Characterizing the Physiological and Physical Correlates to Performance in Highly Trained Artistic Swimmers

by

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A thesis submitted to the
School of Graduate and Postdoctoral Studies in partial
fulfillment of the requirements for the degree of

Master of Health Sciences in Kinesiology

Faculty of Health Sciences

Ontario Tech University

Oshawa, Ontario, Canada

August 2019

THESIS EXAMINATION INFORMATION

Submitted by: **Eric Viana**

Master of Health Sciences in **Kinesiology**

Thesis title: Characterizing the Physiological and Physical Correlates to Performance in Highly Trained Artistic Swimmers

An oral defense of this thesis took place on August 6, 2019 in front of the following examining committee:

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

ABSTRACT

Artistic swimming (AS) is a unique sport which is characterized by prolonged and repeated bouts of apnea, often while performing vigorous movements. AS made its Olympic debut in 1984 and has changed considerably since then. The demands, duration, and number of teammates competing at one time have all changed over the years. In addition to these changes male athletes have been permitted to compete internationally in mixed doubles since 2015 [1], however this thesis will focus solely on the physiological responses of female AS athletes.

Despite AS making its Olympic debut 35 years ago it is a sport poorly represented by the literature. To date no two studies have utilized the same methodology, which makes comparisons between studies challenging. This leaves limited research available to examine the physiological responses present during an AS routine.

Keywords: physiology; physical; artistic swimming; performance; sport

CO-AUTHORSHIP STATEMENT

All manuscripts enclosed within this thesis were primarily written by Eric Viana. Dr. Heather Logan-Sprenger and Dr. David Bentley provided assistance with the writing and editing process. Elton Fernandes, Kiri Langford, Jennifer Koptie and Adam Pinos provided assistance during the data collection portion of this thesis. Dr. Lars MacNaughton provided assistance with data analysis.

AUTHOR'S DECLARATION

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Eric Viana

STATEMENT OF CONTRIBUTIONS

Parts of the work described in Chapter 2 has been published as:

Viana, E., Fernandes, E., Langford, K., Koptie, J., Bentley, D., Logan-Sprenger, H.M. (2018) The relationship between physical and physiological characteristics and simulated artistic swim performance. Proceedings of the European College of Sports Science (ECSS). *Journal of Sports Science,* 21(9): 707-732.

Viana, E., Bentley, D.J., Logan-Sprenger, H.M. (2018). Characterizing the acute physiological responses to a simulated artistic swim competition. Proceedings of the Canadian Society for Exercise Physiology 51st Annual General Meeting - Health in Motion, Science in Exercise. *Applied Physiology, Nutrition and Metabolism*, 43:S43-S108, https://doi.org/10.1139/apnm-2018-0499

Viana, E., Pinos, A., MacNaughton, L., Bentley, D.J., Logan-Sprenger, H.M. (2019). Peak physiological responses in cycling and a new underwater swimming test in highly trained artistic swimmers. Proceedings of the American College of Sports Medicine 66th Annual Meeting. *Medicine & Science in Sports & Exercise*, 51(5):S196.

Parts of the work described in Chapter 3 has been published as:

Viana, E., Bentley, D. J., & Logan-Sprenger, H. M. (2019). A Physiological Overview of the Demands, Characteristics, and Adaptations of Highly Trained Artistic Swimmers: a Literature Review. *Sports medicine-open*, *5*(1), 16

ACKNOWLEDGEMENTS

Thank you to my supervisor, Dr. Heather Logan-Sprenger, for all of your assistance guidance, time and patience during the writing process. I am also grateful for the wealth of knowledge you have passed onto me over the last two years as a MHSc candidate.

I would also like to thank my committee members Dr. David Bentley and Dr. Scott Thomas for their expertise in data analysis, study design and data collection.

Thank you to my lab mates, Joshua Good and Adam Pinos for assisting with the endless hours of data entry, analysis and testing dates. Additionally, thank you to the Canadian Sport Institute Ontario for taking me on as a physiology intern and permitting me to learn from your staff and conduct research on your athletes.

Lastly, thank you to my friends and family for embarking on this journey with me.

I truly could not have done this degree without your support.

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List of Abbreviations

AS Artistic swimming

B Barracuda

BB Body Boost

BG Blood Gas

BH Breath hold

BLa blood lactate

BS Breast stroke

CO_2 Carbon dioxide

EPOC Excess post-exercise oxygen consumption

FEV Forced expiratory volume

FEV1 Forced expiratory volume in one second

FI Facial immersion

FINA Fédération internationale de natation

FVC Forced vital capacity

Hct Hematocrit

HR Heart rate

HVR Hypoxic ventilatory response

La Lactate

La_{peak} Peak lactate

LHTH Live high-train high

LHTL Live high-train low

LOC Levels of consciousness

MSST Multi-stage shuttle test

O_2 Oxygen

$PaCO_2$ Partial pressure of arterial carbon dioxide

PaO_2 Partial pressure of arterial oxygen

pCO_2 Partial pressure of carbon dioxide

$_{PET}CO_2$ Partial pressure of end tidal carbon dioxide

$_{PET}O_2$ Partial pressure of end tidal oxygen

pO_2 Partial pressure of oxygen

RBC Red blood cells

UW Underwater

UWST Underwater swim test

VE Minute ventilation

VO_{2max} Maximal oxygen uptake

VO_{2peak} Peak oxygen uptake

W Watts

WANT Wingate anaerobic test

Chapter 1. Thesis Introduction

1.1 Thesis Overview

Artistic swimming (AS) is a unique sport which is characterized by prolonged and repeated bouts of apnea, often while performing vigorous movements. AS made its Olympic debut in 1984 and has changed considerably since then. The demands, duration, and number of teammates competing at one time have all changed over the years. In addition to these changes male athletes have been permitted to compete internationally in mixed doubles since 2015 [1], however this thesis will focus solely on the physiological responses of female AS athletes.

