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Investigation of Swimming Physiology and Swimming Kinematics while Wearing Different Triathlon Wetsuit Styles at Submaximal Front Crawl Swimming in Recreational Population

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INVESTIGATION OF SWIMMING PHYSIOLOGY AND SWIMMING KINEMATICS WHILE WEARING DIFFERENT TRIATHLON WETSUIT STYLES AT SUBMAXIMAL FRONT CRAWL SWIMMING IN RECREATIONAL POPULATION

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Abstract

Triathlon wetsuits are commonly used due to the potential benefits in swimming performance and thermoregulation. Triathletes may select different wetsuit styles depending on many factors such as temperature regulation, swimming technique, body type, and training purpose. However, there is a lack of empirical evidence for how different wetsuit styles affect physiological responses and swimming kinematics during submaximal swimming intensity. Therefore, this study aimed to investigate the physiological responses and swimming kinematics during submaximal intensity front crawl swimming while wearing different wetsuit styles.

Fourteen participants (n=6 male, n=8 female; all recreational triathletes or swimmers) completed a swimming graded exercise test (GXT) wearing only a swimsuit to determine maximal oxygen consumption ($\dot{V}O_2$max). The test swimming pace for the experimental sessions was calculated as 80% of $\dot{V}O_2$max from the GXT. Participants then completed four wetsuit conditions: regular swimsuit (NWS), buoyancy short (BS), sleeveless (SLW), and full sleeve wetsuit (FSW). Each swim was 4-minutes submaximal at the same test swimming pace. The order of the wetsuit conditions was randomized. All conditions were conducted in a swimming flume and metabolic measurements were made using a metabolic cart with a mixing chamber. The rate of oxygen consumption ($\dot{V}O_2$; $ml \cdot kg^{-1} \cdot min^{-1}$), rate of carbon dioxide production ($\dot{V}CO_2$; $L \cdot min^{-1}$), ventilation (V_E; $L \cdot min^{-1}$), heart rate (HR; bpm), respiratory exchange ratio (RER), and cost of transport (COT; $J \cdot kg^{-1} \cdot m^{-1}$) were determined as the average for the last minute of each condition. The rating of perceived exertion (RPE) was assessed after each condition. Also, the time to completion of 10 strokes was measured for further general stroke characteristics analysis such as stroke rate (SR; Hz), stroke length (SL; m), and stroke index (SI; m^2/s).

$\dot{V}O_2$, $\dot{V}CO_2$, V_E, HR, and COT were each significantly different in the main effect by wetsuit conditions ($p < 0.001$). RER and RPE were significantly influenced by wetsuit conditions ($p < 0.05$). Based on the pairwise comparison, swimming without a wetsuit was significantly higher in $\dot{V}O_2$, $\dot{V}CO_2$, V_E, HR, and RPE relative to the other wetsuit conditions ($p < 0.05$). Furthermore, $\dot{V}O_2$, $\dot{V}CO_2$, and COT during swimming with buoyancy shorts were significantly higher than SLW and FSW ($p < 0.05$). However, all dependent variables were not statistically different between SLW and FSW ($p > 0.05$). Stroke kinematics were not significantly different across the wetsuit conditions ($p > 0.05$). Positive correlations existed between $\dot{V}O_2$ and HR vs. stroke kinematics (i.e., SR, SL, SI). In addition, there were positive correlations between COT and SR. However, negative correlations existed between COT vs. SL and COT vs. SI.

In conclusion, swimming with a regular swimsuit is the least economical at the test pace. In addition, it seems that either SLW or FSW can be used without significant physiological changes when swimming at 80% of $\dot{V}O_2max$. Stroke kinematics did not change between wetsuit conditions. In addition, improving stroke length and index may be a good strategy for improving swimming efficiency.

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To my heavenly Father, Jesus Christ, I truly appreciate everything you gave me. I couldn't do anything without your grace and unconditional love. This achievement isn't just for me but is dedicated to others who need my knowledge, guidance, advice, and warm helping hands. I am going to do everything to manifest the glory of God in a humble manner.

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Chapter 1: Introduction

Swimming is a physical activity that promotes health-related fitness, mitigates the risk factors of cardiovascular disease, and is used in rehabilitation programs after lower extremity injuries (Gojkovic et al., 2019; Tanaka et al., 2009). Generally, the benefits of swimming are similar to those of other weight-bearing exercises such as running and cycling, but it has less impact on the joints. More than one hundred million people in the U.S. participate in swimming in both the pool and/or open water annually (Baldassarre et al., 2017; Pink et al., 1991; Tipton & Bradford, 2014; Ulsamer et al., 2014). According to the Centers for Disease Control and Prevention (CDC) and the USA Triathlon section of the United States Olympic and Paralympic Committee (USA-Triathlon/About), the number of individuals participating in open water swimming and triathlons has continuously increased over the years. Furthermore, both triathlons and open water swimming were getting attention even more after both events officially became Olympic sports at the Sydney Olympics 2000 and Beijing Olympic 2008, respectively (Baldassarre et al., 2017; Tipton & Bradford, 2014; Ulsamer et al., 2014; Vogt et al., 2013).

A triathlon consists of open water swimming, cycling, and running. Triathlon race events are primarily divided by distance into four categories: Sprint (750m swim, 20-km bike, and 5-km run), Olympic (1.5-km swim, 40-km bike, and 10-km run), Half-Ironman (1.9-km swim, 90-km bike, and 21.1-km run), Ironman (3.8-km swim, 180-km bike, 42.2-km run) (Strock et al., 2006). The swimming distance is typically much shorter when compared to cycling and running distance (Bales & Bales, 2012; Vleck et al., 2006). Event organizers typically place the swimming portion of the triathlon race first to reduce the influence of fatigue from other phases, and may include the risk of drowning, hypo/hyperthermia, and muscle cramps. A successful triathlon swimming is to cover a given distance as fast as possible with less physiological demands (Tomikawa & Nomura, 2009). In addition, swimming performance consecutively affects cycling performance. Swim performance can ultimately affect the overall race even though the swimming portion is merely 10 ~ 15% of the entire race time (Olbrecht, 2011; Peeling et al., 2005; Perrier & Monteil, 2004).

It is a popular race format in the United States and worldwide, and it enjoys both professionally and recreationally (Burns et al., 2003). Triathlon populations were approximately 4.04 million in 2017 and it increased more than four times from 2006 according to the USA triathlon (Gough, 2020). The popularity of triathlons has led to more studies being conducted regarding the factors that influence open water swimming performance (Baldassarre et al., 2017; Tomikawa & Nomura, 2009; Tipton & Bradford, 2014; Vogt et al., 2013; Vural et al., 2019; Zacca et al., 2020). Although there is an overall similarity between swimming in a pool and open water, each environment has unique characteristics (Kjendlie et al., 2013). For example, swimming in open water requires dealing with wind, current, and water temperature. In addition, open water swimmers such as triathletes need proper sighting skills because they must continuously swim without lanes and sometimes through poor water visibility (Olbrecht et al., 2011; Tomikawa et al., 2008). For example, Kjendlie et al. (2013) observed about 8 ~ 14% decreased swimming performance in unstable water conditions, which mimicked open water conditions compared to calm water. Therefore, improper open water swimming techniques and a lack of experience can increase resistance drag forces and anxiety, making it seem like more distance to cover at given swimming routes during open water swimming (Kjendlie et al., 2013).

Both professional and recreational triathletes often wear a wetsuit to prevent hypothermia and get a performance benefit (Nessler et al., 2015; Tipton et al., 2014; Troup, 1999; Vogt et al., 2013). However, triathletes cannot wear a triathlon wetsuit in every race due to temperature regulations and they may choose a different style of wetsuit based on their preferences (Trappe et al., 1996; Ulsamer et al., 2014). Based on previous investigations, swimming with a wetsuit can change swimming mechanics, performance, and physiological responses such as rate of oxygen consumption and heart rate (Chatard et al., 1995; Cordain & Kopriva, 1991; Gay et al., 2020; Hue et al., 2003; Tomikawa et al., 2007). However, only a few studies have examined the effect of different wetsuit types on the swimming economy during front crawl swimming which is the most economical stroke (Barbosa et al., 2010; Chatard et al., 1985). Furthermore, competitive swimmers were recruited in most wetsuit-related swimming research (Barbosa et al., 2006; Cordain et al., 1995; Tomikawa & Nomura, 2009; Toussaint, 1990; Toussaint & Beek, 1992; Vural et al., 2013). Therefore, more research is needed to determine whether there is a relationship between the swimming economy and general swimming kinematics when wearing different wetsuits in recreationally active individuals. Specifically, there is a paucity of research on swimming economy while wearing a full sleeve wetsuit, a sleeveless wetsuit, or buoyancy shorts.

Therefore, this dissertation aimed to compare swimming economy and selected swimming characteristics while swimming in different wetsuits. The additional purpose of this study was to observe if there is either a positive or negative correlation between physiological variables and swimming kinematics across participants. It was hypothesized that the type of wetsuit worn would influence swimming physiology and swimming kinematics. Furthermore, it was hypothesized that there would be an inverse relationship between selected swimming physiology and kinematics.

Chapter 2: Review of Literature

Introduction

Triathlon swimming is generally similar to pool swimming, but it has unique differences such as water temperature, environmental conditions, visibility, and other competitors. In order to get the benefits of thermoregulation and potential performance improvement, triathletes typically wear a wetsuit during the swimming portion of the triathlon (Cordain & Kopriva, 1991; Gay et al., 2020; Høiseth et al., 2021). However, triathletes are not allowed to wear a wetsuit for all events due to temperature regulations (Ulsamer et al., 2014). In addition, triathletes are not allowed to wear a wetsuit or any buoyant object, such as buoyancy shorts or floating devices, when the water temperature is above 84 ° Fahrenheit (28.9° C). The USA Triathlon allows triathletes to wear a wetsuit or buoyancy shorts when the water temperature is between 78 ° and 84 ° Fahrenheit (25.6° and 28.9° C), but they will not be awarded a podium. Furthermore, triathletes choose to wear different wetsuits based on their preferences and body types. However, many studies have been conducted to compare changes in swimming physiology (Chatard et al., 1990; Nielsen, 1972) and biomechanics (Toussaint et al., 1988 & 1989; Hollander et al., 1986; Formosa et al., 2012) when swimming with or without a wetsuit. Since the wetsuit industry has been growing rapidly over the past few decades, there is an increased need to investigate how different wetsuits affect swimming physiology and biomechanics variables. Additionally, changes in swimming physiology and biomechanics are ultimately related to swimming performance.

The aim of this review of literature is, therefore, to summarize previous literature to obtain a better understanding regarding front crawl as aspects of exercise physiology and biomechanics. More specifically, we aimed to identify a gap in the literature as to the effect of wetsuits on front crawl in both swimming physiology and biomechanics.

Methods

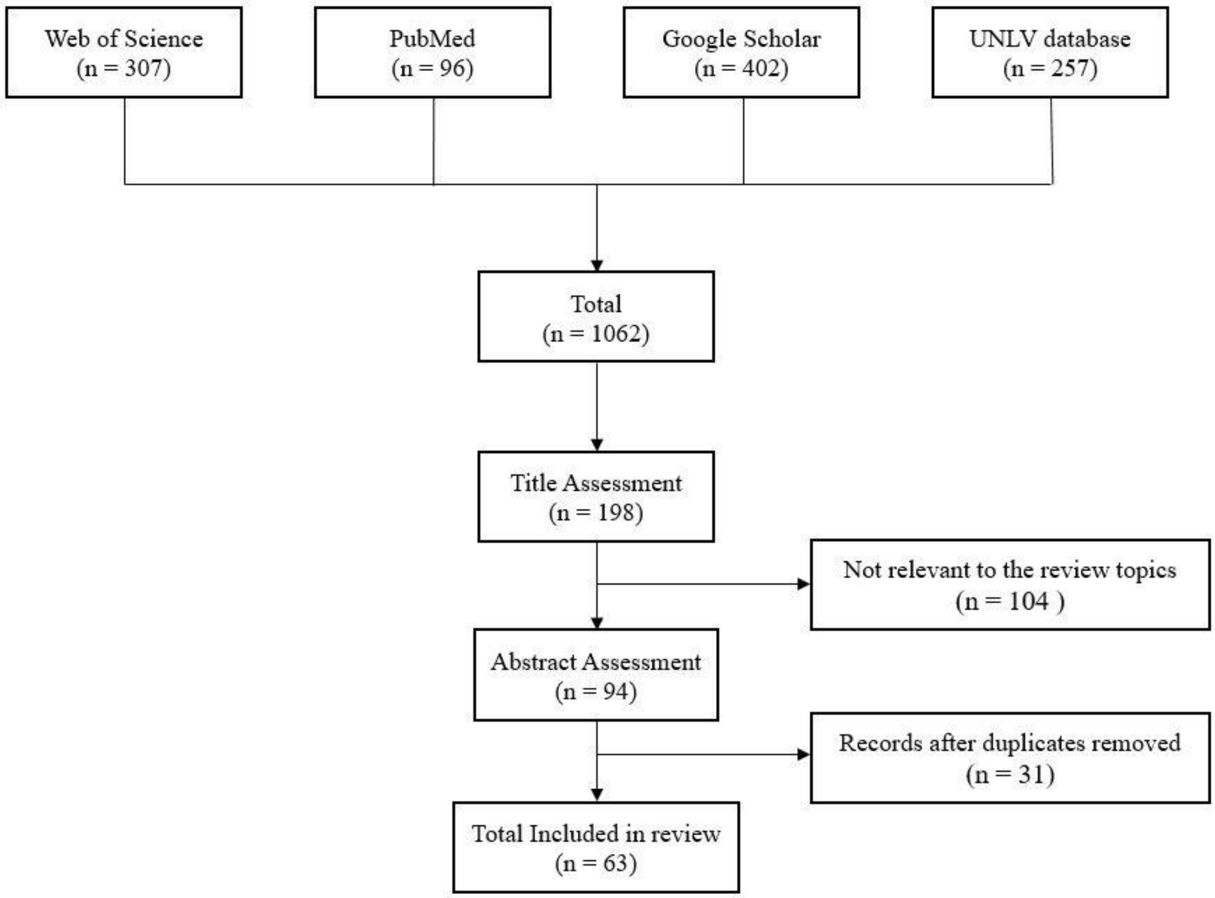
The search strategy to identify specific articles about triathlon swimming was to use the Web of Science, PubMed, Google Scholar, and the UNLV library database. First, the electronic databases were searched, and further searches for the relevant topic were completed from the reference lists of identified articles. The investigations used various combinations of keywords: ‘front crawl’, ‘swimming economy’, ‘the energetic cost of swimming’, ‘swimming kinematics’, ‘open water’, ‘swimming flume’, ‘triathlon swimming’, and ‘triathlon wetsuit’.

All articles found from the four major journal search engines subjectively underwent a title and abstract assessment to determine whether research articles matched the primary purpose of the literature review. Proceeding papers, conference abstracts, and graduate thesis or dissertations were excluded if they fit the search keywords. The advanced search options filtered the results to contain exclusively full-text articles in English. Furthermore, animal research was considered an irrelevant topic in this literature review. No publication date range was selected in order to comprehensively grasp research trends and histories, such as research equipment and methodology.

Results

The database search through four major search engines resulted in 1062 articles related to the keywords. Many articles were excluded after the title assessment, and the pool was narrowed down to 198 articles. A further 104 articles were removed from the list because they were not directly related to the review topics. Next, the abstract assessment was performed on 94 articles, and then 31 of them were removed as they were duplicated articles. Therefore, the total number of articles that underwent a full-text assessment was 63 (Figure 1).

Figure 1. Preferred reporting items for systematic reviews flow chart for article search



Physiology of Swimming

Many research articles regarding swimming physiology are well-documented since a swimming flume was invented in the early 1970s (Holmer, 1992). Previous investigations have tried to understand physiological responses (e.g., $\dot{V}O_2$, energy expenditure, blood lactate) by using the Douglas bag system in a pool or tethered swimming (Costill et al., 1985; Kjendlie et al., 2004; Klentrou & Montpetit, 1991; Toussaint et al., 1988), swimming flume with a designed snorkel for gas analysis (Chatard & Wilson, 2008; Gay et al., 2020; Kudo et al., 2017; Tomikawa et al., 2008; Tomikawa & Nomura, 2009; Wakayoshi et al., 1995), arm pulling ergometer, (Konstantaki et al., 2008), and a portable metabolic measurement system (Aspenes et al., 2009; Barbosa et al., 2006; Ribeiro et al., 2017; Silveira et al., 2019).

Successful swimming performance from a physiology perspective is to swim with less physiological input and more mechanical output at a given intensity. Mechanical power output transforms from chemical energy using three main energy systems: 1) phosphagen (also known as ATP-PC), 2) anaerobic/aerobic glycolytic, and 3) oxidative (mitochondria respiration) systems depending on swimming distance and intensity (Rodriguez & Mader, 2011). The energy system contributions depend on both swimming distance and intensity, but they are not solely dependent on only one energy source. For instance, endurance distance swimming relies heavily, more than 80%, on the oxidative energy system. However, the rest of the energy is supplied from both the phosphagen and glycolytic systems. Furthermore, triathletes recommend strategically building their anaerobic capacity through sprint swimming training in order to avoid 'battle swims' at the beginning of the swimming portion, even though they primarily require a high endurance capacity (Tomikawa & Nomura, 2009).

The proportion of total energy production and mechanical efficiency is important in swimming physiology (Rodriguez & Mader, 2011). In particular, swimming velocity is defined as the total energy production multiplied by the ratio of mechanical efficiency and resistive drag force (Barbosa et al., 2010; Holmer, 1992). Since the human body system is not quite efficient when considering that most energy is dissociated as heat, the key is to utilize energy appropriately to move forward through the water (Troup, 1999; Rodriguez & Mader, 2011). In this respect, swimmers should improve their energy production rate through proper training and reduce their resistive drag force to enhance their propelling efficiency (Holmer, 1992; Rodriguez & Mader, 2011).

