Ventilatory Challenge of Swimming and Cycling in the Development of Global Respiratory Muscle Fatigue

by

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Submitted in partial fulfillment of the requirements
for the degree
Master of Science in Kinesiology
in the School of Public Health,
Indiana University

July 2013

Accepted by the Graduate Faculty, Indiana University, in partial fulfillment of the requirements for the degree of Master of Science in Kinesiology.

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Date of Defense: July 23, 2013

Chapter 1

Introduction

1.0 OVERVIEW

Breathing while swimming cannot occur ad libitum; rather, it relies heavily on the coordination of tidal volume and breathing frequency with stroke timing and mechanics. In addition, both inspiration and expiration may occur with added resistance as swimmers tend to fit their breathing frequency to their stroke timing (Mickleborough, Stager, Chatham, Lindley, & Ionescu, 2008). This has suggested to result in a lower breathing frequency and higher tidal volume than during cycling or running when breathing can be more spontaneous (Rodriguez, 2000). Inspiration during swimming is thus more of "gasp" inhalation against hydrostatic pressure surrounding the chest wall (L. Cordain & Stager, 1988), with expiration being prolonged against added hydrodynamic resistance (Mickleborough et al., 2008). Because of this rather unique form of inspiration, it is thought that swimming evokes a distinctive conditioning stimulus that strengthens the inspiratory muscles (Courteix, Obert, Lecoq, Guenon, & Koch, 1997).

Another method of strengthening inspiratory muscles is inspiratory muscle training (IMT) whereby an individual forcefully inhales against a device that adds resistance to inspiratory flow. It has been shown to increase exercise performance in both trained (Boutellier, Buchel, Kundert, & Spengler, 1992) and sedentary (Boutellier et al., 1992) subjects as early as 1976 (Leith & Bradley, 1976). The mechanism(s) behind such physiological gains are still being investigated. Studies have found evidence such as decreased blood lactate levels following exercise (C.M. Spengler, Roos, Laube, & Boutellier, 1999) and diaphragm hypertrophy (Downey et al., 2007) associated with IMT. These adaptations following IMT have reportedly led to inspiratory muscle fatigue (IMF) resistance (Boutellier et al., 1992) and respiratory muscle strength gains (Sonetti, Wetter, Pegelow, & Dempsey, 2001). However, additional gains from IMT are not apparent when IMT is performed concurrently with swim training (Clanton, Dixon, Drake, & Gadek, 1987; Mickleborough et al., 2008; Wells, Plyley, Thomas, Goodman, & Duffin, 2005). Thus, it has been suggested that competitive swim training evokes a conditioning stimulus similar to IMT in strengthening the inspiratory muscles.

By sharing similar mechanisms of effecting respiratory muscle development, competitive swim training and IMT may cause fatigue of the muscles and subsequent gains in endurance and strength similar to resistive training of other skeletal muscles. Maximum inspiratory mouth pressure (MIP) is a measure of global respiratory muscle strength, and a decrease in MIP is generally accepted as representative of fatigue in the respiratory muscles (Romer, McConnell, & Jones, 2002). Nevertheless, decreases in MIP have been shown to occur after swimming distances as short as 100m (Brown & Kilding, 2011) and 200m (Jakovljevic & McConnell, 2009; Lomax & McConnell, 2003), swim efforts that last about 60.8 seconds and 2.7 minutes, respectively. This is startlingly shorter than previous reports showing declines in MIP after marathon running that averaged 3 hours and 24 minutes (Loke, Mahler, & Virgulto, 1982).

The study by Loke et al. (1982) began the trend of discovering respiratory muscle fatigue occurrence after land-based endurance events. As time progressed, research began showing respiratory muscle fatigue after shorter events as well. Inspiratory muscle fatigue was noted after 20- and 40-kilometer time trials in cyclists, lasting 30 to 60 minutes (Romer et al., 2002). Exercise testing to volitional fatigue has also been shown to elicit significant diaphragmatic fatigue. Johnson et al. (1993) had subjects exercise at 95% and 85% of maximal oxygen consumption ($\dot{V}O_{2max}$), lasting on average 14 to 31 minutes. More recently, Volianitis et al. (2001) showed declines in respiratory muscle function after 6-minutes of all-out rowing. All of this information begins to put the results of the aforementioned swimming research studies into context. Declines in respiratory muscle function are being realized in the shorter and shorter amounts of time, the quickest responses coming after swimming. The study of respiratory physiology in the sport of swimming is still in its infancy, and this study seeks to determine the possible uniqueness in the ventilatory challenge that swimming imposes. By comparing two exercise modes that result in similar ventilations, progress can be made in this field.

1.1 STATEMENT OF PROBLEM

Inspiratory and expiratory pressures measured at the mouth have been frequently used as indicators of global respiratory muscle function. Decrements in these mouth pressures represent fatigue development, and it would appear from the available literature that such fatigue may occur more rapidly in swimming as opposed to land-based exercises such as cycling. Currently, no research exists comparing respiratory muscle function after swimming to respiratory muscle function after land-based exercise that presents a similar ventilatory challenge.

1.2 PURPOSE OF THE STUDY

The aim of the current study is to examine potential differences in respiratory muscle function after swimming and cycling when matched for duration of exercise and ventilatory "challenge."

1.3 NEED FOR THE STUDY

As previously stated, no research exists comparing respiratory muscle function after swimming to similar function after land-based exercise. Specifically, there is no data on individuals who have been asked to complete two modes of exercise at a similar metabolic and or ventilatory challenge. Research using the proposed assessment methodology is a logical "next step" for research in fields of exercise-induced respiratory muscle fatigue. There is an emerging idea that swimming imposes a unique challenge to the ventilatory muscles; and while this may be the case, it certainly warrants examination at workloads of the respective exercises that elicit similar ventilations.

1.4 DELIMITATIONS

This study is delimited to the following:

1. A minimum of 8 male subjects, between the ages of 18 and 40 years, having partaken in swim or triathlon training in the past and still participate recreationally and/or train in either or both of these sports.
2. Dependent variables: maximal inspiratory pressure and maximal expiratory pressure.
3. The use of a handheld mouth pressure meter to measure maximal inspiratory and expiratory pressures.

1.5 LIMITATIONS

The following points represent limitations to the current study:

1. The subjects will be recruited from the same geographical area.
2. Results of this study may not be generalizable to the field, as this study will be conducted in a controlled environment.
3. Results of this study are not generalizable to outside of the subject population of recreational or trained swimmers or triathletes.
4. Expired minute ventilation will not be measured during the experimental trials.

1.6 ASSUMPTIONS

The following points represent assumptions that will be applied:

1. The subjects of this study are representative of other recreational or trained swimmers or triathletes.

2. The subjects will be highly motivated to complete the maximal inspiratory and expiratory pressures portions of the exercise treatment.
3. The subjects will be highly motivated to complete the swim or cycle bouts of the exercise treatment.
4. Any change in dependent variables will be due to the exercise treatment.
5. Expired minute ventilations will be similar between exercise modes during the experimental trials.
6. Average 100-yd pace during a 5 x 100-yd (on 10s rest) swim workout will be indicative of 400-m pace.
7. The subjects will abstain from caffeine and alcohol for 8 hours and exercise for 24 hours prior to laboratory visit.

1.7 HYPOTHESES

The following are expected outcomes of the experimental trials:

1. Maximum inspiratory pressure will be lower than pre-exercise values following swimming exercise.
2. Maximum inspiratory pressure will not be different from pre-exercise values following cycling exercise.
3. Maximum expiratory pressure will be lower than pre-exercise values following swimming exercise.
4. Maximum expiratory pressure will not be different from pre-exercise values following cycling exercise.

1.8 DEFINITION OF TERMS

The following terms are defined to clarify their use in the study:

Cardiac output ($\dot{Q}$) - The volume of blood that passes through the systemic and pulmonary circulations per unit of time; all of the output of the left ventricle passes through the systemic circulation, while all of output of the right ventricle passes through the pulmonary circulation (West, 2004, p.42).

Expiratory time (T_E) – The time from the beginning to the end of expiration; it also includes the expiratory pause when present (Lind & Hesser, 1984).

Fatigue – The acute inability to produce a desired force and concurrent increase in the perception of effort to produce a given force, reversible with rest (Enoka & Stuart, 1992).

Forced expiratory volume in one second (FEV_1) - The maximum volume of air that can be forced out in the first second of expiration from a maximal inspiration, an important measure of pulmonary function (Miller et al., 2005).

Forced mid-expiratory flow ($FEF_{25\text{-}75\%}$) - The average expiratory flow over the middle half, from 25 to 75%, of the FVC (Miller et al., 2005).

Forced vital capacity (FVC) - The volume of air expelled by a forced maximal expiration to residual volume from a maximal inspiration (Miller et al., 2005).

Maximal aerobic capacity ($\dot{V}O_{2max}$) - The maximal ability of an individual to take up, transport, and deliver oxygen to the working muscles (Rusko, Havu, & Karvinen, 1978).

Maximal expiratory mouth pressure (P_{Emax}) – The maximum pressure generated at the mouth during a maximal expiratory maneuver from total lung capacity ("ATS/ERS Statement on respiratory muscle testing," 2002).

Maximal inspiratory mouth pressure (P_{Imax}) – The maximum pressure generated at the mouth during a maximal inspiratory maneuver from residual volume ("ATS/ERS Statement on respiratory muscle testing," 2002).

Maximal ventilation ($\dot{V}_{Emax}$) - The highest minute ventilation achieved during exhaustive exercise (Blackie et al., 1991).

Maximum voluntary ventilation (MVV) - The maximum volume of air that can be breathed over a specified period of time, typically 12 s (Miller et al., 2005).

Oxygen consumption ($\dot{V}O_2$) - The volume of oxygen consumed per minute (Brooks, Fahey, & Baldwin, 2005, p.6).

Peak expiratory flow rate (PEFR) - The maximum flow rate achieved during a forced maximal expiration (Miller et al., 2005).

Peak inspiratory flow rate (PIFR) – The peak inspiratory flow rate achieved during a maximal inspiration (Miller et al., 2005).

Residual volume (RV) – The volume of air within the lungs at the end of a maximal expiration (West, 2004, p.15).

Tidal volume (V_T) – The volume of air moved in and out of the lungs during each breath (West, 2004, p.13).

Total lung capacity (TLC) – The total volume of air within the lungs following a maximal inspiration (Miller et al., 2005).

Ventilation ($\dot{V}_E$) - The volume of air expired from the lungs in one minute. Also called pulmonary ventilation, minute ventilation, or total ventilation (West, 2012, p.17).

Vital capacity (VC) – The maximum volume of air that can be expired after a maximum inhalation (West, 2012, p.13).

Chapter 2

Review of Related Literature

2.0 RESPIRATORY MUSCLE FATIGUE OCCURRENCE DURING LAND-BASED EXERCISE

Fatigue can occur in all voluntary muscle, and is likewise true for respiratory muscles (C. S. Roussos & Macklem, 1977). This fatigue can be brought on by decreased neural drive from the central nervous system and/or an inadequate energy supply/demand ratio for the required physical work (Aubier, 1989). During exercise, fatigue of the respiratory muscles has been shown to occur.

Study	Subjects	Conclusions
C. S. Roussos and Macklem (1977)	3 UT	When energy consumption of the respiratory muscles exceed a critical level, fatigue develops
C. Roussos, Fixley, Gross, and Macklem (1979)	5 UT	The contribution of the diaphragm and intercostal accessory muscles alternated in time, possibly postponing the onset of fatigue
Johnson, Babcock, Suman, and Dempsey (1993)	12 T	Significant diaphragmatic fatigue is caused by the ventilatory requirements of heavy endurance exercise in healthy persons; magnitude and likelihood of its occurrence increases as the relative intensity of exercise exceeds 85% VO_{2max}
Yan, Lichros, Zakynthinos, and Macklem (1993)	6 UT	Diaphragmatic fatigue induces proportionately greater contributions of inspiratory rib cage muscles than of the diaphragm, which results in the preservation of ventilatory response to CO_2
Babcock, Pegelow, McClaran, Suman, and Dempsey (1995)	9 T	Exercise-induced diaphragmatic fatigue is attributable to an interaction between power output of the diaphragm and effects imposed by locomotor muscles
Harms et al. (1997)	8 T	Respiratory muscle work normally expended during maximal exercise has two significant effects on the cardiovascular system: 1) up to 14-16% of the cardiac output is directed to the respiratory muscles, and 2) local reflex vasoconstriction significantly compromises blood flow to leg locomotor muscles

UT = untrained; T = trained

Table 1. Highlighted research regarding land exercise-induced respiratory muscle fatigue.