Despite AS making its Olympic debut 35 years ago it is a sport poorly represented by the literature. To date no two studies have utilized the same methodology, which makes comparisons between studies challenging. This leaves limited research available to examine the physiological responses present during an AS routine.

This thesis will begin with a published literature review of the physiology of AS athletes, which is presented in chapter two. Chapter three is an original study which outlines the relationship between a sport-specific underwater swim test (UWST) and a laboratory-based measurement of maximal oxygen uptake (VO_{2max}). Lastly, chapter four will depict the acute physiological responses to a simulated AS routine.

Based on the available literature it is currently unknown as to what makes a proficient AS athlete. Physical and physiological correlates to performance are not known at this time. Additionally, a standardized VO_{2max} protocol has not been developed for this population. These are two gaps that this thesis aims to fill.

1.2 Research Questions

1.1.1 Study 1 (Chapter 4)

What are the cardiorespiratory responses to a swim test in trained female artistic swimmers?

What changes in acid-base balance occur after a cycling and swim test in trained female artistic swimmers?

1.1.2 Study 2 (Chapter 5)

What are the physiological and physical correlates to performance during a simulated solo artistic swim performance?

Chapter 2: Published Abstracts

2.1 The relationship between physical and physiological characteristics and simulated artistic swim performance.

Viana, E., Fernandes, E., Langford, K., Koptie, J., Bentley, D., Logan-Sprenger, H.M. (2018) The relationship between physical and physiological characteristics and simulated artistic swim performance. Proceedings of the European College of Sports Science (ECSS). *Journal of Sports Science,* 21(9): 707-732.

The purpose of this study was to examine the relationship between laboratory performance testing and the results of a simulated artistic swimming competition. Highly trained artistic swimmers (n=12, 15.83 ± 0.83 yrs) who were members of a provincial and national squad program completed a series of laboratory and pool-based testing, as well as a simulated competition where artistic swimming elements were evaluated by three neutral and trained adjudicators, all of whom were blinded to the laboratory testing. The laboratory-based testing used (1) a maximal incremental cycle test to exhaustion to determine peak oxygen uptake (VO_{2max}), (2) a vertical jump test to establish jump height (3) pull ups (4) the number of pike crunches in 30 sec as a measure of abdominal endurance. The pool based tested comprised a 275m swim (overall swim time) comprising underwater swimming freestyle and other form strokes to simulate the duration of an artistic swimming competition. Blood lactate (LT) concentration (mM) was determined 3 min after the swim test using a portable lactate analyser (L-Lactate Pro). The boost and barracuda movements were performed before and after the 275m swim test and the change (delta, Δ) determined. There were no significant correlations between vertical jump height (23.92 ± 2.62cm), pre swim boost (13.45 ± 3.38cm), pre swim barracuda (24.72 ± 7.5cm), post swim boost (11.18 ± 2.42cm), post swim barracuda (25.87 ± 7.12cm), Δ boost (-0.99 ± 10.85cm) and Δ barracuda (1.29 ± 4.48cm) ($r=0.28$, $r=0.03$, $r=0.12$, $r=0.14$, $r=-0.28$, $r=0.13$, respectively, $p<0.05$). VO_{2peak} (48 ± 4 $ml \cdot kg^{-1} \cdot min^{-1}$) was positively correlated with six of the nine group elements ($R=0.60$, $r=0.60$, $r=0.66$, $r=0.66$, $r=0.69$, $r=0.66$, $p<0.05$), the overall performance score ($r=0.59$, $p<0.05$), and one of the five solo elements ($r=0.59$, $p<0.05$). The LT obtained three minutes after the simulated competition (8.73 ± 2.07mM) revealed significant negative correlations to all elements during the simulated competition ($r=-0.68$, $r=-0.61$, $r=-0.6$, $r=-0.67$, $r=-0.6$, $r=-0.66$, $r=-0.65$, $r=-0.64$, $r=-0.62$, $p<0.05$, $r=-0.69$, $r=-0.7$, $r=-0.76$, $r=-0.71$, $r=-0.71$. $r=-0.69$, $r=-0.73$, $p<0.01$). There was a decrease in boost (13.45 ± 3.38 vs 11.17 ± 2.42 cm) but not barracuda (24.72 ± 7.5 vs 25.87 ± 7.11 cm) height after the 275m swim. The 275m swim time (181 ± 13 sec) and the heart rate ($b \cdot min^{-1}$) (172 ± 10) were negatively correlated to overall performance score in the group elements ($r=-0.59$, $r=-0.69$ respectively, $p<0.05$). The LT after the 275m swim (7.19 ± 1.91 mM) was positively correlated with the change in boost height (-0.99 ± 10.85cm) before and after the 275m swim ($r=-0.76$, $p<0.01$). These data indicate greater aerobic fitness is correlated with higher scores during simulated artistic swimming competition. In contrast, performance of two important components (boost and barracuda) before and after a 275m swim was not related to any competition elements. The greatest improvement in competition score is correlated to greater aerobic fitness rather than jump heights.