Body Composition and Anthropometrics

Anthropometrics data (i.e., height, body mass, arm length, fat mass, and fat-free mass) is associated with energy costs in the front crawl (Chatard et al., 1985; Klentrou & Montpetit, 1991). Chartard et al. (1985) demonstrated that $\dot{V}O_2$ has a positive correlation with height and body surface area. Another research has shown no difference in swimming economy between three performance groups even though one group had a better swimming technique, more training duration, taller, and longer arm length than the other two groups (Chatard et al., 1990). Longer arm length is beneficial for long stroke length, but tall swimmers have larger body surface areas which negatively affects drag force. In line with this information, endurance swimmers such as triathletes are relatively shorter and smaller than pool swimmers (Baldassarre et al., 2017; Chatard et al., 1990; Millet et al., 2002). Conversely, elite swimmers are tall and have more muscle mass to generate more power output via anaerobic metabolism (Chatard et al., 1990; Troup, 1999).

Body density depends on body composition (i.e., fat-free mass vs. fat mass). Fat-free mass is denser than fat mass but is also more viscous than water. Therefore, swimmers with a relatively high body fat percentage may have more benefits of buoyancy and insulation than others of a similar body mass but less percent body fat (Baldassarre et al., 2017). Otherwise, lean swimmers need more energy to maintain a horizontal body position because the lower extremity is denser than the upper body (Cordain & Kopriva, 1991; De Lucas et al., 2000; Ulsamer et al., 2014; Vogt et al., 2013). In addition, female swimmers usually have less muscle mass and more body fat percentages than male swimmers. In this manner, female swimmers may swim more efficiently when it supposes that males and females have similar swimming techniques (Ulsamer et al., 2014). Also, swimmers and coaches should take into account muscle strength, training program, optimal body fat percentage, and swimming technique according to the swimming distance and training purpose depending on which distance to compete (Baldassarre et al., 2017; Troup, 1999). The variability of the swimming economy due to buoyancy is around 5% (Chatard et al., 1990; Costill et al., 1985). However, the relationship between body fat percentages and buoyancy is unknown, and excessive body fat percentage often represents poor endurance performance.

Swimming Economy

The swimming economy is often defined to measure the rate of oxygen consumption ($\dot{V}O_2$) at a given intensity. It shows a linear relationship with swimming velocity (Chatard et al., 1990; Holmer, 1992; Kjendlie et al., 2004). Improved swimming economy revealed that lower $\dot{V}O_2$ at a constant swimming velocity or being able to swim at a higher velocity could achieve the same physiological parameters such as $\dot{V}O_2$ and blood lactate concentration (Tomikawa et al., 2008; Trapper et al., 1996). Therefore, $\dot{V}O_2$max is considered to be a good predictor of swimming performance. Furthermore, several studies pointed out that $\dot{V}O_2$max may not be a good predictor of swimming performance in elite swimmers, but the swimming economy becomes a more critical determinant of swimming performance (Klentrou & Montpetit, 1991). Swimming typically elicits lower energy expenditure, based on $\dot{V}O_2$ than running and cycling (Baldassarre et al., 2017; Zacca et al., 2020). However, the cardiac output during swimming has been shown to be quite similar to running when $\dot{V}O_2$ was approximately the same because of their predisposition to increase stroke volume and decrease heart rate (Homer, 1992).

Swimming techniques (e.g., stroke pattern, coordination, and shoulder roll) are also important variables that affect the swimming economy (Chatard et al., 1990). When it comes to mechanical efficiency and resistive drag force, swimming with poor techniques requires greater energy consumption at a given intensity to compensate for the increasing resistive drag force and body surface area (Barbosa et al., 2010; Holmer, 1992). Thus, it is recommended that novice swimmers must learn appropriate swimming techniques to improve their swimming economy.

The stroke index, the product of stroke length and velocity, is also strongly associated with the swimming economy (Barbosa et al., 2010; Costill et al., 1985). The front crawl stroke has a higher swimming index and is the most economical swim stroke compared to backstroke, butterfly, and breaststroke (Barbosa et al., 2010; Chatard et al., 1985). Elite swimmers show a higher stroke index due to long stroke length and fast swimming velocity. Arm length is positively correlated with stroke length, such that long stroke length is associated with stroke index (Zamparo et al., 2020). Chatard et al. (1990) pointed out that $\dot{V}O_2$ showed approximately 12% lower when swimmers' arm lengths were about 4cm longer than the other swimmers. Furthermore, swimming with only arms revealed more efficiency than whole-body swimming, including leg kicks (Konstantaki et al., 2008; Hollander et al., 1986; Toussaint et al., 2006).

Cost of Transport

Cost of transport (COT) indicates the total amount of energy demand to cover a given unit of distance per body mass in kilograms (Crocker et al., 2021; Tucker, 1975). The rate of oxygen consumption ($\dot{V}O_2$) indicates how fast oxygen is supplied to exercising muscles and utilized oxygen during exercise at a given intensity. For instance, $\dot{V}O_2$ will change based on swimming velocity regardless of the given distance. Otherwise, the COT may theoretically stay the same to cover a given distance during running. The COT is higher in water locomotion, such as swimming and kayaking than in land locomotion, such as walking and running at any given intensity, because water locomotion must combat resistive drag force much more than land-based exercise (Tucker, 1975; Zamparo et al., 2019). Furthermore, COT ($J \cdot kg^{-1} \cdot min^{-1}$ or $kcal \cdot kg^{-1} \cdot min^{-1}$) is considered to be a better predictor of exercise performance compared to the rate of oxygen consumption at a given distance (Fletcher et al., 2009).

Biomechanics of Swimming

An understanding of swimming biomechanics is crucial to improving swimming performance. Drag forces are the major influencing factor that significantly affects swimming performance regardless of swimming strokes and distance (Barbosa et al., 2010; Hollander et al., 1986; Millet et al., 2002; Narita et al., 2017; Ribeiro et al., 2017; Toussaint & Beek, 1992). The resistive drag forces are form, wave, and frictional drag. On the other hand, propulsive drag forces are the lift and horizontal propulsion drag forces (Narita et al., 2017; Troup, 1999). Therefore, the key to a successful swimming performance is to reduce all resistive drag forces and improve propulsion forces.

The main goal of competitive swimmers and triathletes is to cover a fixed distance as fast as possible (Barbosa et al., 2010; Ribeiro et al., 2017). The combination of resistive and propulsive drag forces influences swimming kinematics, physiological parameters (e.g., energy expenditure, $\dot{V}O_2$), and, ultimately, swimming performance (Hue et al., 2003; Toussaint & Beek, 1992). For these reasons, many studies have been conducted regarding measuring active or passive drag force using a unique device system (Chatard et al., 2008; De Lucas et al., 2000; Hollander et al.,1986; Narita et al., 2017; Ribeiro et al., 2017; Toussaint et al., 1989), stroke rate, stroke length (Silveira et al., 2019; Payton et al., 1999), index of coordination (Millet et al., 2002), muscle activity using electromyography (EMG) system (Pink et al., 1991), and power output (Ribeiro et al., 2017).

Swimming Kinetics

Understanding swimming mechanics is essential because active and passive drag force generation cause either improvements or decreases in swimming performance. (Hollander et al., 1986;

Toussaint et al., 1988). During the 1970s and early 1980s, researchers measured active drag indirectly using estimation and extrapolations. The measuring the active drag (MAD) system was introduced about two decades ago (Toussaint et al., 2006). The MAD system is a piece of excellent equipment to measure propulsive drag forces during a front crawl, and then passive drag forces were able to predict by using Newton's second law. Furthermore, a constant swimming pace indicates the same proportion of active and passive drag forces in accordance with Newton's second law of motion (Toussaint & Beek, 1992).

Despite its many benefits in measuring underwater active propulsive force, the MAD system has limitations. For instance, stroke length has little variability because the force transducer is set up a fixed distance apart (e.g., 1.35m). Therefore, swimmers need to adjust their stroke rate to swim slower or faster. Additionally, swimming velocity is seen to be faster when swimming with the MAD system vs. free arm swimming due to the nature of the system. Swimmers must push the force transducer directly to move forward, which may exaggerate the propulsion force used compared to swimming naturally. Besides, the MAD system ignored the 10 ~ 15% propulsion force from lower limbs even though swimming with only arms led to a better swimming economy (Toussaint et al., 2006). However, swimmers use leg kicks and shoulder rolls during front crawl swimming to get additional propulsion forces and maintain a horizontal body position due to lifting force (Kudo et al., 2017; Hollander et al., 1985). For instance, swimmers preferred to select two-beat kicks rather than four or six-beat kicks to avoid excessive energy costs during endurance swim events such as the Ironman distance (3.8-km swim). Also, competitive pool swimmers predominantly use six-beat kicks in sprint races (Millet et al., 2002). Kudo et al. (2017) researched the relationship between shoulder rolls and hand propulsion forces using an underwater camera and motion capture system. The research demonstrated that swimmers might get more performance benefits from more hand propulsive lift force by increasing shoulder rolling velocity when in the push phase.

Kjendlie et al. (2004) demonstrated that minimizing underwater passive torque is important to improve swimming performance. Passive torque is related to the swimmer's height, body density, and the distance between the center of volume at the lung and the swimmer's feet. A tall swimmer with a large body surface area shows large passive torque and increased passive drag. This passive torque is three times higher in males than females (Zamparo et al., 1996). Theoretically, people who are tall and have more fat-free mass may not have 'ideal' characteristics for swimming based solely on this information about passive torque. Therefore, tall swimmers need to overcome the disadvantage and reduce their passive torque using proper swimming techniques. For example, world-class level swimmers are tall and lean. However, they are more than enough to cancel the disadvantage of passive torque out because of their sound swimming techniques.

Swimming Kinematics

Front crawl is divided either into two different stroke phases: pull and recovery (Pink et al., 1991), five phases: entry, catch, in-sweep, finish, and recovery (Troup, 1999), or five different phases: entry, down-sweep, in-sweep, out-sweep, upsweep (Chatard et al., 1990). However, the most commonly used division for the front crawl stroke is four phases: entry and catch, push, pull, and recovery (Gourgoulis et al.,2014; Millet et al., 2002).

Experienced swimmers typically demonstrate a longer stroke and higher stroke rate when compared to inexperienced swimmers (Klentrou & Montpetit, 1991). Therefore, skilled swimmers can achieve greater swimming velocity than novice swimmers due to better stroke efficiency and swimming techniques (Tomikawa & Nomura, 2009; Troup, 1999). Millet et al. (2002) compared arm coordination during front crawl between elite swimmers and triathletes to see the ratio of stroke length and height. This study was done in order to avoid bias when directly comparing stroke length without considering anthropometric data between swimmers and triathletes. This research showed that swimmers demonstrated a reduced recovery phase and increased underwater propulsive phase (i.e., pull and push) as swimming velocity increased. By contrast, triathletes tended to show a more extended recovery phase and reduced the propulsive phase to be able to increase swimming velocity. Interestingly, there were no statistical differences in the stroke rate observed between swimmers and triathletes across swimming velocity from 80% to the maximal (100%) velocity. Based on this study, experienced swimmers increased stroke length with more glide and took a little longer during the pull phase to generate more propulsive force and achieve faster swimming velocity.

Muscle Activity during Swimming

The stroke technique affects muscle activity patterns during the front crawl (Pink et al., 1991). Upper body muscle activity patterns are dependent upon stroke phases and coordination of stroke (Millet et al., 2017; Troup, 1999). Improper stroke technique elicits more upper body muscle fatigue, especially in muscle groups involving the pull phase (Millet et al., 2017; Nuber et al., 1986). Thus, local muscle fatigue may decrease stroke length, propulsive forces, mechanical power output, and ultimately swimming velocity as a whole (Toussaint et al., 2006; Troup, 1999).

During the pull phase, the latissimus dorsi, pectoralis major, and teres major are the primary muscle groups. In addition, three heads of deltoid, supra- and infraspinatus activate mainly during the recovery phase (Nuber et al., 1986; Pink et al., 1991). The glenohumeral joint plays a significant role in shoulder movement and muscle activity. Shoulder abduction and external rotation occur during the recovery phase and adduction and internal rotation occur during the catch and pull phase (Troup, 1999). However, upper body movement and muscle activation happen synchronously during both pull and recovery phases.

Triathletes had poor swimming technique compared to competitive swimmers mainly because of differences in training time and regime. Triathletes typically train in all three disciplines within a week, but swimming training takes approximately less or about one-third of the entire training duration (Chatard et al., 1995). For instance, triathletes demonstrated a slow swimming velocity (Chatard et al., 1995) and a tendency to take longer recovery phases (Millet et al., 2017). Pink et al. (1991) elucidated that the anterior deltoid activated the most between the late pull and early recovery phases as well as the posterior deltoid activated the most during the late pull phase. The average anterior and posterior muscle activations showed a significant difference between swimming with or without a wetsuit, but this was not the case with the trapezius and triceps (Agnelli & Mercer, 2018).

The Effect of Wetsuit on Open Water Swimming

Swimmers are allowed to wear a wetsuit during open water swims and triathlon swimming to prevent hypothermia (Chatard et al., 1995; Parsons & Day, 1986; Ulamer et al., 2014). Other than the thermoregulation, triathletes can expect to have performance benefits while wearing a wetsuit due to the enhanced buoyancy and reduced body density they offer (Hue et al., 2003; Nuber et al., 1986; Pink et al., 1991; Tomikawa et al., 2008; Toussaint et al., 1989; Trapper et al., 2020). In addition, since swimming with a wetsuit allows the swimmers to maintain a streamlined position more efficiently, they could use less energy due to decreasing drag force and generate more propulsive force (Hue et al., 2003; Pink et al., 1991; Tomikawa et al., 2009; Ulsamer et al., 2014). Besides, swimming with a wetsuit helps recreational triathletes by migrating or minimizing drowning anxiety they might have due to the buoyancy of the suit (Trapper et al., 1996; Ulsamer et al., 2014). For these reasons, a triathlon wetsuit is considered vital equipment that triathletes commonly wear during the swimming portion of the race (Chatard et al., 1995; De Lucas et al., 2000; Gay et al., 2020).

Two popular wetsuit types are 'full sleeve' and 'sleeveless' (Agnelli & Mercer, 2018; Trappe et al., 2020). Many investigations have been conducted to observe the differences between full sleeve wetsuit vs. a regular swimsuit (Chatard et al., 1995; Gay et al.,2020; De Lucas et al., 2000; Hue et al., 2003; Tomikawa et al., 2007) or between sleeveless wetsuit vs. a regular swimsuit (Cordain & Kopriva, 1991; Toussaint et al., 1989). However, triathletes are not always permitted to wear a wetsuit during race events due to temperature regulations (Baldassarre et al., 2017; Parsons & Day, 2986; Toussaint et al., 1989; Ulsamer et al., 2014; Vogt et al., 2013). During the triathlon swimming portion, triathletes can wear a wetsuit when the temperature is 78° F or colder. Triathletes can still wear a wetsuit when the water temperature is between 78° F and 84° F if the purpose of the race participation is to complete the race without being considered for any awards or qualifying slots for the World Championship (Ulasmer et al., 2014). In this manner, triathletes should train for open water swimming with or without a wetsuit if a wetsuit is not permitted (Chatard et al., 1995). Trappe et al. (1995) postulated that the amount of body covering provided by a wetsuit might affect physiological responses (i.e., $\dot{V}O_2$, $V_{E.}$, RER, and HR) in front crawl stroke with different types of wetsuits. The study confirmed a full sleeve wetsuit is the most effective in enhancing swimming velocity rather than a sleeveless or short sleeve wetsuit.

Previous studies found that swimming velocity increased ~3 - 10% due to increased stroke rate (Toussaint et al., 1989) and stroke length (Gay et al., 2020; Hue et al., 2003). Increased stroke length may induce more extended entry and catch phases, as well as the possible reason could be the additional buoyancy from a wetsuit. Interestingly, $\dot{V}O_2$ and blood lactate concentration levels were not statistically different even though swimming performance was improved when participants swam with a wetsuit. Chatard et al. (1995) pointed out that elite swimmers did not significantly differ when swimming with or without a wetsuit. However, when wearing wetsuits, triathletes showed a reduced swimming time, $\dot{V}O_2$, blood lactate concentration, and stroke rate. Based on the result of the studies, it appears as if inexperienced swimmers can get more benefits from wetsuits than well-trained swimmers (Hue et al., 2003). Agnelli and Mercer (2017) conducted a study that showed muscle activity with or without a wetsuit while mimicking the front crawl stroke on land. The study observed that the average EMG on both anterior and posterior deltoids was increased with a wetsuit by 66.8% and 40%, respectively. According to the previous study, we can postulate that swimming with a wetsuit may increase shoulder muscle activities in both pull and recovery phases (Pink et al., 1991). Besides, the benefits of a wetsuit may be differently affected by anthropometrics, training status, gender, and swimming techniques. For example, lean swimmers may experience more benefits than those with higher percent body fat (Cordain & Kopriva, 1991). In line with this, females would have a less performance enhancement due to the use of a wetsuit than male swimmers (Toussaint et al., 1989).

Conclusion

In summary, swimming performance is concurrently influenced by many perspectives. Among many variables, swimming efficiency plays a vital role in a successful endurance swimming performance, such as the swimming portion of a triathlon. The critical factors in improving swimming performance are how swimmers utilize oxygen while swimming effectively, generate more propulsion force, reduce resistive drag force, and sound stroke technique.

Many researchers have comprehensively documented swimming’s influencing factors: power output, the interaction between stroke length and stroke rate, swimming economy, interlimb coordination, active drag force, anthropometrics, muscle activity, overuse injury, differences between swimming in a pool and open water, and the effect of wetsuits on front crawl. Based on the gathered information, it can be concluded that there are some gaps in the literature. Regarding triathlon's popularity, more research is needed to see if any differences in swimming kinematics are observed when wearing different wetsuit types beyond comparing a single wetsuit vs. no wetsuit. Furthermore, there is a missing link regarding swimming kinematics and swimming economy by different wetsuit types. The primary purpose of a triathlon race is to complete the designated swimming route as soon as possible with the least possible amount of effort. Therefore, swimming physiology and stroke characteristics are essential variables to estimate swimming performance and the entire triathlon performance.