As seen in Table 1, the increased ventilation that occurs with exercise has been proposed to initiate a competition for blood flow, especially at higher exercise intensities (Harms et al., 1997). This is due to the increased power output of the diaphragm and metabolic requirements of the locomotor muscles (M. Babcock et al., 1995), which may cause changes in perfusion and vascular resistance with regards to locomotor muscles (Harms et al., 1997). Possibly reflecting a maintenance of ventilatory responsiveness to CO_2 after diaphragmatic fatigue, inspiration can also be channeled with greater proportion initiated through the intercostal muscles (Yan et al., 1993). This shift in muscle recruitment reduces the mechanical efficiency of breathing (Dodd, Yarom, Loring, & Engel, 1988; Hart et al., 2002); it requires greater work of breathing, requiring greater metabolic demand, which results in the aforementioned competition for blood flow.

The intensity of exercise plays a large role in the development of respiratory muscle fatigue (RMF), and this may be due to the muscle afferent feedback to ventilatory responses to exercise (Amann et al., 2010). In an study performed by Johnson et al. (1993), subjects exercised at 85 or 95% of $\dot{V}O_{2max}$ to exhaustion, and diaphragmatic fatigue occurred after each bout: however, fatigue occurred in about half of the time at 95% $\dot{V}O_{2max}$ (14 ± 3 minutes) compared to the 85% $\dot{V}O_{2max}$ condition (31 ± 8 minutes). Fascinatingly, this fatigue was still present after over an hour of recovery from the exercise (Johnson et al., 1993)! Such a lasting effect of diaphragmatic fatigue occurred in a study by Mador et al. (1993) as well. Subjects recovered to only 93 ± 7% of pre-exercise (the exercise being 80% of maximal working capacity until exhaustion), control values following 60 minutes of recovery (M. J. Mador, Magalang, Rodis, & Kufel, 1993). In a separate look, Mador and Dahuja (1996) had subjects exercise at 70-75% of $\dot{V}O_{2max}$ to volitional exhaustion and similarly noted fatigue of the diaphragm. They concluded that post-exercise diaphragmatic fatigue was not solely due to changes in the surrounding environment of the diaphragm (such as metabolic acidosis) (M.J. Mador & Dahuja, 1996), but it can also be attributed to fatigue of the diaphragm itself. Thus, high-intensity, whole-body exercise to exhaustion can fatigue not only leg muscles but also the main inspiratory muscle, the diaphragm.[1]

[1] However, sub-ventilatory threshold exercise has been shown to not fatigue the diaphragm or respiratory muscles (M. A. Babcock et al., 1995; M. J. Mador et al., 1993).

	Control 1	Control 2	Fatigue
$\dot{V}O_2$, ml/min	2,388±563	2,336±447	2,234±472
$\dot{V}_I$, l/min	78.1±18.4	78.3±17.5	87.2±17.9*
V_T, liters	2.63±0.77	2.70±0.84	2.50±0.81
f, breaths/min	30.8±6.5	30.7±7.4	36.8±8.5*
T_I, s	0.91±0.22	0.95±0.27	0.78±0.18
T_E, s	0.93±0.21	1.03±0.34	0.82±0.21†
T_I/T_T	0.49±0.05	0.49±0.05	0.49±0.04
V_T/T_I, l/s	2.80±0.68	2.78±0.70	3.13±0.75†
VAS, mm	73±24	69±17	83±26‡
$F_{ET_{CO_2}}$, %	5.4±0.5	5.6±0.7	5.1±0.3

Table 2 Values of various parameters after induced respiratory muscle fatigue (M. J. Mador & Acevedo, 1991).

The data represented by Table 2 is from a study by Mador and Acevedo (1991). In this study, subjects cycled at 90% of their maximal capacity three times; two trials acted as control exercises ("Control 1" and "Control 2", above), and one trial occurred after invoked respiratory muscle fatigue ("Fatigue", above). Respiratory muscle fatigue was presumably caused by loading inspiration, and subjects were encouraged to meet 80% of their predetermined mouth pressure until they could no longer meet that pressure. Values of oxygen consumption ($\dot{V}O_2$), inspired minute ventilation ($\dot{V}_I$), tidal volume (V_T), and breathing frequency (f) (Table 2) were compared between control trials and the trial after invoked respiratory fatigue. After pre-exercise respiratory muscle fatigue, $\dot{V}_I$ and breathing frequency were both higher during the cycling exercise (M. J. Mador & Acevedo, 1991). Actually, this tends to be the case with exercise following respiratory muscle fatigue: ventilation increases primarily by breathing frequency increases with little to no decrease in tidal volume (Gallagher, Hof, & Younes, 1985; M. J. Mador & Acevedo, 1991; C. M. Spengler, Knopfli-Lenzin, Birchler, Trapletti, & Boutellier, 2000; Verges, Notter, & Spengler, 2006). However, in sports of high entrainment, whereby breathing is intimately linked to rhythmic movement, respiratory muscle fatigue and its effect on breathing parameters is very interesting. For instance, breathing must be linked to stroke mechanics in swimming, so respiratory muscle fatigue may be present even despite the lack of increase in breathing frequency. And, an increase in breathing frequency would need to be accompanied by an increase in stroke frequency. Thus, the next few sections explore the uniqueness of breathing in the sport of swimming (how it may "train" the respiratory muscles) and exercise-induced respiratory muscle fatigue that may occur.

2.1 INSPIRATORY MUSCLE TRAINING AND SWIM TRAINING

Some researchers believe that ventilation can be a limiting factor to exercise regardless of training status in normal subjects, in that specific respiratory training produced a 50% increase in cycling endurance (Boutellier et al., 1992). As evidence, trained and untrained subjects who completed four weeks of respiratory muscle training, 30 minutes per day, 5 days per week, performed significantly better on a cycling endurance task when compared to their control measure (38% and 50% improvement, respectively). While interesting, the theory that the respiratory system limits performance in the study performed by Boutellier & Piwko (1992) is fairly meaningless with regards to sedentary subjects' day-to-day lives. A person who is performing less than 1 hour per week of sport activities (Boutellier et al., 1992) has less of a concern with what limits exercise performance than those who train consistently and/or professionally, for example. For this latter group of individuals, the study of respiratory limitation to exercise is much more meaningful; as such, research on training inspiratory muscles has grown.

Inspiratory muscle training (IMT), whereby the endurance capacity of the inspiratory muscles is increased via resistive exercises, has been shown to better performance in a variety of sports: cycling (Romer et al., 2002), rowing (Volianitis et al., 2001), and running (Edwards, Wells, & Butterly, 2008). As mentioned previously, studies have found evidence such as decreased blood lactate levels during exercise (C.M. Spengler et al., 1999) and diaphragm hypertrophy (Downey et al., 2007) associated with IMT. Inspiratory muscle training has also been shown to decrease the oxygen cost of breathing during voluntary hyperpnea, which could potentially increase the availability of oxygen for working muscles during exercise (Turner et al., 2012). In addition, Edwards et al. (2008) found a significantly lower rating of perceived exertion (RPE) after IMT without any changes in $\dot{V}O_{2max.}$ Comparisons were made among an IMT group, a cardiovascular + IMT group and cardiovascular + placebo group. Because of their results, Edwards et al. (2008) concluded that IMT may decrease an individual's perceived effort (especially at higher ventilations). The combination of these effects may provide an explanation for the increases in exercise performance.

Research indicates that swim training evokes a training stimulus similar to IMT alone; subjects who underwent concurrent swim training and IMT show no added performance benefits compared to subjects who underwent swim training alone (Mickleborough et al., 2008; Wells et al., 2005). That is, IMT produced further changes to performance than swim training alone; this brings about the idea that swimming may be unique in its effect on the respiratory muscles. The method of breathing during swimming, in which inhalation can be considered a "gasp" and expiration is against added pressure from the water, may lend itself to being a similar training stimulus to IMT. Additionally, hydrostatic pressure against the chest wall contributes to a greater work of breathing (Hong, Cerretelli, Cruz, & Rahn, 1969). The combination of these factors and previous studies has led to expanded research in the realm of respiratory muscle fatigue as it relates to swimming.

2.2 RESPIRATORY MUSCLE FATIGUE AFTER SWIMMING

Respiratory muscle fatigue has been shown to occur after swimming distances of 100m (Brown & Kilding, 2011) and 200m (Jakovljevic & McConnell, 2009; Lomax & McConnell, 2003) as reflected by decreases in maximum inspiratory pressure (MIP). In trained swimmers (4 females, 3 males; age 29.9 + 6.4 years; experience 13.4 ± 5.3 years), Lomax and McConnell (2003) noted a 29% decrease in MIP approximately 30 seconds after subjects swam a single 200m corresponding to 90-95% of race pace. Maximum inspiratory pressures pre- and post-exercise (112 ± 20.4 cmH_2O and 80 ± 15.7 cmH_2O, respectively) were obtained while the subject was in a supine position in the pool. There were additional MIP measurements taken pre-exercise with the subject in an upright position (133 ± 16.7 cmH_2O), but this position was not repeated post-exercise. Lomax and McConnell (2003), after baseline values, had their subjects perform a regimented warm-up procedure including a previously described respiratory warm-up portion that may inflate pre-trial MIP values (Volianitis et al., 2001). This respiratory warm-up included an inspiratory muscle loading protocol and used a commercially available inspiratory muscle trainer (POWERbreathe®, Leisure Systems International Ltd, UK) described in Volianitis et al. (2001).

In a later study, Jakovljevic and McConnell (2009) investigated the effects of different breathing strategies on the development of IMF in swimming. Subjects (10 male, collegiate swimmers; age 21.2 ± 1.9 years; experience 8.2 ± 2.1 years) either took a breath every second stroke (B2) or every fourth stroke (B4) during a 200m swim. After the 200m swim using the more constrained breathing frequency (B4), a greater decrease in MIP occurred (21% compared to 11% during B2) (Jakovljevic & McConnell, 2009). Average pre-trial MIP measurements were 126.7 and 128.1 cmH_2O for B2 and B4 conditions, respectively, dropping to 112.6 (B2) and 99.4 (B4) cmH_2O. Breathing every four strokes (B4) was determined to result in significantly less MIP from breathing every two strokes (B2). The interesting aspect of this study, obviously, is the idea of exacerbating the breathing pattern, lengthening the time between breaths in the B4 condition. This can be thought of as a good method of controlling breathing phases during swimming, such that the respiratory muscle resistance experienced is controlled by the experimenter. Maximum inspiratory pressure measurements were taken with the subject poolside and upright; post-exercise, MIP was taken within one minute of the cessation of the swim bout. The same respiratory warm-up that was used in Lomax and McConnell (2003) was employed with those subjects in the study by Jakovljevic and McConnell (2009).

A couple years later, a study performed by Brown and Kilding (2011) using ten well-trained swimmers (age 19.1 ± 2.1 years; experience 6.8 ± 3.1 years) examined the effect of different swim events on inspiratory muscle fatigue (IMF). Comparing before and after 100m, 200m and 400m swims, decreases in MIP ranged from 4.6-8.2%, with the highest (and only statistically significant) decline of 8.2% occurring after the 100m event swim (Brown & Kilding, 2011). However, the pre- and post-trial values of MIP did not statistically differ among the trials. The MIP measurement was performed within 45-60 seconds of completing each time trial with the subject standing upright. Important to note, Brown and Kilding (2011) did not use the aforementioned respiratory warm-up by Lomax and McConnell (2003) and Jakovljevic and McConnell (2009); thus, they believe that the lesser drop in MIP reported may be due to not having subject perform this respiratory warm-up.