2.2 Characterizing the acute physiological responses to a simulated artistic swim competition

Viana, E., Bentley, D.J., Logan-Sprenger, H.M. (2018). Characterizing the acute physiological responses to a simulated artistic swim competition. Proceedings of the Canadian Society for Exercise Physiology 51st Annual General Meeting - Health in Motion, Science in Exercise. *Applied Physiology, Nutrition and Metabolism*, 43:S43-S108, https://doi.org/10.1139/apnm-2018-0499

The purpose of this study was to investigate the acute changes in acid-base balance in highly trained artistic swimmers (AS) during short (≤2:45) and long (>2:45) simulated solo performances. 15 athletes (15.8 ± 0.8 yrs) who competed at the provincial level participated in this study. Following a standardized warm-up, each athlete completed a solo performance assessed by FINA certified judges. Water-resistant HR monitors continuously collected HR data. Capillary blood gas (BG) samples were collected pre and post-routine and analyzed for $_PO_2$, $_PCO_2$, pH, HCO_3^- and K^+. Blood lactate (BLA) was measured before and 3 min post-routine. Routines were divided into either long or short for analysis. There was a significant increase in $_PO_2$ (21.2%, t=-2.4, p=0.02) and $_PCO_2$ (2.4%, t=0.7, p=0.48) at the end of the routine. pH decreased significantly by 0.9% (t=4.0, p<0.01) and HCO_3^- decreased significantly by 12.8% (t=4.2, p<0.01). K^+ increased significantly by 6.8% (t=2.4, p=0.03) and BLA increased by 77.2% (t=4.1, p<0.01). There were significant differences between $_PO_2$ (t=-2.3, p=0.04) between the long and short routines. However, none of the other BG differed significantly between the long and short routines. The HR_{mean} was 122 bpm and mean RPE of 15. The study results indicate a significant correlation between average HR and $_{P}O_2$ (r=0.55, p=0.03). The main finding is the significant change in acid-base balance after a simulated solo performance, which indicates a significant anaerobic energy contribution. The decreases in pH and HCO_3^- indicate blood acidification, which likely stems from the repeated apneic exposures. Performance interventions should be aimed at accommodating the decrease in pH and increasing fatigue resistance during AS competitions.

2.3 Peak physiological responses in cycling and a new underwater swimming test in highly trained artistic swimmers.

Viana, E., Pinos, A., MacNaughton, L., Bentley, D.J., Logan-Sprenger, H.M. (2019). Peak physiological responses in cycling and a new underwater swimming test in highly trained artistic swimmers. Proceedings of the American College of Sports Medicine 66th Annual Meeting. *Medicine & Science in Sports & Exercise*, 51(5):S196.

Purpose: The purpose of this study was to compare peak oxygen uptake (VO_{2peak}) measured in an underwater swim test (UWST) and during a maximal aerobic capacity test on a cycle ergometer (Velotron Pro, Seattle, WA, USA). **Methods:** Highly trained artistic swimmers (n=14, 14.9 ± 1.9 yrs) completed a synchronised swimming specific test (275m UWST) in a 25m pool an incremental exercise test to volitional fatigue (15 W every 30 sec to exhaustion) on a cycle ergometer to determine VO_{2peak}. The UWST and maximal aerobic capacity testing occurred on consecutive days. The 275m UWST comprised 50m freestyle followed by 25m underwater breast stroke three times, with an additional 50m freestyle. During the UWST participants wore water-resistant HR monitors (Polar OH1) and had expired gases collected (Cosmed K4 b^2) in the 20 sec immediately upon completion of the UWST to determine VO_{2peak}. During the cycle test, HR (Polar Electro, Kempele, Finland) and expired gases were collected using a MOXUS metabolic cart (AEI Technologies, Pittsburgh, PA, USA). Peak physical work capacity (PWC) (W) was measured as the highest completed 30 sec stage of the test. **Results:** VO_{2peak} achieved after the UWST (44.3 ± 8.0 $ml \cdot kg^{-1} \cdot min^{-1}$) and cycle ergometer (42.3 ±

7.2 ml·kg^{-1}·min^{-1}) did not differ significantly from each other (t=-0.59, df=13, p=0.563, d=0.21). HR_{peak} was significantly lower during the UWST (162.5 ± 18.4 bpm) (t=7.812, df=12, p<0.00, d=2.10) when compared to the cycle test (194.6 ± 11.6 bpm) . The UWST time and PWC during the bike test were not significantly correlated to each other (r=-0.25, p=0.393). There was no significant correlation between the VO_{2peak} achieved during the UWST and the duration of the UWST (r=-0.39, p=0.17). HR_{peak} during the UWST was significantly correlated with the VO_{2peak} (r=0.62 p=0.03 CI_{95} [38.93, 46.44]) and HR_{peak} achieved on the cycle ergometer (r=0.59, p=0.04 CI_{95} [188.79, 200.92]).
Conclusion: The similarities in VO_2 data during the UWST and VO_{2peak} protocol suggest the UWST is a valid method of determining VO_{2peak} in highly trained artistic swimmers. A goal when selecting a VO_2 protocol is to mimic the demands of the sport. In this population, the UWST is likely better than the cycle ergometer, as the modality of swimming with breath holding more closely matches the demands of an artistic swim routine.