The specific purpose of this dissertation project was to [1)] determine whether the swimming economy changes according to different wetsuit conditions, [2)] determine the effect of wetsuit conditions on swimming kinematics, and [3)] Identify the relationship between swimming physiology (e.g., rate of oxygen consumption, heart rate, cost of transport) and swimming kinematics (i.e., stroke rate, stroke length, stroke index) in each wetsuit condition. We hypothesized that [1)] physiological variables during swimming would decrease during trials in which wetsuits were worn, with greater reductions occurring in full body suit than sleeveless, buoyancy shorts, and no wetsuit conditions, [2)] three swimming kinematics will be influenced by wetsuit conditions, [3)] a negative correlation will exist between swimming physiology and three swimming kinematics variables at the submaximal swimming intensity. Ultimately, this study enables us to fill in the gaps in the existing literature. We also expected to provide insight into the triathlon community regarding selecting wetsuit types for training and races as a practical application.

Chapter 3: Methods

Experimental Design

The experimental approach to this study was a repeated measures design in which all subjects performed all conditions on the same day. Furthermore, each subject completed all conditions at a specific test speed. The test speed was determined as the speed that elicited 80% $\dot{V}O_2max$ while swimming in a regular swimsuit only. The dependent variables were the rate of volume of oxygen consumption ($\dot{V}O_2$), rate of volume of carbon dioxide production ($\dot{V}CO_2$), ventilation (V_E), heart rate (HR), respiratory exchange ratio (RER), rating of perceived exertion (RPE), Cost of transport (COT), stroke rate (Hz), stroke length (m), and stroke index (m^2/s). The independent variable was 'wetsuit' with four levels (no wetsuit (NWS), buoyancy shorts (BS), sleeveless Wetsuit (SLW), and full sleeve wetsuits (FSW).

Overall experimental sessions, including GXT, were performed in a swimming flume (Endless Pools, Aston, PA, USA) and four swim conditions were randomized. The written informed consent form (Appendix I) was provided to all participants to understand the purpose, benefits, and possible risks of the study prior to the testing. The research protocol was approved by the host institution (#1570149-2).

Participants

The number of participants was obtained based on the power analysis ($\alpha = 0.05$ and a power of 0.9) using previous research (Trappe et al., 1995). According to the power analysis, the appropriate number of participants to detect significant influence by different wetsuit designs was 13. Therefore, a total of 14 participants (6 males, 8 females) were recruited for this study, and they were either recreational triathletes or swimmers. They were recruited from the local triathlon and master's swim clubs through social media and word of mouth. Potential participants received an email regarding the test purpose, procedure, and inclusion criteria before deciding whether to take part in this study. The descriptive statistics of participants are shown in Table 1. Anthropometric data were measured prior to the warmup swimming and experimental sessions. Arm length was measured using a tape measure in centimeters from the acromion process to the longest fingertips when participants stretched out their fingers. Body fat percentage was estimated using the equation: 64 – [20 × (height/waist circumference)] + (12 × sex: male = 0, female = 1) (Bergman & Woolcott, 2018). The inclusion criteria were that participants needed to swim comfortably at least a minimum of 3000m per week regularly for the previous four weeks and have no current injuries on both extremities that would possibly affect their ability to perform the front crawl stroke.

Table 1. Descriptive statistics of participants (N = 14).

Age (years)	31.00 ± 8.20
Height (m)	1.69 ± 1.09
Body Mass (kg)	68.48 ± 9.38
Waists Circumference (cm)	77.46. ± 6.81
Arm Length (cm)	74.89. ± 5.10
Body Fat (%)	26.77 ± 6.62
$\dot{V}O_2max$ (ml·kg^{-1}·min^{-1})	46.74 ± 7.05
80% of $\dot{V}O_2max$ (ml·kg^{-1}·min^{-1})	37.01 ±5.64

Note. All data represented as mean and standard deviations

Experimental Sessions

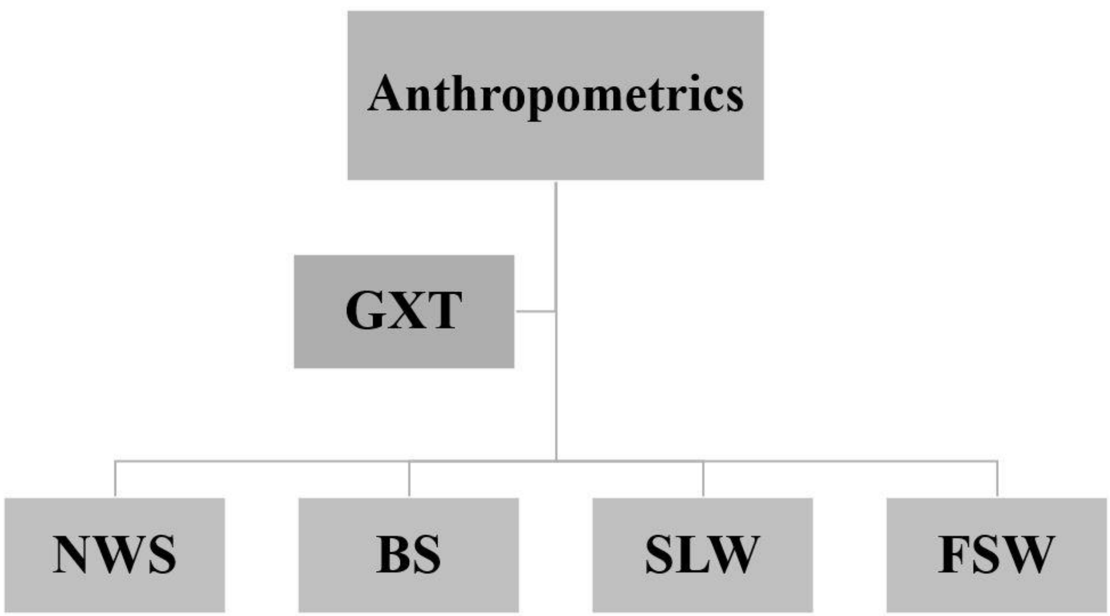
Participants were instructed to complete a standardized warm-up swim (4 x 100-yard; self-selected pace, 8 x 25-yard; Fast and slow pace each 25-yard) in the 25-yard outdoor pool. Then, they performed graded exercise testing (GXT) to determine the maximum oxygen uptake ($\dot{V}O_2max$) in the swimming flume (Endless Pools, Aston, PA, USA). The starting pace was 0.93m/s (1-minute 47second pace to cover 100m) and increased pace by 0.09 ± 0.01 m/s every two minutes until they could not keep up with the pace. The starting pace was adjusted to complete GXT between 8 ~ 12 minutes based on their subjective warm-up swimming pace. For instance, we measured the time to complete four 100-yard swimming and determined whether or not to adjust starting pace. The rate of perceived exertion (RPE; 6 – 20 scale) was obtained from participants when they stopped swimming (Borg, 1982). After GXT, participants had a cool down swim in the 25-yard pool and took sufficient rest prior to the swimming session under different wetsuit conditions.

While participants were taking a rest after GXT, the research team estimated 80% of $\dot{V}O_2max$ swim pace (m/min) using the second-order polynomial plot pace vs. percentage of $\dot{V}O_2$ for the submaximal swim sessions. Previous studies have demonstrated that the typical triathlon swimming intensity in a race is about 60 ~ 80% (Tomikawa et al., 2008), as well as 80% of maximal swimming velocity, revealed the least overall triathlon time trials when compared to higher than 80% maximal swimming effort (Peeling et al., 2005). Furthermore, the rate of oxygen consumption was typically lower than in land-based exercises such as running and cycling due to the different gravitational forces and supine position during swimming. Therefore, the test pace was set as the pace that would elicit 80% of $\dot{V}O_2max$. Furthermore, the submaximal swimming sessions were conducted in a pre-determined, randomized order that was unique for each participant (Figure 2). Finally, participants were instructed to perform four-minute submaximal swimming bouts with four wetsuit conditions in a swimming flume. The four-minute swimming duration was selected based on a previous study that demonstrated that this time frame is appropriate for measuring aerobic contribution (Zamparo et al., 2019 & 2020).

Both wetsuits (i.e., SLW and FSW) and buoyancy shorts were provided to participants following size charts from HUUB Design and anthropometric measurement. Furthermore, the thickness of both wetsuits was 3mm on the upper body and 5mm on the lower body, even though the model names and designs were not all the same. The research team actively helped participants put on the wetsuits appropriately to minimize any adverse effects on swimming performance. All participants were asked to report their wetsuit fit and comfort levels using a scale (Appendix III).

Before data collection, participants had a familiarization swim for any required adjustments. Physiological variables (i.e., $\dot{V}O_2$, $\dot{V}CO_2$, V_E, RER) were collected breath by breath in 10-second intervals using a metabolic cart with a mixing chamber (Quark CPET; Cosmed, Rome, Italy) during each four-minute swimming session. Additionally, heart rate was measured using the heart rate chest strap (Polar T31, Kempele, Finland) and continuously monitored. The time to complete ten strokes was measured at the three-minute mark using a stopwatch for further calculation to determine stroke rate in Hz. RPE was asked and recorded right after each swimming session. A sufficient rest time of at least 5 minutes was given to participants between sessions.

Figure 2. Experimental Design



Note. NWS: No wetsuit. BS: Buoyancy short, SLW: Sleeveless wetsuit, FSW: Full sleeve wetsuit Graded Exercise Testing (GXT) was performed with a regular swimsuit to determine $\dot{V}O_2$max. Wetsuit conditions were randomized, and swimming sessions were 80% of $\dot{V}O_2$max.

Data Reduction

The physiological variables were determined as being the last-minute average of each four-minute submaximal swim session. The cost of transport ($J \cdot kg^{-1} \cdot m^{-1}$) was calculated based on the kilocalories used during each swimming session, body mass, and the estimated swimming distance. Furthermore, kilocalorie data exported from the metabolic cart were calculated using the Weir equation that is computed energy expenditure using both $\dot{V}O_2$ and $\dot{V}CO_2$ values.

$$\text{Weir equation (EE: kcal)} = [3.9 \times (\dot{V}O_2) + 1.1 \times (\dot{V}CO_2)] \times 1.44$$

$$1\text{kcal} = 4184\text{J}$$

$$\text{Estimated swimming distance (m)} = \text{swimming velocity (m/s)} \times 240 \text{ secs}$$

The stroke rate (Hz) was determined by measuring the time to complete ten strokes. Stroke length (m) and stroke index were calculated based on the swimming velocity (m/s) and stroke rate (Hz):

$$\text{Swimming velocity (m/s)} = \text{Stroke rate} \times \text{Stroke length}$$

$$\text{Stroke rate (Hz)} = 10 \text{ strokes/time (s) to complete 10 strokes}$$

$$\text{Stroke length (m)} = \text{Swimming velocity (m/s)} / \text{Stroke rate (strokes/s)}$$

$$\text{Stroke index } (m^2/s) = \text{Stroke length (m)} \times \text{Swimming velocity (m/s)}$$

Statistical Analysis

The dependent variables were the rate of volume of oxygen consumption ($\dot{V}O_2$), rate of volume of carbon dioxide production ($\dot{V}CO_2$), ventilation (V_E), heart rate (HR), respiratory exchange ratio (RER), rating of perceived exertion (RPE), cost of transport ($J \cdot kg^{-1} \cdot m^{-1}$), stroke rate (Hz), stroke length (m), and stroke index (m^2/s). The data were presented as mean ± standard deviation (SD), and statistical analyses were performed using SPSS 28 (IBM Corp, Armonk, NY). Data presented as mean ± standard deviation (SD) and statistical analyses will be performed using SPSS 28 (IBM Corp, Armonk, NY).

The one-way analyses of variance (ANOVA) were conducted with repeated measures to assess each dependent variable to see whether wetsuit conditions lead to significant main effects. Alpha level was set at 0.05. If Mauchly's Test of Sphericity was violated, then F-ratio and p-value were adjusted using Greenhouse-Geisser rather than Sphericity Assumed. When the F-ratio was found to be significant, a planned pairwise comparison analysis was performed using Least Significant Difference (LSD) to see if there were significant differences between conditions. Furthermore, effect size (η^2) was reported for each variable using Eta-squared. The effect size was determined as small (0.01), medium (0.06), and large (0.14).

Additionally, Pearson's correlation coefficient tests were performed to see if there were any relationships between the three main physiological variables (i.e., $\dot{V}O_2$, HR, COT) and stroke characteristics (i.e., SR, SL, SI) per each wetsuit condition. The strength of the correlations was reported as low ($r = 0.1$ and $r \leq 0.3$), moderate ($r \geq 0.3$ and $r \leq 0.5$), and strong ($r \geq 0.5$ and $r = 1.0$).

Chapter 4: Results

All physiological data are presented in Table 2. The mean and standard deviation for $\dot{V}O_2max$ from GXT was 46.74 ± 7.05 ml·kg^{-1}·min^{-1}. The mean value of $\dot{V}O_2$ when participants swam with NWS condition was 37.49 ± 5.86 ml·kg^{-1}·min^{-1}. This $\dot{V}O_2$ value was quite close to the prescribed swimming pace (i.e., 37.01 ± 5.64 ml·kg^{-1}·min^{-1}). Therefore, we confirmed that 80% of $\dot{V}O_2max$ was appropriately estimated and prescribed to the participants.

Table 2. Mean values for each dependent variable

Wetsuit Condition	NWS	BS	SLW	FSW
$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	37.49 ± 5.86	33.99 ± 6.40	31.37 ± 4.91	32.23 ± 5.25
$\dot{V}CO_2$ (L/min)	1969.12 ± 561.44	1768.90 ± 576.67	1599.29 ± 461.35	1630.08 ± 473.45
V_E (L/min)	64. 76 ± 12.25	56.74 ± 12.44	53.19 ± 9.98	54.12 ± 10.61
HR (bpm)	148.0 ± 11.6	140.2 ± 13.1	137.0 ± 12.2	138.5 ± 11.8
RER	0.77 ± 0.08	0.75 ± 0.07	0.75 ± 0.06	0.73 ± 0.60
RPE	13.4 ± 2.9	11.7 ± 1.8	11.4 ± 2.1	11.8 ± 1.6
COT (J·kg^{-1}·m^{-1})	7.36 ± 1.63	7.06 ± 1.78	6.41 ± 1.47	6.51 ± 1.43
Stroke Rate (Hz)	0.49 ± 0.06	0.49 ± 0.05	0.48 ± 0.06	0.49 ± 0.06
Stroke length (m)	2.30 ± 0.36	2.27 ± 0.34	2.33 ± 0.39	2.29 ± 0.38
Stroke Index (m^2/s)	2.58 ± 0.71	2.54 ± 0.69	2.62 ± 0.75	2.57 ± 0.72

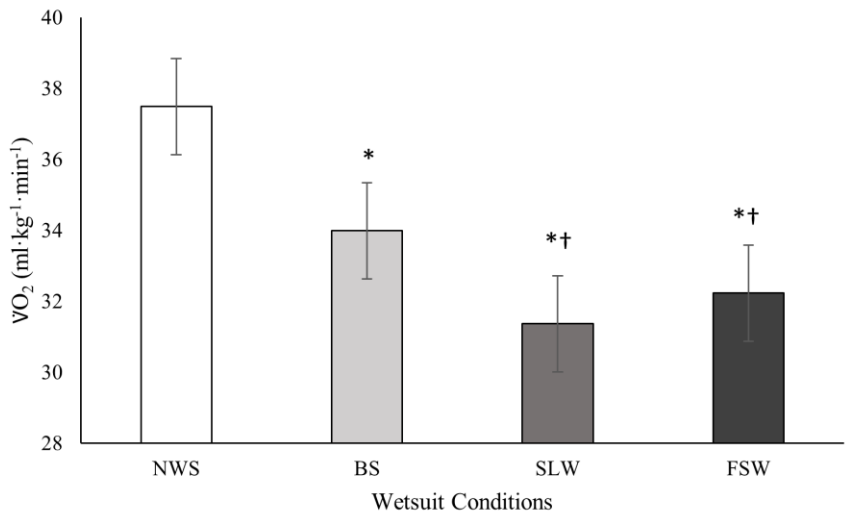
Note. All data were represented as mean and standard deviations.
NWS: No wetsuit. BS: Buoyancy short, SLW: Sleeveless wetsuit, FSW: Full sleeve wetsuit

Rate of Oxygen Consumption ($\dot{V}O_2$)

$\dot{V}O_2$ was significantly influenced by wetsuit conditions ($F_{3, 39} = 32.370$, $p < 0.001$, Table 3). The effect size was calculated using the Partial Eta Squared, and it was revealed the large ($\eta^2 = 0.713$).

Using planned comparisons, $\dot{V}O_2$ during NWS was higher compared to the BS ($p < 0.001$), SLW ($p < 0.001$), and FSW ($p < 0.001$). Also, $\dot{V}O_2$ during BS was higher between SLW ($p = 0.004$) and FSW ($p = 0.006$) conditions. However, there was no difference in $\dot{V}O_2$ between SLW and FSW conditions ($p = 0.078$).

Figure 3. Rate of oxygen consumption by wetsuit conditions



Note. NWS: No wetsuit. BS: Buoyancy short, SLW: Sleeveless wetsuit, FSW: Full sleeve wetsuit
*Significant different from NWS (no wetsuit) condition ($p < 0.05$).
†Significant different from BS (buoyancy shorts) condition ($p < 0.05$).