It is interesting, however, that Brown and Kilding (2011) did not show a significant decline in respiratory muscle strength after the longer swim events (200m and 400m). As 100m events are still classified as “sprint” events (lasting around 60 seconds), it may be that in this particular instance the subjects of the study decreased their breathing frequency in order to achieve higher speeds. This would cause carbon dioxide retention, which has been shown to decrease the contractility of the diaphragm (Juan, Calverley, Talamo, Schnader, & Roussos, 1984). There have been a number of studies to show that a 400m swim event is both a good test of $\dot{V}O_{2peak}$ and increased ventilation (Costill et al., 1985; Laffite et al., 2004; Rinehardt, Kraemer, Gormely, & Colan, 1991; Rodriguez, 2000). Therefore, it may be said that this particular swim may maximally tax the respiratory system. In a study performed by Thomaidis et al. (2009), the authors sought to quantify changes in MIP throughout the course of a 400m swim because of this hypothesis. . The researchers separated a 400m swim by 100m, 200m, 300m, and 400m lengths on different days; each event was swum at velocities corresponding to a 400m swim trial. In 11 well-trained competitive swimmers (17.6 ± 0.8 years; experience 9.4 ± 0.8 years), the authors found MIP significantly decreased after only the 300m and 400m swim bouts (Thomaidis et al., 2009). Thomaidis et al. (2009) concluded that a reduction of inspiratory strength during an all-out 400m front crawl swim occurs after 300m and recommended considering such findings in constructing respiratory muscle training for certain swim distances.

2.3 THE UNIQUENESS OF BREATHING DURING SWIMMING

Through all of this research, respiratory muscle fatigue has been shown to occur in swimmers after short swimming events, but comparisons have yet to be made in the same study of both water- and land-based events and their respective effects on respiratory muscle strength. While this comparison may seem like a step backward, it truly represents the next logical step forward in the growing trend of respiratory physiology in swimming. Matching workloads for similar ventilations in swimming and a land-based exercise such as cycling (matching "ventilatory workloads") would certainly strengthen the case for the uniqueness of the breathing strategy employed during swimming. Breathing during swimming appears to be unique in its challenge to the ventilatory muscles in several ways: there are effects of stroke mechanics (which deeply influence breathing mechanics), hydrostatic pressure surrounding the chest wall, as well as posture effects on ventilation. These influences on breathing will be discussed in greater depth in Chapter 5. Substantiating the argument for a unique challenge to the respiratory muscles in the sport of swimming in the context of respiratory muscle fatigue has yet to be present in current literature, and thus is the purpose of this study.

Chapter 3

Procedures for Collecting Data

3.0 SUBJECTS

Eight healthy, recreational swimmers or triathletes who are active and with no preexisting conditions were recruited for this study. The number of subjects needed was determined by power analysis (G-Power Statistical Software™) at a power level of 0.80, using previous related research (Brown & Kilding, 2011). Subjects were informed of the details of the study before acceptance and made aware that all participation is strictly voluntary. All procedures have been approved by the Indiana University Institutional Review Board, and all subjects signed forms of informed consent.

Subjects had refrained from exercise for 24 hours and caffeine and alcohol for 8 hours prior to testing. Subjects completed a Modified Physical Activity Readiness Questionnaire (PAR-Q) before enrollment, and were screened for and excluded if they had a history of asthma, heart disease, hyperlipidemia, hypertension, diabetes, smoking tobacco, or were otherwise considered unhealthy.

3.1 STUDY DESIGN AND PROTOCOL

This study was conducted in the lower levels of the School of Public Health at Indiana University and the Royer Pool of the Counsilman Center for the Science of Swimming whereby the means of such measurements (listed later) are made possible. Timeline: 3 days (1 "Pace-setting" day and 2 Experimental days). All subjects underwent the same treatment conditions, and all swimming was the front-crawl stroke.

3.1.0 *Study Design*

Upon obtaining consent, subjects reported to the laboratory at about the same time each day to complete the testing procedures on four (4) separate occasions. The first visit lasted approximately 45 minutes, the second visit approximately 90 minutes, and the third and fourth visits lasted approximately 30 minutes; each visit was separated by approximately one to four days.

On day #1, subjects completed a standard medical questionnaire (modified PAR-Q; attached), had their resting blood pressure taken, and underwent a swimming workout in a 25-yd pool to establish

Endless Pool pace for swimming experimental trial (day 3 or 4). On day #2, subjects underwent two brief exercise tests to establish cycling workload for the cycling experimental trial (day 3 or 4). After completing the modified PAR-Q, subjects were familiarized with maximum inspiratory and expiratory pressure (MIP and MEP, respectively) maneuvers, lasting about 10-15 minutes. Then, subjects warmed up as desired before swimming a 5 x 100-yard swim with 10 seconds of rest in between (lasting about 30 minutes, including warm-up) to establish pace for flume swimming. For the next session, subjects then swam in the flume for 3 minutes at the average 100-yd pace previously established (after some time to warm-up), while on a mouthpiece in order to obtain expired minute ventilation ($\dot{V}_E$) (lasting about 15-30 minutes). For the final portion of the first day, subjects cycled at three incremental workloads to establish a workload that corresponds to the $\dot{V}_E$ during flume swimming (lasting about 15-30 minutes). The time between these exercises may vary, but was typically between 10-20 minutes.

On days #3 and 4, subjects completed an experimental trial either at the flume speed pace previously determined on day #1 or on the cycle ergometer at the workload determined by its corresponding $\dot{V}_E$, also determined on day #1. Each exercise lasted between 4 and 6 minutes; exact time was determined by the average 100-yard pace, extrapolated to the amount of time to complete a 400-meter swim event.

Day #1: The first exercise session is meant purely as a means to set water current speed in an Endless Pool (or "pace" for the swimmer in the flume). The swimmer warmed up as desired, then swam five 100-yard intervals with 10 seconds of rest in between. This enabled the experimenters to name a pace for the swimmer in the flume, as explained later.

Day #2: The second exercise session (after having obtained flume speed) needed some warm-up beforehand. This also served as some time for the subject to familiarize themselves with swimming in a flume setting, as well as swimming with a mouthpiece that enables free-breathing if needed. After familiarization, the subject swam at the desired flume speed for 3 minutes so that steady state conditions were met. Metabolic measurements of expired minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) were obtained during this trial.

The third exercise session (after having obtained $\dot{V}_E$ during flume swimming), needed minimal additional warm-up, however adjusting the cycle ergometer (Monark Cycle Ergometer) was necessary. This cycling exercise (explained in detail later) was composed of stages of 3 minutes each, separated by 1 minute of rest. Metabolic measurements of expired minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) were obtained during this trial. The purpose of this exercise was to determine the cycling workload that best corresponds to the $\dot{V}_E$ measured during the previous flume swimming trial and then use this workload for the cycling exercise in day #2 or 3.

Days #2 & 3: The exercise session for days #2 and 3 was randomly assigned: subjects either underwent a flume swimming trial or a cycling trial on day #2, and then the alternative on day #3. During each trial, subjects breathed normally (no mouthpiece) for the respective exercise. Additionally, each trial lasted as long as a 400-meter swim, the determination of which relied on the initial swimming pace. Maximum inspiratory and expiratory pressures were assessed prior to and immediately after each trial.

3.1.1 *Study Procedures*

Determination of flume speed: Time (in seconds and hundredths of seconds) was taken during each of the 100-yard swims in the 5 x 100-yard bout. Subjects were told to swim each 100 yards at "the maximum sustainable intensity for the workout." The average time per 100-yards was used as the speed to set the water current speed in the flume (Endless Pools, Aston, PA).

Determination of 400-meter time: Time (in seconds and hundredths of seconds) was taken during each of the 100-yard swims in the 5 x 100-yard bout. Subjects were told to swim each 100 yards at "the maximal sustainable intensity." The average time per 100 yards was converted to average time per 100 meters, which was then be multiplied by 4 to result in 400-meter time. This time (in seconds and hundredths of seconds) represented the time that subjects exercised (swimming or cycling) on days #3 and 4.

Maximum inspiratory pressure (MIP): Subjects required 5-10 familiarization trials on day #1 with this maneuver, as well as performed it 3 times before every exercise bout on days #3-4 for baseline readings and 1-2 times immediately after (within two minutes) each exercise bout for post-exercise results. This measurement is indicative of global inspiratory muscle strength. Subjects will be told to "exhale all of the air in your lungs, place the mouthpiece in your mouth, and inhale as forcefully as you can." There is a small air leak of approximately 50 $mL \cdot s^{-1}$ that increases the comfort of this maneuver, as it requires forceful inhalation of at least 2 seconds. During this maneuver, subjects were wearing noseclips and actively encouraged by the experimenter. This maneuver resulted in the highest average pressure generated by the inspiratory muscles over 1 second. Three repetitions prior to exercise are necessary for consistency of the measurement; at least two of these measurements were within 10% of one another, and the higher of these two was used for baseline value. Two post-exercise measurements were taken within 30-60 seconds after exercise cessation; if the experimenter was not convinced that the maneuver was performed maximally, an additional maneuver was requested. MIP measurements was obtained using a portable, handheld mouth pressure meter which was calibrated against a water monometer (MicroRPM, MicroMedical Ltd, Kent, United Kingdom).

Maximum expiratory pressure (MEP): Subjects required 5-10 familiarization trials on day #1 with this maneuver, as well as performed it 3 times before every exercise bout on days #3-4 for baseline readings and 1-2 times immediately after (within two minutes) each exercise bout for post-exercise results. This measurement is indicative of global expiratory muscle strength. Subjects will be told to "inhale as much air as possible, place the mouthpiece in your mouth, and exhale as forcefully as you can." There is a small air leak of approximately 50 $mL \cdot s^{-1}$ that increases the comfort of this maneuver, as it requires forceful exhalation of at least 2 seconds. During this maneuver, subjects were wearing noseclips and actively encouraged by the experimenter. This maneuver resulted in the highest average pressure generated by the expiratory muscles over 1 second. Three repetitions prior to exercise are necessary for consistency of the measurement; at least two of these measurements were within 10% of one another, and the higher of these two were used for baseline value. Two post-exercise measurements were taken within 60-120 seconds after exercise cessation; if the experimenter was not convinced that the maneuver was performed maximally, an additional maneuver was requested. MEP measurements were obtained using a portable, handheld mouth pressure meter (MicroRPM, MicroMedical Ltd, Kent, United Kingdom).

Metabolic measurements: Minute ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) were monitored via open circuit spirometry. While wearing a nose clip, subjects breathed through a low resistance two-way non-rebreathing valve connected to a snorkel-like mouthpiece (dead space volume 190 mL), from which expired gases entered a 5-L mixing chamber. Fractional concentrations of O_2 and CO_2 were sampled from the mixing chamber at a constant rate (300 mL•min^{-1}) using gas analyzers (Applied Electrochemistry, Pittsburgh, PA). A flow probe placed on the inspired side that measures changes in flow by changes in temperature across a thermistor was used in the measurement of $\dot{V}_E$. Analog signals from all equipment were continuously monitored and averaged over each min using a data acquisition program. Breathing frequency was visually counted for the last 30 seconds of the third minute of every exercise session after the 5 x 100-yd swim.

Determination of Cycling Workload: This cycling exercise was composed of 3-5 stages of 3 minutes each, separated by 2 minutes of rest. Metabolic measurements of expired minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) were obtained during this trial. Analog signals from all equipment were continuously monitored and averaged over each min using a data acquisition program. Revolutions per minute (RPM) was held constant throughout the stages of the cycling protocol by metronome, chosen by the subjects. The first three stages were as follows: 2kg, 3kg, and 4kg; if adequate ventilations are not met at the end of the third stage, a fourth stage was added (and the same criterion applies for the fifth stage). If the appropriate ventilation (that which matches the ventilation achieved in the swim flume) was between values of the incremental cycling exercise, power was calculated using a line of best fit.

3.1.2 *Data Analysis*

Data was analyzed using SPSS version 20 statistical software (SPSS Inc., Chicago, IL). A 2x2 repeated measures analysis of variance (groups of exercise mode and MIP/MEP measurement time) was used to determine differences between exercise modes. Paired-samples t-tests were run (Confidence Interval 95%) in order to compare pre-exercise and post-exercise values of MIP and MEP. In the comparisons of metabolic data and respiratory muscle function (MIP/MEP), two-tailed paired-samples t-tests were utilized. Data are expressed using mean ± standard deviation, except where noted.

Chapter 4

Analysis of Data

4.0 SUBJECT INFORMATION

Eight male swimmers (25 ± 6 years; 1.84 ± 0.09 meters; 75.2 ± 8.8 kilograms) were enrolled and completed the study. All subjects were identified as currently active swimmers who had 4+ years of competitive experience. The results of day #1 (pace-setting exercise sessions) are shown below.