Chapter 3: Literature Review

Physiological Demands of Artistic Swimming Events Underwater Demands of Artistic Swimming

Publication Citation:

Viana, E., Bentley, D. J., & Logan-Sprenger, H. M. (2019). A Physiological Overview of the Demands, Characteristics, and Adaptations of Highly Trained Artistic Swimmers: a Literature Review. *Sports medicine-open*, *5*(1), 16.

3.1 Physiological demands of artistic swimming events

Artistic swimming places unique demands on the athlete, and perhaps, the most unique to AS is the bradycardic response that is stimulated by the long apneic periods spent underwater (UW) while performing strenuous movements [9]. Indeed, during all AS routines, athletes are required to hold their breath UW during a major portion of a routine while performing vigorous physical activity [9–14]. In previous FINA regulations, select elements, such as the “heron” required the athlete to remain immersed for 45– 50 s (s), with a higher score being awarded the more slowly this element is performed [9]: however, anecdotal remarks made by members of Canada Artistic Swimming have suggested that a greater movement frequency improves scoring during international competitions. Some elements require athletes to be inverted during apneic periods, making the breath hold (BH) period more difficult than BH with facial immersion (FI) alone [2].

Davies et al. [9] conducted an analysis of time spent above and under water during free routines and observed BH times ranged from 33 to 66 s, with an average of 43 s. In another study, time-motion analysis was used to record BH times during a Canadian synchronized swimming national championship where the routines of the top 11 Canadian soloists were recorded and subject to time motion analysis [11]. The average BH time was 6.8 s, and any BH shorter than 6.8 s occupied 13% of the total swim routine and 27% of the FI time [15]. As well, Alentejano et al. [11] performed a time-motion analysis of AS during a solo routine and found the longest BH period occurred within the first third of the routine, followed by several short and repetitive BH periods and longer BH towards the end of the routine [11]. Interestingly, the longest BH event was not followed by the longest breathing period [11]. Anecdotal reasoning for the longest BH period at the beginning of the routine may be for the coach/choreographer to ensure a lengthy BH (25.5 ± 6.2 s) is incorporated into the routine, prior the onset of fatigue [10]. However, it is unknown if this trend for the longest BH times in the first third of an AS routine is based purely on artistic choice or if there is some physiological merit to this decision [11]. Some potential physiological reasoning for the long initial BH period may provide a strong stimulus for the bradycardic response, which was followed by several short (< 6.8 s) periods of FI with the athlete able to breathe. These shorter BH periods may not be long enough to stimulate the bradycardic response in AS athletes and more frequent breathing periods could facilitate the exchange of gases in the respiratory system.

It has also been found that solo routines typically have a greater amount of apneic time than duets, team combination, and highlight routines [11], with BH times lasting ~ 40s in length [12, 16]; however, these findings were based on outdated FINA regulations that have changed since these data were published. Free routines may last as long as 4 min (min) with the longest BH time lasting 30s. The team routine is performed with 8 athletes and is ~ 4–5 min with ~ 50% of the routine spent UW [17]. While the variation of physiological responses and effort perception of individual athletes during a team event has yet to clearly demonstrated, some athletes will spend a greater amount of time UW than their teammates. Some athletes may experience UW times closer to 60 s, to support their teammates so they can perform movements above the surface of the water, whose UW times may be closer to 30 s [17]. Additionally, combination and highlight routines are performed with ten athletes, and similar to the team routine, there is a greater variance in UW time when comparing the elements and aerobatic maneuvers seen in current AS routines to those during the sport's Olympic debut in 1984 [1]. The use of aerobatic maneuvers may alter the athletic and technical skill requirements of the sport and influence the specificity of training prescription. As well, aerobatic maneuvers will increase the UW time of athletes who are positioned at the bottom of a lift and are required to launch a teammate into the air with increased explosiveness [5]. Therefore, during team routines, the roles of team members may differ, influencing the demands of individual athletes within each event. Currently, little is known about individual responses of athletes in team performances. Further research is required to investigate the physiological responses in team compared to solo and duet routines.

3.2 Physiological Consequences of Breath Hold

The BH and UW effect of AS has a number of implications not least reducing gas exchange and increasing the physiological stress of the sport [13, 18, 19]. The combination of UW exposure and intense rapid muscle contractions creates a physiological environment where gas exchange is limited for the athletes as the vast majority of the energy required during apneic periods must be produced with carbon dioxide accumulation and reduced oxygen availability [13, 19]. Under normal physiologic conditions, respiration is governed by chemoreceptors that are sensitive to the rise in CO_2 [20]. Therefore, the urge to breathe is governed by the increase in CO_2, rather than the decrease in O_2. It has been suggested that the reduction in pH is due to the accumulation of CO2 as it cannot be expelled during BH and will accumulate within the blood and muscle tissue [21–23]. In addition to altered physical sensations resulting from long and repeated BH bouts, the accumulation of CO2 can impair performance by way of altered cognitive function and in-turn decision-making [24, 25]. This results in a slight increase in the partial pressure of carbon dioxide (pCO_2) and increase in the partial pressure of oxygen (pO_2), which can lead to “a dulling of consciousness” and memory impairment [24, 26]. The dulled consciousness and memory impairment may increase the number of errors made during the routine, such as drifting out of position or losing synchronization with the music and teammates, particularly during team and combination routines where there are multiple athletes in the water. Indeed, the number and length of UW exposures has been shown to influence perceived difficulty in AS [19].

