and scientists as to the relative effects of the upper and lower limbs. In front-crawl, it has been estimated that ~90% of the total propulsive force eliciting forward movement is by the arms, while the role of the legs is restricted to maintaining posture in the water by reducing the trunk inclination and subsequent drag (J A Hawley & Noakes, 1992). There are many factors that need to be taken into account when trying to assess a swimmer's performance, including and not limited to swim technique, economy, training load, swim age, and energy system development (J. C. Chatard, Lavoie, & Lacour, 1990; Termin & Pendergast, 2000).

In addition to drag, other individual factors such as swimming technique may be part of the reason why it can be challenging for researchers to quantify energy cost contribution of swimming. Swimming (performance) speed is a function of the balance between propulsive force and drag forces, both of which will influence the energy cost of movement. Without efficient swimming technique, it can be very difficult for someone to effectively translate the improvements in stroke pull and kicking power to increased swimming speed. To better understand this one must understand the energy cost of swimming (Cs). It is also important to consider the influence of underwater torque, one of the main determinants of Cs. Zamparo and colleagues in 1996 demonstrated that underwater torque was highly correlated (r=0.87) with frontal body surface area (Zamparo, Capelli, Termin, Pendergast, & Di Prampero, 1996). If a swimmer has a larger frontal surface area, they will subsequently experience more underwater opposing forces (i.e. drag). At faster speeds, drag is off-set by the greater hydrostatic pressure generated by the increased propulsive forces which elevate the body to a more horizontal position in the water (Zamparo et al., 1996). Moreover, drag is considerably affected by a swimmer's technique, which can minimize the frontal surface area of a swimmer (Zamparo, Turri, Peterson Silveira, & Poli, 2014).

2.2 Bioenergetics of Sprint and Middle-Distance Swimming

Swimming performance is achieved via the transformation of the swimmers' metabolic power into mechanical power (and subsequently speed) with a given energetic efficiency, while also trying to minimise drag (Ferran A Rodriguez & Mader, 2011). Three major energy systems are involved in the systematic process of adenosine triphosphate (ATP) metabolism and resynthesize for the purpose of intramuscular ATP utilization: phosphagen, glycolytic, and aerobic.

The phosphocreatine system (ATP-PCr) reaches its peak energy yield 10 seconds into maximal intensity exercise (Houston, 2001). This energy system does not require oxygen and relies on the dephosphorylation of phosphocreatine to produce ATP from adenosine diphosphate (ADP) by the enzyme creatine kinase. The rate and capacity of the phosphagen system's contribution to ATP production is limited by the amount of intramuscular creatine. The glycolytic lactic energy system maximizes its energy production within the first three seconds of exercise and can be maintained for ~45-60 seconds. This system relies on the breakdown of glucose-6-phosphate into pyruvate and lactate (glycolysis) to produce ATP. Glycolytic energy production is regulated by two major processes: transportation of glucose into the cell and phosphorylation of glucose to glucose-6-phosphate (Houston, 2001). Glucose is primarily transported into the cell by a membrane transporter named GLUT-4, who's activity is predominantly regulated by insulin levels. Within the cell, the rate limiting enzymes of the glycolysis are hexokinase and phosphofructokinase (PFK), which are allosterically regulated and can speed-up or slow-down the rate of glycolysis and the production of ATP from the breakdown of glucose and glucose-6-phosphate respectively (Houston, 2001). Lastly, the aerobic, or oxidative system, requires the presence of oxygen to produce energy and requires between 40-90 seconds to reach its maximal power, (i.e. its maximal production rate of ATP), which can be maintained for ~5-7 mins in elite endurance athletes (Houston, 2001).

In 2011 Rodriguez and Mader published a review paper on modelling the energy system contributions for each major swimming event length (50-100m, 200-400m, 800m+) (Ferran A Rodriguez & Mader, 2011). Estimation of each energy system's contribution to swimming was calculated using the following theoretical input parameters: VO_2, blood lactate concentration (BLa), and body mass (b_m) in kilograms (kg). By assuming all three energy systems are constantly contributing to ATP production during exercise, Rodriguez and Mader concluded that metabolic power is the sum of all three energy systems' ATP production during exercise (Ferran A Rodriguez & Mader, 2011). Therefore, at different intensities, contribution of energy from each individual system can be calculated from the previously mentioned values. All energy system contributions are expressed in relation to O_2 outputs in millilitres (mL) per kg of body mass. Below 80% intensities, aerobic contribution can be assumed to be the VO_2 measured from either flume or backwards extrapolation techniques (will be discussed later) (Ferran A Rodriguez & Mader, 2011). Lactic anaerobic contribution was calculated using the following formula: 2.7 * (BLapostexercise- BLarest (ΔBLa)) * b_m / time in seconds (*t*). Alactic anaerobic contribution was calculated using the following formula: 18 * b_m / *t* (Di Prampero, Pendergast, Wilson, & Rennie, 1978). From these assumptions, authors concluded that total energy expenditure could be calculated from VO_2 and BLa concentrations alone. By combining the formulas from above the total energy expenditure could be calculated using the following formula: $VO_2 + (2.7 * \Delta BLa / t) + (18 * b_m / t)$ (Di Prampero et al., 1978). Each event's distribution of energy contribution could be calculated by first determining the total energy expenditure, and then determining contribution from each energy system could be done by determining the O_2 contribution from each individual energy system represented in O_2mL/kg.

Rodriguez and colleagues concluded that sprint swimmers rely more on high glycolytic power, interpreted as higher lactate and ATP-PCr contribution and less on low aerobic power (less O_2 contributed from the aerobic system) (Ferran A Rodriguez & Mader, 2011). Long-distance swimmers however are able to produce higher aerobic power and require lower glycolytic power during a race. During 50m and 100m swimming events, the ATP-PCr system is strongly utilized due to the short duration of the event itself; however, it also requires athletes to be able to produce a higher glycolytic power, which is subsequently measured by the athlete's blood lactate accumulation (Ferran A Rodriguez & Mader, 2011). In the first 3-5 seconds of maximal effort swimming, the ATP-PCr system is depleted. As availability of creatine stores diminish, the ability to produce energy rapidly also diminishes, limiting this system immensely. Once PCr stores deplete, the anaerobic lactic system is relied on more heavily to produce large amounts of ATP and is responsible for providing the muscles' fast twitch fibres the energy necessary for the remaining duration of the event. Because of the short duration of the 50m event (<30 seconds), the body's glycolytic system does not produce massive amounts of lactate (12-14 mmol/l) (Ferran A Rodriguez & Mader, 2011). During sprint races, the aerobic system is not utilized as much as the anaerobic system to contribute to high energy demands. However, one study by Ribeiro and colleagues in 2014 found that about 50% of energy contribution to the 100m swimming performance came from the aerobic system (Ribeiro et al., 2015). This adds controversy to the debate as to how much aerobic contribution exists in sprint swimming, which has been reported to be highly anaerobic in nature in the past. The aerobic system can produce large amounts of ATP, but requires more time for the energy to be produced. In contrast to sprint swimmers, 200m (~2 min) and 400m (~4 min) middle-distance swimmers demonstrate the ability to produce a much higher aerobic power (J. F. Reis, Alves, Bruno, Vleck, & Millet, 2012; Ferran A Rodriguez & Mader, 2011). Surprisingly, the review found that much higher glycolytic power is required for the 200m and 400m event in comparison to the sprint events, with maximal blood lactate concentrations ranging in 16-18 mmol/l and 14-16 mmol/l, respectively (Mader, Heck, & Hollmann, 1978). In addition, it is interesting to note that the fastest middle-distance swimmers will also be able to swim faster at low blood-lactate concentrations (Ferran A Rodriguez & Mader, 2011). This could indicate that the fastest swimmers' anaerobic systems have a greater efficiency in utilizing their anaerobic and aerobic energy systems for energy production at higher speeds.

Understanding the metabolic demands across varying distances of swimming may aid in the determination of what event a swimmer should choose to become proficient in based on the athlete's testing profile. As such, having the knowledge of the physiological requirements through appropriate performance testing of different swimming events and strokes may benefit the coach (Ferran A Rodriguez & Mader, 2011). For example, having a swimmer with a greater aerobic response to training may be more suitable to long-distance events conversely those athletes demonstrating a more oxidative response to a performance task may require greater levels of anaerobic training if their event is of shorter distance. Metabolic capacities can be improved, maintained, or decreased through training if proper testing is performed with the athlete.

2.3 Physiological Assessment of Swimming Performance

There are a number of exercise protocols and accompanying physiological measurements that exist today for assessing competitive swimmers. The following sections will outline some of the practical methods currently used for tracking metabolic changes and their influence on training prescription for swimmers. The first section will give a brief overview of the history of aerobic testing and its importance for training prescription, program design, goal setting, and program with swimmers. The second section will describe the importance and practicalities of anaerobic testing and how it differs from aerobic testing, as well as the importance of anaerobic power and capacity in swimmers of different stroke distances.

2.3.1 Incremental Exercise Testing

A common way of determining both anaerobic and aerobic energy contribution of swimmers is through the use of lactate testing (K L Keskinen, Komi, & Rusko, 1989; Matsumoto et al., 1999; P. Pelayo, Mujika, Sidney, & Chatard, 1996; Patrick Pelayo et al., 1995). Blood lactate testing is a non-invasive technique that requires a small capillary sample of blood, and provides practitioners with an indirect measurement of exercise intensity and metabolic adaptation. When exercise commences, the demand for energy from ATP hydrolysis increases as more energy is required for exercise to continue at the desired rate. During intensive muscle contractions, phosphocreatine stores deplete and there is a greater reliance on anaerobic glycolytic metabolism. In this scenario, fatigue manifestation is evident and is accompanied by increases in blood lactate concentration (Allen, Lamb, & Westerblad, 2008; Fitts, 2019; Gladden, 2004). This onset of blood lactate accumulation is produced during glycolysis (Connett, 1990; Gladden, 2004). The body utilizes the anaerobic glycolytic system to produce large quantities of ATP through the breakdown of glucose and glycogen without the need for oxygen to be present (Gladden, 2004). Some have argued that metabolic fatigue during exercise is caused by the breakdown of lactic acid in the muscle leading to an accumulation of hydrogen ions; however, more recent literature suggests this is coincidental acidosis and not causal. Instead at high intensity exercise, ATP hydrolysis and subsequent accumulation of non-mitochondrial hydrogen ions, drop intramuscular pH and may affect enzyme kinetics (Houston, 2001).

Moreover, there are several factors that cause an increase in muscle and blood lactate concentration at submaximal and maximal exercise intensities, such as accelerated glycolysis and lactate metabolism, fast twitch fibre recruitment, and decelerated blood lactate removal (Fitts, 2019). Accelerated lactate removal can be improved through aerobic training. By increasing monocarboxylate transporter utilization to clear lactate from fast twitch muscle fibres to slow twitch muscle fibres, aerobic-focused training can increase the body's lactate buffering capacity (Houston, 2001).

In order to measure lactate response in the blood, a blood sample is drawn after a prescribed exercise intensity (Allen et al., 2008; Gladden, 2004; Heck et al., 1985). Blood lactate can be analyzed to understand both anaerobic and aerobic demands of exercise (Brooks, 2007; Heck et al., 1985; P. Pelayo et al., 1996). Lactate threshold (LT) has also sometimes been referred to specifically as anaerobic threshold (Heck et al., 1985). The work rate above the baseline LT initiates glycolytic metabolic acidosis, which can contribute to the onset of metabolic fatigue as previously mentioned. Exercise at an intensity above LT also increases respiratory rate, which hinders work rate sustainability of exercise (Connett, 1990; Wasserman, 1984). Different incremental tests have been utilized in the past to validly evaluate LT in swimmers (Anderson, Hopkins, Roberts, & Pyne, 2006; Pyne, Lee, & Swanwick, 2001). LT and performance measurement allowed for significant monitoring of metabolic and mechanical demands throughout the season to see specific improvements made by each of the world-ranked swimmers (Anderson et al., 2006). Improvement in maximal 200-m test time and LT in training supports the belief that aerobic fitness and in-pool middle-distance performance can simultaneously be improved in already highly trained swimmers through aerobic-based training (Pyne et al., 2001).

A recent incremental test used by Pyne et al in 2001 and Anderson et al. in 2006 consisted of seven 200-m swims in a 50-m pool on a 5-minute cycle, with each 200m swim progressively harder, starting at an easy pace and ending at a difficult pace. The starting pace for the test was 30 seconds slower than their best time in the 200 and each increment was 3-4 seconds faster. The graded incremental protocol involves cardiovascular (heart rate), metabolic (blood lactate), and mechanical (stroke rate and stroke count) measures of the swimmers' response to each of the increasing speeds (Anderson et al., 2006; Pyne et al., 2001). This test is now widely used by the scientific swimming community to provide objective information on the aerobic fitness of the swimmer (Pyne et al., 2001). A past study conducted on world-ranked swimmers found that blood lactate measures obtained during the 7 x 200-m incremental step test accurately identified significant improvements in aerobic power over the course of a 20-week training season (Anderson et al., 2006). Improvements in aerobic power were defined as their improvement in lactate threshold during the incremental test. As the season progressed, athletes demonstrated faster times while accumulating less lactate, indicating improved glycolytic efficiency through less lactate production and/or blood clearance. Lactate threshold for the swimmers was the 4 mmol/L y-intercept on the blood lactate-time curve (Anderson et al., 2006). This procedure was then repeated for the other measures, with the log of time plotted against the log of heart rate, stroke rate, stroke count and stroke length (Anderson et al., 2006). In addition to LT improvement, decreased heart rate response to submaximal efforts was observed as a result of this specific aerobic training (Pyne et al., 2001). Prescribed swimming speed determined from the 4 mmol/L blood lactate has been used in the past to structure training plans (E W Maglischo, Maglischo, & Bishop, 1982). The incremental test is also highly correlated (r=0.91) with 400-m maximum swimming speed (Wakayoshi et al., 1993). Both of the groups that were tested elicited an average increase of 1-2% swim performance when training their elite swimmers using the 4 mmol/L pace (Wakayoshi et al., 1993).

Incremental lactate testing can be utilized to test and guide aerobic exercise prescription for swimmers. Coaches and sports scientists have been able to observe real changes in performance of individual swimmers using pool-based blood lactate testing (Anderson et al., 2006). However, lactate analysis after high intensity exercise efforts can be utilized to assess anaerobic demands of sport as well, which could be useful in determining anaerobic demands of sprint swimming.

2.3.2 Post Exercise Lactate Analysis

A close relationship (r= 0.89) has been found between blood lactate level and average velocity maintained over 400-m and 800-m top-level running competitions, with durations of 3 minutes or less, similar to that of the middle-distance events in swimming (Lacour, Bouvat, & Barthelemy, 1990). Evidence of this in middle distance running provides a rationale for studying anaerobic capacity of the athletes who participate in middle distance swimming events. However, another study performed would suggest that anaerobic glycolysis contributes to about 55% of metabolic energy production during 100-m and 200-m sprints in running, these races being similar in length to the 50-m and 100-m sprints in swimming (Hautier et al., 1994). The authors found a strong correlation (r=0.76) between blood lactate and performance suggesting again that this is a major contributor to success. With both of these studies suggesting that blood lactate production over their respective events improve performance, it would be interesting to discern which event more heavily relies on anaerobic glycolysis, i.e. an athlete's anaerobic power.

The maximal anaerobic lactic test (MANLT) was originally developed to simulate a competitive effort of swimmers' 200-m event (Patrick Pelayo et al., 1995). The MANLT consists of four 50m swims with a 10-second rest between each effort. The total swimming time of the test was less than or equal to the swimmer's competitive time of a 200m race, approximately two minutes in duration, and blood lactate is taken 3- and 12-minutes after to measure the athlete's maximal anaerobic contribution (every swimmer passively recovers in a sitting position). The MANLT was useful for determining changes in anaerobic power and capacity throughout the course of a season. The test was also utilized with para and able-bodied swimmers to assess the relationship between improvements in MANLT and swimming performance (P. Pelayo et al., 1996; Patrick Pelayo et al., 1995). The main finding from the article published in 1996, was that the lactate recovery % calculated from 3- and 12-min BLa measurements was positively correlated with aerobic training and negatively correlated with anaerobic training with elite adult 200-m freestyle swimmers throughout the course of a 23-week season (P. Pelayo et al., 1996). The researchers concluded that the MANLT may be used as an anaerobic test to shed light on the athlete's training history based on the post-test blood lactate concentrations seen in adult swimmers after a training block of either aerobic or anaerobic based training.