Rate of Carbon Dioxide Consumption ($\dot{V}CO_2$)

$\dot{V}CO_2$ was different between wetsuit conditions ($F_{3, 39} = 20.847$, $p < 0.001$) and effect size was large ($\eta^2 = 0.616$). Based on the pairwise comparison, $\dot{V}CO_2$ in NWS was higher than during BS ($p = 0.004$), SLW ($p < 0.001$) and FSW ($p < 0.001$). Furthermore, there were differences in $\dot{V}CO_2$ between BS vs. SLW ($p = 0.006$) and BS vs FSW ($p = 0.012$). However, there was no difference between SLW and FSW ($p = 0.464$).

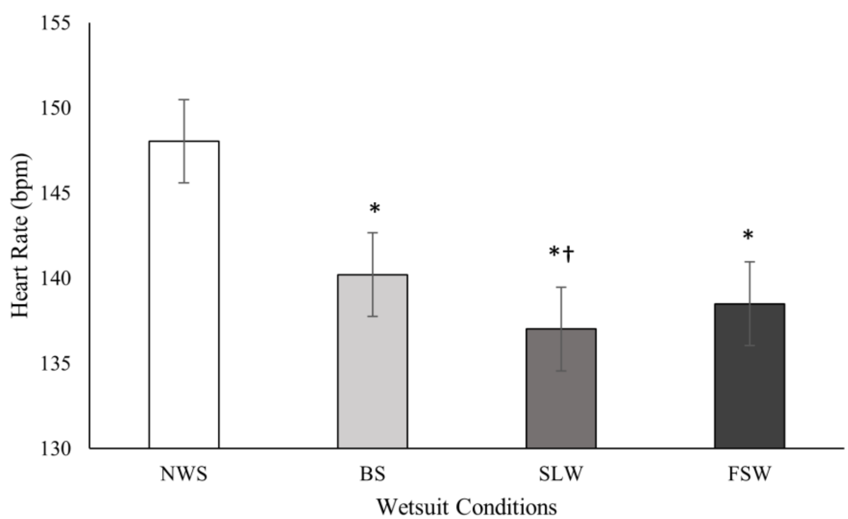
Ventilation (V_E)

V_E was found to be significantly influenced by the wetsuit condition ($F_{3, 39} = 17.741$, $p < 0.001$). The effect size was large ($\eta^2 = 0.577$). According to the pairwise comparison, V_E was significantly the higher at NWS condition when compared to BS ($p = 0.004$), SLW ($p < 0.001$), and FSW ($p < 0.001$). However, V_E during BS was not different from SLW ($p = 0.059$) and FSW ($p = 0.104$). Additionally, there was no difference between SLW and FSW ($p = 0.432$).

Heart Rate (HR)

HR was significantly different in the main effect ($F_{3, 39} = 27.730$, $p < 0.001$). The effect size was large ($\eta^2 = 0.681$). Based on the pairwise comparison, HR was higher in NWS than in other wetsuit conditions ($p < 0.001$). In addition, HR was different between BS and SLW ($p < 0.05$), but there was no difference between BS and FSW ($p = 0.186$). Also, there was no difference between SLW and FSW ($p = 0.151$).

Figure 4. Heart rate by wetsuit conditions



Note. NWS: No wetsuit. BS: Buoyancy short, SLW: Sleeveless wetsuit, FSW: Full sleeve wetsuit
*Significant different from NWS (no wetsuit) condition (p < 0.05).
†Significant different from BS (buoyancy shorts) condition (p < 0.05).

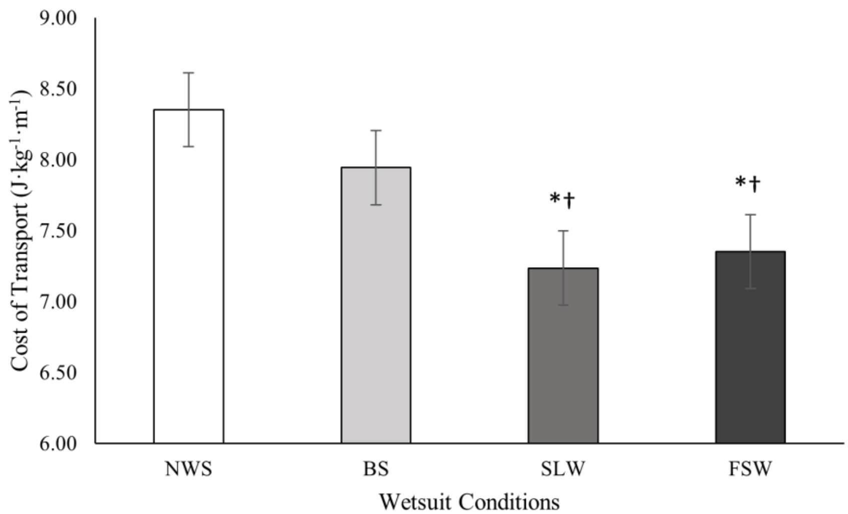
Respiratory Exchange Ratio (RER)

RER was significantly influenced by wetsuit conditions ($F_{3, 39}$ = 3.586, $p < 0.05$). The effect size was large (η^2 = 0.216). RER was higher during NWS compared to SLW ($p < 0.05$) and FSW ($p < 0.05$), but not BS ($p = 0.110$). Furthermore, there were no differences between BS vs. SLW ($p = 0.736$), BS vs. FSW ($p = 0.097$), and SLW vs. FSW ($p = 0.270$).

Cost of Transport (COT)

COT was significantly influenced by wetsuit conditions ($F_{2.22, 28.83}$ = 8.549, $p < 0.001$). The F-ratio was adjusted using Greenhouse-Geisser instead of Sphericity Assumed because Mauchly's Test of Sphericity was violated ($p < 0.05$). The effect size was large (η^2 = 0.417). COT during NWS was found to be higher than SLW ($p < 0.01$) and FSW ($p < 0.01$), but there was no difference between NWS and BS ($p = 0.183$). Additionally, COT during BS was higher than SLW ($p < 0.05$) and FSW ($p < 0.05$). Furthermore, there was no difference between SLW and FSW ($p = 0.317$).

Figure 5. Cost of transport by wetsuit conditions



Note. NWS: No wetsuit. BS: Buoyancy short, SLW: Sleeveless wetsuit, FSW: Full sleeve wetsuit
*Significant different from NWS (no wetsuit) condition ($p < 0.05$).
†Significant different from BS (buoyancy shorts) condition ($p < 0.05$).

Rating of Perceived Exertion (RPE)

RPE was significantly influenced by wetsuit conditions ($F_{1.75, 22.78} = 5.904$, $p < 0.05$). Since the Mauchly's Test of Sphericity was violated ($p < 0.05$), the F-ratio was adjusted by using Greenhouse-Geisser instead of Sphericity Assumed. Based on pairwise comparison, RPE was higher during NWS compared to BS ($p = 0.05$), SLW ($p < 0.001$), and FSW ($p = 0.05$). However, there were no differences between BS vs. SLW ($p = 0.336$) and BS vs. FSW ($p = 0.850$). Also, there were no differences between SLW and FSW conditions ($p = 0.535$). The effect size was large ($\eta^2 = 0.312$).

Stroke Rate (SR; Hz)

SR was not significantly different depending on wetsuit conditions ($F_{1.86, 24.21} = 1.425$, $p = 0.26$). The F-ratio was adjusted using Greenhouse-Geisser instead of Sphericity Assumed because Mauchly's Test of Sphericity was violated ($p < 0.05$). The mean values of SR were quite consistent across wetsuit conditions (Table 2). The effect size was above medium, but it was not large ($\eta^2 = 0.099$).

Stroke Length (SL; m)

SL was not significantly different across the wetsuit conditions ($F_{3, 39} = 1.983$, $p = 0.132$) and effect size was small ($\eta^2 = 0.132$). The mean values were found to be within a narrow range (Table 2).

Stroke Index (SI; m^2/s)

SI was not statistically significant depending on wetsuit conditions ($F_{3, 39} = 2.422$, $p = 0.08$). The effect size was small ($\eta^2 = 0.157$). SI was affected by SL only because the swim flume controlled swimming velocity. The mean value of SI was a little higher in SLW conditions compared to the other conditions (Table 2), even though the main effect was not significantly different.

Table 3. Statistical main effects for each dependent variable

	F-ratio	P - value	η^2
$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	32.370	< 0.001*	0.713
$\dot{V}CO_2$ (L/min)	20.847	< 0.001*	0.616
V_E (L/min)	17.732	< 0.001*	0.577
HR (bpm)	27.730	< 0.001*	0.681
COT (J/kg/m)	8.549	< 0.001*	0.417
RER	3.586	< 0.05‡	0.216
RPE	5.904	< 0.05‡	0.312
Stroke Rate (Hz)	5.904	0.26	0.099
Stroke length (m)	1.983	0.132	0.132
Stroke Index (m^2/s)	2.422	0.08	0.157

Note. Effect size (η^2): small = 0.01, medium = 0.06, large = 0.14
*Significant different by wetsuit conditions (p < 0.01)
‡Significant different by wetsuit conditions (p < 0.05)

Correlation Between Physiological Variables and Stroke Kinematics

Correlation between the three main physiological variables (i.e., $\dot{V}O_2$, HR, and COT) and stroke characteristics (i.e., SR, SL, and SI) was performed for each wetsuit condition because the measures are considered good indicators of swimming performance.

We observed a low positive correlation between $\dot{V}O_2$ and SR across the wetsuit condition (Table 4) indicating that participants who had a long SR also had a higher $\dot{V}O_2$ for each condition. $\dot{V}O_2$ and SL showed a positive moderate correlation during BS ($r = 0.401$, $p = 0.155$), SLW ($r = 0.322$, $p = 0.247$), and FSW ($r = 0.418$, $p = 0.137$), but not for the NWS condition ($r = 0.297$, $p = 0.303$). $\dot{V}O_2$ and SI during NWS and SLW conditions revealed moderate positive correlation. However, $\dot{V}O_2$ and SI during BS ($r = 0.549$, $p = 0.042$) and FSW ($r = 0.563$, $p = 0.036$) conditions showed strong correlations (Table 4 and Figure 5).

HR and SR showed a moderate positive correlation during NWS ($r = 0.366$, $p = 0.198$), BS ($r = 0.403$, $p = 0.153$), and SLW ($r = 0.355$, $p = 0.242$). However, HR and SR during FSW showed a low correlation ($r = 0.230$, $p = 0.430$). HR and SL have positive moderate correlation during BS ($r = 0.355$, $p = 0.213$), SLW ($r = 0.383$, $p = 0.176$), and FSW ($r = 0.417$, $p = 0.138$). However, there was a low correlation between HR and SL during the NWS condition ($r = 0.267$, $p = 0.357$). Also, there were strong correlations between the HR and SI during BS ($r = 0.544$, $p < 0.05$), SLW ($r = 0.555$, $p < 0.05$), and FSW ($r = 0.591$, $p < 0.05$). However, the NWS condition saw a moderate correlation between HR and SI ($r = 0.464$, $p = 0.095$).

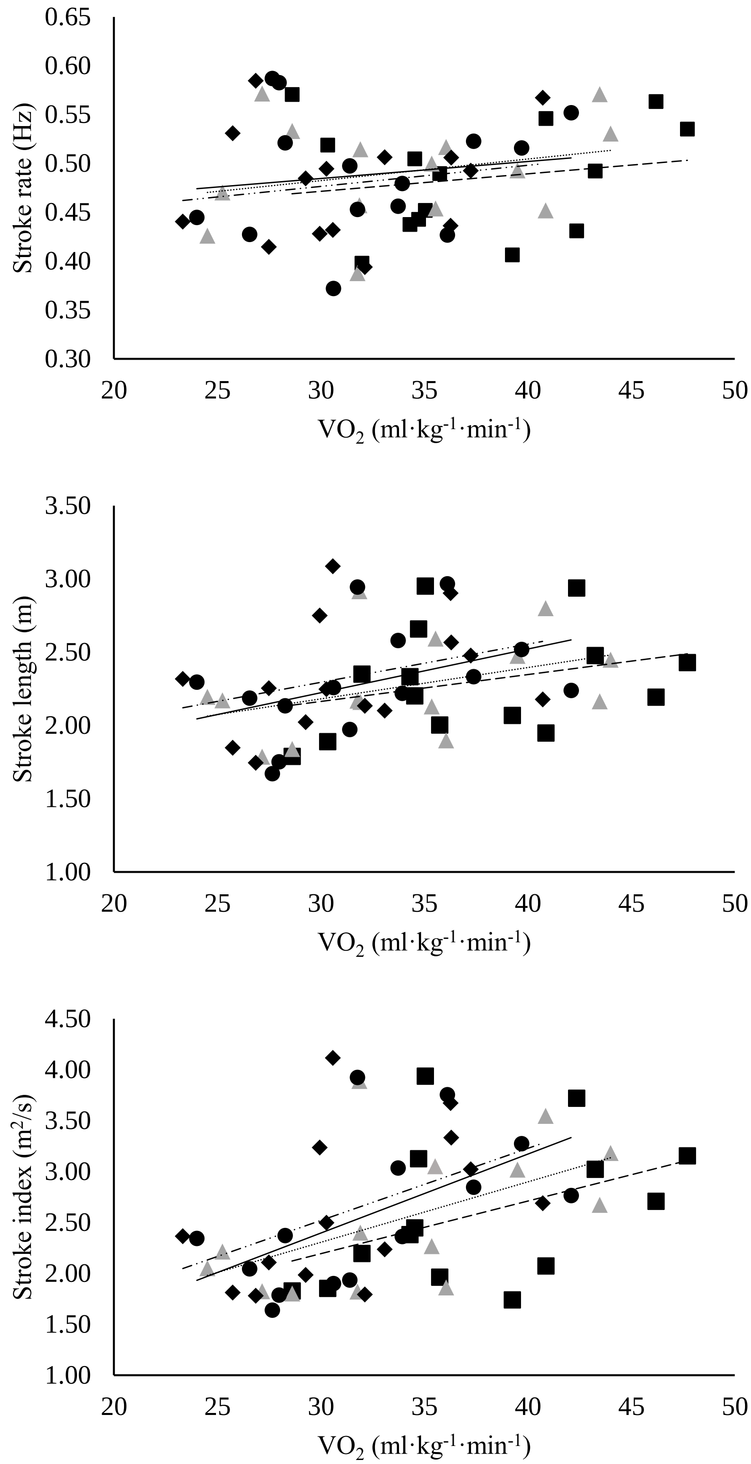
COT and SR have positive low correlations regardless of wetsuit conditions (Table 4). There were moderate negative correlations between the COT and SL during all wetsuit conditions (NWS: $r = -0.471$, $p = 0.089$; BS: $r = -0.329$, $p = -0.251$; SLW: $r = -0.406$, $p = 0.150$; FSW: $r = -0.308$, $p = 0.283$, respectively). Furthermore, COT and SI have moderate negative correlations across all wetsuit conditions (NWS: r = -0.425, p = 0.130; BS: r = -0.352, p = 0.217; SLW: r = -0.399, p = 0.157; FSW: r = -0.349, p = 0.221, respectively).

Table 4. Correlation between three physiological variables and stroke kinematics

		SR (Hz)		SL (m)		SI (m^2/s)	
	Wetsuit	r	p	r	p	r	p
$\dot{V}O_2$ ($ml\cdot kg^{-1}\cdot min^{-1}$)	NWS	0.189	0.517	0.297	0.303	0.425	0.129
	BS	0.259	0.372	0.401	0.155	0.549	0.042*
	SLW	0.214	0.463	0.332	0.247	0.464	0.095
	FSW	0.157	0.592	0.418	0.137	0.563	0.036*
HR (bpm)	NWS	0.366	0.198	0.267	0.357	0.464	0.095
	BS	0.403	0.153	0.355	0.213	0.544	0.044*
	SLW	0.335	0.242	0.383	0.176	0.555	0.039*
	FSW	0.230	0.430	0.417	0.138	0.591	0.026*
COT ($J\cdot kg^{-1}\cdot m^{-1}$)	NWS	0.225	0.439	-0.471	0.089	-0.425	0.130
	BS	0.030	0.919	-0.329	0.251	-0.352	0.217
	SLW	0.130	0.657	-0.406	0.150	-0.399	0.157
	FSW	0.040	0.893	-0.308	0.283	-0.349	0.221

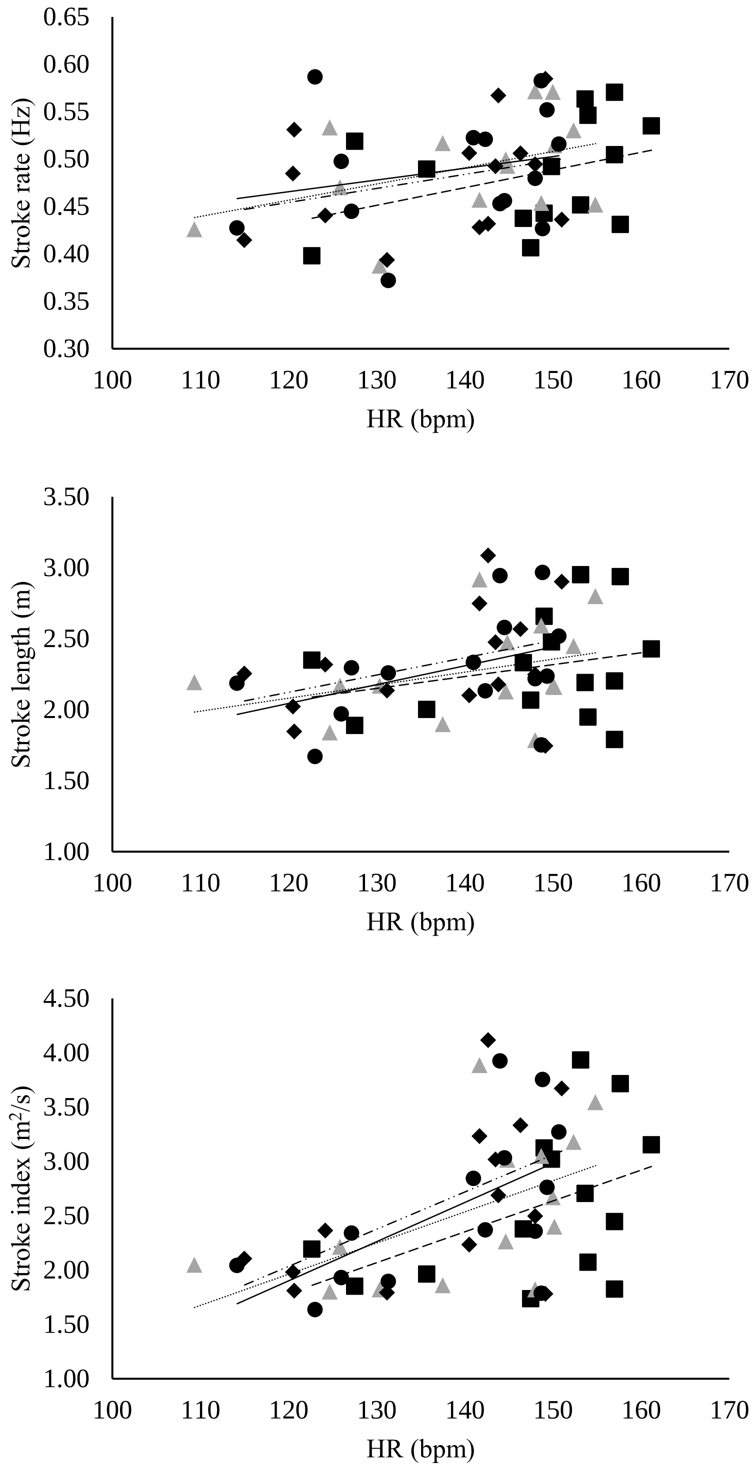
Note. *Significant difference between variables ($p < 0.05$)
The strength of correlation was reported as low ($r = 0.1$ and $r \leq 0.3$), moderate ($r \geq 0.3$ and $r \leq 0.5$), and strong ($r \geq 0.5$ and $r = 1.0$).