3.3 Pulmonary and Autonomic Physiological Adaptations in Artistic Swimmers

Artistic swimmers are frequently exposed to repeated bouts of UW swimming during training and competition. AS athletes appear to have developed unique physiological characteristics as a result of repeated apneic exposure during training [12, 19, 21, 22, 27]. One possible mechanism, the diving response, decreases cardiac output and causes peripheral vasoconstriction to prioritize the brain and heart with oxygenated blood [26, 28, 29].

When comparing AS athletes to age-matched controls Alentejano et al. [15] demonstrated that AS athletes were able to maintain a BH for a longer period of time compared to their counterparts (110 ± 39 vs. 78 ± 25 s). The AS athletes also showed a greater bradycardic response despite similar end BH pCO_2. While these experiments were conducted at rest, another study by the same author [15] showed that during upper body exercise (arm cranking), AS athletes demonstrated a greater diving reflex response with FI for 20–25 s compared to a control group. AS athletes were also able to recover better from BH than controls through a more rapid decline in heart rate (HR) and minute ventilation (VE) despite having a greater reduction in $PETO_2$ and greater increase in $PETCO_2$ [15]. Based upon this greater bradycardic response, more rapid ventilatory recovery from BH, and less blood lactate (La) produced during BH, Alentejano et al. [15] theorized AS may be more efficient at aerobic energy production during apnea.

Naranjo et al. [30] also found that AS athletes were able to better tolerate cycle exercise during BH (without FI) compared to a control group. While the difficulty in routine and elements within a routine may influence the cardiovascular response to exercise in water [31], AS athletes demonstrate more efficient pulmonary function and a greater bradycardic response to exercise in water compared to untrained controls which suggests elite AS athletes may be more efficient at conserving oxygen under exercise stress. It is currently unknown what training age (the number of years engaging in a specific method of training or sport) is required to observe the bradycardic response in AS athletes or whether elite AS athletes display a greater magnitude of response. Therefore, further studies are required to examine the magnitude of physiological and metabolic responses in simulated AS routines and how these responses link to pulmonary characteristics of the athletes.

To help enhance BH times trained artistic swimmers have developed lung adaptations such as a greater vital capacity, total lung capacity, inspiratory capacity, forced expiratory volume (FEV), and forced expiratory volume in one second (FEV_1) when compared to controls who were matched for seated height [10, 12]. These adaptations have been thought to allow artistic swimmers to increase their BH time at a lower HR by providing a larger reservoir for pulmonary gas exchange [12, 32]. It has been speculated that these respiratory adaptations have led AS athletes to be more efficient at aerobic energy production during BH [30].

There is some speculation that artistic swimmers have a blunted respiratory chemosensitivity and hypoxic ventilatory response (HVR) [12, 15, 33]. Respiratory chemosensitivity is defined as the ability of the brain to detect changes in CO_2 and alter physiological systems to regulate its levels within tightly controlled parameters [20, 34]. The HVR is the rise in VE associated with decreased O_2 availability such as acute altitude exposure [35–37], where the respiratory drive is no longer primarily stimulated by hypercapnia (i.e., increase in CO_2), but hypoxia (i.e., reduction in O_2) [37, 38].

The relationship between the blunted chemosensitivity, HVR, repeated apneic exposure, and FI might allow artistic swimmers to withstand larger decreases in end-tidal oxygen partial pressure ($PETO_2$) without altering levels of consciousness (LOC) [10, 33, 39]. Previous authors [12, 21, 22] have theorized that individuals with a lower ventilatory drive are able to withstand a higher partial pressure of arterial carbon dioxide ($PaCO_2$) before the urge to breathe overwhelms the will to hold one's breath and may self-select to sports where this is a benefit, such as AS [22]. Interestingly, in the study conducted by Alentejano et al. [10], they noted the longest BH did not occur on the first trial and hypothesized that anxiety may decrease with subsequent BH trials [40]. These respiratory adaptations to repeated apnea can allow athletes competing in AS to hold their breath longer and at a lower HR despite experiencing greater reductions in SaO_2 and similar changes in alveolar gases as controls [10]. The respiratory adaptations in AS athletes when compared to controls has been documented; however, the relationship between cardio-respiratory parameters such as forced vital capacity (FVC), FEV_1, and performance level in AS together with interventions that could improve these parameters have not been well investigated.

3.4 Circulatory Responses

It has been proposed that splenic contractions may prolong subsequent apneic periods by increasing dissolved gas storage through the release of hematocrit (Hct) after the first BH [41] and prolong future BH times [42, 43]. Hct is the volume of red blood cells (RBC) to the total blood volume of an individual. In mammals, the spleen can serve as a reservoir for RBC, which can be introduced into the circulatory system during exercise and diving [44–46]. The increase in circulating RBC increase the total Hct, which may improve the oxygen-carrying capacity of a given volume of blood and prolong BH times in humans [41].