4.1 5 X 100-YARD SWIM

100-yd Times (s)					
First 100-yd	**Second 100-yd**	**Third 100-yd**	**Fourth 100-yd**	**Fifth 100-yd**	**Average**
59.3 ± 3.9	62.5 ± 6.0	63.6 ± 7.4	64.9 ± 8.8	64.7 ± 8.6	63.0 ± 6.9

Table 3. Swim workout to establish 400m pace.

This average 100-yd time to completion, converted to meters·second^{-1}, did not differ from the displayed water current speed for the Endless Pool during the metabolic data collection and experimental trials: 1.46 ± 0.14 m·s^{-1} to 1.45 ± 0.13 m·s^{-1}, respectively (t=1.482, P=0.182).

4.2 METABOLIC DATA COLLECTION

Exercise Mode	**$\dot{V}_E$ STPD (L·min^{-1})**	**$\dot{V}O_2$ (L·min^{-1})**	**$\dot{V}CO_2$ (L·min^{-1})**	**$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})**	**RER**	**$\dot{V}_E$ BTPS (L·min^{-1})**	**f_b (breaths·min^{-1})**	**V_T (L)**
Swimming	93.4 ± 22.9	3.80 ± 0.66	3.88 ± 0.55	50.5 ± 7.2	1.03 ± 0.13	116.1 ± 28.4	46.6 ± 18.1	2.62 ± 0.47
1st Cycling Stage (148.3 ± 17.2W)	38.6 ± 3.7	1.82 ± 0.25	1.62 ± 0.23	25.2 ± 3.7	0.89 ± 0.06	48.0 ± 4.7	22.7 ± 3.8	2.15 ± 0.27
2nd Cycling Stage (228.8 ± 25.4W)	62.3 ± 6.8	2.66 ± 0.36	2.68 ± 0.40	35.6 ± 4.6	1.01 ± 0.06	78.4 ± 8.7	26.9 ± 3.6	2.97 ± 0.54
3rd Cycling Stage (305.0 ± 33.4W)	96.8 ± 15.1	3.51 ± 0.51	3.85 ± 0.54	46.8 ± 6.3	1.10 ± 0.08	123.6 ± 17.6	38.9 ± 6.4	3.21 ± 0.40
4th Cycling Stage *(400W)*	*105.5*	*4.44*	*4.40*	*47.8*	*0.99*	*131.2*	-	-

Table 4. Metabolic data during the third minute of each exercise or cycling stage.

In the above table, the average values from the third minute of each exercise mode and cycling workload are shown. Three minutes of a fourth cycling stage was only completed by one subject. In agreement with the purpose of the current study, comparisons were made between swimming and the third cycling stage because they elicited similar ventilations: 93.4 ± 22.9 (swimming) and 96.8 ± 15.1 (cycling) L•min^{-1} STPD, (t=0.335, P=0.748). At these ventilations, swimming produced significantly higher $\dot{V}O_2$ values (t=2.978, P=0.21) and lower tidal volumes (V_T) (t=2.465, P=0.049), visible in Table 3. Breathing frequencies during swimming (46.6 ± 18.1) did not statistically differ from breathing frequencies during cycling (38.9 ± 6.4) at the third cycling stage that elicited similar ventilations (P=0.366).

4.3 EXPERIMENTAL TRIAL RESULTS

The average time to completion ("400-meter time") was 275 ± 29 seconds. The results of the experimental trials are summarized in Table 4.

Exercise	Pace/Workload	Pre-Exercise (cmH_2O)		Post-Exercise (cmH_2O)		Percent Decline
Swimming	63.6 ± 6.1 s/100yd	MIP	138.9 ± 17.5	MIP	121.9 ± 20.5	12.4 ± 8.2
		MEP	174.1 ± 31.4	MEP	151.8 ± 23.2	11.7 ± 11.5
Cycling	305.1 ± 78.5 W	MIP	137.3 ± 17.1	MIP	132.5 ± 19.3	3.4 ± 8.4
		MEP	181.7 ± 36.1	MEP	176.0 ± 42.0	3.7 ± 5.2

Table 5. The effect of swimming or cycling on respiratory muscle strength post-exercise.

Pre-exercise values for both exercise modes did not statistically differ (MIP t=0.471, P=0.652; MEP t=0.290, P=0.782). Similarly, measurement times post-exercise did not differ between trials: the average amount of time before the first MIP maneuver was 34.0 ± 11.0 s (swimming) and 33.8 ± 23.6 s (cycling) (t=0.027, P=0.979). For MEP, the average amount of time was 82.1 ± 19.8 s (swimming) and 77.1 ± 9.9 s (cycling) (t=0.691, P=0.515). Post-cycling values did not elicit a statistically significant decline in either MIP (t=1.121, P=0.299) or MEP (t=1.609, P=0.159). Declines in maximum inspiratory and expiratory pressures post-swimming, however, were statistically significant: MIP t=4.395, P=0.003; MEP t=2.685, P=0.031. These declines are illustrated in Figure 2. Breathing frequencies during the experimental trials did differ, according to a one-tailed paired-samples t-test (P=0.045); swimming resulted in a breathing frequency of 28.0 ± 6.7, whereas cycling resulted in a breathing frequency of 36.5 ± 12.5 breaths·min^{-1}.

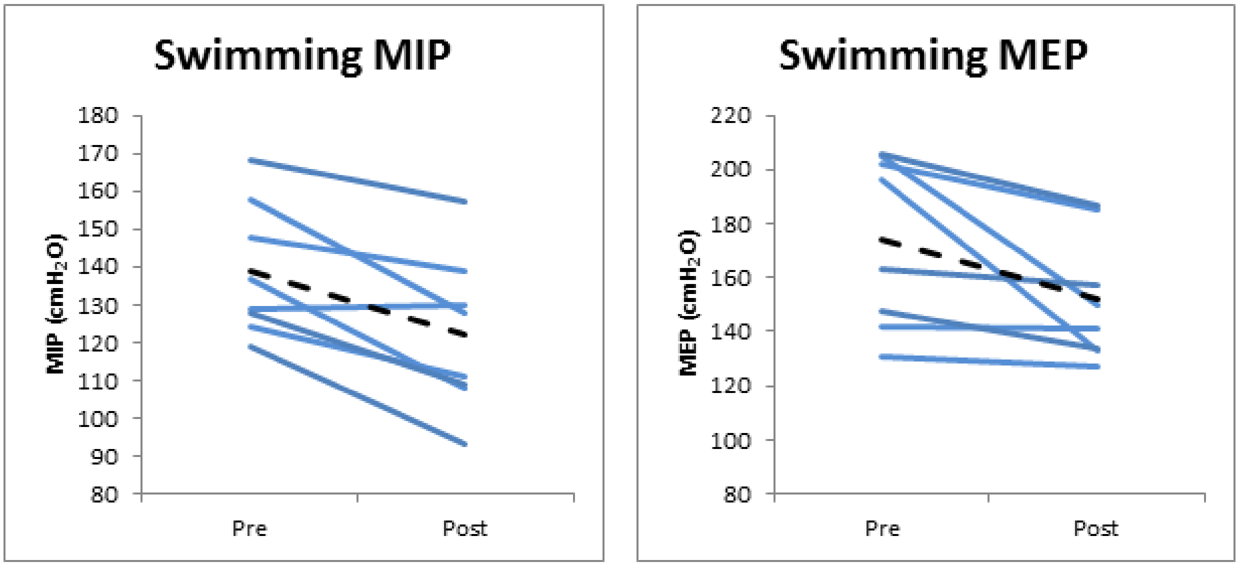

Figure 1. Pre- and post-exercise values of maximum inspiratory pressure (MIP) and maximum expiratory pressure (MEP) following swimming exercise.

Results of the 2x2 repeated measures ANOVA indicated a significant interaction between modes of exercise in their changes in inspiratory muscle function, $F(1,7)=7.285$, $P=0.031$. There was not a significant interaction between modes of exercise and their changes in expiratory muscle function, $F(1,7)=4.372$, $P=0.081$. In Figure 3, MIP and MEP values pre- and post-cycling are illustrated.

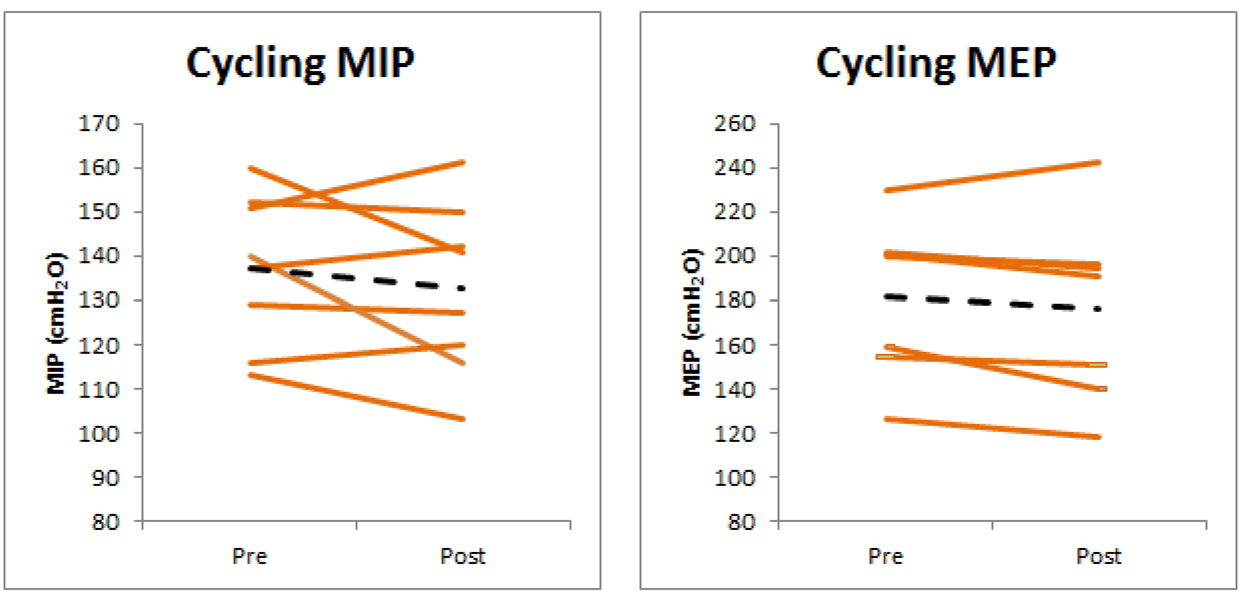

Figure 2. Pre- and post-exercise values of maximum inspiratory pressure (MIP) and maximum expiratory pressure (MEP) following cycling exercise.

Chapter 5

Conclusions

5.0 IN AGREEMENT WITH AVAILABLE LITERATURE

The current study is in agreement with previous studies that have shown significant respiratory muscle strength decline after high-intensity swimming exercise, summarized in Table 5. This study is the first to take place in a resource such as an Endless Pool, as opposed to a lap pool, thereby allowing better control of swimming effort and allowing isolation of breathing parameters. Additionally, this study is the first to compare exercise modes utilizing such a protocol of measurement post-exercise. These results support the hypothesis of previous research that swimming is unique in its challenge to the respiratory muscles.

	Current Study	Lomax & McConnell (2003)	Jakovljevic & McConnell (2009)	Thomaidis et al. (2009)	Brown & Kilding (2011)
Event	400m*	200m⁺	200m⁺	400m	100m, 200m, & 400m
Subjects	8 (M)	7 (3M, 4F)	10 (M)	11 (6M, 5 F)	10 (M)
MIP	138.9 ± 17.5	133 ± 16.7	128.1 ± 19.1	141 ± 8.9	123 ± 22
% Decline	12.4 ± 8.2	29	21†	15.3 ± 5.6	8.2‡

Table 6. Previous MIP values and percent decline after swim event. *=Swimming took place in an Endless Pool; ⁺="Respiratory warm-up" used pre-trial; †=Breathing frequency was controlled, this percent decline was after breathing every four strokes; ‡=Percent decline only after 100m event.