2.3.3 VO_2 **Testing**

Another method for characterizing the fitness of a swimming athlete is by conducting oxygen uptake (VO_2) analysis during or directly after exercise. There are two validated methods for measuring pool-based VO_2 demands: snorkel testing and the use of the backwards extrapolation (BE) technique. Both of these techniques can be conducted while traditional free swimming in a pool or while swimming in a flume. Flume testing requires an individual to swim in smaller, speed-controlled pool. One advantage of using a flume is that, similar to a treadmill, the individual's swimming speed can be controlled by the machine. Another advantage of flume testing or practitioners is the ability to gather VO_2 data without having to move with the athlete as they swim. Conversely, one disadvantage to this and subsequent advantage to free swimming is the flume is not where the athlete will be regularly practicing or competing outside of swimming.

Breath by breath analysis of VO_2while swimming requires swimmers to wear a specialized piece of snorkel equipment. Attached at the end of the swimmer's snorkel is a tube that is connected directly to a gas analysis machine that calculates the oxygen uptake of the swimmer instantaneously. One advantage to this technique is it gives practitioners real time gas analysis during swimming. One of the major problems of measuring VO_2 using the flume swimming method in the past was that the use of snorkel equipment increased the swimming resistance on the swimmer and alter the athlete's body position (Kapus, Ušaj, Kapus, & Štrumbelj, 2004). Since the ideas conception however, a validated snorkel and valve systems with reduced drag has been developed to work with the validated wireless K4b2 system (Cosmed, Rome, Italy) for real time measurement of VO_2 (Baldari et al., 2013; F A Rodriguez, Keskinen, Kusch, & Hoffmann, 2008; Toussaint et al., 1987). The newly developed system has been shown to be comparable in validity to the normal facemask system used with breath by breath analysis for treadmill and cycle ergometer testing (Kari L Keskinen, Rodríguez, & Keskinen, 2003). Unfortunately, the measurement of VO_2using a swimming snorkel cause the following changes to normal movement: stroke kinematics, swimming technique (e.g. reducing body rolling), normal breathing pattern, and inability to perform diving starts and flip turns (T. Barbosa et al., 2010; Chaverri, Iglesias, Hoffmann, & Rodríguez, 2015; Kari Lasse Keskinen, 2001). These changes increase the energetic costs of the swimming and could affect the VO_2. Techniques for measuring oxygen uptake should focus on the athlete's ability to perform their work minimal influence on the swimming and physiological response.

The BE method, developed by Montpetit and colleagues in 1981, is an effective method that does not require any respiratory equipment during swim testing. Instead, breathe-by-breathe analysis is conducted directly post-exercise using the respiratory equipment to calculate VO_2measurements. The researchers concluded that in order for the backwards extrapolation technique to work validly four major conditions had to be fulfilled:

(1) that the exercise is progressive and continuous and leads to exhaustion in more than 4-5 min; (2) that no delay exists between the end of the exercise and the beginning of the gas collections; (3) that the gas collection is started at the beginning of expiration and stopped approximately 20 s later at the end of expiration and (4) that the exercise is not of supramaximal intensity or of short duration (<5 min) (Montpetit, Léger, Lavoie, & Cazorla, 1981).

Additionally, BE is a technique that allows athletes to swim freely, without any modification of their technique, and permits them to push themselves to perform to maximal exertion without any restriction whatsoever (Chaverri et al., 2015). Furthermore, VO_2 can be measured directly on the athlete after the maximal effort is completed through the BE technique. There have been errors associated with the BE measurement of VO_2 in the past (Di Prampero, Peeters, & Margaria, 1973; Lavoie, Léger, Montpetit, & Chabot, 1983). The errors have been linked with the delay in VO_2recognition from the respiratory hardware (Chaverri et al., 2015). This delay has been described to last anywhere from 5 to 35 seconds after the exercise, and this time delay has been reported to elicit a ~20% overestimation of VO_{2peak} when BE was used 400-m maximal swim (Di Prampero et al., 1973; Lavoie et al., 1983). To fix this problem, researchers proposed a longer collection period post-exercise (~20 seconds minimum), in order to reduce the chance of error seen in this method (Di Prampero et al., 1973; Lavoie et al., 1983). Since this correction in technique for the BE method was made, calculating VO_2using the BE method has recently been strongly correlated R^2=0.962) recently with the flume testing method (Chaverri et al., 2015; Costill et al., 1985). Additionally, VO_{2peak} at time zero BE was not found to be significantly different (0.5-1.1%) from that of the VO_{2peak} directly measured during the free-swimming test using a HR (heart rate) - VO_2 modelling technique (Chaverri et al., 2015). Although it has been seen as a controversial topic in the past, recent results indicate BE method may be used as a valid method to measure VO_{2peak} in swimming effectively, however it has been determined that it is less reliable than flume swimming.

2.3.4 Maximal Accumulated Oxygen Deficit (MAOD)

A validated used to determine anaerobic capacity in athletes is through the calculation of maximal accumulated oxygen deficit (MAOD), defined as the difference between the estimated O_2 demand relative to VO_{2max} and actual O_2 uptake (Medbo et al., 1988). The method for accumulated oxygen deficit was first introduced in 1920, and has also been characterized as an expression of anaerobic energy derived from exercise (Toussaint et al., 1998). This method estimates the oxygen demand of supramaximal exercise from the known relationship between oxygen uptake and submaximal exercise intensities. Since oxygen uptake at submaximal intensities during swimming increases in proportion to the cube of swimming speed, estimation of peak oxygen uptake during supramaximal swimming is possible (Toussaint et al., 1998).

In 1988, Medbo et al. systematically investigated the MAOD method. They proposed that if the exercise time of running and bicycling testing lasted 2-3 minutes, the O_2 deficit during exhaustive exercise would represent the athlete's anaerobic capacity (Medbo et al., 1988). When compared to another measure of anaerobic demands, such as peak lactate, no relationship was found between the accumulated O_2 deficit during exhaustive exercise (J. Bangsbo, Michalsik, & Petersen, 1993). Consequently, MAOD may not be a valid measure of the anaerobic energy production during intense exercise due to its inability to illustrate a linear relationship between energy demand and supramaximal running exercise intensity (Jens Bangsbo, 1996). Another study however found that there was a significant correlation (r=0.73) between MAOD and anaerobic contribution in an 'all-out' 100-m and 200-m swimming test (V. M. Reis et al., 2010). However, Reis and colleagues also suggest that maximal MAOD may not be able to be reliably calculated in the pool due to low frequency of movement and the liquid medium athletes must travel through.

Repeated sprint ability in sport is principally affected by the body's buffering capacity (i.e. hydrogen ion regulation) (Aziz & Chuan, 2004) and their aerobic fitness. However, a study by Bangsbo et al. (1993) found highly-trained subjects, such as rowers, soccer players, and distance runners, neither muscle buffering capacity nor fibre type distribution were dominant factors of the anaerobic energy production during intense exhaustive exercise, thus having little effect on MAOD measures (J. Bangsbo et al., 1993). Ogita and colleagues determined both MAOD and VO_{2max} during arm stroke (A), leg kicking (K), and whole-body swimming (S), and were interested in their differences to determine energy contribution from each (Ogita, Hara, & Tabata, 1996). Their study reports lower total energy production, calculated from VO_2 and MAOD, during S is lower than the sum of A and K. The authors suggest that anaerobic and aerobic demands of S are consequently lower than the combined demands of A and K. Additionally, a recent study assessed the relationship between whole-body, arm, and cycle ergometer power output and maximal swimming speed (Gatta, Cortesi, Swaine, & Zamparo, 2018). Some of their participants, similar to the Ogita study, did not achieve an equal power output on the whole-body swimming ergometer from the sum of the arm and cycle ergometer power outputs. As a result, anaerobic and aerobic dryland ergometer training for both A and K could provide combined improvements in energy system utilization and whole-body power output.

2.3.5 Assessment of Anaerobic capacity in swimming

Anaerobic testing is comprised of an all-out exercise task (<30 sec) that has either a set workload prescribed by the researcher or no set workload but the participant must work at a 'supramaximal' rate (Wasserman, 1984). Physiologically testing anaerobic capacity is typically comprised of oxygen uptake (VO_2) and metabolic (blood lactate) measures (Dalamitros, Manou, & Pelarigo, 2014; K L Keskinen et al., 1989; Ogita et al., 1996; P. Pelayo et al., 1996; Patrick Pelayo et al., 1995; Smolka & Ochmann, 2013). The measurement of VO_2 and BLa can be used to determine one's anaerobic capacity (Medbo et al., 1988). For example, measuring post-exercise BLa can indicate one's anaerobic capacity, i.e. higher lactate may reflect greater anaerobic energy metabolism (Lacour et al., 1990). Conversely, a lower VO_2 during supramaximal exercise compared to VO_{2max} reflects greater anaerobic capacity (Noordhof, De Koning, & Foster, 2010).

A high power output over a short duration is a measure of anaerobic power, so anaerobic athletes whose sports are higher in intensity and shorter duration typically have higher anaerobic power (Guilherme, Guglielmo, & Denadai, 2000). When measuring an athlete's anaerobic power, it is important that the athlete reaches maximal speed or intensity in the shortest amount of time (Dalamitros et al., 2014). Conversely, one's ability to maintain supramaximal speed or intensity for longer durations is a measure of their anaerobic capacity (Dalamitros et al., 2014). Measuring the race time in comparison to the athlete's time upon completing exercise can ensure the athlete performed at their maximal speed. Tracking performance power output and physiological responses to training is important for practitioners and coaches to understand athletes' response to training prescription.

Sprint swimming relies heavily on an athlete's anaerobic power and swimming technique, especially in adolescent swimmers (Strzala & Tyka, 2009). Therefore, the importance of aerobic assessment is highly debatable for athletes who were specialised in power events (i.e. sprinting), and for athletes who primarily utilize anaerobic metabolic power for their event (Driss & Vandewalle, 2013). Anaerobic testing may be more appropriate for sprint swimmers in comparison to long-distance swimmers because of the greater anaerobic contribution to sprint distance swimming events (Ferran A Rodriguez & Mader, 2011). Sprint events are heavily reliant on the anaerobic energy processes, but research has shown that children's ability to generate less energy through the anaerobic (Taylor, MacLaren, Stratton, & Lees, 2003).

The short duration of 50 and 100m races requires the body supply a significant amount of ATP by the PCr system (Ferran A Rodriguez & Mader, 2011). With a large portion of energy coming from the PCr system and less ATP needed from the glycolytic system for 50 and 100m races; however, blood lactate concentration has been seen to be higher in 200 and 400 m events (Ferran A Rodriguez & Mader, 2011; Vescovi, Falenchuk, & Wells, 2011). Middle distance (400m) swimming performance has also been positively associated with a swimmer's VO_{2max} in the past (Kalva-Filho et al., 2015; Ferran A Rodriguez, 2000). However, there is very little research that VO_2 correlates with improved swim performance for sprint or middle-distance swimmers. As previously mentioned however, middle-distance events require a larger amount of energy to come from the aerobic system than sprint events. As previously mentioned, high post exercise BLa measurements in sprint or even middle-distance swimming events are an indication of an athlete's anaerobic potential. Conversely however, if an athlete is training to improve their aerobic power, being able to exercise at higher intensities while maintaining lower BLa values is an indication that the athlete is able to utilize their aerobic system more efficiently, which would be more beneficial for distance events of 400 or more metres when they will be swimming for longer periods of time. It is by having a greater oxidative reserve to metabolise lactate for energy via oxidative phosphorylation these athletes are capable of using oxidative energy processing at a higher sustained work rate (Houston, 2001).

In a review of physiological, biomechanical, and anthropometrical predictors of sprint swimming performance in adolescent swimmers, Latt and colleagues, in 2001, found little variance between stroke index (stroke efficiency) (R^2= 0.788), arm span (R^2= 0.485), and change in blood lactate levels (R^2= 0.317), subsequently concluding these measures were the best overall predictors of 100-m performance in adolescent swimmers (Lätt et al., 2010). They concluded that the anaerobic contributions to maximal exercise are inversely related to exercise duration (Lätt et al., 2010). Another study performed on national-level swimmers also supports the idea that post-lactate testing can be utilized as an indicator of anaerobic contribution as a whole (lactic and alactic) in sprint swimmers (Vescovi et al., 2011). Sprint and middle-distance anaerobic differences exist for a variety of physiological reasons, and quantifying these variances is important for future athlete development.

2.4 Relationship between Dryland Testing and Swimming Performance

2.4.1 Dryland Strength Testing

There is good evidence to suggest that resistance strength testing performance is related to single maximal effort sports, such as sprint cycling, running, kayaking, and swimming. For instance, 3 repetition max (3RM) leg press testing of a mixed population of 18 moderately trained athletes (hockey, netball, and soccer) has been related to sprint cycling performance in the past (Edge, Hill-Haas, Goodman, & Bishop, 2006). Additionally, a relationship has also been found between 1RM back squat strength testing and 40-m sprint running performance in trained soccer players (Ronnestad, Kvamme, Sunde, & Raastad, 2008). In upper body strength testing, Uali and colleagues in 2012 found a strong relationship (r=0.75-0.84) between 1RM strength testing of bilateral bench pull and one-arm cable row and kayak sprint performance in 10 elite junior kayakers (Ualí et al., 2012). Traditional resistance strength testing has been shown to be related to sprint performance in upper and lower body dominant sports (Edge et al., 2006; Ronnestad et al., 2008; Ualí et al., 2012). Swimming is a sport that requires muscular contribution from both upper and lower body muscle groups, and strength testing in both could be beneficial for identifying improved sprint performance after sprint-specific training.

Simple dryland strength and power testing have been significantly correlated (r=0.74) with sprint swimming performance in young competitive swimmers (Loturco et al., 2016). However, specificity of exercise movement should be taken in consideration for testing, as it may be a contributing factor to translational improvement in swimming performance (Loturco et al., 2016). The ‘lat pull down’ strength test, which primarily requires the latissimus dorsi, has been proven in the past to be strongly related to in pool sprint performance (Lehman, Buchan, Lundy, Myers, & Nalborczyk, 2004; Signorile, Zink, & Szwed, 2002). Similarly, the pull-up exercise activates the latissimus dorsi muscle (Lehman et al., 2004; Signorile et al., 2002). An article published by Perez-Olea and colleagues in 2018 demonstrated the validity of using a testing protocol to analyze pull-up velocity in relation to swim performance. The purpose of this testing, with their 12 well-trained adolescent swimmers, was to determine the strength and power in the swimmers' latissimus dorsi. Their research concluded mean pull-up velocity for repetitions to fatigue (r= 0.88), pull-up relative power (r=0.80), and pull-up mean velocity (r=0.80) could accurately predict short-distance (50m) swimming performance in trained swimmers (Pérez-Olea, Valenzuela, Aponte, & Izquierdo, 2018). This research helped re-emphasize the importance of specific upper limb strength testing for swim performance in young swimmers.

Biomechanically, lower limb explosive strength contributes to start and flip turn performance (Vantorre, Chollet, & Seifert, 2014). Additionally, the start has been associated with improved sprint performance (García-Ramos et al., 2016; Vantorre et al., 2014). Some authors have reported a significant relationship between dryland lower-limb strength and swimming performance (Keiner, Yaghobi, Sander, Wirth, & Hartmann, 2015; P. Morouço et al., 2011). These close relationships have been seen in short distance events where the start and the flip turn play a larger role on the overall swimming performance. Therefore, based on this and previous studies, the dry-land strength of the lower limb may be a valid determinant of performance in non-swimming elements such as the start or the flip turn and contribute to sprint swimming performance.