3.5 Metabolic Responses to Artistic Swimming and Competition

Research has demonstrated that artistic swimmers are exposed to considerable metabolic demand because of the combination of BH and vigorous exercise [9]. Results from Rodríguez-Zamora et al. [13] indicated moderate to high La_{peak} in junior and senior age categories, ranging from ∼ 5 to 13 mmol·L^{-1}, with an overall average of 7.3 mmol·L^{-1} as the mean across all routines. This possibly indicates a considerable anaerobic contribution to the sport. Unfortunately, La_{peak} values from competition are limited with reports on lactate responses during training being more extensive [17, 21, 23, 31, 47]. During training, La values have been documented for individual elements [16, 18, 31, 48], whole routines [17, 18, 47], and other swim tests such as 400-m freestyle [17, 21]. However, extrapolating the La values for individual elements to whole routines is difficult due to most studies not defining what elements were used in each routine. Additionally, the La values for individual elements were obtained under previous technical regulations, and these elements may not be used as frequently since the September 2017 revision [3]. Interestingly, Jamnik et al. [48] reported a La_{mean} of 12.7 ± 1.3 mmol·L^{-1} in five elite artistic swimmers during competition, surprisingly higher than the 7.0 ± 1.3 $mmol \cdot L^{-1}$ when performing the same routine during practice. This finding might indicate that high level AS performers can better tolerate increases in metabolic acidosis or represent a greater glycolytic demand with the reasoning largely unknown. This discrepancy between La_{mean} during practice and competition may be in part due to a period of greater anticipatory pre-activation during competition when compared to practicing the same routines. This has also been theorized by Rodríguez-Zamora et al. [13] to describe the physiological reasoning behind a brief period of tachycardia prior to starting a routine during competition. Additionally, this anticipatory pre-activation may be used to maximize aerobic and anaerobic metabolic stores. This would be achieved through increased pre-competition HR and potentially through increased V_E, since apneic diving capacity is determined by asphyxiation tolerance, which is dependant on how rapidly these stores are exhausted during the routine [14, 50]. The available literature has estimated the anaerobic contributions to AS through excess post-exercise oxygen consumption (EPOC) during the first 3 min of recovery, as well as La measurements [21]. Bante et al. [21] speculated the EPOC was used for phosphocreatine resysnthesis, since bursts of anaerobic power are more common during an AS routine rather than a single effort [6]. However, the prolonged and repeated apneic exposures in AS may increase the anaerobic contributions more than other aquatic sports [13, 14]. Though quantifying the anaerobic contributions to an AS routine is difficult, the anaerobic contributions are estimated to be less than that of a 400-m freestyle swim [21], but less than a 200 m freestyle swim

[51–53]. Based upon this information, and the work put forth by Rodríguez and Mader [54], one could estimate 40% of the energy demands of an AS routine may be produced anaerobically. However, no literature has quantified the anaerobic contributions of an AS routine which means sport scientists can only speculate on or estimate these anaerobic contributions based on freestyle swimming.

Homma [16] reported that the time spent UW in international competitions was highest in solo (62.2%), followed by duets (56.1%), and then teams (51.2%). It has therefore been speculated that the greater the reduction in peripheral O_2 delivery, due to the longer or more frequent BH times, the higher the La production due to hypoxemia [12, 16]. This is in line with the results from Rodríguez-Zamora et al. [13] who demonstrated that the highest La_{peak} values were obtained in free solo and duet programs. The authors suggest that the La_{peak} values can be analyzed in terms of the specific influence of the BH periods, the activation of the glycolytic metabolism in the exercising muscles, and the specific training adaptations of the athlete [13]. It has been suggested that the peripheral vasoconstriction associated with the diving response during the BH periods would reduce the blood supply to the muscles and lower their O_2 stores. As a result, if the energy turnover in the exercising muscles is sustained or increased, a greater proportion of energy will be derived via glycolytic metabolism and result in greater La production [28, 55, 56].

The higher La_{peak} values obtained in solo and duet competitive routines (~ 3–3.5 min) suggest a more intense activation of anaerobic glycolysis [23]. It has been documented that free programs usually start with an UW sequence, with highly placed contestants incorporating longer BH times into their routines, with some BH times in excess of 45 s [9]. In light of the diver's response and subsequent peripheral vasoconstriction and redistribution, oxygen stores may be reduced at the onset of the routine causing the working muscles to receive less oxygen than required resulting in the muscle-derived energy from glycolytic metabolism [13, 16]. Additionally, authors have suggested that the difficulty and order of the figures could influence the course of activation of glycolysis in the exercising muscles [13, 16]. For instance, the rate of execution of skill elements has a tendency to be higher in the solo (50%) than in duet and team (32%) events [8, 16]. As such, the solo is composed of more figure parts implying a higher physiological stress, potentially demanding a greater reliance on glycolytic metabolism contributing to the higher La during competition [13]. Moreover, pool-based and dryland training to enhance the athlete's lactate handling and profile should be a focus of training with the intention of preventing premature fatigue during competition. However, it is yet to be determined whether minimizing La appearance through potential ergogenic aids (e.g., sodium bicarbonate) is associated with better performance or reduced perceived effort during competition.