5.1 EXPLORING THE UNIQUENESS OF BREATHING DURING SWIMMING

The results of this study continue the trend in research in respiratory physiology pointing to the uniqueness of the challenge that the sport of swimming imposes on the ventilatory muscles. The noted declines post-swimming of 12.4 and 11.7% in maximum inspiratory pressure (MIP) and maximum expiratory pressure (MEP), respectively, are not present post-cycling. Conditions that may influence respiratory muscle strength post-exercise were controlled: pre-trial MIP/MEP measurements and post-exercise time to first MIP/MEP measurement were reported between the two conditions of swimming and cycling. Yet, declines in respiratory muscle strength were only significant after the swimming condition. The following sections will serve to provide possible explanations for the observed results, referencing different aspects of breathing during the sport of swimming.

5.1.1 *Breathing Mechanics*

Due to the aquatic nature of the sport, breathing during swimming cannot occur as freely as breathing during land-based exercises. Instead, it must be coordinated with stroke mechanics in order to not slow the momentum of the swimmer; this produces both lower breathing frequencies and greater tidal volumes (Dicker, Lofthus, Thornton, & Brooks, 1980; Rodriguez, 2000). These larger tidal volumes also tend to invade inspiratory reserve volume, resulting in two consequences. Advantageously, the first consequence is a more buoyant swimmer due to the increased volume of air in the lungs for longer periods of time, allowing the swimmer to achieve a higher body position in the water. The second consequence of decreased inspiratory reserve volume is the resultant shortened diaphragm and its lowered effectiveness as an inspiratory pressure generator (Smith & Bellemare, 1987). In Figure 4, expiratory (positive y-axis) and inspiratory flows (negative y-axis) are plotted against lung volume (x-axis). The outer loops are the maximum voluntary generation of flow and lung volume, and the inner loops represent tidal breathing at near peak exercise.

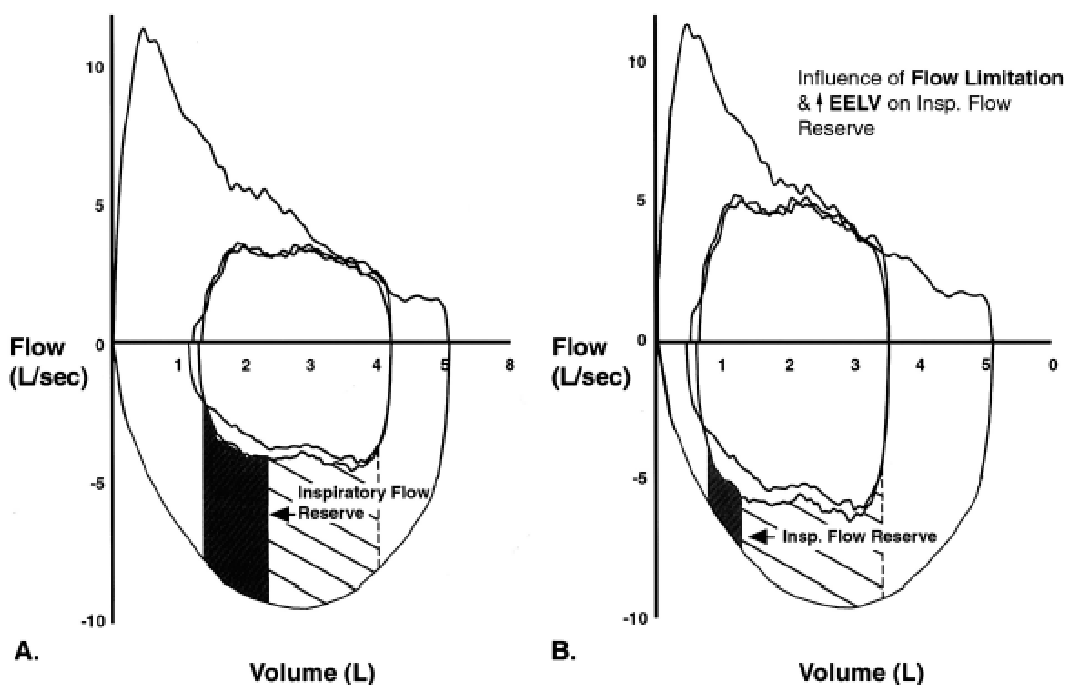

Figure 3. Tidal flow-volume diagrams for (A) normal adults near peak exercise and (B) reaching expiratory flow limitation, requiring increased end-expiratory lung volume (EELV) (Johnson, Weisman, Zeballos, & Beck, 1999).

If tidal volumes during swimming occur at higher lung volumes (and thus inspiratory reserve volume is less), inspiratory flow reserve is likely diminished, similar to Figure 4B. In a review article examining ventilatory limitation during exercise, Johnson et al. (1999) references two studies (Johnson, Reddan, Seow, & Dempsey, 1991; Johnson, Saupe, & Dempsey, 1992) that suggest that for every 1% increase in lung volume above functional residual capacity (FRC, the amount of air in the lungs after a normal expiration), there is a 0.65-0.97% reduction in the ability to produce inspiratory pressure. Additionally, these studies suggest a 4-5% decline in the production of inspiratory pressure with every 1 L/s increase in inspiratory flow. Knowing all of this, a story begins to unfold with regards to the breathing mechanics of swimmers: large tidal volumes that may be very close to inspiratory capacity (IC, when no more air can be inspired) fit into a "gasp" in between strokes. Thus, it is fair to say that when swimmers inhale, they may in fact be doing so at a very high percentage of inspiratory flow reserve, requiring a very high percentage of potential inspiratory pressure.

This method by which a swimmer manufactures an inhalation may serve as the primary reasoning behind the observed disparate results post-swimming or cycling of this study. Because ventilations between the exercise modes were matched, it is likely that the way that these ventilations were achieved differed. The significant decline in respiratory muscle strength post-swimming, with the assumption that these swimmers were breathing with minimal inspiratory reserve volume (and thus minimal inspiratory flow reserve), lends itself to the idea of a greater work of breathing occurred during swimming than cycling. Volumetric work is the change in volume for a certain pressure, shown in the equation below.

$$W = \int_{V_i}^{V_f} P \cdot dV$$

Visible in Figure 5, as tidal volumes begin to invade inspiratory reserve volume and reach vital capacity, greater pressure is needed to move the same volume. Referencing the above equation, this increase in pressure for the same volume will result in greater work performed.

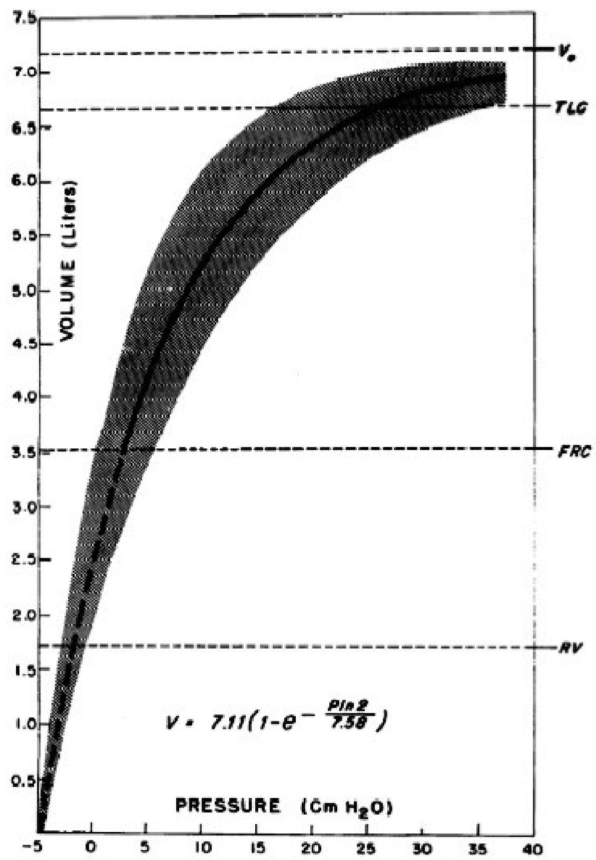

Figure 4. Pressure-volume curve for the lung, created by subjects inspiring progressively larger tidal volumes from FRC (Salazar & Knowles, 1964).

With regards to the results of the current study demonstrating differences between modes of exercise in post-exercise respiratory muscle strength, the added work of ventilation during swimming would seem to be a large part of the explanation; however, more than likely is it a combination of factors.

5.1.2 *Posture and Hydrostatic Pressure*

Those other factors will certainly include both the posture differences between exercises and the added hydrostatic pressure during swimming. Breathing muscle recruitment at rest changes between upright and supine postures. When an individual adopts a supine position, the postural control of the rib cage and abdominal muscles lessen (Druz & Sharp, 1981). However, this is not necessary the case during swimming: rather, accessory breathing muscles may actually be used in the swimming stroke. Additionally, a supine position increases blood flow apically in the lung, resulting in increased blood volume; this effect is compounded by blood volume shifts from the periphery to the chest, intensified by compression due to the immersion in water (Frangolias & Rhodes, 1996). The increased blood volume in the pulmonary compartments decreases lung compliance (lessening a change in volume for a change in pressure), which may add to the ventilatory work needed for breathing.

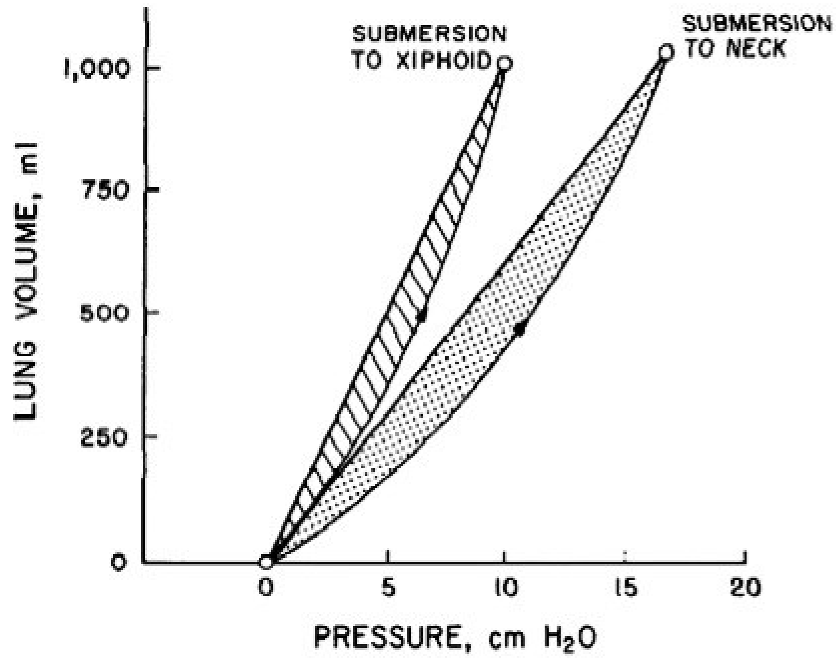

Figure 5. The difference in pressure generation required for tidal volume immersed to xiphoid and neck (Hong et al., 1969).

Above, in Figure 6, represents differences in pressure needed for tidal volumes in two different immersion conditions. From these data, Hong et al. (1969) determined that greater ventilatory work is performed while breathing with the entire chest submersed. Specifically, Hong et al. stated that 75% of this added ventilatory work is elastic work. The swimming stroke requires that most of the chest is immersed in water. So, in addition to the fixed breathing pattern and postural effects of swimming, the immersion in water adds further difficulty to breathing. In the three differences discussed that may play a role in the discrepancy between exercise modes, the common ground is ventilatory work. The respiratory muscles are required to perform more work (i.e., generate higher pressures in addition to larger tidal volumes) per breath during swimming.

5.2 CONSIDERATIONS

Some considerations must be made with interpreting the current results. First and most importantly, the measurements of maximum inspiratory and expiratory pressures (MIP and MEP) do require discussion. The device used for these maneuvers (MicroRPM, MicroMedical Ltd, Kent, United Kingdom) has been validated in current literature (Hamnegard et al., 1994), so it is safe to assume that the measured pressures are accurate. However, the maneuvers are voluntary and can be somewhat uncomfortable, requiring a learning/familiarization period for each subject for consistency in measurements. On average, the highest maximum inspiratory pressure (used in calculations) across all pre-exercise values only differed 3.6 ± 2.1% from the average of the three values taken pre-exercise. Likewise, the highest maximum expiratory pressure (used in calculations) across all pre-exercise values only differed 4.3 ± 3.2% from the average of the three values taken pre-exercise.