For shorter competitive distances, strength is considered one of the most influential factors involved in the generation of swimming speed (P. G. Morouço, Marinho, Amaro, Peréz-Turpin, & Marques, 2012). Strength can be defined as one's ability to apply large amounts of muscular force under sport-specific conditions (Schumann & Rønnestad, 2019). Improvements in upper limb strength could be hypothesized to translate to higher maximum force per stroke, resulting in higher swimming velocities, specifically in shorter distances. Compared with technical parameters, it is assumed that the strength role is increasingly more important to swimmers as the swim distance diminishes (P. Morouço et al., 2011). With these results, we can confirm the importance of including an appropriate dry-land strength-training program in combination with swimming and technical training for the improvement of swimming performance in young competitive swimmers.

2.4.2 Anaerobic Dryland Power Testing in Swimming

Maximal 'all out' testing has been used in the past to measure peak and average power output in swimmers to determine training progress and exercise prescription (Costa, Bragada, Marinho, Silva, & Bbarbosa, 2012; Driss & Vandewalle, 2013; Guilherme et al., 2000; Smolka & Ochmann, 2013). However, short duration dryland tests have been used sparingly to determine the relationship with sprint swimming performance (John A. Hawley, Williams, Vickovic, & Handcock, 1992).

Strong relationships (r=0.83) between upper and lower body power output for both sprint (50 m) and middle-distance (400 m) freestyle-swim performance in competitive youth swimmers have been established in the past (John A. Hawley et al., 1992). Estimation of peak power output enables accurate prediction of maximum speed during swimming, especially in short distances; as velocities become higher, necessity for greater power output also increases (P. G. Morouço et al., 2012). The fastest swimmers not only display high anaerobic power outputs but also high peak sustained power outputs, as determined by the maximal workload achieved during a progressive, incremental maximal arm power test (John A. Hawley et al., 1992). Hawley and colleagues in 1992 concluded that 'muscle power' is an important determinant of both sprint and middle-distance swimming performance, and that swimmers in events up to 400m may benefit from training which aims to improve arm and leg power. In another study, a significant correlation (r=0.76) was found between maximum swim power, a 12.5m all-out swim with resistance, and maximum swim speed over 25 meters in competitive adult swimmers (Dominguez-Castells, Izquierdo, & Arellano, 2012).

Johnson and colleagues in 1993 found a significant relationship (r=0.91) between power output and sprint (25yd) freestyle performance (Johnson, Sharp, & Hedrick, 1993). The relationship weakened once the swimmer was able to produce at the 500 watt 'threshold', illustrating a point of diminishing returns in swimmers who possess a high level of arm and leg power (Johnson et al., 1993). As a result, other technical aspects such as stroke mechanics may be more of a contributing factor to a swimmers' success once a certain threshold is reached in this population (John A. Hawley et al., 1992)From these findings, it is evident that upper limb power output holds validity and significance to swimmers interested in improving performance. Additionally, tracking swim power could be relatively simple to implement and would provide swimmers and coaches with quick feedback.

2.4.3 Power Output during Swim Bench Exercise

For shorter competitive distances, muscular power has been proven to be one of the main factors that may enhance swimming speed (John A. Hawley et al., 1992;

Loturco et al., 2016). Estimation of peak power output allows for an accurate prediction of maximum speed during swimming, especially in shorter distance events (smith 2002, Johnson 1993). As a result, necessity for greater power output is increased as the desire for higher swim velocities in the pool increases (T. M. Barbosa et al., 2010)

In front-crawl, about 90% of the total propulsive force is generated by the arm stroke, while the role of the legs is restricted to maintain the body in a proper posture in the water by reducing the trunk inclination (Dalamitros et al., 2014). A significant advantage swim bench exercise (SB) has over many other forms of dry land exercise is that swimmers are able to simulate the arm stroke movement patterns of butterfly and freestyle swimming (Smith, Norris, & Hogg, 2002). Although it cannot completely mimic water and its effect on the body's movement in the pool, the swimmer is able to utilize similar muscle groups and mechanics they use for swimming (I. Swaine & Reilly, 1983). A swimmer's technique is widely accepted as more important than a swimmer's ability to produce high SB power, but the SB has been suggested as a possible tool for evaluating the swimmer's muscular power out of the water (Kari L Keskinen, 1994).

The swim bench offers an objective way of monitoring arm power in swimmers (Sharp & Troup, 1982). Early studies using SB have demonstrated a strong relationship (r=0.91) between upper body instantaneous pull power and 25-yard sprint swimming performance (Johnson et al., 1993). Participants pulled at four different speed settings on the SB and power outputs were recorded for each. Sharpe and colleagues found power output from a 45-second max test using a SB significantly correlated (r=0.90) with the 25-yard sprint swimming speed of 40 competitive adolescent (15-16-year-old) swimmers (Sharp & Troup, 1982). These authors concluded that improvements in upper body power, whether it be instantaneous or over 45 seconds, may result in higher maximum force per stroke, and subsequently increase swim speed, specifically in shorter (sprint) distances (Sharp & Troup, 1982). Even though both kinds of exercise use similar upper body muscle groups, active muscle groups involved during SB are different and/or smaller. Additionally, measures of stress such as heart rate, have been shown to be lower in SB in comparison to arm-stroke (A) swimming (Ogita et al., 1996). Exercise duration at peak exercise was also significantly shorter in SB than that in A (Ogita et al., 1996). These results would suggest that even though the movement characteristics in SB may ave appeared similar to the actual arm stroke, muscle mass recruited during SB was smaller and maximal stress on the cardio-respiratory system was lower when compared to A (Ogita et al., 1996). Dry-land exercise with swimmers has limitations in its direct application to free swimming. Future studies utilizing SB as testing or training modality should examine the extent to which power output from just the upper limbs are reflective of the demands of swimming itself (I. L. Swaine, Hunter, Carlton, Wiles, & Coleman, 2009).

2.4.4 Training and Performance for Swimmers

Outside of practice, in any sport, athletes should train in a manner that reflects the physiological demands of their sport. Specificity in training in and outside of the pool for swimmers can be broken down into each portion of the race or discipline. A swim race can be broken down into three major segments: the start, the transitional turns at the wall, and the swimming itself. Swimming is a highly technical sport, and technique becoming increasingly more important in higher levels of competition, i.e. national or international. Specificity in exercise prescription for athletes who swim different disciplines (breaststroke vs. freestyle) or distances (sprint vs. middle-distance) will and should be completely different once athletes reach an age or level that requires them to specialize in their strongest event. Lastly, as previously discussed, sprint swimming demands a large amount of energy to be produced anaerobically. Therefore, to improve performance in sprint events, it is beneficial for athletes to train at higher intensities to improve physiologically. Anaerobic power training consists of supramaximal training intensities for short durations, physiologically targeting the glycolytic pathway to stimulate the production of large amounts of ATP to meet short-term muscular energy demands. Anaerobic power training for swimmers occurs in the pool and on dryland with heavy resistance and power training. The following sections will review literature on various forms of training utilized to improve sprint swimming performance.

2.4.5 Pool Based Training Approaches to Improve Sprint Performance

In general, swimming aerobic capacity has been proven to improve over the course of the season through various forms of training (Vasile, 2014). Increased weekly and daily training volume in the pool has been reported generate aerobic adaptations (Costa et al., 2012). Sharp et al. in 1984 found that the most effect aerobic adaptations to training occur in the first few months of the yearly training plan for swimmers, allowing for more specific and higher intensity training to occur later in the season. Later in the season coaches include low-moderate intensity swimming sets for a number of reasons. Some coaches include this non-specific training as an easy method to reach the target training load prescribed for the training session (Stewart & Hopkins, 2000). Additionally, it is believed that this extra low intensity volume in the pool is a good time to focus on technique and balance the hard work in the swim sessions with light active recovery between sets (Stewart & Hopkins, 2000).

In sprint swimming (50–100 m), the literature reveals two types of training load distributions in champion sprinters and Olympic medallists (Ernest W Maglischo, 2003). Total training load (TTL) for swimmers has been defined as the combination of volume swum, intensity of effort, frequency of workout (J.-C. Chatard & Mujika, 1999). The first annual TTL for sprinters consisted of a medium-high volume of ~2000-2500 km of swimming, and ~90% of this swimming was done at less than 4 mmol speed (Pyne & Touretski, 1993). The second annual TTL consisted of ≤1500 km of swimming at less than 2 mmol speed for more than 70% of the volume, and 15% of which was swam at greater than 4 mmol speed (Hellard et al., 2019). In 1995, Mujika et al. demonstrated an annual training volume ranging from 749 to 1475 km did not significantly correlate with improved sprint performance for 18 international-level sprint swimmers (Mujika et al., 1995). A recent systematic review concluded the optimal sprint swimming yearly training plans should include longer macrocycles, medium TTL, and swimming intensities of roughly 88% moderate-to-heavy intensity (>4 mmol), 8% severe intensity (4-6 mmol) and 4% extreme-intensity training (>6 mmol) (Hellard et al., 2019; Hellard, Scordia, Avalos, Mujika, & Pyne, 2017).

Sports characterized by High Volume Training (HVT) such as cycling, long distance running, rowing, and swimming have been found to benefit from High Intensity Training (HIT) interventions (Laursen, 2010). Current literature suggests that the anaerobic power and capacity of muscle can be increased with targeted anaerobic exercise such as HIT and resistance training (Hellard et al., 2017; Richmond, Buell, Pfeil,

& Crowderd, 2015). Sports characterized to be more anaerobic-based have been reported greater training responses to HIT than those that are more aerobically based (Buchheit & Laursen, 2013). Some sports, such as sprint track and field, have this high glycolytic (lasting <30s) training strategies in the past to improve performance (Iaia & Bangsbo, 2010).

Sperlich et al. (2010) compared a HIT and HVT intervention during a 5-week randomized crossover study involving 26 youth swimmers. Swimming performance was found to significantly improve during 50 and 100m free competition performance (CP) for the HIT group (Sperlich et al., 2010). The authors suggested that the 20.1% increase in peak BLa may have influenced the 14.8% increase in 50 and 100-m CP for the HIT group. A similar study by Termin and Pendergast (2000) investigated the effects of a HIT intervention during a four-year uncontrolled longitudinal study involving 22 university swimmers (Termin & Pendergast, 2000). The intervention resulted in a 27% increase in peak BLa during the first year ($p<0.05$); however, peak BLa was not found to significantly increase in year 2, 3, and 4 (Termin & Pendergast, 2000). Overall, these authors found that there was a 10% improvement in the 100-yard CP over the four-year period. Furthermore, these authors observed increases in performance during this period could be attributed to HIT. In these studies, the authors suggest volume prescribed to highly trained swimmers is valuable up to a certain threshold, after which raising training intensity is hypothesized to be more impactful on sprint swimming performance (J.-C. Chatard & Mujika, 1999; Hellard et al., 2017).

2.4.6 Strength Training in Swimming

Resistance exercise training can be functionally defined as the progressive overload of a skeletal muscle that is characterized by high muscle contraction force and anaerobic ATP resynthesis (Schumann & Rønnestad, 2019). Past studies involving a dryland resistance strength training intervention added to swimming training load have reported significant improvements in performance (N M Amaro et al., 2019; Crowley, Harrison, & Lyons, 2017; Schumann & Rønnestad, 2019).

Girold et al. (2012), Girold et al. (2007), Strass (1988) and Aspenes et al. (2009) all found that traditional upper-limb resistance-training methods increased dryland strength and consequently improved swimming performance (Aspenes, Kjendlie, Hoff, & Helgerud, 2009; Sébastien Girold et al., 2012; Sebastien Girold, Maurin, Dugue, Chatard, & Millet, 2007; Strass, 1988)Each of these studies employed training plans with low repetition ranges (1–6 repetitions), a low number of sets (≤3 sets), and high velocity movements. Strass in 1998 prescribed a 6-week barbell training program with sets of low (1-3) repetitions and high (90-100+%) intensity of one rep max (1RM). Aspenes and colleagues prescribed a cable resistance strength training program of five maximal repetitions for three sets, with the latissimus dorsi, triceps brachii, and rotator cuff being the targeted muscles for the training (Aspenes et al., 2009). Girold and colleagues in 2007 prescribed a full body barbell strength training program for the intervention group, targeting biceps and triceps brachii, the back, the pectorals, the deltoids, the quadriceps, gluteal muscles, and the calf (Sebastien Girold et al., 2007). The participants completed 3 exercises per muscular group, 3 times per session, at between 80 and 90% of their 1RM. Girold and colleagues in 2012 prescribed 3 sets of 3 exercises primarily targeting the latissimus dorsi. The exercise sets included of 6 repetitions of pull-ups and draws with pulleys (Sébastien Girold et al., 2012)

Girold et al. (2012) found a 2% increase in 50-m performance from training, Strass (1998) reported a 2.1% increase, and lastly Girold et al. (2007) reported a 2.8% increase. Strass (1998) also found improvements in maximal explosive force production compared with maximal force production, which the authors attributed to neuromuscular adaptations. Conversely, Tanaka et al. (1993) and Trappe and Pearson (1994) found increases in strength throughout a season with a dryland strength program, but did not observe any increases in swimming performance (Tanaka, Costill, Thomas, Fink, & Widrick, 1993; Trappe & Pearson, 1994). Trappe and Pearson (1994) had participants completed strength training, one group performed weight assisted latissimus dorsi and tricep exercises, and the other group did traditional free-weight training program. Over six weeks the groups did strength training twice a week, and they found no significant improvement for either group in the 25-yard freestyle. Tanaka and colleagues in 1993 had two groups participate in an 8-week training intervention, and one group followed a swim-only protocol and the other group did a similar traditional free weight training program as the Trappe and Pearson intervention. Similar to Trappe and Pearson. Tanaka et al. found no significant relationship between resistance exercise strength training and 25-yard sprint performance. The authors hypothesized that the heavy demands of both swimming and resistance training may have caused local muscular fatigue and inhibited the development of improved swimming power (Crowley et al., 2017).

It is highly controversial whether an increase in dryland strength will necessarily translate to improved sprint swimming performance, especially in a younger population

(Crowley et al., 2017; Garrido et al., 2010; Morais et al., 2016; Schumann & Rønnestad, 2019). Swimmers not only have to develop high levels of force, but must also apply them in an effective way to maximize propulsion (Crowley et al., 2017). For example, high level of importance is placed on the technical factors associated with each stroke. One study conducted by Garrido and colleagues in 2010 found that strength tests, bench press and leg extension, in younger (~12 years old) swimmers were moderately associated with 25 and 50m sprint performance. However, there have been studies previously that reported increases in muscular force after dryland resistance exercise strength training programs with either minor or no changes in swimming speed (Crowley et al., 2017). This absence of improvement could be attributed to a number of reasons, but the most common reason is that the athletes' technique did not improve and they were not able to translate increased force production out of the pool into increased force production in the pool (Vorontsov, 2011). Ultimately, these results confirm the importance of including an appropriate dryland strength-training program in combination with swimming and technical training. This combination is pivotal for improving sprint swimming performance in young athletes (Crowley et al., 2017; Schumann & Rønnestad, 2019). The main aim of the mechanical work performed by a swimmer is to overcome hydrodynamic resistance, i.e. drag (Schumann & Rønnestad, 2019). Therefore, any increase in swimming speed demands a proportional increase of muscular force applied to propulsion during the arm stroke to overcome active drag (Carl, Leslie, Dickerson, Griffin, & Marksteiner, 2010; Vorontsov, 2011). This hypothesis suggest dryland strength training could improve sprint swimming performance.