3.6 Physiological Characteristics Influencing Performance of Artistic Swimming

Aerobic Capacity

Given the unique constraints on respiratory exchange and metabolic demands in AS, it is important to examine the significance of key physiological and performance in AS athletes. An elevated maximal oxygen uptake (VO_{2max}) has been shown to be an important requirement of a number of other sports [57–60]. The majority of studies conducted in AS athletes have examined VO_{2max} in mixed cohorts and have used a variety of exercise challenge tests to induce a maximal response. Roby et al. [61] found a mean VO_{2max} of 43 $ml \cdot kg^{-1} \cdot min^{-1}$ when measured in tethered swimming which did not differ from a group of untrained individuals. Therefore, these authors concluded that aerobic capacity was not a factor in AS performance. In another study, Poole et al. [62] ascertained a similar mean VO_{2max} of 44 $ml \cdot kg^{-1} \cdot min^{-1}$ during cycling in the Canadian national artistic swimming team. Of interest is the VO_{2max} ascertained correlated with scores during a solo routine ($r = 0.41$, $p = 0.06$) with the authors concluding that aerobic capacity was an important factor in fatigue during AS routine. Yamamura et al. [53] confirmed this finding and found performance scores in a group of well-trained AS correlated with relative VO_{2max} (50.8 ± 2.8 $ml \cdot kg^{-1} \cdot min^{-1}$) when tested in a swimming flume ($r = 0.71$, $p < 0.05$). Other studies have attempted to examine peak VO_2 during free swimming and compared to that obtained during a simulated event. Bante et al. [21] found VO_2 was significantly higher after a 400-m swim versus a simulated AS routine, Chatard et al. [17] found that VO_{2max} measured after a 400-m freestyle swim improved with a 5-week period of AS training and the change in VO_{2max} was positively correlated with performance during a synchronized swimming routine. Finally, Sajber et al. [63] used a variation of the land-based multi-stage shuttle test (MSST) in a 25-m pool and found the total duration of the MSST strongly correlated with AS performance score at a national championship ($r = -0.81$) indicating the longer the swim time, the higher the score. This study also demonstrates that measuring VO_{2max} of AS athletes while swimming might be more appropriate than doing so when running or cycling.

It has also been suggested that AS is a sport that requires both aerobic and anaerobic power [6], largely due to the long apneic periods spent UW while performing strenuous movements [9]. Despite this, there is a scarcity of literature that has examined the anaerobic power or capacity of AS athletes. The lack of literature may be in part due to the absence of a valid sport specific assessment and the difficulty of conducting metabolic measurements in AS, however a 3 minute swim may be a useful tool to examine anaerobic capacity in AS athletes [21]. Anaerobic capacity is typically determined by a maximal exercise test with accompanying oxygen costs measured relative to maximal aerobic capacity, such as the Wingate anaerobic test (WANT) [64–68]. Based on these data presented by Jamnik et al. [49], the anaerobic power produced during the WANT (6.0 ± 0.2 watts/kg) ranked the participants poorly when compared to active young adults, falling between the 10th and 20th percentile for females [69]. In order for this approach to be valid, an in-water test specific to the demands of AS should be conducted, despite the WANT being the gold standard field test for measuring anaerobic power [70]. The lack of significant correlation between anaerobic capacity and performance score may be due to the low specificity of conventional anaerobic tests, like WANT, where the anaerobic tests require a sustained high-intensity effort. Unlike in AS, there are shorter, high-intensity efforts interspersed with lower intensity periods where the athletes have the opportunity to recover [53]. As in other aquatic sports, collecting oxygen cost data is challenging. In AS, anaerobic fitness may prove to be an important measure due to the prolonged and repeated bouts of BH with FI. In summary, the relative importance and aerobic and anaerobic fitness in AS athletes is not clear because of the means of assessment and cohort that has been tested. There is further work required to establish whether aerobic fitness is important in elite AS athletes and how this variable is related to response to simulated routines.