Figure 6. Correlation between stroke kinematics and rate of oxygen consumption



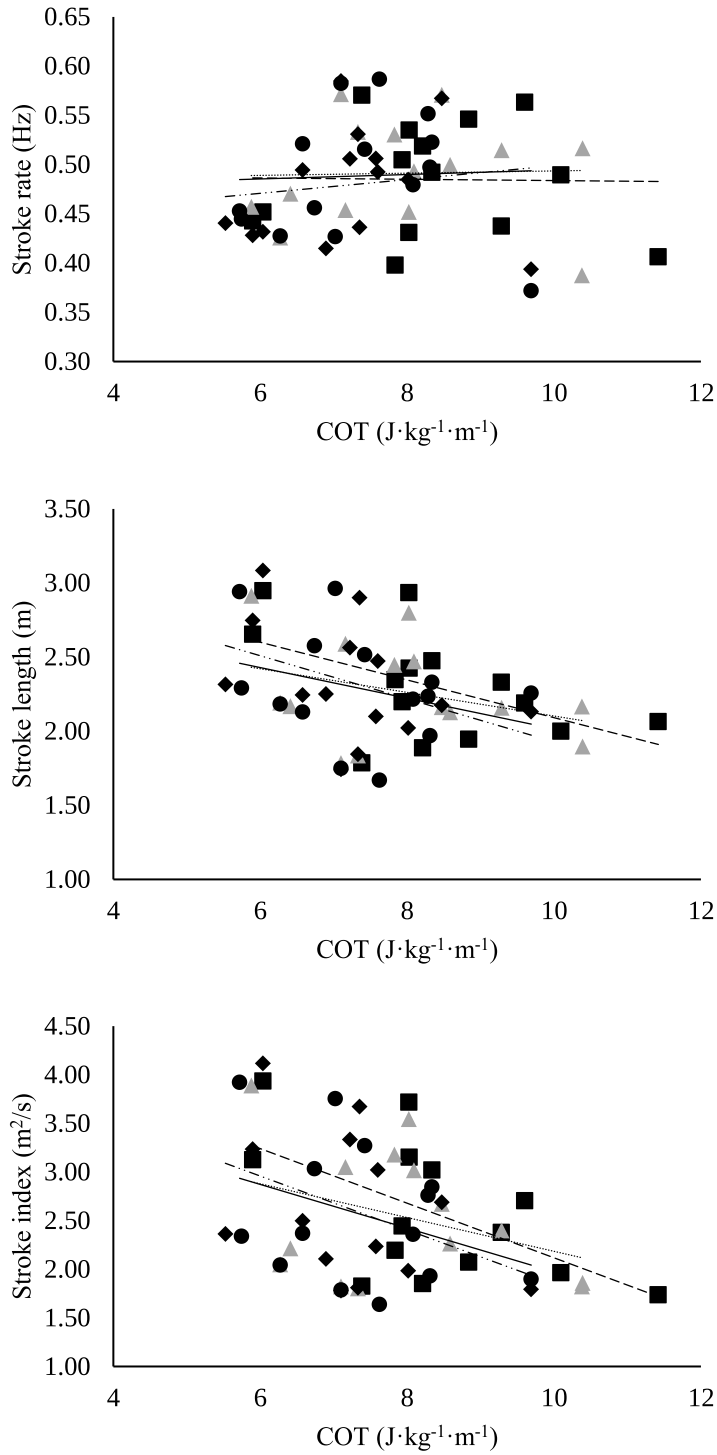
Note. ■ = No wetsuit, ▲ = Buoyancy shorts, ♦ = Sleeveless wetsuit, ● = Full sleeve wetsuit
Trendlines represent: Dashed line = No wetsuit, Round dots line = Buoyancy shorts, Long dashed dots line = Sleeveless wetsuit, Solid line = Full sleeve wetsuit

Figure 7. Correlation between stroke kinematics and heart rate



Note. ■ = No wetsuit, ▲ = Buoyancy shorts, ♦ = Sleeveless wetsuit, ● = Full sleeve wetsuit
Trendlines represent: Dashed line = No wetsuit, Round dots line = Buoyancy shorts, Long dashed dots line = Sleeveless wetsuit, Solid line = Full sleeve wetsuit

Figure 8. Correlation between stroke kinematics and cost of transport



Note. ■ = No wetsuit, ▲ = Buoyancy shorts, ♦ = Sleeveless wetsuit, ● = Full sleeve wetsuit
Trendlines represent: Dashed line = No wetsuit, Round dots line = Buoyancy shorts, Long dashed dots line = Sleeveless wetsuit, Solid line = Full sleeve wetsuit

Chapter 5: Discussion

This dissertation aimed to compare swimming economy and selected swimming kinematics if participants swim in different wetsuits at the submaximal intensity. The additional purpose of this study was to determine whether or not relationships exist between three physiological variables and swimming kinematics. It was hypothesized that physiological variables during swimming would decrease during trials in which wetsuits were worn, with more significant reductions occurring in a full-body suit than in sleeveless, buoyancy shorts, and no wetsuit conditions. In addition, we postulated that stroke kinematics would be different between wetsuit conditions. We confirmed that differences within all physiological variables were present, as indicated by the main effect of varying wetsuit conditions. However, there was no difference between SLW and FSW conditions in each physiological parameter.

Additionally, this study observed no differences in swimming kinematics across the wetsuit conditions. Specifically, participants maintained their stroke patterns across all wetsuit conditions. Furthermore, correlations between three swimming physiological variables and swimming kinematics across subjects showed that there were only negative correlations between stroke length vs. cost of transport and stroke index vs. cost of transport for each swim condition. Therefore, overall, the hypothesis was accepted in terms of the influence of wetsuits on parameters inspected, but the hypothesis was rejected when comparing parameters between wetsuit conditions.

Taken together our results provide evidence that swimming with some type of wetsuit reduced the physiological cost of swimming at a specific pace without any significant changes in stroke kinematics. In addition, stroke length and index are good indicators of lowering the cost of swimming at a given swimming pace.

Swimming Physiology

The results of physiological responses were consistent with previous studies that compared those variables between no wetsuit and a single type of wetsuit (Chatard et al., 1995; Gay et al.,2020; De Lucas et al., 2000; Hue et al., 2003; Tomikawa et al., 2007). Furthermore, a previous study examined the rate of oxygen consumption, ventilation, and heart rate while swimming at four different paces with three different wetsuits: short, long, and full (Trappe et al., 1995). However, the study recruited only five male participants and it needed to be re-examined due to the developments in the wetsuit industry (Ishikura et al., 2014). Therefore, the current study investigated both swimming physiology and stroke kinematics as well as the correlation between physiological responses and swimming kinematics with state-of-the-art triathlon wetsuits and recruited more participants (n =14; 6 male and 8 female) based on power analysis.

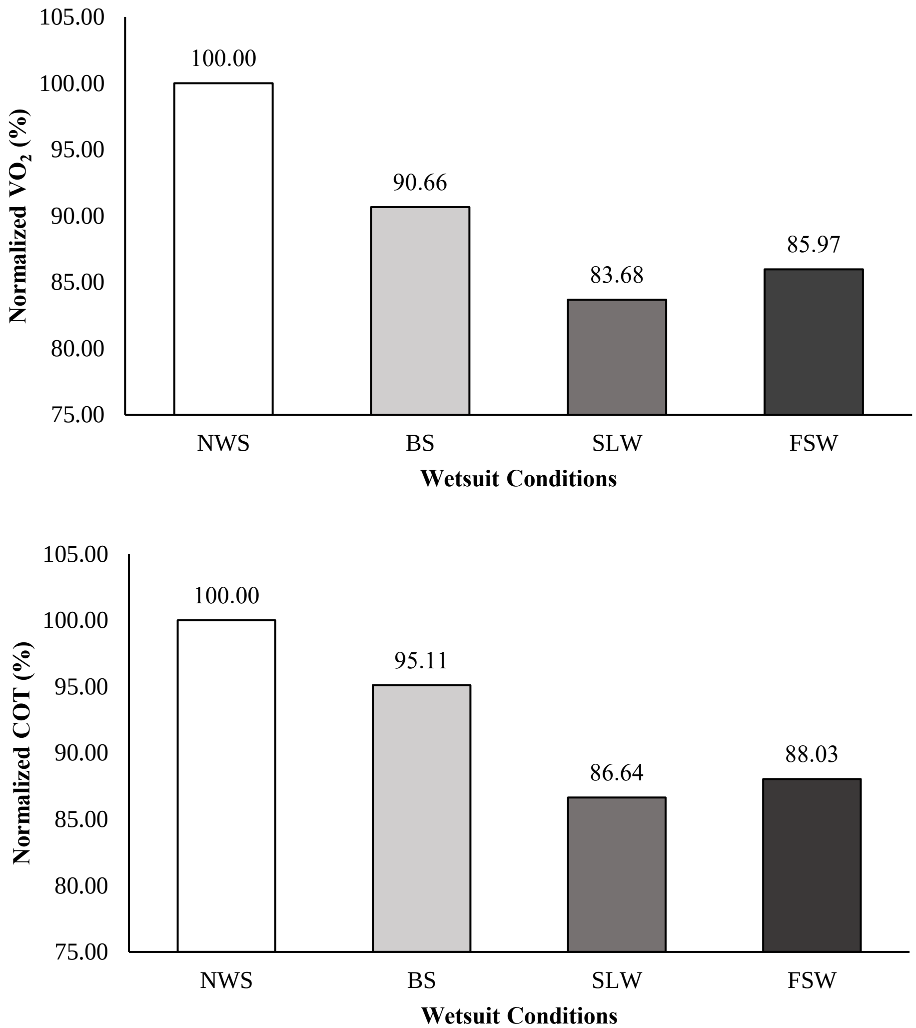
The plausible explanations about the results are caused by the reduction of resistive drag force, additional buoyancy, and smoothness of wetsuit material. Chartard and Wilson (2008) investigated the differences between resistive drag force and physiological responses in a full-body skin, waist-to-ankle swimsuit, and regular swimsuit. They observed that a full-body skin reduced resistive drag force (4 ~ 8%) and energy cost (3 ~ 5%) compared to swimming with a waist-to-ankle and regular swimsuit. Additionally, previous studies confirmed that additional buoyancy forces were approximately 26N ~ 39N while swimming with a wetsuit as well as reduced energy costs by up to 22% (Chartard et al., 1995; Tomikawa & Nomura, 2009).

To better understand how individual subjects responded to each condition, the percent difference in a parameter was calculated as compared to the NWS condition (Figure 9). Overall, the subjects all responded in the same direction. Specifically, our study observed the similar reduction in $\dot{V}O_2$ and COT when participants swam with buoyancy shorts ($\dot{V}O_2$: 9.34%, COT:

4.89%), sleeveless wetsuit ($\dot{V}O_2$: 16.32%, COT: 13.36%), and full sleeve wetsuit ($\dot{V}O_2$: 14.03%, COT: 11.97%) comparing to no wetsuit conditions (Figure 9). That is, when the group mean indicated that $\dot{V}O_2$ was less during wetsuit conditions vs. NWS, all participants responded in that same direction. Furthermore, the additional buoyancy helps swimmers maintain their streamline easier than swimming without a wetsuit (Hue et al., 2003; Nuber et al., 1986; Pink et al., 1991; Tomikawa et al., 2008; Toussaint et al., 1989; Trapper et al., 2020). The typical wetsuit is designed to be thicker on the lower body part because body density on the lower body is denser than the upper body. 'Floating leg' due to a wetsuit not only requires less kick to propel forward but also reduces passive torque (Kjendlie et al., 2004). These factors are highly associated with lowering physiological demand while swimming at a constant pace.

From a practical standpoint, triathletes possibly save energy during the swimming portion of the triathlon so that it is beneficial for the consecutive cycling portion (Olbrecht, 2011; Peeling et al., 2005; Perrier & Monteil, 2004). Additionally, previous studies demonstrated that novice or inexperienced swimmers and lean swimmers could get greater 'body positioning' benefits, which is highly related to hydrodynamic drag force (Cordain & Kopriva, 1991). Specifically, novice or inexperienced swimmers tend to push down water and lift their upper body to breathe while swimming in a pool and open water. Additionally, open water swimming requires checking their sight often to swim straight and see other competitors avoid swimming more than the given distance. When novice or inexperienced triathletes check their sight and breath, both resistive drag and passive torque increase because of lower leg submersion (Kjendlie et al., 2004), therefore, swimming with a wetsuit may play a vital role in reducing resistive drag force and passive torque against a poor body position.

Figure 9. Normalized $\dot{V}O_2$ and COT percentages compared to the NWS condition



Note. NWS: No wetsuit. BS: Buoyancy short, SLW: Sleeveless wetsuit, FSW: Full sleeve wetsuit

In addition, this present study also investigated the effect of buoyancy shorts on swimming physiology and kinematics besides two types of wetsuits. It was observed that buoyancy shorts decrease physiological demand compared to swimming in a regular swimsuit (Appendix IV). Anecdotally, the buoyancy shorts provide a similar buoyancy to a pull buoy, but the shorts do not require swimmers to ‘squeeze’ them between legs during swimming. Sprint triathlon swimming (i.e., 750m) may use energy from the aerobic system 65 ~ 83% when it comes to the energy system and utilization (Rodriguez and Mader, 2011). On the other hand, 78 ~ 90% of energy is used from the aerobic system in Olympic distances (i.e., 1500m) or longer distances (Rodriguez and Mader, 2011). For these reasons, swimmers can wear buoyancy shorts during training sessions to increase swimming mileage, save energy costs at a given intensity, and focus on their stroke technique.

Interestingly, all physiological variables were similar between sleeveless and full sleeve wetsuit conditions. A previous study expected a full sleeve wetsuit would reveal the statistical significance and less physiological demand when compared to a sleeveless wetsuit because of covering the whole upper body (Trapper et al., 1996). In contrast to the expectation, we observed that the mean value of each physiological variable was slightly lower in a sleeveless wetsuit than in a full sleeve wetsuit (Table 2). A possible explanation will be the low density of arms and the cyclical arm movement during every stroke. Participants anecdotally reported full sleeve wetsuits to be 'very comfortable' or 'comfortable' using the wetsuit fit comfort scale (Appendix III). However, based on the scale and their comments, some participants reported being slightly uncomfortable in the shoulder area even after our research team adjusted their wetsuit fit, especially arm fit and neck area. We speculated that the sleeveless wetsuits would allow participants to move their shoulders more freely. Also, the 'central governor' may detect uncomfortable shoulder movements while swimming with a full sleeve wetsuit, which increases physiological variables slightly more than a sleeveless wetsuit would (Gibson & Noakes, 2004).

Additionally, there is a possibility that lower physiological demands may lead to better performance while swimming long distances in a sleeveless wetsuit, even though there were no statistically significant differences between the sleeveless and full sleeve wetsuit in the current study. It is important to note that swim pace (m/s) was prescribed on set as constant between conditions in the present study. Therefore, we do not know if participants would prefer to swim faster (or slower) in different wetsuits. Future investigations should be designed to swim in a different environment (e.g., lake) and longer distances to answer the question.

It is also important to note that subjects completed four minutes of swimming duration per condition. Although this time is sufficient to measure the rate of oxygen consumption because swimmers could reach their steady state during submaximal swimming (Zamparo et al., 2020), we do not know that the time was sufficient in replicating the type of swim distances used in triathlon. The shortest swimming distance in the sprint triathlon is 750 m, and the greatest distance is up to 3.8 km in the Ironman triathlon. Therefore, small changes in physiological variables may significantly affect swimming performance, especially in long-distance swimming.