2.4.7 Power Training for Sprint Performance

It is not clear whether training for strength or power is more important for sprint swimming performance (N M Amaro et al., 2019; Nuno M Amaro, Marinho, Marques, Batalha, & Morouço, 2017; Manning, Dooly-Manning, Terrell, & Salas, 1986; Sadowski, Mastalerz, Gromisz, & Niźnikowski, 2012). A recent systematic review found training for power positively influences short-distance swimming (N M Amaro et al., 2019). A training program based on power was applied to a group of adolescent swimmers (16.49 ± 0.84 years) (Sadowski et al., 2012). Each training session consisted of 11 exercises (upper and lower body), performed in two sets of the maximum number of repetitions during one minute. This was performed three times a week over nine weeks, using weight lifting equipment and a cycle ergometer. Intensities varied from 30 to 50% of their one repetition max in each exercise, with a progressive increase of 10% every three weeks. Although there were no significant differences, authors presented improvements of -0.98 s, -0.06 s and -1.30 s for the 50, 100, and 200-yard freestyle tests, respectively. In swimming, these small improvements can be remarkable, particularly in short swimming distances. In fact, an additional study with prepubescent swimmers found improvements in 50-m front-crawl swimming time after a six-week power-based dryland weight training plan (Nuno M Amaro et al., 2017). Authors compared the new explosiveness-focused training plan to the normal swimming training program the team was following. The explosiveness group was asked to perform as many repetitions as they could in a specific time, while the control group had no restrictions on the time of execution to complete the reps/sets (N M Amaro et al., 2019). Both groups observed improvements in dryland strength, but no swimming improvements were reported at the end of the six-week training plan.

However, authors allowed a four-week adaptation period, where swimmers followed only their normal swimming regimen. After this period, only the group that performed the resistance-exercise program based on explosiveness presented a 2.21% improvement in 50 m swimming time. Similarly, in 1986 Manning and colleagues designed a training plan to target the specific muscle groups activated in the freestyle stroke, where exercises were instructed to be completed with maximum velocity. Although they found an increase in muscle power, there was no indication of a significant increase in swimming performance (Manning et al., 1986). Researchers attributed this lack of improvement to the residual fatigue that may have been present (N M Amaro et al., 2019). This reinforces the importance of allowing swimmers enough time to adapt to new dryland strength improvements prior to competition (N M Amaro et al., 2019). Further investigations with different ages, competitive levels and post-evaluation periodization must be conducted to clarify this hypothesis (N M Amaro et al., 2019).

2.4.8 Swim Bench Ergometry Training

Anaerobic sprint interval training in other sports using stationary ergometers comprising multiple repetitions of short duration has been used to improved anaerobic power (Schumann & Rønnestad, 2019). In swimming, the research so far has primarily examined the effects of ergometry training on the adult population. The controversy surrounding the literature appears to be related to the age and experience of the athletes being tested, as well as the effectiveness of the swimming ergometer as a training modality. Little literature exists on utilizing a swimming ergometer for training well-trained adolescent swimmers. The maximal power output produced on the biokinetic swim bench has a strong relationship (r=0.92) with swimming speed in semi-tethered conditions (Schumann & Rønnestad, 2019). Another study designed an intervention combines high intensity swim training with sessions on the swim bench (Roberts, Termin, Reilly, & Pendergast, 1991). Participants completed swim bench training three times a week for three weeks, and intensity was increased as each participant improved (Roberts et al., 1991). The control group completed a high intensity swim-only protocol, and the swim bench (SB) group completed the same training as the control group coupled with a repeated sprint SB protocol. Participants in the SB group reported a higher level of fatigue than the control group as a result of the intervention period, but neither groups improved in 100-yard freestyle performance more significantly than the other. Lack of significant differential improvement from the SB group may be a result of a number of reasons. For example, participants have more stability on the SB than in the water. Additionally, the inability to replicate drag and propulsion produced by movement of the hand through water on the SB could have contributed to the lack of improvement experienced by the SB group. This lack of improvement, however, could also be attributed to the age and swimming level of those involved in this study (Roberts et al., 1991). Because the athletes involved in the study were older and already highly trained, the ergometer training may not have provided a large enough stimulus to positively affect performance (Roberts et al., 1991). With limited research and conflicting results between the previously listed studies, it is difficult to determine the transferability of biokinetic swim-bench training to swimming performance in a well-trained adult population. The results are conflicting because although the athletes were able to pull at a harder resistance at the end of the intervention and the experimental group improved their 100-

yard freestyle performance, they did not improve significantly more than the control group over the 10-week period.

As a result, future studies should aim to examine whether a significant improvement is possible with a younger sample of competitive swimmers. As well, swim bench research needs to expand and attempt to find more conclusive evidence verifying it is a valid testing and training modality for the sport.

Chapter 3. Study Rationale, Objectives and Hypothesis

3.1 Gaps in Literature

The physiological demands of sprint swimming have been quantified in the past, however there is minimal literature on the effectiveness of a training intervention utilizing a swim ergometer (Barbosa et al., 2010; Hellard et al., 2019; Lätt et al., 2010; Reis, Alves, Bruno, Vleck, & Millet, 2012; Schumann & Rønnestad, 2019). Given that upper body power production is a well published indicator for sprint swimming success (Hawley, Williams, Vickovic, & Handcock, 1992; Johnson, Sharp, & Hedrick, 1993; Loturco et al., 2016). Ergometer-based speed training is likely to be an effective method to increase upper body power production. Understanding the relationship between swim ergometer training and swim performance will provide important information to guide land-based coaching as well as the strength and conditioning.

The high intensity upper body demands experienced from an in-pool sprint session can be replicated using a swim ergometer, but this limits its replicability to in-pool swimming since it only targets the muscles of the upper body (Ogita & Taniguchi, 1995). The use of an isokinetic swim bench, such as the VASA SwimErg, to mimic the movement patterns and intensity of a swimming workout has been researched in the past (Ogita & Taniguchi, 1995; Swaine, 1997). Few studies have examined the level of agreement between isokinetic swim benches as a training modality and their effect on swim sprint performance and anaerobic improvements in competitive swimmers.

3.2 Research Objectives

The overall objective of this research was to determine the effects of a 4-week pool-based (PST) and swim ergometer (ERG) sprint interval training (SIT) intervention on the maximal anaerobic lactate test (MANLT) and associated anaerobic swim ergometer performances. Specifically, the purpose of this research was to:

1. Compare 4-weeks of pool-based sprint interval training (SIT) with a similar ergometer training intervention on a maximal anaerobic lactate test (MANLT) and associated anaerobic swim ergometer performances
2. Determine the effectiveness and viability of using a swimming ergometer as a dryland training modality to improve performance in the pool

3.3 Hypotheses

The hypotheses of this study include:

1. The ERG group will improve their 50m sprint and MANLT velocities more than the PST group
2. Sprint interval training will significantly increase BLa production after 4 weeks of both the ERG and PST group in the MANLT, 30-second maximal ergometer test, and 50m freestyle performance.

Chapter 4. The Effects of Anaerobic Swim Ergometer Training on Sprint Performance in Adolescent Swimmers

4.1 Introduction

Competitive swimming is a unique sport comprising a variety of strokes (freestyle, butterfly, breaststroke, and backstroke), and different durations. As such, each stroke and duration will exhibit contrasting physiological demands and biomechanical characteristics (Rodriguez & Mader, 2011). For example, short high-intensity efforts of less than 60 seconds (sec) have been shown to elicit a significant anaerobic glycolytic component to energy metabolism in comparison to longer high-intensity efforts >60 seconds in middle and distance swimming competitions (Rodriguez & Mader, 2011; Serresse, Lortie, Bouchard, & Boulay, 1988). Furthermore, it has been demonstrated that sprint swimming (<100 meters or 20-50 seconds) relies on a greater proportion of cellular energy derived via anaerobic glycolysis as reflected by higher elevations in blood lactate concentration compared distance (>400 m) events (Hellard, Pla, Rodríguez, Simbana, & Pyne, 2018; Lawsirirat & Chaisumrej, 2017; Rodriguez & Mader, 2011). In the assessment of sports performance, a variety of testing procedures have been used to establish aerobic and anaerobic capacities, including but not limited to oxygen uptake during and after exercise (to establish oxygen deficit and debit), blood lactate responses, and recovery from all out exercise (Artioli et al., 2012; Gastin, 2001). Moreover, metabolic analysis during exercise has also been used to determine aerobic and anaerobic potential (Lätt et al., 2010; Pyne, Lee, & Swanwick, 2001) using oxygen uptake (VO_2) and blood lactate concentrations. Despite this, the physiological assessment of swimmers is usually accomplished through generic incremental swimming tests used to quantify aerobic indices of performance, such as the lactate threshold (LT) and the training response (Anderson, Hopkins, Roberts, & Pyne, 2006; Pyne et al., 2001). Existing literature supports the benefits of dryland strength and power training for swim sprint performance (J A Hawley & Noakes, 1992; Morouço et al., 2011; Pérez-Olea, Valenzuela, Aponte, & Izquierdo, 2018; Swaine, 1997). Maximal 'all out' testing has been used in the past to measure peak and average power output in swimmers to determine training progress and exercise prescription (Dalamitros, Manou, & Pelarigo, 2014). Quantifying comparable "dryland" testing in swimming is relevant for establishing sport-specific anaerobic and aerobic capacities. Understanding energy system utilization for the classification of a competitive swimmer (sprint or distance) may be useful for both training prescription and event specialization (Rodriguez & Mader, 2011). Whilst the concept of specificity between dryland modalities and pool swimming, no studies have directly examined the relationship between the metabolic and performance responses of dryland (swim ergometer) power testing and in-pool sprint performance in trained swimmers.

The maximal anaerobic lactic test (MANLT) was developed to evaluate the competitive effort of swimmers in a 200 m event while assessing anaerobic capacity (Patrick Pelayo et al., 1995). The MANLT consists of four 50 m swims (a 'broken' 200m effort) with a 10 sec rest between each effort. Blood lactate (BLa) is measured during 3- and 12-minutes (min) post-exercise passive recovery in a sitting position, as an indication of the athlete's maximal anaerobic contribution and rate of lactate clearance (Patrick Pelayo et al., 1995). For example, Pelayo and colleagues concluded that the recovery response of blood lactate over the course of a season was significantly related to in-pool sprint performance of able-bodied 200 meter freestyle trained swimmers (P. Pelayo, Mujika, Sidney, & Chatard, 1996). As of late, there is no known research evaluating the peak BLa concentration and BLa recovery following the MANLT in trained adolescent swimmers.

Furthermore, there is little known about physiological and physical contributors to success in adolescent swimmers. Anthropometric and biomechanical advantages, such as longer limb length and distance per stroke, have been correlated with improved swimming performance in 11-13 year old swimmers (Barbosa, Bartolomeu, Morais, & Costa, 2019); however, additional understanding of the physiological contributions to swimming in this age group may provide valuable information for specific training prescription. Moreover, there is little known literature on the physiological and performance characteristics of sprint swimmers and the relationship to sprint swimming performance. Likewise, research comparing the physiological characteristics between sprint and distance swimmers especially in 'young' (14-18) developmental age group athletes is also limited (Patrick Pelayo et al., 1995; Rodriguez & Mader, 2011). While an anaerobic contribution to the100 m sprint in this age group has been identified, coupled with the fact that physiological parameters account for ~46% of a swim athlete's success, there is little published on the 'physiological' characteristics of young swimmers (Rodriguez & Mader, 2011). There is strong evidence to suggest that high intensity training (HIT) is an effective strategy to improve 100m FS time; however, there is a lack of studies investigating the impact of HIT on performance (Schumann & Rønnestad, 2019; Sperlich et al., 2010). Sharpe and colleagues in 1982 discovered a strong correlation between 45-second power output on a swim bench (SB) was strongly correlated (r=0.90) with the 25-yard sprint swimming speed in adolescent swimmers (Sharp & Troup, 1982). However, studies in the past involving training on the SB has been primarily with the adult population (Roberts, Termin, Reilly, & Pendergast, 1991).

Therefore, the purpose of this study was first to compare 4-weeks of pool-based sprint interval training (SIT) with a similar ergometer training intervention on a maximal anaerobic lactate test (MANLT), 50m freestyle performance, and 6 and 30 second maximal swimming ergometer performances. Secondly, the purpose of this study was to determine the effectiveness and viability of using a swimming ergometer as a dryland training modality to improve performance in the pool.

4.2 Methods

4.2.1 Subjects

Fourteen (n=14) trained swimmers (~12-15 hours of training/week) from the same homogenous training group voluntarily participated in this study. Swimmers were randomly placed into two sex matched groups (males n=4; females n=3), in either the ergometer-sprint training (ERG) (N=7) or the pool-sprint training (PST) (N=7) group. Both groups had an average age of 16.5 ± 0.9 years, height of 176.2 ± 8.3 centimeters (cm), weight of 64.9 ± 7.3 kilograms (kg), and arm span of 80.8 ± 10.2 cm. All athletes have competed at provincial and national swimming events. Participants were recruited through their coach and received written details of the testing procedure prior to participation. The study was approved by the Research Ethics Board at the Canadian Sport Institute Ontario and Ontario Tech University. Participants were informed of the benefits and risks of the investigation prior to starting. All participants and parents signed an informed consent prior to the testing.

4.2.2 Design

Each participant underwent a preliminary anthropometric assessment, measuring height (cm), body mass (kg), and arm span (cm). All participants completed three performance tests before and after a 4-week training intervention period, two of which were conducted in a 25-metre pool and one in a laboratory-based setting. Athletes followed the same training plan for ten weeks prior to testing and during the intervention period. The laboratory testing consisted of an ‘all out’ 6 and 30 sec sprint test on a stationary swim ergometer (VASA, Essex Junction, VT), measuring average power over the course of the 6 and 30 seconds (Roberts et al., 1991). The in-pool testing consisted of two tests: (1) 4x50 m (MANLT) test, and (2) 50 m freestyle race to determine average sprint speed and lactate recovery profile (post swim lactate analysis at 3 and 12 min post exercise). Dryland and in-pool testing occurred on separate days over a two-week period with a minimum of 48 hours between testing days. Athletes completed the same standardized warm-up protocol before every test session, consisting of a 10 min dry-land warm-up followed by a 10 min in-pool warm-up. The in-pool warm-up included both general swimming and skill focused drills such as kicking and pulling. All in-pool testing was conducted in a 25 m pool. The MANLT began with a push start from the wall with one hand and two feet on the wall to start, whereas the 50 m freestyle race started from a block using a dive start with an auditory cue. Each participant completed the swimming testing using the freestyle stroke. Participants in both the control and experimental group completed the same dryland strength training program over an eight-week period, four weeks before and four weeks during the intervention. The study was designed this way in order to standardize the training load outside of the pool for both the control and experimental group.

4.2.3 Testing

4.2.3.1 Maximal Anaerobic Lactate Test (MANLT)

The MANLT consisted of four consecutive short-course 50 m sprints with 10 seconds rest between each effort. Each 50 m sprint time and stroke rate were recorded. Stroke rate (SR) was measured for both laps by manually timing three complete stroke cycles with a stopwatch (Marathon ST083020, MarathonWatch, Concord, Canada). At the end of the last 50 m effort, the athlete immediately breathed into a face mask (COSMED The Metabolic Company, Rome, Italy), collecting volume of oxygen consumed (VO_2) for 30 seconds. Simultaneously, heart rate (HR) and peripheral capillary oxygen saturation (SpO_2) were measured using a pulse oximeter (Nonin Medical, Plymouth, MN, USA) (Chaverri, Schuller, Iglesias, Hoffmann, & Rodríguez, 2016; Montpetit, Léger, Lavoie, & Cazorla, 1981; Rodríguez, Chaverri, Iglesias, Schuller, & Hoffmann, 2017). Upon completion of the fourth 50 m, the athlete was assisted from the pool and rested in a seated position. A 3 and 12 min post-exercise BLa sample was obtained by puncturing the fingertip with an automatic lancet, and approximately 25 µl of blood was analyzed using a portable hand-held blood lactate analyzer (EDGE, Warszawa, Poland) (Bonaventura et al., 2015). Blood lactate recovery was calculated by subtracting (Δ) the 12-min post BLa measure from the 3-min post BLa measure to determine BLa difference in absolute (mmol/L) and relative (%).