Additionally, despite previous research showing increased tidal volumes during swimming (Dicker et al., 1980; Rodriguez, 2000), this increased tidal volume was not shown to be the case while the subjects of this study breathed through the mouthpiece setup. The subjects were intentionally not provided with instructions on breathing pattern while swimming, which probably led to the increased breathing frequency measured while swimming (as well as the increased variance in breathing frequency). When asked, subjects reported fitting a breathing pattern to their stroke mechanics, although this may have been more frequent than ordinarily performed when not breathing through a snorkel device. Not having to turn their head to breath may have influenced this behavior.

Further, a limitation of this study is not having metabolic information or ventilation during the experimental trials. Breathing frequency was acquired for the third minute of both exercises, while the subjects breathed through the mouthpiece setup as well as without the mouthpiece. For the purposes of comparison, cycling at 305.0 ± 33.4W during the incremental cycling exercise will be compared to cycling at 305.1 ± 78.5W during the experimental trials. Breathing frequency during cycling with the mouthpiece (38.9 ± 6.4 breaths$\cdot$min^{-1}) was not statistically different from breathing frequency without the mouthpiece (37.0 ± 11.5), P=0.747. Thus, it is not unreasonable to assume that ventilation during the cycling experimental trial was comparable to ventilation reached during the incremental cycling stage. On the other hand, the difference between breathing frequencies with and without the mouthpiece setup was undoubtedly approaching significance at $P=0.054$ (two-tailed, paired-samples t-test): with the mouthpiece, f_b was 46.6 ± 18.1 versus 28.0 ± 6.7 breaths·min^{-1} without the mouthpiece. If we assume that $\dot{V}_E$ during the experimental swim trial was consistent with that of the metabolic swim trial (BTPS 116.1 ± 28.4 L·min^{-1}), it would result in a calculated tidal volume of 4.15 L, substantially larger than the average V_T during cycling (3.21 ± 0.40 L). This calculated tidal volume does seem too extreme, even considering the greater than predicted lung volumes, vital capacities and total lung capacities that appear to be inherent in swimmers (Andrew, Becklake, Guleria, & Bates, 1972; Loren Cordain, Tucker, Moon, & Stager, 1990; Doherty & Dimitriou, 1997; Pherwani, Desai, & Solepure, 1988; Zinman & Gaultier, 1986), but this may indicate that during the experimental swim trials subjects were in fact breathing less.

5.3 FUTURE DIRECTIONS

This study continues the trend in respiratory physiology research in the sport of swimming that shows its uniqueness in the challenge to respiratory muscles. Swimming is inherently more difficult to research because of its aquatic nature and lack of equivalents to running's treadmills or cycling's ergometers. However, future studies should begin to take a more mechanistic approach to swimming research, especially in the realm of respiratory physiology. Included in this is research involving lung volumes and flows (like those shown in Figure 4) as well as pressures along these volumes. With pressure and volume comes ventilatory work, which is a necessary component in deciphering swimming's unique challenge to the respiratory muscles and the fatigue that may follow.

References

Amann, M., Blain, G. M., Proctor, L. T., Sebranek, J. J., Pegelow, D. F., & Dempsey, J. A. (2010). Group III and IV muscle afferents contribute to ventilatory and cardiovascular response to rhythmic exercise in humans. *Journal of Applied Physiology, 109*(4), 966-976. doi: DOI 10.1152/japplphysiol.00462.2010

Andrew, G. M., Becklake, M. R., Guleria, J., & Bates, D. (1972). Heart and lung functions in swimmers and nonathletes during growth. *Journal of Applied physiology, 32*(2), 245-251.

ATS/ERS Statement on respiratory muscle testing. (2002). *Am J Respir Crit Care Med, 166*(4), 518-624.

Aubier, M. (1989). Respiratory Muscle Fatigue. *Intensive Care Medicine, 15*, S17-S20.

Babcock, M., Pegelow, D., McClaran, S., Suman, O., & Dempsey, J. (1995). Contribution of diaphragmatic power output to exercise-induced diaphragm fatigue. *Journal of Applied Physiology, 78*(5), 1710-1719.

Babcock, M. A., Johnson, B. D., Pegelow, D. F., Suman, O. E., Griffin, D., & Dempsey, J. A. (1995). Hypoxic Effects on Exercise-Induced Diaphragmatic Fatigue in Normal Healthy Humans. *Journal of Applied Physiology, 78*(1), 82-92.

Blackie, S. P., Fairbarn, M. S., McElvaney, N. G., Wilcox, P. G., Morrison, N. J., & Pardy, R. L. (1991). Normal values and ranges for ventilation and breathing pattern at maximal exercise. *Chest, 100*(1), 136-142.

Boutellier, U., Buchel, R., Kundert, A., & Spengler, C. (1992). The Respiratory System as an Exercise Limiting Factor in Normal Trained Subjects. *European Journal of Applied Physiology and Occupational Physiology, 65*(4), 347-353.

Brown, S., & Kilding, A. E. (2011). Exercise-Induced Inspiratory Muscle Fatigue During Swimming: The Effect of Race Distance. *The Journal of Strength & Conditioning Research, 25*(5), 1204.

Clanton, T., Dixon, G., Drake, J., & Gadek, J. (1987). Effects of swim training on lung volumes and inspiratory muscle conditioning. *Journal of Applied Physiology, 62*(1), 39-46.

Cordain, L., & Stager, J. (1988). Pulmonary structure and function in swimmers. *Sports medicine, 6*(5), 271-278.

Cordain, L., Tucker, A., Moon, D., & Stager, J. M. (1990). Lung volumes and maximal respiratory pressures in collegiate swimmers and runners. *Research quarterly for exercise and sport, 61*(1), 70-74.

Costill, D., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., & King, D. (1985). Energy expenditure during front crawl swimming: predicting success in middle-distance events. *International Journal of Sports Medicine, 6*(05), 266-270.

Courteix, D., Obert, P., Lecoq, A. M., Guenon, P., & Koch, G. (1997). Effect of intensive swimming training on lung volumes, airway resistances and on the maximal expiratory flow-volume relationship in prepubertal girls. *European journal of applied physiology and occupational physiology, 76*(3), 264-269.

Dicker, S. G., Lofthus, G. K., Thornton, N. W., & Brooks, G. A. (1980). Respiratory and heart rate responses to tethered controlled frequency breathing swimming. *Med Sci Sports Exerc, 12*(1), 20-23.

Dodd, D., Yarom, J., Loring, S., & Engel, L. (1988). O2 cost of inspiratory and expiratory resistive breathing in humans. *Journal of Applied Physiology, 65*(6), 2518-2523.

Doherty, M., & Dimitriou, L. (1997). Comparison of lung volume in Greek swimmers, land based athletes, and sedentary controls using allometric scaling. *British journal of sports medicine, 31*(4), 337-341.

Downey, A. E., Chenoweth, L. M., Townsend, D. K., Ranum, J. D., Ferguson, C. S., & Harms, C. A. (2007). Effects of inspiratory muscle training on exercise responses in normoxia and hypoxia. *Respiratory physiology & neurobiology, 156*(2), 137-146.

Druz, W. S., & Sharp, J. T. (1981). Activity of respiratory muscles in upright and recumbent humans. *Journal of Applied Physiology, 51*(6), 1552-1561.

Edwards, A. M., Wells, C., & Butterly, R. (2008). Concurrent inspiratory muscle and cardiovascular training differentially improves both perceptions of effort and 5000 m running performance compared with cardiovascular training alone. *British journal of sports medicine, 42*(10), 823-827.

Enoka, R. M., & Stuart, D. G. (1992). Neurobiology of muscle fatigue. *J Appl Physiol, 72*(5), 1631-1648.

Frangolias, D. D., & Rhodes, E. C. (1996). Metabolic responses and mechanisms during water immersion running and exercise. *Sports Medicine, 22*(1), 38-53.

Gallagher, C., Hof, V., & Younes, M. (1985). Effect of inspiratory muscle fatigue on breathing pattern. *Journal of Applied Physiology, 59*(4), 1152-1158.

Hamnegard, C., Wragg, S., Kyroussis, D., Aquilina, R., Moxham, J., & Green, M. (1994). Portable measurement of maximum mouth pressures. *European Respiratory Journal, 7*(2), 398-401.

Harms, C. A., Babcock, M. A., McClaran, S. R., Pegelow, D. F., Nickele, G. A., Nelson, W. B., & Dempsey, J. A. (1997). Respiratory muscle work compromises leg blood flow during maximal exercise. *Journal of Applied Physiology, 82*(5), 1573-1583.

Hart, N., Nickol, A. H., Cramer, D., Ward, S. P., Lofaso, F., Pride, N. B., . . . Polkey, M. I. (2002). Effect of severe isolated unilateral and bilateral diaphragm weakness on exercise performance. *American journal of respiratory and critical care medicine, 165*(9), 1265-1270.

Hong, S., Cerretelli, P., Cruz, J., & Rahn, H. (1969). Mechanics of respiration during submersion in water. *Journal of Applied Physiology, 27*(4), 535-538.

Jakovljevic, D. G., & McConnell, A. K. (2009). Influence of different breathing frequencies on the severity of inspiratory muscle fatigue induced by high-intensity front crawl swimming. *The Journal of Strength & Conditioning Research, 23*(4), 1169-1174.

Johnson, B. D., Babcock, M. A., Suman, O. E., & Dempsey, J. A. (1993). Exercise-induced diaphragmatic fatigue in healthy humans. *The Journal of physiology, 460*(1), 385-405.

Johnson, B. D., Reddan, W. G., Seow, K. C., & Dempsey, J. A. (1991). Mechanical constraints on exercise hyperpnea in a fit aging population. *The American review of respiratory disease, 143*(5 Pt 1), 968.

Johnson, B. D., Saupe, K. W., & Dempsey, J. A. (1992). Mechanical constraints on exercise hyperpnea in endurance athletes. *Journal of Applied Physiology, 73*(3), 874-886.

Johnson, B. D., Weisman, I. M., Zeballos, R. J., & Beck, K. C. (1999). Emerging Concepts in the Evaluation of Ventilatory Limitation During ExerciseThe Exercise Tidal Flow-Volume Loop. *CHEST Journal, 116*(2), 488-503.

Juan, G., Calverley, P., Talamo, C., Schnader, J., & Roussos, C. (1984). Effect of carbon dioxide on diaphragmatic function in human beings. *New England Journal of Medicine, 310*(14), 874-879.

Laffite, L. P., Vilas-Boas, J. P., Demarle, A., Silva, J., Fernandes, R., & Louise Billat, V. (2004). Changes in physiological and stroke parameters during a maximal 400-m free swimming test in elite swimmers. *Canadian journal of applied physiology, 29*(S1), S17-S31.

Leith, D. E., & Bradley, M. (1976). Ventilatory muscle strength and endurance training. *Journal of Applied Physiology, 41*(4), 508-516.

Lind, F., & Hesser, C. M. (1984). Breathing pattern and lung volumes during exercise. *Acta Physiol Scand, 120*(1), 123-129.

Loke, J., Mahler, D. A., & Virgulto, J. A. (1982). Respiratory Muscle Fatigue after Marathon Running. *Journal of Applied Physiology, 52*(4), 821-824.

Lomax, M., & McConnell, A. (2003). Inspiratory muscle fatigue in swimmers after a single 200 m swim. *Journal of sports sciences, 21*(8), 659-664.

Mador, M. J., & Acevedo, F. A. (1991). Effect of Respiratory Muscle Fatigue on Breathing Pattern during Incremental Exercise. *American Review of Respiratory Disease, 143*(3), 462-468.

Mador, M. J., & Dahuja, M. (1996). Mechanisms for diaphragmatic fatigue following high-intensity leg exercise. *American journal of respiratory and critical care medicine, 154*(5), 1484-1489.

Mador, M. J., Magalang, U. J., Rodis, A., & Kufel, T. J. (1993). Diaphragmatic Fatigue after Exercise in Healthy-Human Subjects. *American Review of Respiratory Disease, 148*(6), 1571-1575.