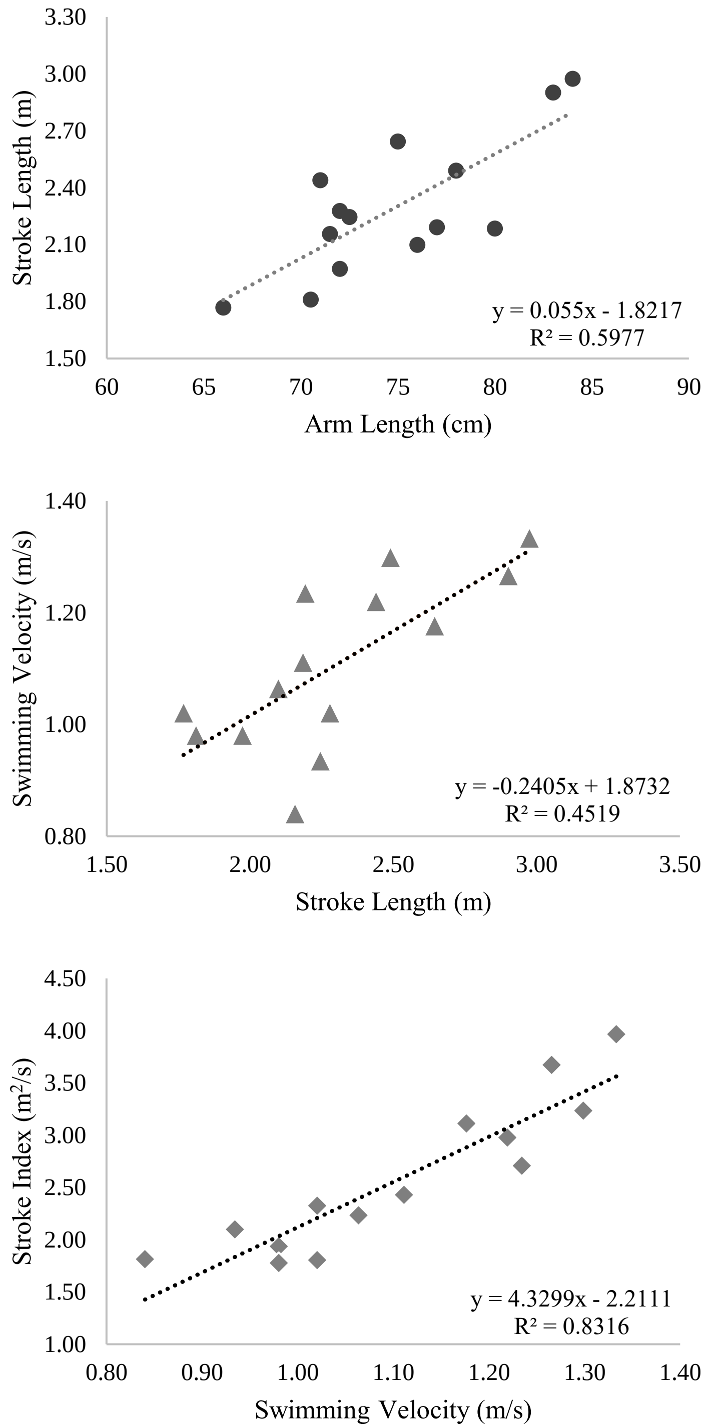
Swimming Kinematics

All participants swam at a constant pace, the equivalent of 80% of $\dot{V}O_2max$, across the four wetsuit conditions. The results of the swimming kinematics were understandable even though we expected changes in swimming kinematics by wetsuit conditions in terms of the swimming velocity unit and equation (i.e., swimming velocity = stroke rate × stroke length). Swimming velocity was the same across the four wetsuit conditions. Therefore, there was a trade-off between stroke rate and length to keep up the given swimming velocity in a flume. For instance, the stroke rate decreased due to increasing stroke length and vice versa. However, previous studies observed inconsistent results while swimming with or without a wetsuit. They observed either increased stroke rate (Perrier & Monteil, 2004), increased stroke length (Hue et al.,2003; Gay et al., 2020), or an increase in both parameters (Tomikawa & Nomira, 2009).

Participants maintained their stroke rate and length throughout the swimming sessions at the set race pace (i.e., 80% of $\dot{V}O_2max$). We expected to observe that participants change stroke rate and length because of extra buoyancy and smooth materials from the wetsuit. However, this was not observed. Therefore, the hypothesis which stated that stroke kinematics would be different according to the different wetsuit conditions was not accepted. Participants' level of swimming ability may explain this observation. Previous studies pointed out that novice and inexperienced swimmers are unable to maintain a stable stroke rate and stroke length compared to experienced swimmers (Klentrou & Montpetit, 1991). Even though the participants were not competitive elite swimmers, they were well-trained recreationally based on their health screening and questionnaire. The participants who participated in the current study regularly swam for about 246 min/week (i.e., 55 minutes per session and 4.4 days per week) and had several years of swimming experience. Also, they all currently swim in the US Masters Swimming club. In addition, the average $\dot{V}O_2max$ value was 46.74 ± 7.05 $ml \cdot kg^{-1} \cdot min^{-1,}$ which is possibly considered they were recreationally well-trained swimmers when it comes to swimming $\dot{V}O_2max$ is typically 13 ~ 18% lower than running GXT (O'Toole & Douglas, 1995). These could be the possible reasons why stroke rate and stroke length were not noticeably changed.

Before the data collection, arm length (74.89 ± 5.10 cm) was measured to see whether arm length is associated with stroke kinematics. In line with the previous research (Zamparo et al., 2020), we confirmed the consistent results that arm length showed positively correlated to stroke length as we expected (Figure 10). Furthermore, higher stroke length was positively associated with a faster swimming pace (Figure 10). This was consistent with a previous study that mentioned that faster swimmers typically have a longer stroke length (Millet et al., 2002). From our observations about the relationship between stroke kinematics, increasing stroke length may be a good way to swim more efficiently and faster. Furthermore, other studies confirmed that a higher stroke index is associated with longer stroke length and more efficient swimming performance at a given intensity (Barbosa et al., 2010; Costill et al., 1985).

Figure 10. Correlations between stroke length, arm length, swimming velocity, and stroke index.



Note. Stroke length data were the mean values of all four conditions in each participant.
Swimming velocity (m/s) was swimming test pace (i.e., 80% of $\dot{V}O_2max$).
Arm length was measured from acromion to the longest fingertip.

Correlations Between Physiological Variables and Swimming Kinematics

Reducing physiological demand at a submaximal intensity swimming indicates that swimmers can swim faster at a given distance or swim further at a given intensity (Tomikawa et al., 2008; Trapper et al., 1996). Previous studies demonstrated that the rate of oxygen consumption and cost of transport were good indicators of swimming performance rather than the $\dot{V}O_2max$ value (Komar et al., 2012). The rate of oxygen consumption is directly related to the heart rate in terms of the Fick equation. In addition, a sound swimming technique requires a better swimming efficiency rather than having solely higher cardiorespiratory capacity. Additionally, stroke kinematics are related to swimming pace, muscle activations, fatigue, propulsive, and resistive force productions. Thus, we investigated correlations between physiological variables and stroke kinematics for understanding the possible relationships according to different types of wetsuits.

$\dot{V}O_2$ and HR positively correlate with stroke kinematics across wetsuit conditions for each participant (Figure 6 and Figure 7). Based upon the analysis, the third hypothesis that there will be a negative correlation between all three physiological variables and stroke kinematics was rejected. Based on the results, however, stroke length and index have negative correlations to cost of transport. That is, participants who had a greater stroke length had a lower COT.

Our findings indicate that swimmers need to consider improving their stroke index, regardless of wetsuit use. For instance, swimmers could improve underwater movement such as the catch and pull phase to propel their body forward and extend in the gliding phase to increase stroke length. Based on previous investigations (Chatard et al., 1995), competitive swimmers typically have a longer stroke length than novice swimmers and triathletes. Even though stroke length is generally longer while swimming in a flume than in a pool and/or open water (Gay at el., 2020), increasing stroke length is essential to improve stroke index when it comes to the stroke index equation and unit (m^2/s). Furthermore, swimmers and coaches can design upper body strength and endurance training programs in muscle groups (e.g., latissimus dorsi and pectoralis major) during the pull phase to generate more propulsive forces (Number et al., 1986; Pink et al., 1991). That might effectively propel forward and take more gliding phases, which is critical to increasing stroke index.

Previous studies demonstrated that arm-only swimming is more efficient than swimming with arms and leg kicks (Konstantaki et al., 2008). The possible explanation regarding reduction in physiological variables when participants swim with buoyancy shorts and two types of wetsuits could be related to fewer leg kicks from additional buoyancy on the lower extremity. The thickness of the lower body part in both wetsuit types used for this current study is 5mm, which is 2mm thicker than the upper body. That might play an essential role in minimizing underwater torque so that participants may reduce the frontal area and resistive drag force (Kjendlie et al., 2004; Zamparo et al., 1996). Furthermore, buoyancy shorts have the same thickness on the legs and sides (i.e., 5mm). The similar effect of buoyancy shorts may explain that $\dot{V}O_2$, $\dot{V}CO_2$, V_E, HR, and RPE values were lower than when participants swam in a regular swimsuit.

Furthermore, as a way to get a sense of the relationship between parameters, the residuals were calculated. The predicted and observed scores for each subject were calculated and were fit with a linear line of best fit. In all cases, less than 31% of the explained variance of the residuals were explained by the observed data. Therefore, based upon this initial analysis, it seems that the correlations between the parameters were not influenced by the observed value.

Limitations and Confounding Factors

A limitation of this study was conducting swim conditions using a swim flume. Although this allowed for continuous swimming, it is unknown if the swimming flume fully replicates open water swimming. The major similarity between swimming in a flume and open water was that participants were able to swim continuously without having to turn at every 25- or 50-meter mark. Furthermore, swimming in a flume allowed participants to maintain the same swimming pace throughout the experimental sessions, which may not be ideal for an actual race situation due to the current, visibility, fatigue, and other variable factors. Based on the literature review, we selected the test intensity as 80% of $\dot{V}O_2max$ based on the literature review. However, a swimming pace during the actual race will vary depending on the distance, training status, and race strategies.

Additionally, there were no standard criteria to measure the wetsuit fit between participants. The manufacturer provided a wetsuit size chart, but the size chart was based on the users' height and weight. Therefore, there were some issues with choosing the right size. For instance, water gets in between the wetsuit and body if the wetsuit is too baggy. That may cause less effective thermoregulation and result in the participant carrying more weight when the water gets inside a wetsuit. In the other case, wetsuits that are too tight may increase blood pressure due to pressure on the carotid artery and restrict the range of motion of the shoulder area. That might increase shoulder muscle activity to overcome the resistance from the wetsuit itself. It ultimately makes swimmers experience shoulder fatigue earlier than they should be. When swimmers get fatigued, stroke length tends to decrease (Troup, 1999). That being said, swimmers have to increase the stroke rate to keep up with their targeted swimming pace.

A potential confounding factor in this study was the anthropometric differences across participants. We observed the differences in height, body mass, waist circumference, and percent body fat (Table 5). Furthermore, arm length is difference approximately 5cm between male and female participants (Table 5). Previous study observed the lower $\dot{V}O_2$ about 12% in swimmers who have a little bit of longer arm than the other swimmers (Chatard et al., 1990). Body surface area, body density, and percent body fat differed between males and females, but $\dot{V}O_2max$ and the test swimming pace were similar (Table 5). Although gender differences are not the primary purpose of this study, we performed an additional statistical analysis to see whether or not gender difference plays a huge role in the current study. We confirmed no interaction existed between wetsuit conditions and gender ($p > 0.05$). In addition, there were only statistically significant differences in $\dot{V}CO_2$ and RER ($p < 0.001$) between gender. The considerable difference in $\dot{V}CO_2$ (males: 2433.42 ± 421.56 L/min, females: 1620.89 ± 367.55 L/min) and RER between gender (males: 0.83 ± 0.03, females: 0.73 ± 0.09) is plausible result in terms of RER is a proportion between $\dot{V}CO_2$ and $\dot{V}O_2$. Other than $\dot{V}CO_2$ and RER, no differences were observed in all other dependent variables (Table 6). The possible explanation for the differences between those two variables was that male participants tend to use carbohydrates as an energy substrate more than female participants based on their nutrition or natural body responses when they swam at the prescribed swimming pace (i.e., 80% of $\dot{V}O_2max$).

Table 5. Descriptive statistics between male and female participants

	Male (n = 6)	Female (n = 8)
Age (years)	31.00 ± 8.20	39.75 ± 11.54
Height (m)	174.52 ± 11.45	166.06 ± 9.68
Body Mass (kg)	76.34 ± 8.56	62.58 ± 4.29
Waists Circumference (cm)	81.92 ± 7.14	74.13 ± 4.49
Arm Length (cm)	77.92 ± 5.37	72.63 ± 3.73
Body Fat (%)	21.35 ± 4.5	31.00 ± 4.4
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	46.27 ± 6.21	47.09 ± 8.03
80% of $\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	37.01 ± 4.96	37.67 ± 6.42
Swimming pace (m/s)	1.13 ± 0.18	1.08 ± 0.13

Note. All data represented as mean and standard deviation

In addition, the percent $\dot{V}O_2$ differences were compared to $\dot{V}O_2$ during no wetsuit condition in each individual and both gender (Figure 11). The additional data analysis to compare the gender differences showed no difference in $\dot{V}O_2$ between male and female participants Also, we observed male participants reduced mean $\dot{V}O_2$ value slightly more than female participants in all wetsuit conditions (Table 7). It could be explained that two slow male participants got more benefits from the buoyancy short and two wetsuit conditions (Figure 11). This result was not in line with a previous study that demonstrated that male swimmers had a greater benefit from wetsuits than females due to different body density and other anthropometrics (Cordain & Kopriva, 1991). However, it indicates that slow swimmers likely will have more benefits from wearing a wetsuit than faster swimmers (Hue et al., 2003).

Taken together, it is not clear how body composition and/or body type influence the outcome of the results in the present study because the number of participants was small and unequal (male: n = 6, female: n = 8). Additionally, there continues to be a lack of manufacturing consensus on proper wetsuit design/fit for either gender. Anecdotally, a recent trend is for manufacturers to create unisex-sized wetsuits (vs. male and female-specific designs). Therefore, more research is needed to understand better the interaction between body composition (and distribution of body fat) and wetsuit design on swim economy and swim kinematics.

Table 6. Mean values for each dependent variable between males and females

	NWS		BS		SLW		FSW	
	Male	Female	Male	Female	Male	Female	Male	Female
$\dot{V}O_2$	38.61 ± 4.90	36.65 ± 6.71	34.18 ± 6.75	33.84 ± 6.59	32.21 ± 5.90	30.73 ± 4.35	32.14 ± 6.30	32.29 ± 4.78
$\dot{V}CO_2$	2433.42 ± 421.56	1620.89 ± 367.55	2112.39 ± 615.79	1511.28 ± 412.0	1934.94 ± 460.58	1347.56 ± 273.43	1906.54 ± 522.53	1422.74 ± 326.54
V_E	69.59 ± 9.16	61.13 ± 13.54	58.18 ± 13.93	55.65 ± 12.07	56.08 ± 11.78	51.03 ± 8.57	54.78 ± 11.98	53.63 ± 10.29
HR	152.6 ± 4.6	144.6 ± 14.2	142.1 ± 11.8	138.8 ± 14.7	140.1 ± 10.4	134.7 ± 13.6	140.5 ± 9.2	137.0 ± 13.9
RER	0.83 ± 0.03	0.73 ±0.09	0.80 ± 0.06	0.71 ± 0.06	0.78 ± 0.04	0.72 ± 0.06	0.77 ± 0.06	0.71 ± 0.05
RPE	14.5 ± 2.3	12.5 ± 3.1	12.2 ± 1.8	11.4 ± 1.9	11.8 ± 1.7	11.1 ± 2.4	11.7 ± 1.4	11.9 ± 1.9
COT	8.72 ± 1.83	8.08 ± 1.20	8.08 ± 1.71	7.84 ± 1.25	7.28 ± 1.57	7.21 ± 0.63	7.17 ± 1.56	7.49 ± 0.75
SR	0.47 ± 0.06	0.50 ± 0.06	0.48 ± 0.06	0.50 ± 0.05	0.46 ± 0.06	0.49 ± 0.05	0.46 ± 0.07	0.51 ± 0.06
SL	2.45 ± 0.39	2.19 ± 0.32	2.40 ± 0.36	2.17 ± 0.31	2.48 ± 0.41	2.22 ± 0.36	2.47 ± 0.38	2.15 ± 0.33
SI	2.82 ± 0.84	2.40 ± 0.59	2.76 ± 0.80	2.38 ± 0.60	2.85 ± 0.87	2.44 ± 0.65	2.84 ± 0.82	2.36 ± 0.62