4.2.3.2 6- and 30- second Swim Ergometer Tests

Participants performed a 6- and 30-second all out swimming test using a stationary swim ergometer (VASA, Essex Junction, VT). Upon arrival, a resting BLa sample was obtained using the method previously described. Prior to testing, participants completed a standardized warm-up on the swimming erg, consisting of ten incremental pulls increasing from light to submaximal intensity. Upon completion of the warmup, participants performed a 6 second maximal sprint on the isokinetic swim bench. The lowest resistance was set for the test to ensure standardization across testing days and that every athlete could pull with maximal power from beginning to end. A BLa sample was obtained after the test using the method previously described. The testing protocol used was based on a previous study showing relationship between anaerobic swim bench power and in-pool sprint performance (Roberts et al., 1991). After each participant had completed the 6 sec test, participants then performed a 30 second max test. Power output was recorded every stroke and was subsequently averaged to determine 5 second averages in splits of 0-5 seconds, 5-10 seconds, and 25-30 seconds. A 3- and a 12-min post-test BLa sample was obtained using the method previously described.

4.2.3.1 50 m Freestyle Race

On a separate testing day, participants completed a short-course 50 m freestyle race. The testing environment was under official swimming competition conditions, and participants wore racing suits and raced swimmers who were similar in speed. Prior to testing, a resting and pre-race BLa sample was obtained. Participants started each trial with a dive start initiated by an auditory cue from the swimming starting device (Startime III, Swiss Timing, Corgemont, Switzerland). At 3- and 12-min post test, swimmers' BLa was measured as previously described. The average swim speed for the 50 m effort was determined using Kinovea video analysis software (Kinovea Software, Boston, USA). The time started when the visual cue of a flash from the starting device appeared in the video and ended when the participant touched the wall.

4.2.4 Pool Training

During the four-week intervention, all participants followed the same training plan dictated by the coach. For participants in the control group, all sprint training was performed in a 25m pool. Each sprint session lasted approximately 40 minutes, including the warm-up and recovery. On the first day of training, the control group completed 'breakout' (12.5m) swims from a wall push once every minute ten times, followed by 25m sprints from a dive start once every minute ten times. The control group on the second day of training completed twelve 25m sprints from a wall push with 1 minute and 15 seconds of passive recovery at the wall in between each sprint. On both days of sprint training, participants were instructed to kick as little as possible during the sprints to isolate the upper body. Ratings of Perceived Exertion (RPE) were assessed using a Borg Scale (Borg, 1982) after each training session to assess similarity in perceived exertion between groups. In addition, every participant in the study rated their shoulder pain before and after each sprint session using a Likert scale to reduce possible injury risk among groups.

4.2.5 Ergometer Training

All participants trained in the pool as one group in other training forms. The experimental group trained at the end of practice twice a week using a swimming ergometer (VASA, Essex Junction, VT), while the control group trained in the pool. The training occupied the same amount of time in the experimental and control group all four weeks. During the sprints on the ergometer, participants used a double arm pull to maximize the power produced during each stroke and reduce the risk of shoulder injury by limiting internal glenohumeral rotation. Participants recovered passively between each sprint by standing beside the swimming ergometer. During the first two weeks of the training intervention, participants trained at an intensity of 1/9 on the swim ergometer, and then progressed to training intensity of 2/9 during weeks three and four of the intervention. The training protocol for all four weeks began with a 10-pull warm-up, with the first pull being at a self-selected low intensity and progressing up to a submaximal (80%) pull to finish.

The sprint training on the ergometer consisted of two different protocols. The first day of training was designed to have repetitions shorter in duration, consisting of ten 6-second sprints with 54 seconds of rest, followed by ten 10-second sprints with 50 seconds rest. The second day of training consisted of twelve 15-second sprints with 1 minute and 15 seconds of passive rest as described before. RPE and shoulder pain were assessed at the end of each training session. The work to rest ratio of 1:5 was designed to maximally engage the anaerobic ATP-PCr and glycolytic systems. It has been previously shown that this amount of rest is beneficial for SIT as it allows for the athlete to completely recover for the next effort (Schumann & Rønnestad, 2019).

4.2.6 Statistical Analysis

Data analysis was performed using SPSS (IBM Analytics) statistical software. Mean and standard deviation (SD) (95% confidence interval) was calculated for each measure in each group (ERG versus PST). Population was assessed for normalcy using a

Shapiro-Wilk test and was reported a value >0.05, determining the data was normally distributed. Two-way repeated-measured analysis of variance were utilized to establish whether a significant difference ($p<0.05$) between time and groups existed for each measure. Effect sizes (ES) were calculated to supplement important findings as the ratio of the mean difference to the pooled SD of the difference. The magnitude of the ES was classed as small (0.01–0.06), moderate (0.06–0.14), and large (>0.14) based on previous published guidelines (Cohen, 1988).

4.3 Results

4.3.1 Maximal Anaerobic Lactate Test (MANLT)

Group intervention results from the MANLT are shown in Table 1. Participants in the ERG and PST group experienced an increase in the swim speed of the 3rd 50m effort following the intervention period (ERG +2.7% ± 1.6% vs. PST +1.9% ± 4.6%, $p=0.02$, ES=0.37). Additionally, participants in the ERG and PST group experienced a decrease in MANLT fatigue following the intervention period (-32.4% ± 25.4% vs. -12.5% ± 16.1%, $p<0.01$, ES=0.53). Mean measures of the fatigue are shown in Figure 1. Participants in both the ERG and PST group demonstrated an improvement in the speed of the 4th 50m effort following the intervention period (+4.1% ± 2.5% vs. +1.1% ± 2.0%, $p<0.01$, ES=0.58). There was no statistical difference in pre to post-intervention results for the 1st and 2nd 50m velocities ($p=0.16$ and $p=0.42$), stroke rates ($p=0.11$, $p=0.48$, $p=0.48$, $p=0.98$) 1st - 4th 50 respectively. peak or average speed ($p=1.0$ and $p=0.12$), VO_2 ($p=0.16$), or 3-min, 12-min, and BLa recovery ($p=0.33$, $p=0.15$).

Participants in the ERG group experienced a greater increase in the speed of the 4th 50m effort following the intervention period compared to the PST group (+4.1% ± 2.5% vs. +1.1% ±1.97%, *p*=0.03, ES=0.35; see Figure 2). There was a significant difference between groups in BLa recovery (*p*=0.03) post-intervention, with a greater increase in BLa recovery for the PST group (ERG -13.2% ± 22.2% vs. PST +44% ± 14.5%, ES=0.63). There were no other statistically significant differences observed between groups following the intervention period.

4.3.2 6- and 30- second Swim Ergometer Tests

Results from the 6- and 30-sec maximal ergometer tests are shown in Table 2. Participants in both groups experienced a significant increase in every measure of power output after the intervention period (see Figure 3). The mean (ERG +10.9% ± 13.8%; PST +14.2% ± 11.2%; *p*<0.01, ES=0.54) and peak (ERG +7.9% ± 13.9% ; PST +10.3% ± 11.6%; *p*=0.02, ES=0.37) power for the 6 second test was significantly greater for both the ERG and PST group following the intervention period with no significant difference between groups. Participants in the ERG and PST group increased mean and peak power for 0-5 seconds (mean ERG +26.8% ± 19.9% vs. PST+35.1% ± 25%, *p*<0.01, ES=0.8; peak, +23.7% ± 20.1% vs. +38% ± 27.2%, *p*<0.01, ES=0.79) and the 5-10 seconds (mean, ERG +21.6% ± 13.8% vs. PST +26.2% ± 30%, *p*<0.01, ES=0.6; peak, +20.9% ± 15.4% vs. +25.6% ± 29.9%, *p*<0.01, ES=0.57) increments of the 30 second max ergometer test after the intervention. Additionally, ERG and PST group participants both experienced an increase in mean (+20.9% ± 20.1% vs. +23.8% ± 12.6%; *p*<0.01, ES=0.78) and peak (+16.1% ± 21.7% vs. +21.5% ± 8.6%; *p*<0.01, ES=0.69) power outputs of the 30 second increment after the intervention. Lastly, correlations (r=0.67-

0.75, p=0.01) were found between both peak and mean power outputs of the 6- and the, 10, and 30 increments of the 30-second max test and 50m swimming speed (see Figures 5-7).

After the sprint training intervention, both groups experienced a significant (p=0.04, ES=0.32) increase in BLa production 3-min post (see Figure 4), the ERG group increased 23.6% ± 24.9% and the PST group increased 10.4% ± 20.2%. BLa recovery significantly (p=0.01, ES=0.76) increased for both the ERG (+93.3% ± 4.1%) and PST group (+132.8% ± 13%) after the intervention period, indicating that the rate of blood lactate appearance was significantly enhanced after 4 weeks of sprint interval training. There were no significant differences in 12-min post BLa (p=0.37) and VO_2 (p=0.2) measures for either group between testing time points. Further, there were no significant differences observed for any measure of the 6 & 30-sec tests.

4.3.3 50 m Freestyle Race

50m freestyle race results are illustrated in Table 3. The ERG and PST group improvement in 50m sprint speed approached significance (1.8% ± 2.1% vs. 1.4% ± 3.5%; p=0.053; ES=0.23). However, 3-min post BLa increased for both the ERG and PST participants following their respective 4-week training intervention period (+19.4% ± 31.8% vs. +28.2% ± 52.6%; see Figure 5). No other significance was observed between time points.

4.4 Discussion

The purpose of this investigation was to determine if sprint interval training (SIT) on a swimming ergometer elicits a greater physiological and performance training response than a pool-based program. This was accomplished by comparing maximal anaerobic lactate test (MANLT), 6 and 30 second maximal swimming ergometer, and 50m competition freestyle performance test results after a 4-week training intervention period. To our knowledge, this is the first study to compare training responses to swimming ergometer and traditional pool-based training in a trained adolescent population. We hypothesized that the swimming ergometer training group (ERG) would attain greater training responses than the pool-based sprint training group (PST) as a result of higher pull resistance experienced by the ERG group.

The results of this study demonstrated no significant difference in; 1) mean swim speed of the MANLT; however, there was a significant improvement in the speed of the 4th 50m sprint and the rate of blood lactate recovery, 2) mean power in 6 & 30-second maximal ergometer test, and 3) 50m freestyle performance between the ERG and PST group after 4 weeks of SIT training respectively. Previous studies have shown that upper body strength and pull power have been positively associated with in-pool sprint performance (Pérez-Olea et al., 2018; Schumann & Rønnestad, 2019). It was hypothesized that power output improvements from the swim ergometer training would translate to increased sprint and fatigue resistance during the MANLT. Both groups experienced significant increases in power output for both swim ergometer tests after the intervention period. However, the ERG group experienced a greater performance improvement in the 4th 50m of the MANLT, increasing their swim speed 4.1% in comparison to the PST group who increased 1.1%. By significantly increasing their 4th 50m mean swim speed after the 4-week intervention, the ERG group demonstrated that the swimming ergometer improved the ability to sustain high intensity swimming performance more so than the PST group intervention in the pool. The similarity in training response to ERG and PST SIT over 4 weeks suggests that the swimming ergometer may be utilized as a dryland training modality in swimmers of this age demographic to mirror training response similar to what is seen in pool-based sprint interval training.

4.4.1 Maximal Anaerobic Lactate Test (MANLT)

The MANLT was originally designed to evaluate BLa response to different swimming programs throughout the course of a season and evaluate the testing results' relationship with middle distance swimming performance (P. Pelayo et al., 1996; Patrick Pelayo et al., 1995). Outside of swimming, the MANLT has been utilized for determining physiological characteristics of male professional water polo players (Tsekouras et al., 2005). Additionally, the test has been utilized in the past to determine differences in peak BLa accumulation between female senior and junior national level water polo players (Varamenti & Platanou, 2008). Both of these studies utilized the MANLT as a method for determining aerobic and anaerobic demands of male and female water polo players, but did not utilize the test to evaluate the effects of a training intervention.

In 1996, Pelayo and colleagues discovered that the MANLT was a valuable test for tracking BLa recovery in middle-distance (200m) freestyle swimmers. This group observed a significant decrease in recovery lactate in the swimmers when the training prescription changed from aerobic to anaerobic. With this result, they concluded that the MANLT could be a valuable method for tracking physiological adaptations to swim training. The current study utilized the MANLT before and after a sprint training intervention with trained adolescent swimmers to evaluate aerobic or anaerobic training effects. This is the first study to utilize the MANLT with a swimming sprint training group. The ERG group reported a decrease in BLa recovery from 3- to 12-min post (2.8 ± 0.5 to 2.4 ± 1.2 mmol/L), while the PST group experienced an increase (1.6 ± 1.3 to 2.7 ± 0.9 mmol/L). Despite large variability in performance changes, 3 of 7 athletes observed an increase in MANLT lactate recovery after 4 weeks of SIT on the swim ergometer. Training for the ERG group focused on increasing upper limb power output for improved propulsion. During SIT, the primary difference in training between groups was segmental versus full-body exercise. The back muscles were isolated for the ERG group while the PST group swam using arms, legs, and core. The ERG isolated the upper body only and yet similar improvements in performance between modalities was observed, further elucidating the practicality of swim ergometer training. Pelayo and colleagues, suggested that a decrease in BLa recovery was a practical indicator of anaerobic training improvement and increases were a practical indicator of aerobic improvement. With this said, the MANLT recovery results from the current study suggest that ERG group benefitted more anaerobically from the sprint training than the PST group.

4.4.2 Blood Lactate Response to Training

A significant increase in blood lactate (BLa) accumulation after the 50m freestyle race was observed for both the ERG and PST groups following the interventional periods. Specifically, peak BLa increased 19% and 28% for the ERG and PST group respectively. It has been established that anaerobic glycolytic energy contribution may be estimated through post exercise BLa collections (Buchheit & Laursen, 2013). In relation to the other studies, the results from the current study displayed similar effects. It has been reported in the past that there are several factors that cause an increase in muscle and blood lactate concentration at submaximal and maximal exercise intensities, such as accelerated glycolysis and lactate metabolism, fast twitch fibre recruitment, and accelerated blood lactate removal (Chatard, Lavoie, & Lacour, 1990). Elevated blood lactate responses to high-intensity training (HIT) have been reported as a result of the high work rate and low amount of rest of each interval, allowing less muscle oxygenation to occur, triggering a greater anaerobic energy contribution (Buchheit & Laursen, 2013). Results from a previous study involving intermittent sprint training on a treadmill at speeds of 120% of their max showed high metabolic (BLa) strain with short bouts of HIT training (Price & Moss, 2007). Additionally, when researchers compared differences between high- and low-cadence training with cyclists, a similar relationship to the present study was found between BLa and power output improvement (low: 11% and high: 8% over 4 weeks) (Paton, Hopkins, & Cook, 2009). The reviewed literature suggests that increases in BLa from HIT training are associated with improvements in power output across multiple modalities. Therefore, similar to the results of the present study changes in post exercise lactate accumulation with specific (HIT) training resulted in increases in anaerobic performances.

A previous study compared HIT and high-volume training (HVT) training during a 5-week randomized crossover involving 26 youth swimmers (Sperlich et al., 2010). Results were similar to the present study as peak BLa after the intervention increased 20% relative to baseline. Although improvement in 50m freestyle performance only approached statistical significance in the current study, swimming performance was found to significantly improve for 50 and 100-m free competition performance (CP) for the HIT group from the previous study (Sperlich et al., 2010). Statistically significant improvement seen in the previous study and not in the current study may be due to the increased sample size (26), and 5-week intervention in comparison to the 4-week intervention performed in this study. Swimming performance improved ~15% in both the 50 and 100-m CP and BLa increased 20% as well, which might suggest a relationship between increased BLa and CP may exist. Additionally, a study by Termin and Pendergast (2000) investigating the effects of HIT training during a four-year longitudinal study involving 22 university swimmers, exhibited similar BLa and CP results. With HIT training, a 27% increase in peak BLa during the first year was observed; however, peak BLa was not found to significantly increase in year 2, 3, and 4 (Termin & Pendergast, 2000). From a swimming perspective, performance improved 10% in the 100-yard CP over the four-year period. As such, research suggests that additional volume prescribed to trained swimmers is valuable up to a certain threshold, following that training intensity should the area of focus for improvements in sprint swimming performance (Chatard & Mujika, 1999; Hellard, Scordia, Avalos, Mujika, & Pyne, 2017).