Mickleborough, T. D., Stager, J. M., Chatham, K., Lindley, M. R., & Ionescu, A. A. (2008). Pulmonary adaptations to swim and inspiratory muscle training. *European journal of applied physiology, 103*(6), 635-646.
Miller, M. R., Hankinson, J., Brusasco, V., Burgos, F., Casaburi, R., Coates, A., . . . Wanger, J. (2005). Standardisation of spirometry. *Eur Respir J, 26*(2), 319-338. doi: 26/2/319 [pii]
10.1183/09031936.05.00034805
Pherwani, A. V., Desai, A., & Solepure, A. (1988). A study of pulmonary function of competitive swimmers. *Indian journal of physiology and pharmacology, 33*(4), 228-232.
Rinehardt, K., Kraemer, R., Gormely, S., & Colan, S. (1991). Comparison of maximal oxygen uptakes from the tethered, the 183-and 457-meter unimpeded supramaximal freestyle swims. *International Journal of Sports Medicine, 12*(01), 6-9.
Rodriguez, F. (2000). Maximal oxygen uptake and cardiorespiratory response to maximal 400-m free swimming, running and cycling tests in competitive swimmers. *The Journal of sports medicine and physical fitness, 40*(2), 87.
Romer, L. M., McConnell, A. K., & Jones, D. A. (2002). Inspiratory muscle fatigue in trained cyclists: effects of inspiratory muscle training. *Medicine and Science in Sports and Exercise, 34*(5), 785-792.
Roussos, C., Fixley, M., Gross, D., & Macklem, P. (1979). Fatigue of inspiratory muscles and their synergic behavior. *Journal of Applied Physiology, 46*(5), 897-904.
Roussos, C. S., & Macklem, P. T. (1977). Diaphragmatic Fatigue in Man. *Journal of Applied Physiology, 43*(2), 189-197.
Rusko, H., Havu, M., & Karvinen, E. (1978). Aerobic performance capacity in athletes. *Eur J Appl Physiol Occup Physiol, 38*(2), 151-159.
Salazar, E., & Knowles, J. H. (1964). An analysis of pressure-volume characteristics of the lungs. *Journal of applied physiology, 19*(1), 97-104.
Smith, J., & Bellemare, F. (1987). Effect of lung volume on in vivo contraction characteristics of human diaphragm. *Journal of Applied Physiology, 62*(5), 1893-1900.
Sonetti, D. A., Wetter, T. J., Pegelow, D. F., & Dempsey, J. A. (2001). Effects of respiratory muscle training versus placebo on endurance exercise performance. *Respiration physiology, 127*(2), 185-199.
Spengler, C. M., Knopfli-Lenzin, C., Birchler, K., Trapletti, A., & Boutellier, U. (2000). Breathing pattern and exercise endurance time after exhausting cycling or breathing. *European Journal of Applied Physiology, 81*(5), 368-374.
Spengler, C. M., Roos, M., Laube, S. M., & Boutellier, U. (1999). Decreased exercise blood lactate concentrations after respiratory endurance training in humans. *European journal of applied physiology and occupational physiology, 79*(4), 299-305.
Thomaidis, S., Toubekis, A., Mpousmoukilia, S., Douda, H., Antoniou, P., & Tokmakidis, S. (2009). Alterations in maximal inspiratory mouth pressure during a 400-m maximum effort front-crawl swimming trial. *J Sports Med Phys Fitness, 49*, 194-200.
Turner, L. A., Tecklenburg-Lund, S. L., Chapman, R. F., Stager, J. M., Wilhite, D. P., & Mickleborough, T. D. (2012). Inspiratory muscle training lowers the oxygen cost of voluntary hyperpnea. *Journal of Applied Physiology, 112*(1), 127-134.
Verges, S., Notter, D., & Spengler, C. M. (2006). Influence of diaphragm and rib cage muscle fatigue on breathing during endurance exercise. *Respiratory Physiology & Neurobiology, 154*(3), 431-442.
Volianitis, S., McConnell, A. K., Koutedakis, Y., McNaughton, L. R., Backx, K., & Jones, D. A. (2001). Inspiratory muscle training improves rowing performance. *Medicine & Science in Sports & Exercise, 33*(5), 803-809.
Wells, G. D., Plyley, M., Thomas, S., Goodman, L., & Duffin, J. (2005). Effects of concurrent inspiratory and expiratory muscle training on respiratory and exercise performance in competitive swimmers. *European journal of applied physiology, 94*(5), 527-540.

Yan, S., Lichros, I., Zakynthinos, S., & Macklem, P. T. (1993). Effect of diaphragmatic fatigue on control of respiratory muscles and ventilation during CO2 rebreathing. *Journal of Applied Physiology, 75*(3), 1364-1370.

Zinman, R., & Gaultier, C. (1986). Maximal static pressures and lung volumes in young female swimmers. *Respiration physiology, 64*(2), 229-239.

APPENDIXES

APPENDIX A

Modified Physical Activity Readiness Questionnaire (PAR-Q)

Modified Physical Activity Readiness Questionnaire (PAR-Q)

Name			**Date**
DOB	**Age**	**Home Phone**	**Work Phone**

Regular exercise is associated with many health benefits, yet any change of activity may increase the risk of injury. Please read each question carefully and answer every question honestly:

Yes	**No**	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
Yes	**No**	**2. Do you feel pain in your chest when you do physical activity?**
Yes	**No**	3. **In the past month, have you had chest pain when you were not doing physical activity?**
Yes	**No**	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
Yes	**No**	**5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?**
Yes	**No**	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
Yes	**No**	**7. Do you know of any other reason you should not do physical activity?**
Yes	**No**	**8. Has your doctor ever told you that you have diabetes?**
Yes	**No**	**9. Has your doctor ever told you that you have high blood pressure?**
Yes	**No**	**10. Has your doctor ever told you that you have high cholesterol?**
Yes	**No**	**11. Has your doctor ever told you that you have high blood sugar?**
Yes	**No**	**12. Has your doctor ever told you that you have asthma?**
Yes	**No**	**13. Do you smoke?**
Yes	**No**	**14. Are you currently inactive?**
Yes	**No**	**15. Do you have a father, brother or son with heart disease before the age of 55 years old or a mother, sister or daughter with heart disease before the age of 65 years old?**

16. Measure height and weight to determine BMI: **Height:________** **Weight:________**

Participant Signature	**Date**

<u>Note to ParQ Reader:</u>

A “yes” to any Question 1-8 will eliminate the individual from participation.

A “yes” to 2 or more of Questions 9-14 indicates > low risk.

#15: If over 30 kg/m^2, the individual may have the risk factor of obesity.

IRB Study #1303011023

APPENDIX B

Informed Consent

INDIANA UNIVERSITY INFORMED CONSENT STATEMENT FOR

Ventilatory Challenge of Swimming and Cycling in the Development of Global Respiratory Muscle Fatigue

You are invited to participate in a research study of the impact of swimming on the fatigue of the muscles needed for breathing. You were selected as a possible subject because of your current or previous swim training**.** We ask that you read this form and ask any questions you may have before agreeing to be in the study.

The study is being conducted by Dr. Joel Stager and Mr. Tyler Sossong of the Exercise Physiology program at Indiana University.

STUDY PURPOSE

The purpose of this study is to explore the uniqueness of the challenge to respiratory muscles imposed by the sport of swimming.

NUMBER OF PEOPLE TAKING PART IN THE STUDY:

If you agree to participate, you will be one of a maximum of 8 subjects who will be participating in this research.

PROCEDURES FOR THE STUDY:

If you agree to be in the study, you will do the following things:

Testing procedures will occur on three (3) separate occasions. The first visit will last between 100 and 150 minutes and the second and third visits will last about 30 minutes; each visit will be separated by approximately two to four days. So, the complete course of study will be between 5 and 9 days. You must refrain from ingesting caffeine/alcohol for 8 hours prior to each visit. Additionally, please refrain from participating in any exercise for 24 hours prior to each visit.

On day #1, you will complete a standard medical questionnaire, as well as undergo three brief exercise tests to establish swimming pace and cycling workload for the experimental trials (days 2 & 3). Then, we will show you the maximum inspiratory and expiratory pressure (MIP and MEP, respectively) maneuvers, lasting about 10-15 minutes. Then, you will warm up as desired before swimming a 5 x 100-yard swim with 10 seconds of rest in between (lasting about 30 minutes, including warm-up) so that I can establish pace for flume swimming. A "flume" can be thought of as a swimming treadmill where the water is set to a rate of water flow. You will then swim in the flume for 3 minutes at the average 100-yd pace previously established, while breathing into a mouthpiece. For the final portion of the first day, you will cycle at three to five different workloads. The time between these exercises may vary, but will most likely be between 10-20 minutes.

On days #2 and 3, you will complete an experimental trial either at the flume speed pace previously determined on day #1 or on the cycle ergometer at a specific workload determined on day #1. Each exercise will last about 4 to 5 minutes. Before and after exercises on days #2 and 3, you will be asked to inhale or exhale as forcefully as you can for data acquisition.

RISKS OF TAKING PART IN THE STUDY:

While on the study, the risks and/or discomforts are:

Breathing function testing (MIP/MEP) involves a slight risk of headache, temporary light-headedness, throat dryness or fainting. As you will be comfortable and carefully monitored, fainting is not likely to occur.

Drowning is a risk, though it is extremely unlikely to occur due to your experience in the sport of swimming. Additionally, at least two experimenters will be present during testing.

Submaximal and maximal exercise presents little risk in healthy asymptomatic individuals under the age of 40 years, as described by the American College of Sports Medicine. However, there is a small risk of fatigue, muscle strains, heart abnormalities (arrhythmias), 0.01% chance of death (in cardiac population), 0.02% risk of cardiac arrhythmias requiring hospitalization (in a cardiac population), and change of blood pressure. One death occurs for roughly every 880,000 man hours of submaximal exercise in apparently healthy individuals. Apparently healthy individuals are those free from any signs or symptoms of disease.

Following cycle ergometry there is a risk of blood pooling in the legs. This can lead to low blood pressure, light-headedness, and dizziness following exercise.

There is a potential risk of loss of confidentiality. Specific data storage methods will be used to reduce this risk.

There may also be side effects we cannot predict.

BENEFITS OF TAKING PART IN THE STUDY:

You can expect to receive information on your individual physical and swimming fitness.

ALTERNATIVES TO TAKING PART IN THE STUDY:

You have the option of not participating in this study.

CONFIDENTIALITY

Efforts will be made to keep your personal information confidential. We cannot guarantee absolute confidentiality. Your personal information may be disclosed if required by law. Your identity will be held in confidence in reports in which the study may be published and databases in which results may be stored.

Organizations that may inspect and/or copy your research records for quality assurance and data analysis include groups such as the study investigator and his/her research associates, the Indiana University Institutional Review Board or its designees, and (as allowed by law) state or federal agencies, specifically the Office for Human Research Protections (OHRP), who may need to access your medical and/or research records.

PAYMENT

You will not receive payment for taking part in this study.

COMPENSATION FOR INJURY

In the event of physical injury resulting from your participation in this research, necessary medical treatment will be provided to you and billed as part of your medical expenses. Costs not covered by your health care insurer will be your responsibility. Also, it is your responsibility to determine the extent of your health care coverage. There is no program in place for other monetary compensation for such injuries. However, you are not giving up any legal rights or benefits to which you are otherwise entitled. Because you are participating in research which is not conducted at a medical facility, you will be responsible for seeking medical care and for the expenses associated with any care received.

CONTACTS FOR QUESTIONS OR PROBLEMS

For questions about the study or a research-related injury, contact the researcher Tyler Sossong at 973-668-9668 or Dr. Joel Stager at (812) 855-1637. If you cannot reach the researcher during regular business hours (i.e. 8:00AM-5:00PM), please call the IU Human Subjects Office at (812) 856-4242 or (800) 696-2949.

In the event of an emergency, you may contact Tyler Sossong at 973-668-9668.

For questions about your rights as a research participant or to discuss problems, complaints or concerns about a research study, or to obtain information, or offer input, contact the IU Human Subjects Office at (812) 856-4242 or (800) 696-2949.

VOLUNTARY NATURE OF STUDY

Taking part in this study is voluntary. You may choose not to take part or may leave the study at any time. Leaving the study will not result in any penalty or loss of benefits to which you are entitled. Your decision whether or not to participate in this study will not affect your current or future relations with Indiana University.

SUBJECT'S CONSENT

In consideration of all of the above, I give my consent to participate in this research study.

I will be given a copy of this informed consent document to keep for my records. I agree to take part in this study.