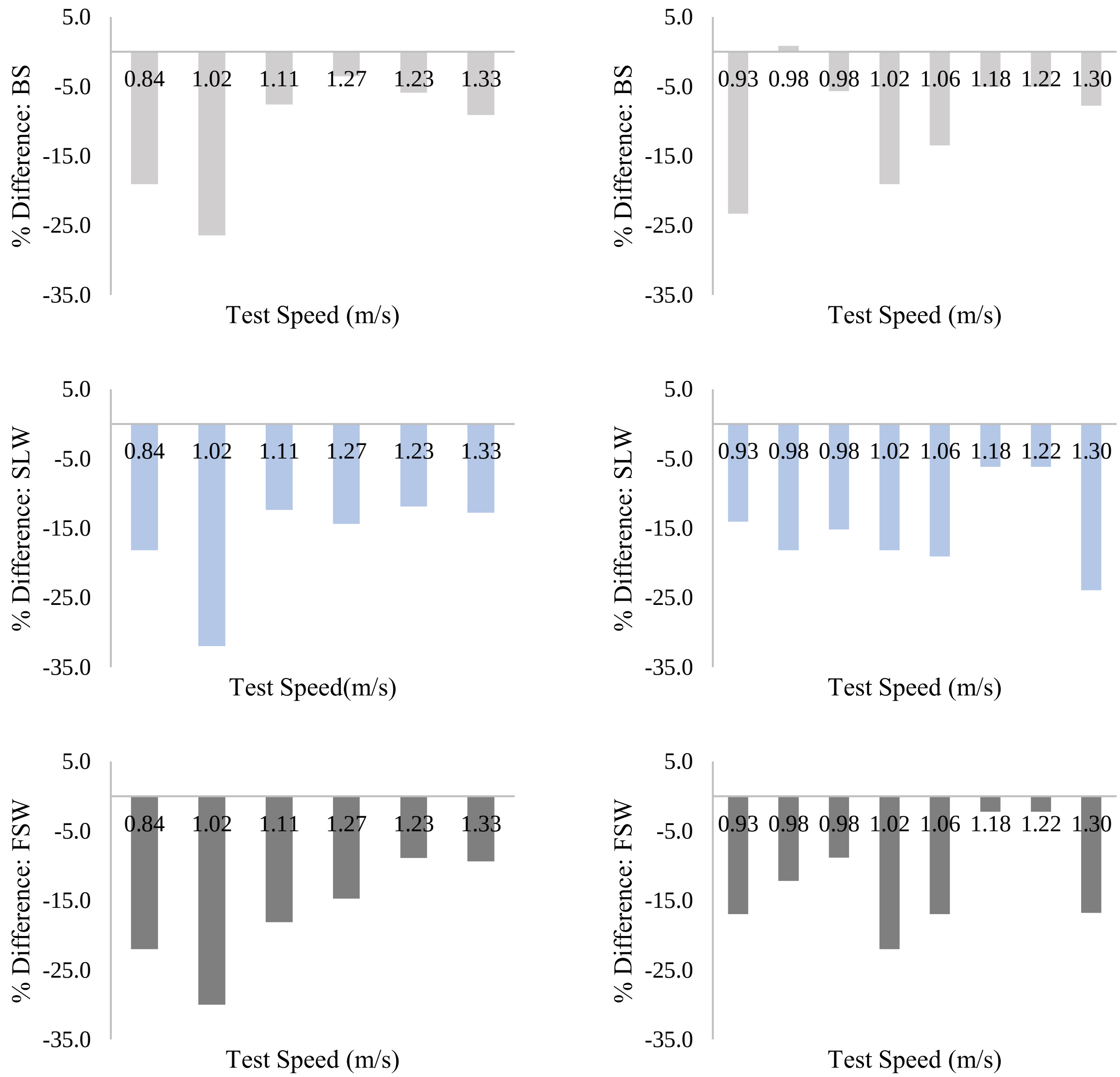
Note. All data were represented as mean and standard deviations.
$\dot{V}O_2$: rate of oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$), $\dot{V}CO_2$: rate of carbon dioxide consumption (L/min), V_E: Ventilation (L/min), HR: heart rate (bpm), RER: respiratory exchange ratio, RPE: rate of perceived exertion, COT: cost of transport ($J \cdot kg^{-1} \cdot m^{-1}$), SR: stroke rate (Hz), SL: stroke length (m), SI: stroke index (m^2/s)
NWS: No wetsuit. BS: Buoyancy short, SLW: Sleeveless wetsuit, FSW: Full sleeve wetsuit

Table 7. Percent $\dot{V}O_2$ reduction compared to NWS in both male and female participants

	Male (n = 6)	Female (n = 8)
BS	-11.93 ± 8.89	-9.83 ± 8.12
SLW	-16.91 ± 7.73	-15.11 ± 6.25
FSW	-17.19 ± 8.06	-12.28 ± 7.30

Note. All data represented as mean and standard deviation

Figure 11. Percent differences in $\dot{V}O_2$ compared to NWS each individual and both gender



Note. Left column: six male participants, Right column: eight female participants
Test speed (m/s) sorted from the slow (left) to fast (right).
Light grey: % differences in BS vs. NWS, Light blue: % differences in SLW vs. NWS, Dark grey: % differences in FSW vs. NWS

Recommendations

Future research will be necessary to conduct investigations in open water conditions where events are commonly held such as a bay or lake. Ideally, these locations would allow for somewhat controlled environmental conditions (i.e., the water current is at a minimum) but would mimic the triathlon race situation such as 750m swimming in the lake. Changes in physiological variables and/or swimming kinematics due to different wetsuit styles may influence the time taken to complete a given distance in an open water setting. Also, this current study recruited recreationally trained swimmers. Therefore, they maintained stroke kinematics throughout swimming sessions irrespective of wetsuit style. The test result may differ with novice swimmers who have swimming experience of less than a year or categorized their best swimming time by a certain distance. In addition, the comparison between genders will be necessary to understand the relationship between anthropometrics and the effect of wetsuits on swimming. Furthermore, it is vital to see if swimming performance with different wetsuits affects the cycling, running, and overall triathlon performance for the practical aspects.

Conclusions

Based on our observations, swimming with any type of wetsuit revealed benefits from reducing the physiological demand at a swimming intensity, a typical triathlon swimming pace. However, stroke kinematics were independent of wetsuit style. Also, we observed that buoyancy shorts reduced some physiological demands compared to swimming with a regular swimsuit. In this manner, swimming with buoyancy shorts may be a good option for recreational triathletes who have less swimming experience. Furthermore, stroke length and index showed an inverse relationship with cost of transport. This indicates that triathletes need to improve their stroke length to reduce the cost of transport. These results may also benefit the cycling and running portion of the triathlon due to the reduced cost of energy required with a longer stroke length while swimming with wetsuits or buoyancy shorts. In conclusion, the current results prove that recreational triathletes can wear any type of wetsuit during training and racing.

However, stroke kinematics were independent of wetsuit style. Also, we observed that buoyancy shorts reduced some physiological demands compared to swimming with a regular swimsuit. In this manner, swimming with buoyancy shorts may be a good option for recreational triathletes who have less swimming experience. Furthermore, stroke length and index showed an inverse relationship with cost of transport. This indicates that triathletes need to improve their stroke length to reduce the cost of transport. These results may also benefit the cycling and running portion of the triathlon due to the reduced cost of energy required with a longer stroke length while swimming with wetsuits or buoyancy shorts.

In conclusion, the current results support the use of any type of wetsuit during training and racing while swimming at a pace the elicits 80% VO2max. Nevertheless, athletes should consider their body types and wetsuit fit for a comfortable swimming when they choose a wetsuit.

Appendix I

Informed Consent

Swimming economy and shoulder muscle activity while swimming with different styles of wetsuits

To Project Participant:

You are invited to take part in a research project led by George Crocker, a faculty member at California State University, Los Angeles. In this study, we hope to learn more about the effect of different styles of swimming wetsuits on swimming economy and shoulder muscle activity. You were selected to participate in this study because you are a trained swimmer between the ages of 18-59 years old, who is performing regular swim training (swimming >3 km per week over the past four weeks). By participating in this study, you will perform an incremental swim test to exhaustion without wearing a wetsuit and submaximal swimming tests while wearing 3 different styles of wetsuits and without a wetsuit. The 3 styles of wetsuits are a full suit, a sleeveless suit and buoyancy shorts. By participating in our research, you will receive measurements of your maximal aerobic capacity and maximal heart rate while swimming. Additionally, you will learn which style of wetsuits enables you to swim most efficiently. The knowledge that may be gained from this study includes understanding the relationship between shoulder muscle electrical activity and swimming economy.

If you choose to participate, you will report to the swimming pool on the Cal State LA campus on one day. The total time commitment for this study is approximately 120 minutes. The first session will take 60 minutes and consist of a swimming maximal aerobic capacity ($\dot{V}O_2max$) test and shoulder muscle activity measurement during swimming with different wetsuits (i.e., full-sleeve, sleeveless, buoyancy shorts, and normal swimsuit). The swimming $\dot{V}O_2max$ test will consist of swimming at increasing speeds until exhaustion in a swim flume (i.e., a water treadmill) with time to warmup before the test and cooldown after the test. Following the $\dot{V}O_2max$ test, the shoulder muscle activity measurement will be conducted by placing waterproofed wireless electrodes on your shoulder and having you swim at one speed for one minute with each wetsuit. For all tests, you breathe through a snorkel, wear a nose clip, have a heart rate monitor around your chest, and the water temperature will be around 70 °F.

On the second session, you will perform a 4-minute submaximal swimming test in the swim flume wearing each of the wetsuits over your swimsuit and with just a swimsuit (i.e., you will not swim naked). The total time commitment on the second day is also up to 60 minutes. You will receive a free parking pass for each testing day. However, you will not be compensated financially for participation in this study. If you are an enrolled student at Cal State LA, you will not receive any course credit for participation in this study.

There is a risk of infection from the snorkel; however, it will be thoroughly cleaned with 10% bleach and rinsed with water before use. Some subjects may have an allergic reaction to the electrodes place on their skin. Loss of confidentiality is another risk of participation in this study. There are some risks involved with performing an exercise test, although the intensity and duration of exercise is similar to what you already do for exercise. Certain changes can occur in response to exercise, for example, abnormal blood pressure changes, dizziness, heart attack, stroke, or death. We do not expect any of these adverse medical effects to occur and you can take a break and drink water should you start feeling ill. In addition, a certified lifeguard will be present at all times. There is also the risk that an undiagnosed medical condition may become apparent as a result of participation in this study. In the event of an injury or illness as the result of participation in this research project, an enrolled/eligible student may seek basic medical and/or mental health care within the scope of the services of the Student Health Center (SHC), as authorized by the Trustees of the California State University, during the Student Health Center's normal operating hours, or see a personal/outside health care provider for care and treatment. For care beyond the scope of services of the SHC, subjects must seek care and treatment from an outside/personal health care provider. A non-student subject is only eligible to receive basic first-aid care from the SHC during its normal operating hours and will need to seek care beyond first aid from an outside/personal health care provider. In all cases, in the event of need for emergency medical care, 911 will be called. Any and all incurred health care costs associated with participation in this research project are the responsibility of the subject.

Subjects will complete Exercise Pre-participation Health Screening Questionnaire from the American College of Sports Medicine prior to participation in the study to reduce the risk for unwanted health complications. Any residual glue from the electrodes will be removed with soap and water to reduce the risk or severity of any allergic reactions to the adhesive on the electrodes. All reports resulting from this study will not identify you as a participant. Subjects will be referred to by a sequential number. All information gathered in this study will remain confidential and be given out only with your permission or as required by law. We will protect your confidentiality whether or not you choose to participate. All data recorded from this study will be stripped of identifiers and stored on password-protected computers and/or locked file cabinets in the principal investigator's office. All files will be kept for 3 years. After this time, they will be deleted or destroyed. However, despite these precautions, there is a risk of loss of confidentiality by participating in this study.

If you have any questions about this research at any time, please call Dr. George Crocker at (323) 343-4667 or email him at gcrocke@calstatela.edu or write him at School of Kinesiology, Nutrition & Food Science, 5151 State University Drive, Los Angeles, CA 90032.

By signing this consent form, you indicate that you have read the form and agree voluntarily to participate in the study. If you choose not to take part, there will be no penalty or loss of benefits to which you are entitled. If you agree to take part, you are free to withdraw from it at any time. Likewise, no penalty or loss of benefits to which you are otherwise entitled will occur.

I agree to participate in "Swimming economy and shoulder muscle activity while swimming with different styles of wetsuits," as set out above.

______________________________________ __________________

Signature Date

THIS PROJECT HAS BEEN REVIEWED BY THE CALIFORNIA STATE UNIVERSITY, LOS ANGELES INSTITUTIONAL REVIEW BOARD FOR THE PROTECTION OF HUMAN SUBJECTS IN RESEARCH. ADDITIONAL CONCERNS AND COMPLAINTS, OR QUESTIONS REGARDING YOUR RIGHTS AS A RESEARCH PARTICIPANT, SHOULD BE DIRECTED TO THE ASSOCIATE VICE PRESIDENT FOR RESEARCH (Phone number: 323-343-5368).

Appendix II

Exercise Preparticipation Health Screening Questionnaire for Exercise Professionals

Assess your client's health needs by marking all true statements.

Step 1: Signs and Symptoms

Does your client experience:

- □ chest discomfort with exertion
- □ unreasonable breathlessness
- □ dizziness, fainting, blackouts
- □ ankle swelling
- □ unpleasant awareness of a forceful, rapid or irregular heart rate
- □ burning or cramping sensations in lower legs when walking short distance
- □ known heart murmur

If you marked any of these statements under the symptoms, STOP, your client should seek medical clearance before engaging in or resuming exercise. Your client may need to use a facility with medically qualified staff.

Step 2: Current Activity

Has your client performed planned, structured physical activity for at least 30 minutes at moderate intensity on at least 3 days per week for at least the last 3 months?

□ Yes □ No

Continue to step 3.

Step 3: Medical Conditions

Has your client had or does he/she currently have:

- □ a heart attack
- □ heart surgery, cardiac catheterization, or coronary angioplasty
- □ pacemaker/implantable cardiac defibrillator/rhythm disturbance
- □ heart valve disease
- □ heart failure
- □ heart transplantation
- □ congenital heart disease
- □ diabetes
- □ renal disease

Evaluating Steps 2 and 3:

- If you did NOT mark any of the statements in Step 3, medical clearance is not necessary.
- If you marked Step 2 "yes" and marked any of the statements in Step 3, your client may continue to exercise at light to moderate intensity without medical clearance. Medical clearance is recommended before engaging in vigorous exercise.
- If you marked Step 2 "no" and marked any of the statements in Step 3, medical clearance is recommended. Your client may need to use a facility with medically qualified staff.

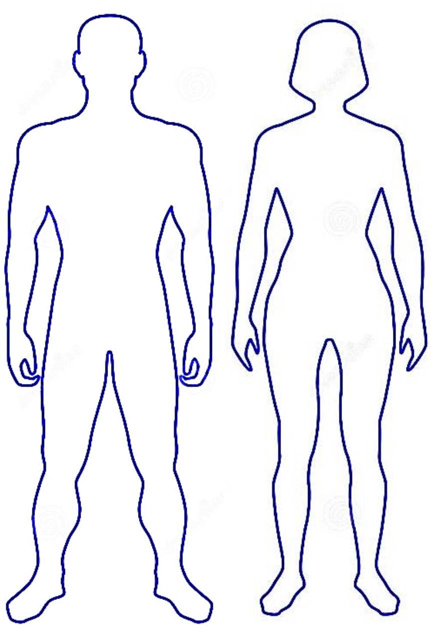
This preparticipation screening form was developed for exercise professionals for use with ACSM's preparticipation screening algorithm, which can be found in ACSM's Guidelines for Exercise Testing and Prescription, 10th edition, 2017.

Appendix III

Wetsuit Fit Comfort Scale (CS)

+5	Very Comfortable
+4	
+3	Comfortable
+2	
+1	Somewhat Comfortable
0	
-1	Somewhat Uncomfortable
-2	
-3	Uncomfortable
-4	
-5	Very Uncomfortable

Wetsuit Fit Data Sheet



Neck		
Shoulder	L :	R :
Armpit	L :	R :
Waist		
Hip		
Groin		
Thigh	L :	R :
Calf	L :	R :
Note.		

Appendix IV

Pairwise Comparisons Tables

Tables and values were used on estimated marginal means
b. Adjustment for multiple comparisons

- Least Significant Differences (equivalent to no adjustments).

- **Rate of Oxygen Consumption ($\dot{V}O_2$)**

(I) Wetsuits	(J) Wetsuits	Mean Difference	Std. Error	Sig.[b]	95% CI for Difference[b] Lower Bound	Upper Bound
NWS	BS	3.507	.787	**<.001**	1.808	5.207
	SLW	6.125	.694	**<.001**	4.625	7.625
	FSW	5.266	.748	**<.001**	3.650	6.882
BS	SLW	2.618	.758	**.004**	.980	4.256
	FSW	1.759	.538	**.006**	.598	2.921
SLW	FSW	-.859	.449	.078	-1.829	.112

- **Rate of Carbon Dioxide Consumption ($\dot{V}CO_2$)**

(I) Wetsuits	(J) Wetsuits	Mean Difference	Std. Error	Sig.[b]	95% CI for Difference[b] Lower Bound	Upper Bound
NWS	BS	200.223	57.307	**.004**	76.418	324.028
	SLW	369.827	49.409	**<.001**	263.085	476.569
	FSW	339.041	63.661	**<.001**	201.509	476.572
BS	SLW	169.604	51.166	**.006**	59.067	280.141
	FSW	138.818	47.785	**.012**	35.585	242.050
SLW	FSW	-30.786	40.836	.464	-119.008	57.435

- **Ventilation (V_E)**

(I) Wetsuits	(J) Wetsuits	Mean Difference	Std. Error	Sig.[b]	95% CI for Difference[b] Lower Bound	Upper Bound
NWS	BS	8.024	2.275	**.004**	3.108	12.939
	SLW	11.574	1.749	**<.001**	7.796	15.351
	FSW	10.637	1.987	**<.001**	6.345	14.929
BS	SLW	3.550	1.718	.059	-.162	7.262
	FSW	2.614	1.494	.104	-.614	5.842
SLW	FSW	-.936	1.155	.432	-3.432	1.559

- **Heart Rate (HR)**

(I) Wetsuits	(J) Wetsuits	Mean Difference	Std. Error	Sig.[b]	95% CI for Difference[b] Lower Bound	Upper Bound
NWS	BS	7.835	1.708	**<.001**	4.146	11.524
	SLW	11.024	1.278	**<.001**	8.264	13.785
	FSW	9.537	1.205	**<.001**	6.933	12.141
BS	SLW	3.189	1.411	**.042**	.142	6.237
	FSW	1.702	1.219	.186	-.931	4.335
SLW	FSW	-1.487	.975	.151	-3.593	.619

- **Cost of Transport (COT)**

(I) Wetsuits	(J) Wetsuits	Mean Difference	Std. Error	Sig.[b]	95% CI for Difference[b] Lower Bound	Upper Bound
NWS	BS	.408	.290	.183	-.219	1.034
	SLW	1.115*	.257	**<.001**	.560	1.670
	FSW	1.000*	.276	**.003**	.404	1.596
BS	SLW	.707*	.249	**.014**	.169	1.246
	FSW	.592*	.228	**.022**	.099	1.085
SLW	FSW	-.115	.110	.317	-.354	.124