In addition to BLa accumulation, BLa recovery following the 30 second maximal swim ergometer test was also differed for both groups after 4 weeks of SIT training. While the PST group experienced a 44% increased BLa recovery, the ERG group experienced a -13% decreased BLa recovery after the intervention. Accelerated lactate removal can be improved through aerobic and anaerobic training by increasing monocarboxylate transporter (MCT) utilization to clear lactate from slow and fast twitch muscle fibres (Houston, 2001). This could be as a result of the active recovery the PST group had in between each of their sprints, which has been reported to help with BLa clearance in the past (Buchheit & Laursen, 2013).

4.4.3 Power Output Improvement

Significant increases in power output for both the 6 and 30-second maximal swimming ergometer tests were observed in both the ERG and PST group following the 4-week SIT intervention period. Strong relationships (r=0.83) between upper and lower body power output for both sprint (50m) freestyle-swim performance in competitive youth swimmers have been established in the past (John A. Hawley, Williams, Vickovic, & Handcock, 1992). Estimation of peak power output enables accurate prediction of maximum speed during swimming, especially in short distances and high velocities (Johnson, Sharp, & Hedrick, 1993). In a previous study, the fastest swimmers not only displayed high anaerobic power outputs but also high mean sustained power outputs, as determined by the maximal workload achieved during a progressive, incremental maximal arm power test (John A. Hawley et al., 1992). In a study by Hawley et al. 1992, they concluded that ‘muscle power' is an important determinant in both sprint and middle-distance swimming performance. Furthermore, they also suggest that events up to 400m may benefit from training which aims to improve arm and leg power. In another study by (Dominguez-Castells, Izquierdo, & Arellano, 2012), a significant correlation (r=0.76) was found between maximum swim power, a 12.5m all-out swim with resistance, and maximum swim speed over 25 meters in competitive adult swimmers. Moreover, Johnson et al. (1993) found a significant relationship (r=0.91) between power output and sprint (25yd) freestyle performance (Johnson et al., 1993). The results from the previously listed studies report associated improvements in sprint swim performance when training to improve peak and mean power output in the upper and lower body outside of the pool. Relative to the present study, a correlation (r=0.67-0.75, p=0.01) was found between both peak and mean power outputs of the 6- and 30-second max test and 50m swimming speed.

Moreover, while results were not statistically significant in the current study, swim time decreased in both the ERG and PST groups, by 0.46 and 0.38 seconds for each group respectively. Although this result is not statistically significant, practically speaking, this result is very significant for swimmers who's 50m time is ~27 seconds. To improve by roughly 1.5% after only four weeks of training is noteworthy in a race that is commonly decided by one-hundredths of a second in competition. Effect sizes from the results of this study indicate that the training worked effectively. For instance, the 50m freestyle performance for each group did not significantly improve (p>0.05), but the effect size was 0.23, indicating a large (>0.14) effect. There has been an association found between upper body pull power and sprint performance in the past, and this study determined that swimming ergometer training was as beneficial as traditional pool-based SIT in adolescent trained swimmers. Six-second mean power output significantly (p<0.01) increased for the ERG and PST groups after 4 weeks of SIT training. Additionally, an increase in the correlation (from r=0.65 to r=0.75) between 6-second mean power output on the swim ergometer and 50m freestyle swim speed was observed (see Figure 5). This result consecutively agrees with previous research that increased anaerobic dryland power is correlated with sprint swim performance in adolescent swimmers.

4.5 Conclusion

This is the first study to demonstrate similarities in training response to 4 weeks of sprint interval training with a swim ergometer and pool-based training. Although, 50m freestyle performance was not significantly improved after 4 weeks of SIT in either group, there were similar and significant improvements in physiological responses to SIT in both training modalities. To illustrate, both training groups experienced improved mean 6-sec power output on the swim ergometer, which was strongly correlated ($r=0.75$, $p<0.01$) with 50m freestyle performance. The main difference between training groups after the 4-week SIT intervention was demonstrated in a significantly faster 4^{th} 50m sprint of the MANLT with a similar 3-min blood lactate response after the 30 second max ergometer test in the ERG group only. This may be due to the nature of ERG training which generates greater force propulsion per stroke, thus recruiting more glycolytic muscle fibers in the upper back, which in turn led to a similar glycolytic training response in comparison to the PST group which utilized the whole body. The results provide novel findings in the field of competitive adolescent sprint swim training; specifically, the results suggest that 4-weeks of SIT is effective at improving anaerobic characteristics and that the use of a swimming ergometer parallels the improvements seen in pool-based sprint training.

4.6 Tables and Figures

Table 1. Differences in mean swim speed efforts 1-4, peak and average speed, fatigue, immediately post-test peripheral capillary oxygen saturation (SpO_2) and volume of oxygen consumed (VO_2), along with 3 and 12-min post blood lactate (BLa) and BLa recovery, of the Maximal Anaerobic Lactate Test (MANLT) before and after the intervention period between the swimming ergometer (ERG) and pool (PST) sprint training groups.

	ERG Group		PST Group	
	Pre	Post	Pre	Post
Speed 1 (m/s)	1.74 ± 0.08	1.72 ± 0.08	1.70 ± 0.1	1.67 ± 0.08
Speed 2 (m/s)	1.60 ± 0.06	1.62 ± 0.06	1.58 ± 18.13	1.54 ± 0.08
Speed 3 (m/s)	1.54 ± 0.04	1.58 ± 0.05	1.51 ± 0.07	1.53 ± 0.09
Speed 4 (m/s)	1.52 ± 0.03	1.58 ± 0.07*†	1.46 ± 0.05	1.48 ± 0.07*†
Stroke Rate 1	45.6 ± 4.1	42.7 ± 1.5	44.7 ± 4.6	44.7 ± 3.2
Stroke Rate 2	40.8 ± 2.2	41.3 ± 2.9	42.2 ± 5.6	40.6 ± 3.0
Stroke Rate 3	39.7 ± 2.3	40.6 ± 3.1	41.1 ± 5.3	40.9 ± 3.4
Stroke Rate 4	38.6 ± 3.9	40.9 ± 2.7	42.5 ± 6.7	40.3 ± 4.2
Peak Speed (m/s)	1.74 ± 0.08	1.72 ± 0.08	1.70 ± 0.10	1.67 ± 0.08
Average Speed (m/s)	1.60 ± 0.05	1.63 ± 0.06	1.57 ± 0.07	1.55 ± 0.07
Fatigue (m/s)	0.22 ± 0.05	0.15 ± 0.05*	0.24 ± 0.08	0.20 ± 0.07*
Heart Rate (bpm)	165.9 ± 16.4	163.7 ± 14.9	160.5 ± 24.2	138 ± 28.3
SpO_2 (%)	90.7 ± 4.8	95.7 ± 3.6	91.3 ± 5.2	85.4 ± 8.3
VO_2 (ml/min/kg)	55.6 ± 19.7	48.9 ± 9.8	49.5 ± 19.7	39.1 ± 6.0
3-min Post BLa (mmol/L)	10.1 ± 3.4	8.9 ± 3.0	9.6 ± 2.5	9.3 ± 1.9
12-min Post BLa (mmol/L)	7.2 ± 3.4	6.5 ± 2.4	7.7 ± 2.2	6.6 ± 1.6
BLa Recovery (mmol/L)	2.8 ± 0.5	2.4 ± 1.2†	1.6 ± 1.3	2.7 ± 0.9†

Values are means ± SD.
*Significantly different from Pre to Post ($p<0.01$). † Significantly different between ERG and PST Group ($p<0.05$).

Table 2. Differences in mean power for the 6-second max test; differences in 5, 10, and 30-second mean and peak power, volume of oxygen consumed (VO_2) throughout the test, 3 and 12-min post blood lactate (BLa) and BLa recovery of the 30 second swimming ergometer max test before and after the intervention period between the swimming ergometer (ERG) and pool (PST) sprint training groups.

	ERG Group		PST Group	
	Pre	Post	Pre	Post
Mean Power 6-sec (W)	199.1 ± 37.1	219.6 ± 41.2**	185 ± 38.3	205.6 ± 51.4**
Peak Power 6-sec (W)	219.3 ± 42.3	234.4 ± 40.6*	203.7 ± 41.7	216.9 ± 53.3*
Mean Power 5-sec (W)	172.7 ± 51	212 ± 42.5**	163.7 ± 46.4	206.8 ± 51.3**
Peak Power 5-sec (W)	185.3 ± 55.5	222 ± 46.3**	171.2 ± 49.4	220.1 ± 53.7**
Mean Power 10-sec (W)	170.3 ± 47	202.1 ± 37.6**	166.4 ± 47.6	193.5 ± 48.7**
Peak Power 10-sec (W)	179.3 ± 51.3	211.4 ± 42.3**	176.2 ± 45.2	204.7 ± 49.9**
Mean Power 30-sec (W)	139.2 ± 37.0	163.6 ± 29.2**	134 ± 28.2	157.9 ± 34.2**
Peak Power 30-sec (W)	153.6 ± 40.8	172.6 ± 31**	144.8 ± 27.9	167.7 ± 37.3**
VO_2 (ml/min/kg)	37.4 ± 2.9	41.4 ± 3.8	38.1 ± 2.3	44 ± 4.2
3-min Post BLa (mmol/L)	5.1 ± 1.3	6.1 ± 0.9*	5.5 ± 1.7	5.8± 1.0*
12-min Post BLa (mmol/L)	3.9 ± 1.3	3.7 ± 1.7	4.6 ± 1.4	3.9 ± 1.0
BLa Recovery (mmol/L)	1.3 ± 1.1	2.5 ± 1.0**	0.8 ± 1.1	1.9 ± 1.0**

Values are means ± SD.
*Significantly different from Pre to Post (p<0.05). ** Significantly different from Pre to Post (p<0.01).

Table 3. Differences in mean time, swim speed, 3 & 12-min post blood lactate (BLa), and BLa recovery of the 50m Freestyle test before and after the intervention period for the swimming ergometer (ERG) and pool (PST) sprint training groups.

	ERG Group		PST Group	
	Pre	Post	Pre	Post
Time (s)	26.9 ± 1.4	26.5 ± 1.4	27.7 ± 1.5	27.3 ± 1.3
Speed (m/s)	1.9 ± 0.1	1.9 ± 0.1	1.8 ± 0.1	1.8 ± 0.1
3-min Post BLa (mmol/L)	7.0 ± 1.7	8.0 ± 0.9*	8.2 ± 2.1	8.9 ± 2.6*
12-min Post BLa (mmol/L)	5.4 ± 0.6	5.5 ± 1.0	5.8 ± 1.5	5.9 ± 2.1
BLa Recovery (mmol/L)	1.6 ± 1.5	2.5 ± 1.1	2.1 ± 2.1	3 ± 1.0

Values are means ± SD.
*Significantly different from Pre to Post (p<0.05).

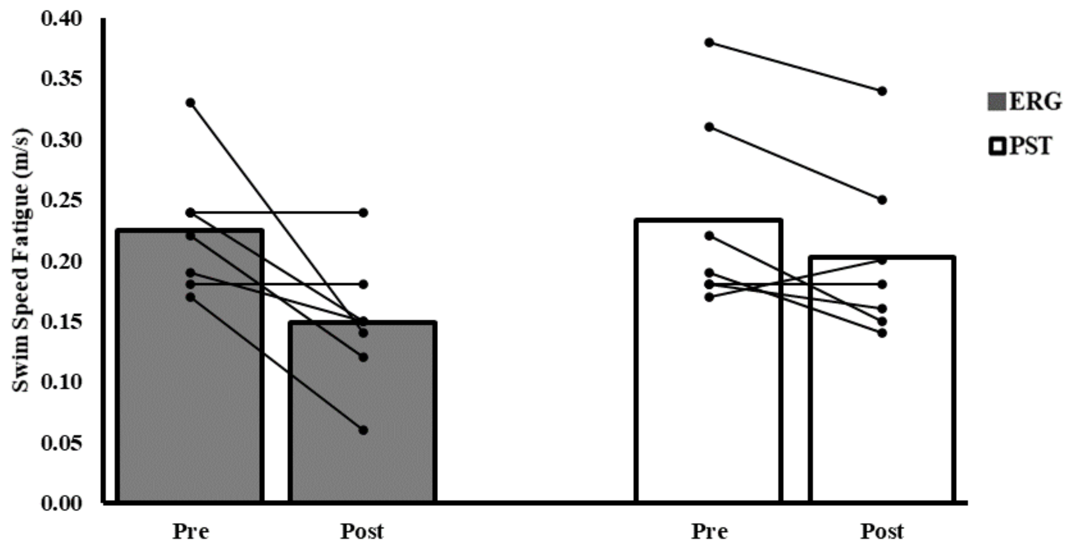

Figure 1. MANLT group mean (in bars) and individual (black circles) swim speed fatigues pre- and post-intervention in both the ERG (n=7) and PST (n=7) groups. * MANLT swim speed fatigue significantly (p<0.01) decreased over time for both the PST (0.24 ± 0.08 to 0.20 ± 0.07 m/s) and ERG (0.22 ± 0.05 to 0.15 ± 0.05 m/s) group. Values are means ± SD.

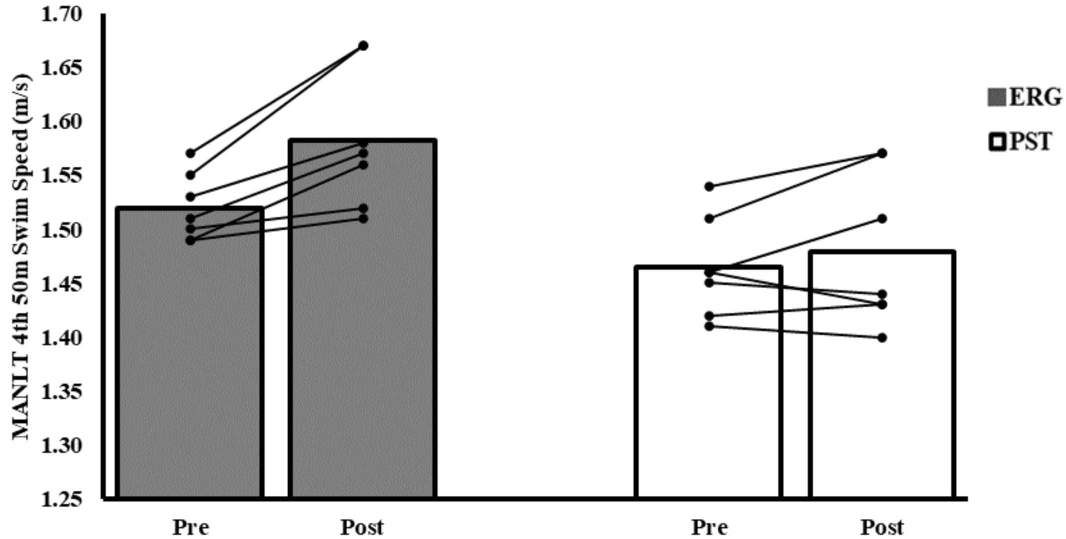

Figure 2. MANLT 4th 50m group mean (in bars) and individual (black circles) swim speed pre- and post-intervention in both the ERG (n=7) and PST (n=7) groups. * MANLT 4th 50m mean speed significantly (p<0.01) increased over time for both the ERG (1.52 ± 0.03 to 1.58 ± 0.07 m/s) and PST group (1.46 ± 0.05 to 1.48 ± 0.07 m/s). The ERG group experienced a significantly greater improvement in 4th 50m mean speed than the PST group (p<0.05). Values are means ± SD.