Subject's Printed Name:____

Subject's Signature:____**Date**:___________________

(must be dated by the subject)

Printed Name of Person Obtaining Consent:________________________________

Signature of Person Obtaining Consent:____________________________________**Date**:___________________

APPENDIX C

Subject Description

Subject Number	Age	Height (m)	Weight (kg)	BMI	Resting BP
1	23	1.82	70.6	21.3	120/78
2	28	1.74	68.59	22.7	112/74
3	25	1.95	92.9	24.4	122/81
4	22	1.96	83.9	21.8	126/75
5	35	1.71	68.6	23.5	112/72
6	21	1.88	75.6	21.4	106/64
7	18	1.78	71.3	22.5	118/78
8	31	1.85	70.38	20.6	118/80
Mean	25	1.84	75.2		
SD	5.6	0.09	8.8		

APPENDIX D

5 x 100-yd Pool Workout

Subject Number	First 100-yd Time (s)	Second 100-yd Time (s)	Third 100-yd Time (s)	Fourth 100-yd Time (s)	Fifth 100-yd Time (s)	Average 100-yd Time (s)	Flume Pace ($s \cdot 100yd^{-1}$)
1	57.0	57.2	57.6	60.2	62.0	58.8	1:02
2	64.3	67.7	69.1	70.1	70.9	68.4	1:08
3	64.0	64.5	65.2	65.4	65.1	64.8	1:04
4	56.1	57.3	58.4	58.0	57.5	57.5	0:58
5	60.5	60.3	60.1	60.3	59.9	60.2	1:02
6	55.3	58.4	56.9	56.9	56.6	56.8	0:56
7	55.3	60.4	62.6	64.6	63.0	61.2	1:02
8	62.1	74.3	78.7	84.0	82.7	76.4	1:16
Mean	59.3	62.5	63.6	64.9	64.7	63.0	1:03.5
SD	3.9	6.0	7.4	8.8	8.6	6.9	6.2

APPENDIX E

Swimming Metabolic Data

Subject Number	F_EO_2	F_ECO_2	V_E (STPD)	$\dot{V}O_2$ ($L \cdot min^{-1}$)	$\dot{V}CO_2$ ($L \cdot min^{-1}$)	$\dot{V}O_2$ ($mL \cdot kg \cdot min^{-1}$)	RER	V_E (BTPS)	f_b ($br \cdot min^{-1}$)	V_T (L)	Pace ($s \cdot 100yd^{-1}$)
1	17.65	3.53	120.2	3.86	4.25	54.7	1.10	149.4	70	2.13	1:02
2	17.04	4.24	83.9	3.18	3.56	46.4	1.12	104.2	38	2.74	1:08
3	16.74	4.07	98.1	4.14	3.99	44.6	0.96	122.2	-	-	1:04
4	16.5	4.24	101.7	4.55	4.31	54.3	0.95	126.4	56	2.26	0:58
5	17.34	4.39	95.2	3.22	4.18	46.9	1.30	118.3	40	2.96	1:02
6	16.61	4.01	102.0	4.49	4.09	59.4	0.91	126.8	41	3.09	0:56
7	16.93	3.88	103.5	4.17	4.02	58.5	0.96	128.6	64	2.01	1:02
8	14.47	6.21	42.6	2.78	2.64	39.5	0.95	53.0	17	3.11	1:16
Average	16.66	4.32	93.4	3.80	3.88	50.5	1.03	116.1	46.6	2.62	1:03.5
SD	0.96	0.81	22.9	0.66	0.55	7.2	0.13	28.4	18.1	0.47	6.2

APPENDIX F

Incremental Cycling Test Metabolic Data

Cycling Stage 1, 2-kg												
Subject Number	F_EO_2	F_ECO_2	$\dot{V}_E$ (STPD)	$\dot{V}O_2$ ($L\cdot min^{-1}$)	$\dot{V}CO_2$ ($L\cdot min^{-1}$)	$\dot{V}O_2$ ($mL\cdot kg\cdot min^{-1}$)	RER	$\dot{V}_E$ (BTPS)	f_b ($br\cdot min^{-1}$)	V_T (L)	RPM	Power
1	16.09	4.26	37.4	1.87	1.59	26.5	0.85	46.5	28	1.66	75	150
2	15.8	4.65	40.5	2.13	1.88	31.0	0.88	50.3	23	2.19	80	160
4	16.19	4.37	39.7	1.92	1.74	22.9	0.90	49.4	21	2.35	85	170
5	16.14	4.05	32.1	1.60	1.30	23.4	0.81	40.0	18	2.22	70	140
7	16.51	4.12	43.1	1.94	1.78	27.2	0.92	53.5	26	2.06	75	150
8	17.24	3.59	38.9	1.45	1.40	20.6	0.97	48.4	20	2.42	60	120
Average	16.33	4.17	38.6	1.82	1.62	25.2	0.89	48.0	22.7	2.15	74.2	148.3
SD	0.50	0.36	3.7	0.25	0.23	3.7	0.06	4.6	3.8	0.27	8.6	17.2

Cycling Stage 2, 3-kg												
Subject Number	F_EO_2	F_ECO_2	$\dot{V}_E$ (STPD)	$\dot{V}O_2$ ($L\cdot min^{-1}$)	$\dot{V}CO_2$ ($L\cdot min^{-1}$)	$\dot{V}O_2$ ($mL\cdot kg\cdot min^{-1}$)	RER	$\dot{V}_E$ (BTPS)	f_b ($br\cdot min^{-1}$)	V_T (L)	RPM	Power
1	16.49	4.41	55.1	2.45	2.43	34.7	0.99	68.5	30	2.28	75	225
2	16.17	4.91	60.1	2.84	2.95	41.4	1.04	74.8	24	3.11	80	240
3	16.25	4.2	57.3	2.75	2.41	29.6	0.88	71.7	-	-	80	240
4	16.45	4.57	67.8	3.02	3.10	36.0	1.03	84.3	24	3.51	85	255
5	16.86	4.08	54.5	2.22	2.22	32.4	1.00	67.8	24	2.82	70	210
6	16.66	4.41	73.3	3.10	3.23	41.0	1.04	91.1	24	3.79	85	255
7	16.78	4.22	67.8	2.80	2.86	39.3	1.02	84.3	32	2.63	75	225
8	17.49	3.56	62.7	2.13	2.24	30.3	1.05	78.0	30	2.60	60	180
Average	16.64	4.30	62.3	2.66	2.68	35.6	1.01	77.5	26.9	2.97	76.3	228.8
SD	0.42	0.39	6.8	0.36	0.40	4.7	0.06	8.4	3.6	0.54	8.3	25.0

Cycling Stage 3, 4-kg												
Subject Number	F_EO_2	F_ECO_2	$\dot{V}_E$ (STPD)	$\dot{V}O_2$ ($L \cdot min^{-1}$)	$\dot{V}CO_2$ ($L \cdot min^{-1}$)	$\dot{V}O_2$ ($mL \cdot kg \cdot min^{-1}$)	RER	$\dot{V}_E$ (BTPS)	f_b ($br \cdot min^{-1}$)	V_T (L)	RPM	Power
1	16.75	4.54	81.6	3.33	3.70	47.2	1.11	101.4	35	2.90	75	300
2	16.81	4.65	84.9	3.38	3.95	49.3	1.17	105.5	30	3.52	80	320
3	16.34	4.28	78.3	3.66	3.36	39.4	0.92	98.3	-	-	80	320
4	16.82	4.39	98.5	3.97	4.32	47.4	1.09	122.5	32	3.83	85	340
5	17.96	3.31	99.5	2.87	3.30	41.8	1.15	123.7	46	2.69	70	280
6	17.55	3.67	124.7	4.12	4.57	54.5	1.11	154.9	45	3.44	85	340
7	17.04	4.2	104.4	3.98	4.38	55.8	1.10	129.8	42	3.09	75	300
8	18.14	3.09	102.7	2.78	3.18	39.5	1.14	127.7	42	3.04	60	240
Average	17.18	4.02	96.8	3.51	3.85	46.9	1.10	120.5	38.9	3.21	76.3	305.0
SD	0.64	0.59	15.1	0.51	0.54	6.3	0.08	18.6	6.4	0.40	8.3	33.4

Cycling Stage 4, 5-kg												
Subject Number	F_EO_2	F_ECO_2	$\dot{V}_E$ (STPD)	$\dot{V}O_2$ ($L \cdot min^{-1}$)	$\dot{V}CO_2$ ($L \cdot min^{-1}$)	$\dot{V}O_2$ ($mL \cdot kg \cdot min^{-1}$)	RER	$\dot{V}_E$ (BTPS)	f_b ($br \cdot min^{-1}$)	V_T (L)	RPM	Power
3	16.73	4.17	105.5	4.44	4.40	47.8	0.99	131.5	-	-	80	400

APPENDIX G

Swimming Experimental Trial Data

	Maximum Inspiratory Pressure (cmH_2O)				
	Pre-Treatment			Post-Treatment	
Subject Number	1st Value	2nd Value	3rd Value	1st Value	2nd Value
1	145	158	155	128	125
2	168	154	142	157	143
3	131	148	138	139	136
4	119	113	110	93	95
5	118	108	124	111	116
6	129	129	123	130	132
7	127	122	128	109	136
8	133	126	137	108	114
Average	133.8	132.3	132.1	121.9	124.6
SD	17.5	19.2	14.7	20.8	16.2

	Maximum Expiratory Pressure (cmH_2O)				
	Pre-Treatment			Post-Treatment	
Subject Number	1st Value	2nd Value	3rd Value	1st Value	2nd Value
1	178	194	202	185	183
2	206	172	201	187	206
3	141	136	142	141	148
4	142	144	148	134	140
5	168	173	205	150	145
6	123	131	126	127	124
7	158	147	163	157	152
8	196	184	194	133	135
Average	164.0	160.1	172.6	151.8	154.1
SD	29.2	23.2	31.4	24.6	29.1

Subject Number	Pace	Trial Time (s)	f_b ($br \cdot min^{-1}$)	Time Post-Exercise (s) MIP 1st Value	MIP 2nd Value	MEP 1st Value	MEP 2nd Value
1	1:02	257	30	25	45	75	100
2	1:08	299	22	30	50	80	105
3	1:04	283	-	30	90	60	120
4	0:59	251	-	37	57	85	110
5	1:02	263	36	60	80	120	140
6	0:56	248	32	30	45	65	85
7	1:02	268	30	30	52	85	105
8	1:16	334	18	30	60	90	115
Average	1:03.5	275.4	28.0	34.0	59.9	82.5	110.0
SD	6.2	29.1	6.7	11.0	16.6	18.3	16.0

APPENDIX H

Cycling Experimental Trial Data

Subject Number	Maximum Inspiratory Pressure (cmH_2O) Pre-Treatment 1st Value	2nd Value	3rd Value	Post-Treatment 1st Value	2nd Value
1	142	155	160	141	148
2	151	144	139	161	157
3	150	152	145	150	148
4	116	116	115	120	122
5	124	118	129	127	112
6	113	107	112	103	100
7	129	128	137	142	142
8	138	139	140	116	104
Average	132.9	132.4	134.6	132.5	129.1
SD	14.7	17.8	15.7	19.3	22.3

Subject Number	Maximum Expiratory Pressure (cmH_2O) Pre-Treatment 1st Value	2nd Value	3rd Value	Post-Treatment 1st Value	2nd Value
1	200	200	197	196	200
2	227	226	230	242	241
3	141	149	147	-	-
4	145	144	154	151	151
5	202	176	166	194	199
6	98	122	126	118	122
7	146	159	158	140	146
8	192	201	195	191	176
Average	168.9	172.1	171.6	176.0	176.4
SD	42.9	34.9	33.4	42.0	40.4

Subject Number	Power	Trial Time (s)	f_b (br·min^{-1})	Time Post-Exercise (s) MIP 1st Value	MIP 2nd Value	MEP 1st Value	MEP 2nd Value
1	375	257	55	25	45	80	100
2	320	299	34	35	55	95	120
3	380	283	-	90	135	-	-
4	348	251	40	30	50	80	105
5	280	263	46	30	50	80	100
6	306	248	28	20	40	65	90
7	300	268	36	25	45	70	100
8	132	334	20	15	35	70	100
Average	305.1	275.4	28.0	33.8	56.9	77.1	102.1
SD	78.5	29.1	6.7	23.6	32.2	9.9	9.1