- **Respiratory Exchange Ratio (RER)**

(I) Wetsuits	(J) Wetsuits	Mean Difference	Std. Error	Sig.[b]	95% CI for Difference[b] Lower Bound	Upper Bound
NWS	BS	.021	.012	.110	-.005	.047
	SLW	.024	.011	**.045**	.001	.048
	FSW	.037	.015	**.024**	.006	.069
BS	SLW	.004	.010	.736	-.019	.026
	FSW	.016	.009	.097	-.003	.036
SLW	FSW	.013	.011	.270	-.011	.037

- **Rate of Perceived Exertion (RPE)**

(I) Wetsuits	(J) Wetsuits	Mean Difference	Std. Error	Sig.[b]	95% CI for Difference[b] Lower Bound	Upper Bound
NWS	BS	1.643	.541	**.010**	.475	2.811
	SLW	1.929	.450	**<.001**	.955	2.902
	FSW	1.571	.716	**.047**	.024	3.119
BS	SLW	.286	.286	.336	-.332	.903
	FSW	-.071	.370	.850	-.871	.728
SLW	FSW	-.357	.561	.535	-1.568	.854

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Zamparo, P., Cortesi, M., & Gatta, G. (2020). The energy cost of swimming and its determinants. *European Journal of Applied Physiology*, *120*(1), 41–66. https://doi.org/10.1007/s00421-019-04270-y

Curriculum Vitae

Boram Lim, ABD

NSCA CSCS., ACSM EP-C

Graduate Assistant
Department of Kinesiology and Nutrition Sciences

College of Integrated Health Science
University of Nevada, Las Vegas

MPE Building, Room 328
4505 S. Maryland Pkwy,
Las Vegas, NV 89154

Email: boram.lim1983@gmail.com

Education

Ph.D. **University of Nevada, Las Vegas (Las Vegas, NV)** **May 2022**
Department of Kinesiology and Nutrition Sciences (***Expected to Graduate)***

Interdisciplinary Health Sciences
Concentration: Biomechanics

Dissertation title: Investigation of Swimming Physiology and Stroke Characteristics while Wearing Different Triathlon Wetsuit Styles at Submaximal Front Crawl Swimming in Recreational Population

Advisor: Dr. John Mercer

M.S. **California State Polytechnic University, Humboldt (Arcata, CA)** **May 2018**
Department of Kinesiology and Recreation Administration

Kinesiology
Concentration: Exercise Physiology

Thesis title: The Effect of Stride Frequency Variations on Running Performance of Time to Exhaustion at the Velocity of $\dot{V}O_2max$

Advisor: Dr. Young Kwon

B.S. **Myong-Ji University (Seoul, Republic of Korea)** **Feb. 2010**
Major: Physical Education

Professional Experience

The International Organization for Health, Sports, and Kinesiology (IOHSK)
Board of Director - Coordinator Jul. 2020 - Present

- Managing membership
- Organize conference and technical support
- Service duties for the biannual virtual conference (i.e., modulator)

The Journal of Health, Sports, and Kinesiology (JOHSK)
Publishing Editorial Committee Jul. 2020 - Present

- Sort submitted papers to appropriate reviewers
- Review abstract and full manuscript

University of Nevada, Las Vegas (UNLV), Las Vegas, NV. Aug. 2018 - Present
Part-time Instructor (*Summer term only*)

- Teaching undergraduate and graduate courses
- Advising students

Graduate Assistant

- Teaching undergraduate courses
- Conducting research, troubleshooting software and equipment
- Advising students
- Service duties for the department and kinesiology program

California State Polytechnic University Humboldt, Arcata, CA. Aug. 2016 - May 2018
Fitness Instructor

- Design and instruct a 12-week fitness training program
  - For special population: Local firefighters and police officers
- Prescribe and modify training program according to progression

Teaching Assistant

- Teaching undergraduate laboratory courses
- Troubleshooting software and equipment

Teaching Experience

University of Nevada, Las Vegas, Las Vegas, NV. Aug. 2018 - Present
Course / Laboratory Instructor

- **Graduate Class**
  - KIN 657: Physiology of Endurance Performance

- **Undergraduate Class**
  - KIN 457: Physiology of Endurance Performance
  - KIN 346: Biomechanics
  - KIN 346L: Biomechanics Laboratory

California State Polytechnic University, Humboldt, Arcata, CA. May 2018 - Aug. 2018
Teaching Assistant

- **Undergraduate Classes**
  - KIN 379 – Exercise Physiology
  - KIN 380 – Fitness Assessment and Prescription Lab
  - KIN 455 – Exercise Prescription and Leadership

Other Experience

Fitness and Swimming Instructor Dec. 2009 - Feb. 2010
National Training Institute of Education, Science, and Technology, Seoul, Republic of Korea.

Strength and Conditioning Coach & Goalkeeper Mar. 2007 - Nov. 2009
Sports Association for the Differently abled (Soccer), Seoul, Republic of Korea.

Lifeguard (Summer season only) 2007 - 2009
Han-river Outdoor Pool, Seoul, Republic of Korea.

Army Sergeant Feb. 2005 - Feb. 2007
Republic of Korea Army (ROKA), Republic of Korea.

Fitness Instructor Feb. 2003 - Feb. 2005
Phoenix physical education institution, Seoul, Republic of Korea.

Student Athletes (Basketball), Seoul, Republic of Korea. Mar. 1996 - Feb. 2002

Peer-reviewed Publications

1. **Lim, B**., Burrus, B. M., Ortega, J. D, & Kwon, Y. S. (2020). The Effect of Stride Frequency on Running Performance at the Speed of $\dot{V}O_2$max. *Journal of Exercise Physiology Online, 23*(6), 1-13.

Manuscript in Preparation

1. **Lim, B**., Crocker, G., & Mercer, J. A. Investigation of Swimming Economy while Wearing Different Triathlon Wetsuit Styles at Submaximal Front Crawl Swimming.
2. **Lim, B**., Swafford, A., Conroy, K., & Mercer, J. A. Shoulder Muscle Activity While Swimming in Different Wetsuits and Across Different Paces.
3. Swafford, A., **Lim, B**., Conroy, K., & Mercer, J. A. Core Temperature while Swimming in a Wetsuit during 1000-m Race Pace Swim.

Presentations

(Podium/Oral presentations)

1. The Effect of Crank Arm Length on Cycling Economy and Performance in Triathlon.
   ➢ *IOHSK 2020 International Virtual Conference, Oct. 16, 2020*

2. Physics and Physiology of Endurance Sport: Swim, Bike. Run.
   - ➢ *ACSM Southwest 2019 Annual Meeting, Newport, CA, Oct. 25, 2019*
3. The Effect of Stride Frequency Variations on Running Performance of Time to Exhaustion at the Velocity of $\dot{V}O_2$max.
   - ➢ *The 32nd CSU Student Research Competition, CSU Sacramento, CA, May 4, 2018*
   - ➢ *ACSM 2018 Annual Meeting, Minnesota, Minneapolis, May 31, 2018*
   - ➢ *2018 Korea United States Applied Physiology Society (KUSAPS) Annual Meeting, Minnesota, Minneapolis, May 31, 2018*

(Poster presentations)

1. Investigation of Swimming Economy while Wearing Different Triathlon Wetsuit Styles at Submaximal Front Crawl Swimming.
   - ➢ *ACSM 2022 Annual Meeting, San Diego, CA, June 2, 2022*
   - ➢ *ACSM Southwest 2021 Annual Meeting, Costa Mesa, CA, Oct. 29, 2021*
2. Case Study: The Effect of Stride Frequency on the Over Ground Running Performance and Running Dynamics.
   - ➢ *ACSM 2021 Annual Meeting, Virtual Conference, Jun. 1, 2021*
   - ➢ *ACSM Southwest 2020 Annual Meeting, Virtual conference, Oct. 28, 2020*
3. Case Study: Shoulder Muscle Activity While Swimming with Different Wetsuit Conditions and Swimming Paces.
   - ➢ *ACSM 2020 Annual Meeting, Virtual conference, May 29, 2020*
4. The Biomechanics Response of Swimming in Triathlon Wetsuits.
   - ➢ *ACSM 2019 Annual Meeting, Orlando, FL, May 29, 2019*
   - ➢ *ACSM Southwest 2018 Annual Meeting, Costa Mesa, CA, Oct. 26, 2018*
5. The Effect of Stride Frequency Variations on Running Performance of Time to Exhaustion at the Velocity of $\dot{V}O_2$max.
   - ➢ *ACSM Southwest 2017 Annual Meeting, Long Beach, CA, Oct. 22, 2017*
6. The Effect of Rest Interval Duration on the Volume Completed During a High-Intensity Bench Press Exercise.
   - ➢ *ACSM 2017 Annual Meeting, Denver, CO, May 31, 2017*

Proceeding Papers / Referred Abstracts

(Proceeding Papers)

1. **Lim, B**. & Mercer, J (2021). The Effect of Crank Arm Length on Cycling Economy and Performance in Triathlon. *Journal of Health, Sports, and Kinesiology*, 2021, *2*(2), 4-7
2. **Lim, B**. & Kwon, Y. (2021). The Effect of Stride Frequency on Running Economy and Running Distance During High Intensity Treadmill Running. *Journal of Health, Sports, and Kinesiology*, *2*(1), 13-14.

3. **Lim, B.,** Villalobos, A., Crocker, G., & Mercer, J (2021). Investigation of Swimming Economy while Wearing Different Triathlon Wetsuit Styles at Submaximal Front Crawl Swimming. *International Journal of Exercise Science*, *14*(1), 37.

(Referred Abstract)

1. **Lim, B**. & Mercer, J. A. (2021). Case Study: The Effect of Stride Frequency on the Over Ground Running Characteristics. *Medicine & Science in Sports & Exercise*, *53*(8S):149.
2. Kwon, Y., Roberts, D., **Lim, B**. Bloedon, T., Ortega, J. (2021). Anaerobic Capacity Measures in Active Healthy Adults Ages 18-29: Normative Reference Values and Differences Between Sex. *Medicine & Science in Sports & Exercise*, *53*(8S):17.
3. Swafford, A., Aure, M. J., **Lim, B.**, Mercer, J. A. (2020). Core Temperature While Swimming in a Wetsuit During 1000-m Race Pace Swim. *Medicine & Science in Sports & Exercise*, *52*(7S), 261.
4. **Lim, B**., Roche, C., Swafford, A., Mercer, J. A. (2020). Case Study: Shoulder Muscle Activity While Swimming with Different Wetsuit Conditions and Swimming Paces. *Medicine & Science in Sports & Exercise, 52*(7S), 701.
5. Mercer, J., **Lim, B.**, Roche, C., Do, A. (2019). Evaluation of Shoulder Muscle Activity Patterns While Swimming in Triathlon Wetsuits. *Medicine and Science in Sports and Exercise*, *51*(6), 54.
6. Aure, M. J., Guzman, G., **Lim, B.**, Roche, C., & Mercer, J. A. (2019). Is Core Temperature Influenced by Triathlon Wetsuit Models When Swimming in Warm Water? *Medicine & Science in Sports & Exercise, 51*(6), 945.
7. **Lim, B**., Roche, C., Do, A., & Mercer, J. A. (2019). Muscle Activity While Swimming in Triathlon Wetsuits. *Medicine & Science in Sports & Exercise*, *51*(6), 41.
8. Girouard, T., **Lim, B.**, Nava, C., Morton, C., & Mercer, J. A. (2019). Determining If a Bike-mounted Aerodynamic Sensor Can Detect Changes in Wheel Rolling Resistance during Cycling with Different Tire Pressures Outdoors. *Medicine & Science in Sports & Exercise, 51*(6), 53.
9. **Lim, B**., Burrus, B., Ortega, J., & Kwon, Y. (2018). The Effect of Stride Frequency Variations on Running Performance at the Velocity of $\dot{V}O_2max$. *Medicine & Science in Sports & Exercise*, *50*(5), 265-266.

Research Interests

- Bioenergetics and human performance (resistance and endurance performance)
- Physiological and biomechanical responses during multi-sport (Triathlon)
- Optimizing exercise protocol for improving sports specific performance

Student Scholarships

- **Graduate Assistantship** Fall 2018 - Present
  Department of Kinesiology and Nutrition Sciences, University of Nevada, Las Vegas, NV.

• **Outstanding Student** - Nonresident Fee Waiver Fall 2016 - Spring 2018
California State Polytechnic University Humboldt, Arcata, CA.

• **Outstanding Student**, Myong-Ji University, Seoul, Republic of Korea.

Semester High Honors for the 2nd Highest GPA	The 2nd term of 2003
Role Model Scholarship III	The 1 st term of 2004
Role Model Scholarship I	The 1 st term of 2008
Role Model Scholarship I	The 1 st term of 2009
Presidential Special Scholarship II	The 1 st term of 2009
Autonomous Student Body Leader Scholarship II	The 1 st term of 2009
Autonomous Student Body Leader Scholarship II	The 2nd term of 2009
Overseas Education Training Scholarship I	The 2nd term of 2009

Grants Awarded or Applied

1. Title: Graduate Student Research Grant – Doctoral
Funding Agency: National Strength and Conditioning Association (NSCA)
Role: Graduate Student Research Investigator
Project Title: The effect of different types of wetsuits on the swimming economy, shoulder muscle activity, and stroke patterns in front crawl.
Amount: $15,000 (***Applied, Not Funded***)

2. Title: Summer Doctoral Research Fellowship
Funding Agency: Graduate & Professional Student Association, UNLV
Role: Graduate Student Research Investigator
Amount: $7,000 (***Applied, Not Funded***)

3. Title: Faculty Top Tier Doctoral Graduate Research Assistantship (TTDGRA)
Funding Agency: Graduate & Professional Student Association, UNLV
Project Title: Bridging the gap between lab-based research and application: Triathlon endurance project.
Co-awardees: John A. Mercer., Graham McGinnis., Tedd Girouard
Amount: $15,000 (***Applied, Not Funded***)

4. Title: Professional Development & Travel Grants
Funding Agency: California State University (CSU) Chancellor's office
Amount: $1,500 (***Applied, Not Funded due to the COVID-19***)

5. Title: Travel / Conference Grant
Funding Agency: Graduate & Professional Student Association, UNLV
Date: Apr. 2019
Amount: $550, (***Funded***)

6. Title: Chancellor's Doctoral Incentive Program (CDIP)
Funding Agency: California State University Chancellor's office, Long Beach, CA
Date: Fall 2018 - Spring 2021
Amount: $30,000, (***Funded***)

Professional Memberships

- USA Triathlon (USAT) 2019 - Present
- Las Vegas Triathlon Club (LVTC) 2019 - Present
- National Strength and Conditioning Association (NSCA) 2019 - Present
- Korea United State Applied Physiological Society (KUSAP) 2018 - Present
- Southwest Regional Chapter of ACSM (SWACSM) 2017 - Present
- American College of Sports Medicine (ACSM) 2016 - Present
- Korean Association of Certified Exercise Professionals (KACEP) 2007 - Present

Community Services / Activities

- **Moderator** (Virtual & Live Event via Zoom) May 8. 2021
  International Organization of Health, Sports, and Kinesiology (IOHSK)
  2021 International Virtual Conference IOHSK
- **Volunteer**, Running USA Feb. 9. 2020
  2020 Running USA Industry Conference, Caesar's Palace, Las Vegas, NV.
- **Volunteer**: BBSC Endurance Sports Apr. 13. 2019
  2019 RAGE Triathlon, Lake Mead Recreational Area, Boulder city, NV.
- **Volunteer**, National Biomechanics Day Apr. 10. 2019
  Biomechanics main Lab, University of Nevada, Las Vegas, NV.
- **Fitness Coordinator & Instructor** Aug. 2016 - May 2018
  Human Performance Lab, California State Polytechnic University Humboldt, Arcata, CA.
- **Student President** Mar. 2009 - Feb. 2010
  College of Art and Physical Education, Myong-Ji University, Seoul, Republic of Korea.

Honors and Awards

- **1st Place, Graduate Research Competition** Oct. 2020
  International Organization for Health, Sports, and Kinesiology (IOHSK)
  2020 International Virtual Conference
- **Research Award, Graduate Research Competition** May 2018
  Korea United States Applied Physiology Society (KUSAPS)
- **Patricia O. McConkey Outstanding Graduate Student Award** Apr. 2018
  California State Polytechnic University Humboldt, Arcata, CA.
- **Outstanding Student Research Project Award** Apr. 2018
  California State Polytechnic University Humboldt, Arcata, CA.
- **Silver medalist (soccer), Goalkeeper (Non-disabled athlete)** Oct. 2008
  The 28th National Para Games, Gwangju, Jeollanam-do, Republic of Korea.

Certifications

- **Lifeguard** 2020
  - *Certification ID: 004DPG7*
  American Red Cross
- **Certified Strength and Conditioning Specialist (CSCS)** 2020
  - *Certification ID: 7248329965*
  National Strength and Conditioning Association (NSCA)
- **Certified Exercise Physiologist (EP-C)** 2016
  - *Certification ID: 1051232*
  American College of Sports Medicine (ACSM)
- **Adult First Aid/CPR/AED** 2016, 2018, & 2020
  American Red Cross
- **Master Diver for Skin Scuba Diving** 2009
  - *Credential ID: LIM042283RAMMSD09*
  Certified by National Association of Underwater Instructors (NAUI)
- **Judo – 1st Dan** (Degree, Black Belt) 2009
  Korea Judo Association, Seoul, Republic of Korea.
- **Certified Personal Trainer, Exercise and Sports Rehabilitation Specialist** 2008
  Korean Association of Certified Exercises Professionals (KACEP), Republic of Korea.
- **Lifeguard** 2007
  Korean Red Cross, Seoul, Republic of Korea.
- **Tae Kwon Do – 1st Dan** (Degree, Black Belt) 2005
  Korea Taekwondo Association, Seoul, Republic of Korea.
- **Certification of Boy Scout Trainer** 2003
  Korea Boy Scout Association, Seoul, Republic of Korea.