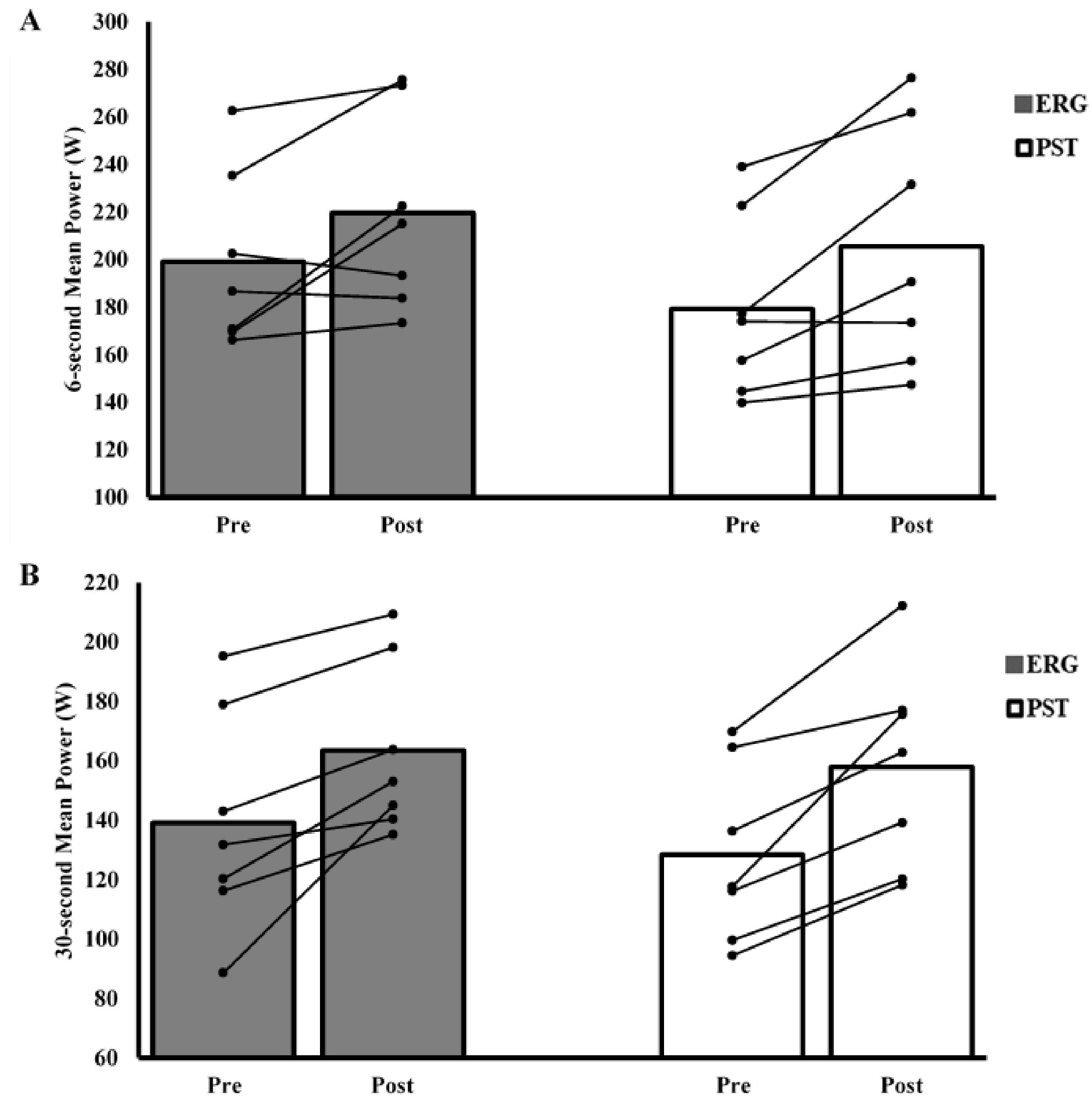

Figure 3. Mean Power from the A) 6-second max test and B) 30-second max test; group mean (in bars) and individual (black circles) pre- and post-intervention in both the ergometer (ERG) (n=7) and pool sprint training (PST) (n=7) groups. The ERG (6sec: Pre 199.1 ± 37.1 vs. Post 219.6 ± 41.2 watts) (W); 30sec: Pre 139.2 ± 37.0 vs. Post 163.6 ± 29.2 W) and PST (6sec: Pre 185 ± 38.3 vs. Post 205.6 ± 51.4 W; 30sec: Pre 134 ± 28.2 vs. 157.9 ± 34.2 W) power for the 6 second test and 30 second test was significantly ($p<0.01$) different over time. Values are means ± SD.

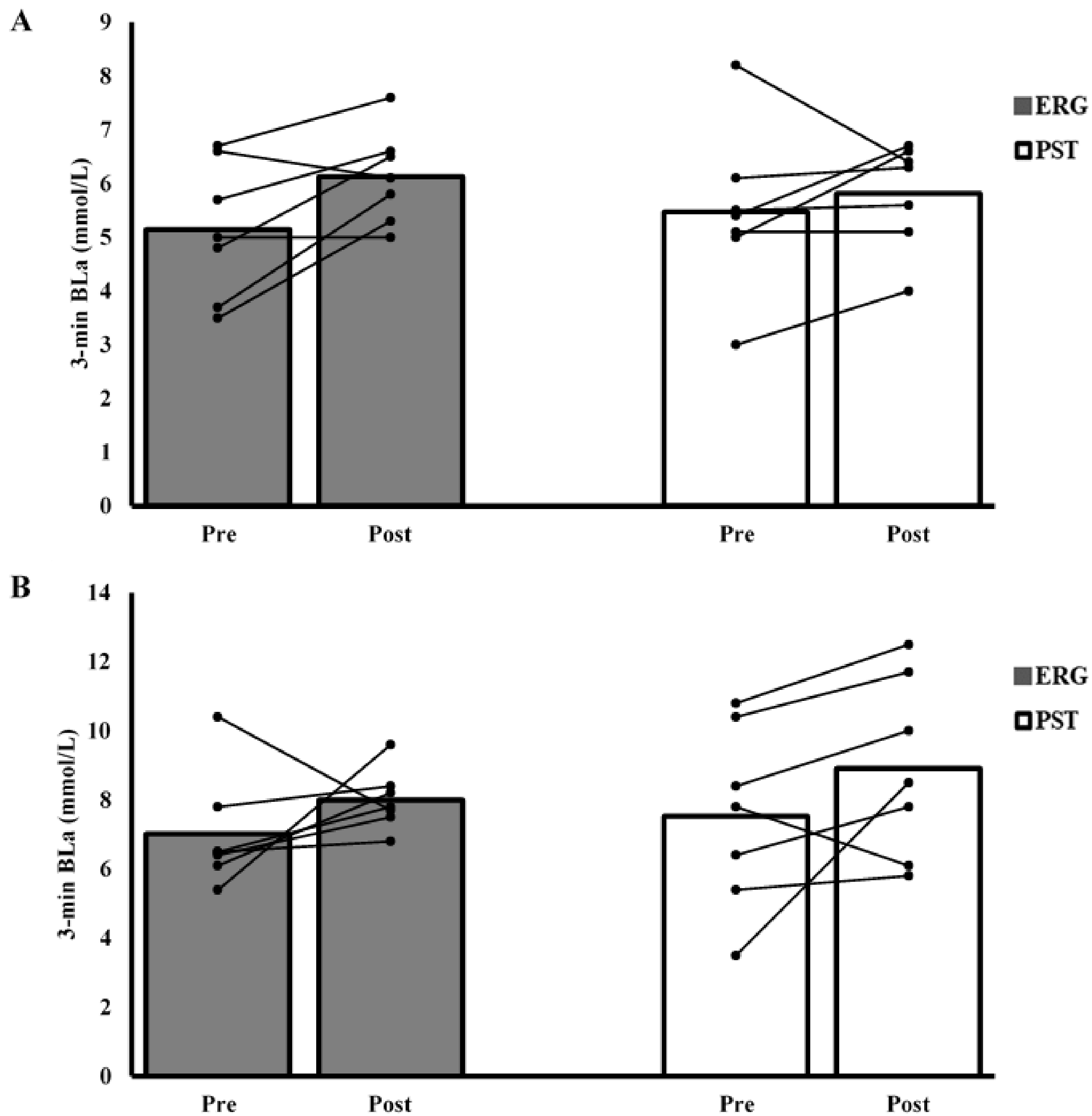

Figure 4. 3-min post BLa from the (A) 30-sec Max Erg Test and (B) 50 metre freestyle race; group mean (in bars) and individual (black circles) BLa measurements pre- and post-intervention in both the ergometer (ERG) (n=7) and pool sprint training (PST) (n=7) groups. The ERG and PST group's 30-sec Max Erg Test 3-min BLa significantly (p<0.01) increased (ERG: Pre 5.1 ± 1.3 vs. Post 6.1 ± 0.9; PST: Pre 5.5 ± 1.7 vs. Post 5.8± 1.0 mmol/L, *p*<0.01) from Pre to Post. The ERG and PST group's 50 metre freestyle race 3-min BLa significantly (p<0.05) increased (ERG: Pre 7.0 ± 1.7 vs. Post 8.0 ± 0.9; PST: Pre 8.2 ± 2.1 vs. Post 8.9 ± 2.6, *p*<0.01) from Pre to Post. Values are means ± SD.

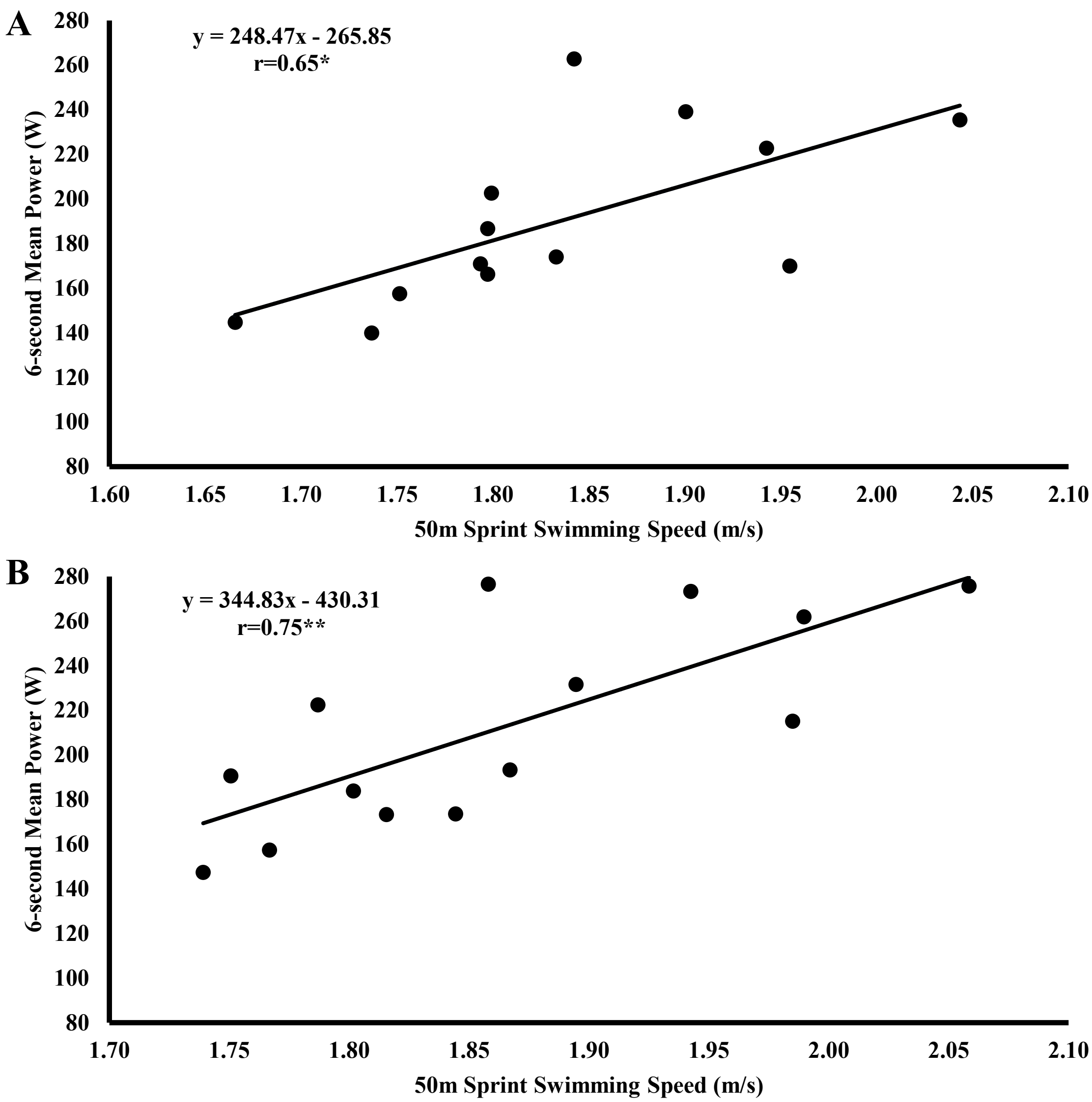

Figure 5. Correlation between mean power of the 6-second max test and 50m freestyle swim speed of PRE (A) (r=0.65, $p<0.05$) and POST (B) (r=0.75, $p<0.01$) measures. * significance ($p<0.05$). ** significance ($p<0.01$).

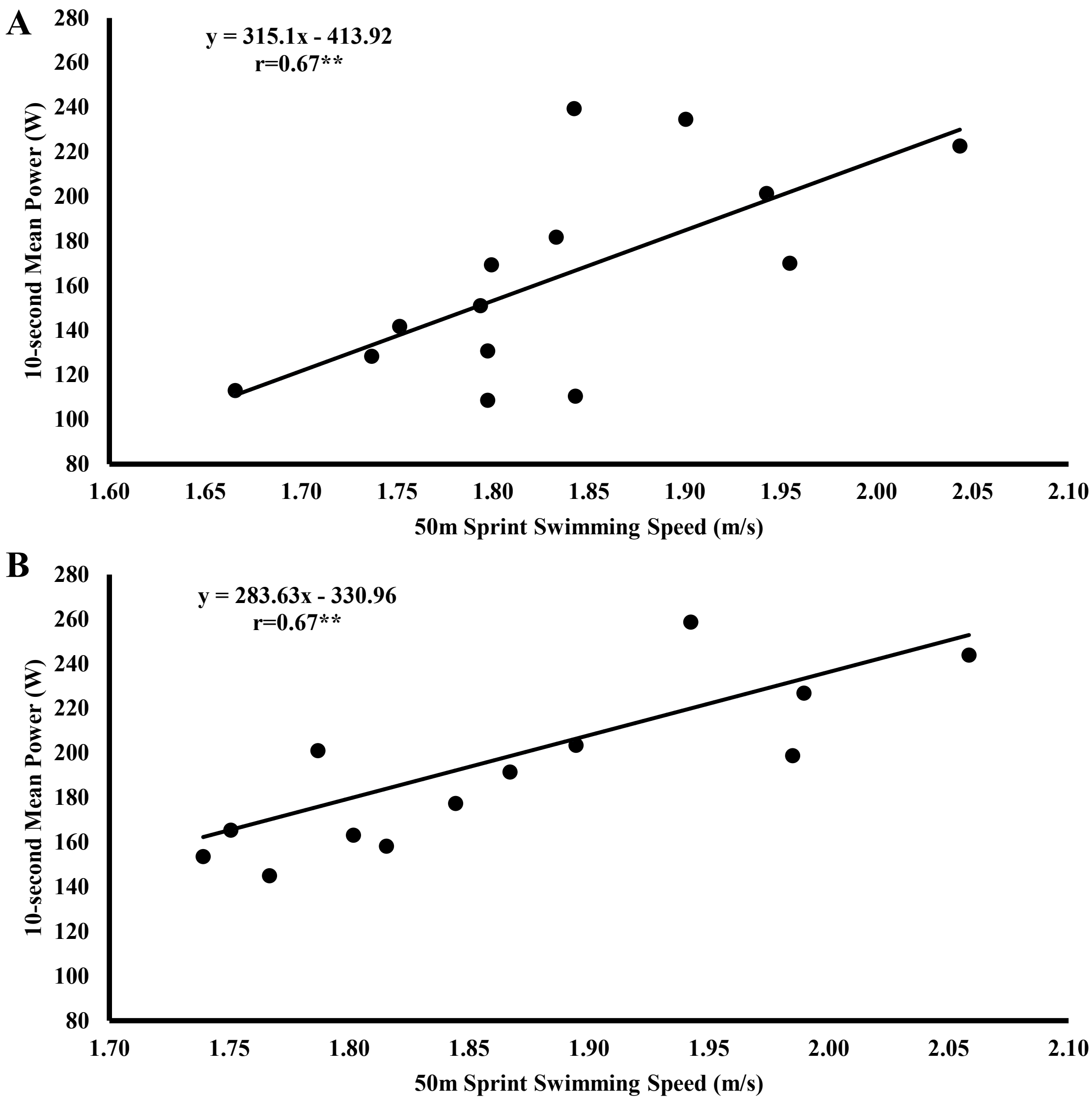

Figure 6. Correlation between 10 second mean power of the 30-second max test and 50m freestyle swim speed of PRE (A) (r=0.67, $p<0.01$) and POST (B) (r=0.67, $p<0.01$). ** significance ($p<0.01$).

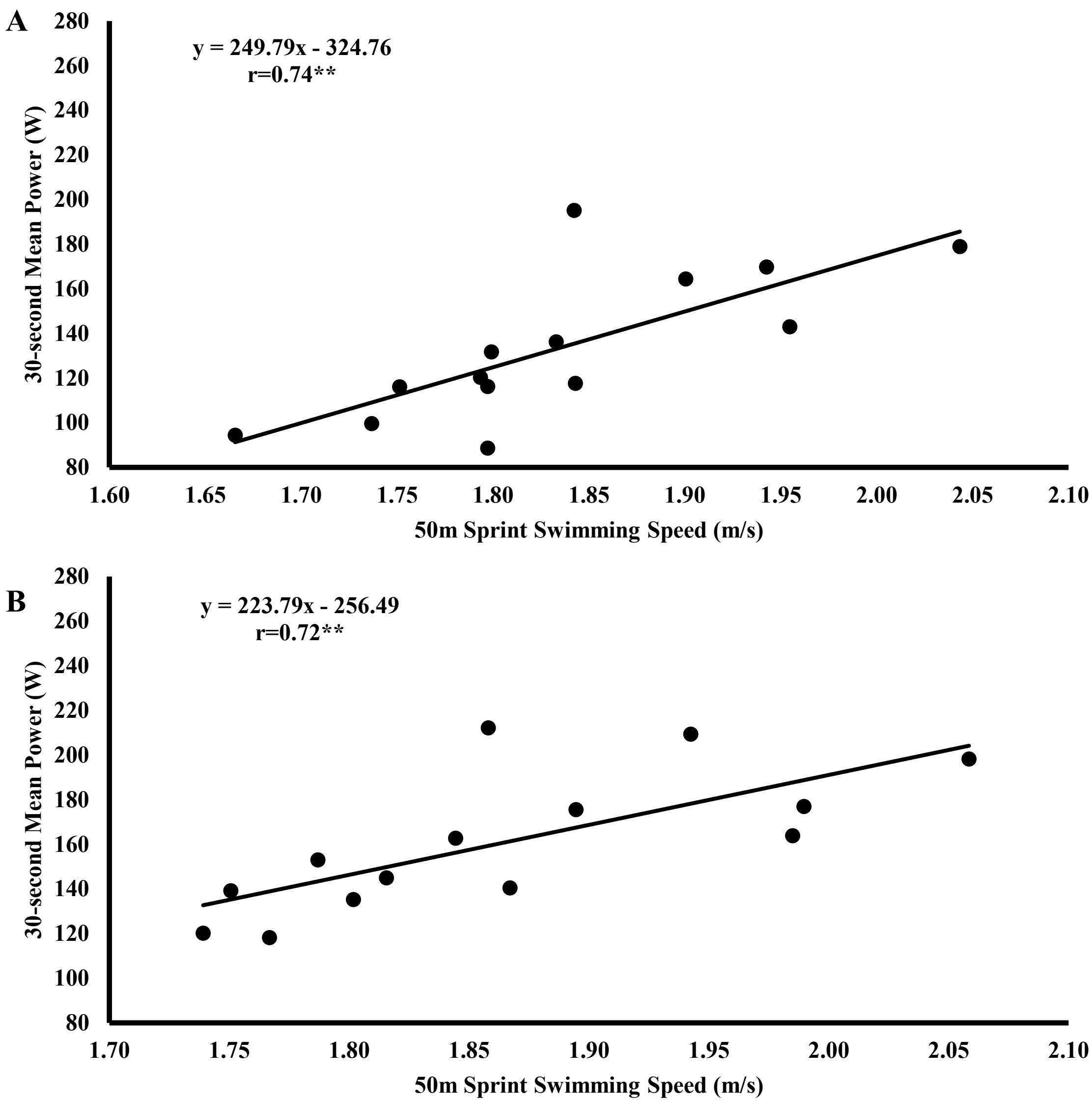

Figure 7. Correlation between 30 second mean power of the 30-second max test and 50m freestyle swim speed of PRE (A) (r=0.74, $p<0.01$) and POST (B) (r=0.72, $p<0.01$). ** significance ($p<0.01$).

Chapter 5. Conclusion

5.1 Limitations

There were a number of limitations that should be considered in the context of the results obtained. Firstly, given that the selected training group is the club's "high performance" cohort and consists of swimmers with national-qualifying times, the program only has 18 athletes that train in the group, with a total of 14 qualifying for the study. Secondly, there was no true control group for this study. It would have been ideal that a group completed no sprint training over the four-week intervention period. Having this additional group would have provided a better comparison group for the ERG group. The control group would not have had any additional training, and because of this, their results would have helped justify if the sprint training was truly impactful on the swimmers' improved sprint performance. Thirdly, most training intervention studies range from 8-12 weeks or even longer. Given that our study was only 4-wks long suggests that results could vary with a longer time frame. Noticeable training adaptations take time to occur, especially when you introduce a new training stimulus (Aspenes, Kjendlie, Hoff, & Helgerud, 2009; Garrido et al., 2010; Girold, Maurin, Dugue, Chatard, & Millet, 2007). Finally, the participants were younger and not yet specialized. As such, some swimmers were stronger sprint swimmers relative to others. Some of the participants were not normally freestyle swimmers in competition and this could have impacted our results. Even though swimmers at this age will spend a large portion of their training time swimming freestyle, some of the participants did not compete in freestyle.

5.2 Future Directions

It is important to note that individual responses to training vary, so it is recommended that future studies should use a larger sample size across with age ranges up to 18 years old. By doing this, researchers could study the impact of age and swim ergometer training. In addition, future research should also utilize mixed populations of male and female swimmers to identify any sex differences in training adaptation across the adolescent population. Understanding how much training is needed outside of the pool is essential for swimming performance, and this topic that has been studied extensively in the past decade (Schumann & Rønnestad, 2019). However, the most optimal type of training or modality has not yet been fully established. Another area of research that could be explored is evaluating differences between traditional resistance exercise and swimming ergometer training on in-pool sprint performance. This would be valuable for future training prescription as it could save time and decrease accumulated fatigue. Moreover, future research study the relevance of power training on the swim ergometer in contrast to traditional dryland resistance power training.

There are a number of potential areas for future research in this area to be explored. Firstly, it is important to note that individual responses to training vary, so it is recommended that future studies should use a larger sample size across with age ranges up to 18 years old. By doing this, these researchers would be able to study whether age has an effect on training responses to swimming ergometer training. Future research should also utilize mixed populations of male and female swimmers to identify any sex differences in training adaptation across the adolescent population.

Understanding how much training is needed outside of the pool is essential for swimmers, and this topic that has been studied extensively in the past decade (Schumann

& Rønnestad, 2019). However, the most optimal type of training or modality has not yet been fully established for each age and/or competitive level of swimmer. Another area of research that could be explored is evaluating differences between traditional resistance exercise and swimming ergometer training on in-pool sprint performance. This would be valuable for future training prescription. Future research should look into the relevance of power training on the erg in comparison to traditional dryland resistance power training in the weight room.

5.3 Practical Applications

The results of this study highlight the importance of dryland anaerobic training with adolescent swimmers. Moreover, the results of the 30 sec swim ergometer maximal test and MANLT demonstrate that the swim ergometer is a valuable modality for sport-specific high intensity training. Therefore, the swim ergometer can be used as an alternative to other traditional modalities used to improve sprint swimming earlier in development.

5.4 Conclusion

The results from this thesis indicate swimming ergometer and pool-based SIT comparably improved dryland upper body power output transfer similarly over to in-pool sprint performance. The swim ergometer isolated the upper body in training but still produced similar improvements in performance between modalities. As well, the swim ergometer training trends to have a more focused glycolytic response as indicated by higher 3-min BLa response in the 30-second max test and a faster 4^{th} 50m freestyle speed in the MANLT while training was focused on one major muscle group. These results suggest that swim ergometer training is more effective than pool-based training at isolating the upper body, and is just as effective as doing whole-body SIT training. These novel findings suggest swim ergometer training is beneficial for improving sprint performance in trained adolescent swimmers.

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APPENDICES

Appendix A. CSEP 2019 Publication

dyspnea (2.2±0.3 vs 3.3±0.3 Borg units, p=0.002) in COPD, while no effect was observed in controls. Resting PASP was reduced in both groups with iNO (COPD p=0.017, Control p=0.035). Arterial O_2 saturation, cardiac output and systemic vascular conductance were unaffected by iNO at rest and during exercise in both groups. The current results suggest that patients with mild COPD demonstrate pulmonary vascular dysfunction which contributes to heightened dyspnea and reduced exercise capacity, secondary to inefficiencies in pulmonary gas-exchange.

Blood flow restricted resistance training improves muscular endurance, irrespective of strength or skeletal muscle mitochondrial and microvascular adaptations

C. Pignanelli,[1] H.L. Petrick,[1] F. Keyvani,[2] G.J.F. Heigenhauser,[3] J. Quadrilatero,[2] G.P. Holloway,[1] and J.F. Burr[1]

[1]Department of Human Health & Nutritional Sciences, University of Guelph, Guelph, ON N1G 2W1 Canada.
[2]Department of Kinesiology, University of Waterloo, Waterloo, ON N2L 3G1 Canada.
[3]Department of Medicine, McMaster University, Hamilton, ON L8S 4L8 Canada.

The application of blood flow restriction (BFR) during resistance exercise is increasingly recognized for its ability to improve rehabilitation and as an effective method for increasing muscular hypertrophy and strength amongst healthy populations. However, direct comparison of the skeletal muscle adaptations to low-load resistance exercise (LL-RE) and low-load blood flow restriction resistance exercise (LL-BFR) performed to repetition failure are lacking. Using a within-subject design, we examined whole-body and skeletal muscle physiological outcomes to 6-weeks of LL-RE and LL-BFR training to repetition failure. We demonstrate both types of training have similar muscle strength and size outcomes despite ~33% lower total exercise volume (load x repetition) with LL-BFR (LL-RE: 28,544±1,771 kg vs. LL-BFR: 18,949±1,541 kg, p=0.004). Following training, both LL-RE and LL-BFR increased power output during the first 10 repetitions of a muscular endurance test. However, only LL-BFR sustained a greater power output during repetitions 11-20 by 14% (p<0.0001), despite histological analysis revealing similar increases in capillary content of type I muscle fibers, which was primarily driven by increased capillary contacts (Pre: 4.53±0.23 vs. LL-RE: 5.33±0.27 and LL-BFR: 5.17±0.25, both p<0.05). Moreover, maximally-supported mitochondrial respiratory capacity increased only in the LL-RE leg by 20% (p=0.006). Overall, this study demonstrates training related differences between LL-RE and LL-BFR with regard to muscle fatigue, which are not explained by muscular strength and size or skeletal muscle mitochondrial and microvascular properties.

Validity of the 'Maximal Anaerobic Lactate Test (MANLT)' and all-out swim ergometer performance in sprint and middle-distance adolescent swimmers

A. Pinos,[1,2] E. Fernandes,[2] E. Viana,[1] D. Bentley,[1] and H.M. Logan-Sprenger[2]

[1]University of Ontario Institute of Technology.
[2]Canadian Sport Institute of Ontario.

There is a scarcity of scientific studies that has compared anaerobic in-pool and laboratory-based performances between competitive swimmers differing in sprint performance ability. The purpose of this study was 1) to examine the relationship between the results of the maximal anaerobic lactate test (MANLT) and the 45-second swimming erg max test, and 2) to compare the performance and lactate recovery responses in the MANLT and 45-second swim ergometer max test. Sixteen (n=16) well-trained swimmers (mean±SD, age 16.8±0.7 yrs; body mass 67.3±9.8 kg) from a homogenous training group voluntarily participated in this study. Swimmers were categorized into two gender matched groups; sprint (n=8) and middle-distance (n=8) based on competitive swim performances. Each athlete performed two tests over a 7-day period; 1) 45 second (sec) max swim erg laboratory test to determine peak and mean power output (watts (w)), 2) MANLT test composed of a broken 200 meters (m) consisting of 4 x 50m max swims with 10 sec rest intervals. Peak and average velocity (m/s) across all four efforts were measured. Blood lactate samples (mM) were taken at 3- and 12-minutes after the 45 sec max swim erg test and the last 50m effort of the MANLT. Significant differences were found between the middle-distance and sprint group in the average (p= 0.026) and peak velocity (p=0.031) of the MANLT, with the sprint group having a higher average and peak velocity. Significant correlations were found between the peak velocity of the MANLT and ergometer measures such as: 10-second power output (r=0.70, p=0.002, ES= 0.52), ergometer 45-second power output (r=0.83, p=0.00, ES= 0.80), ergometer 3-min post lactate (r=0.68, p=0.08, ES= 1.07), and ergometer 12-min post lactate (r=0.62, p=0.01, ES= 1.17). There was a significant correlation (r=0.71, p=0.00, ES= 0.52) between the average velocity of the MANLT and 10 second power output from the ergometer test, but no correlation was found between the 3-min (r=0.43, p= 0.092) and 12-min (r=0.36, p= 0.168) post lactate values. The results of this study indicate the MANLT can be used to distinguish sprint performance in well trained adolescent athletes. The strong relationship between the results of the MANLT and the 45 sec max ergometer test indicates the 'non specific' anaerobic contribution to sprint swimming performance and therefore ergometer testing may be used as both a testing and training modality in sprint swimming preparation. The MANLT and swim ergometer test may be utilized as a testing tool for determination of the anaerobic performance capacity of swimmers in this age and competitive group.

Post-activation potentiation and the potential for non-local effects

G.M.J. Power, E.M. Colwell, M. Elliott, G. Furlong, Z. Thorne, R. George, S.S.G. Caravan, R.R. Dyer, J.M. Combden, and D.G. Behm

School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, NL A1B 3X9, Canada.

Post-activation potentiation (PAP) leads to enhancements of force production and rate of force development in a muscle. PAP is associated with the phosphorylation of myosin regulatory light chains caused by previous activity to the muscle. It is not well known if other mechanisms play a major role in PAP. We explored whether PAP could be elicited in the unconditioned quadriceps from a conditioning activity in the contralateral quadriceps. Finding non-local PAP effects would give evidence for the existence of spinal and/or supraspinal mechanisms. The study included 32 physically active participants, including 16 males (age: 22.9 ± 2.03 years; height: 180.5 ± 5.92 cm; weight: 82.8 ± 9.43 kg;) and 16 females (age: 23.1 ± 2.80 years; height: 166.6 ± 7.35 cm; weight: 66.4 ± 11.09 kg;). Each participant completed two control sessions (1. dominant leg; 2. non-dominant leg) and two intervention sessions (1. Conditioning exercise and test ipsilateral leg; 2. ipsilateral leg conditioning exercise and test contralateral leg). The testing protocol consisted of unilateral isometric maximum voluntary contractions (MVC) of the knee extensors, single-leg drop jumps, single leg countermovement jumps, and a reaction time test. Scores were compared prior to, and 1 and 10 minutes after the conditioning protocol (4 x 5s MVCs). There were no significant PAP effects from pre-test to post-test in any session, but there was evidence for PAP effects from the 1-minute to 10-minute post-tests in the intervention sessions during the countermovement jump and reaction time tests. Significant fatigue effects were found in the MVC and drop-jump test during both intervention and control sessions (p < 0.05). These findings indicate that the conditioning protocol could not effectively elicit PAP effects in the exercised or contralateral leg. Also, the significant findings during control sessions, and between the two post-tests, suggest that the testing protocol itself had a conditioning effect on muscle performance.

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