3.7 Innovative Approaches to Improving Performance in Artistic Swimming

The sport of AS requires a significant contribution from both aerobic and anaerobic metabolism with the contribution of each energy system influenced by prolonged periods UW [13, 19]. Combined with the metabolic demands of the sport, athletes are required to learn and deliver highly choreographed and technical movements under extreme physiological stress. Therefore, innovative approaches to training and competition represent key areas for those working in this sport. While the training specifics required in AS competitors are not well understood, a significant total volume of training has been demonstrated in elite AS athletes [71, 72]. Indeed, the training approaches in AS is not well understood with quantification of training load difficult due to the UW nature of training and competition. Therefore, the optimal training approach for general and sport-specific performance improvements in AS has not been defined. In terms of sport specificity, it makes sense that AS should practice and rehearse the technical requirements of the event but also utilize complementary training approaches in order to target the specific demands of the sport. For instance, due to the UW nature AS competitions, practicing prolonged periods UW combined with intense muscle contraction could be utilized in combination with technical elements to improve overall AS performance. Previous studies in swimming has suggested short term periods of swimming with controlled/regulated breathing frequency or full apnea results in an elevated pulmonary function and capacity [73–75], which in turn may improve oxygen demand during periods UW through repeated periods of hypercapnia and the associated increase in pCO_2 and decrease in pH, all of which serve as mechanisms to encourage physiological adaptation [76–78]. In addition, other studies advocate the use of respiratory muscle training to improve pulmonary function and improve swimming performance [79]. BH training could also be used in relatively young new athletes, or athletes whose bradycardic response is not as pronounced. This could increase BH duration by reducing the anxiety associated with prolonged BH times seen during AS routines [10, 40, 41]. Improving maximal BH could allow greater artistic expression when the athlete, coach, and choreographer are designing a routine ahead of the competition. Additionally, BH training could enhance breath control, allowing athletes to perform elements that require lengthy breath holds, such as the heron, with less difficulty [12, 22]. However, it is currently unknown whether this type of training has the potential to improve performance in AS, as the efficacy of respiratory muscle and BH training have not been investigated in AS. When examining the literature of competitive swimming, improvements in physiological characteristics such as VO_{2max}, La clearance, and improvement in energy efficiency while performing the same workload are thought to be important for performance in other aquatic sports, such as AS [23, 80]. Anecdotal reports indicate that elite AS athletes are able to perform pure swimming (front crawl and form strokes) exceptionally well, and performances in swimming are recognized as a key element of AS preparation. Indeed, after a 5-week training intervention, there was a decrease in VO_2 and La during a 400-m freestyle swim [17], which suggests the athletes became more efficient at aerobic energy production and La handling which could indirectly influence the capacity to perform AS events.

Improvement of sculling and the egg beater kick either with specific water training or dryland training may be of benefit to AS athletes from an injury prevention and locomotion perspective. Sculling and the eggbeater kick are two main methods of movement during AS routines. Sculling is a series of repeated arm movements that can be used for stabilization, locomotion, and altering the body's position such as entering or exiting inversion [81, 82]. The eggbeater kick can occupy as much as 40% of an AS routine and is especially useful in a team and combination routine because there are multiple athletes performing different roles [81]. Ultimately, improving localized fatigue resistance in these movements might result in improved overall efficiency and decrease the demand of the event which in turn may lead to better performance.

The metabolic response during AS events indicates a significant acidic environment which could influence performance during AS competitions [13, 49]. Ergogenic aids such as beta-alanine and sodium bicarbonate may improve performance in other anaerobically orientated and non-esthetic sports, such as water polo [83, 84], which could be introduced to AS athletes and coaches to improve the performance during competition [85–88]. However, the effects of these supplements on the physiological responses and performance in AS events have not yet been investigated.

Finally, it is well known that actual altitude training evokes changes in circulatory markers and endurance performance in other sports [89, 90]. Typically, prolonged periods of living and/or training at moderate altitude [live high-train low (LHTL) or live high-train high (LHTH)] evoke increases in red cell mass which has been linked to concurrent increases in aerobic capacity [91, 92]. Interestingly, improvements in hemoglobin mass in water polo players after 13 days of LHTL [93], which may provide a stimulus to increase VO_{2max} in AS athletes, have been positively correlated with performance [62]. Recently, anaerobic/sprint training in simulated hypoxia has been reported as an alternative hypoxia training approach resulting in improved repeated sprint or anaerobic performance in trained athletes [94, 95]. It seems apparent that such adaptations to simulated or actual hypoxia training could be applied to AS either by way of sport-specific training at moderate altitude or generalized anaerobic training in hypoxia. Future studies are required to examine the efficiency of such approaches for AS performance.

3.8 Summary and Conclusion

AS is a physiologically unique and demanding sport that elicits specific training adaptations as a result of chronic exposure to BH and FI. Research is consistent in demonstrating the novel adaptations to AS training (i.e., bradycardic response); however, little is known about the time course in acquiring these adaptations with AS training. Although there is some research regarding the specific elements of AS, there are few data characterizing the physical and physiological correlates to AS performance and the impact of scored performance and the relationship to physiology. Ultimately, elucidating this information will improve the specificity of training prescription to optimize AS specific physiology, while allowing more time spent on choreography and technical skill. Furthermore, innovative strategies to improve performance are suggested, and while needing to be further explored, these include extending BH duration through respiratory training, AS-specific swim training, the use of dietary ergogenics, and intermittent hypoxic training.

3.9 References

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Chapter 4

Characterizing the cardiorespiratory and acid-base responses to cycling and a swim test in trained female artistic swimmers

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In preparation for the submission to the Journal of Sports Science

4.1 Introduction

Artistic swimming (AS) is a unique aquatic sport which is characterized by prolonged and repeated bouts of breath holding while the face is immersed below the surface of the water [2-5]. During AS routines athletes are judged on technical proficiency, body positioning, synchronicity and artistic expression of the routine as a whole [2, 4, 6]. As such, the complex demands of the sport apply unique physiological stress on the athlete's body. These demands are both aerobic and anaerobic in nature [2]. AS routines can occupy up to four minutes, such as the free team and free combination routines [7], which will have the majority of the energy demands met by the aerobic energy system [8]. Therefore, the sport specific assessment of maximal oxygen uptake (VO_{2max}) and related physiological measures is important in artistic swimmers.

AS athletes have been shown to produce average VO_{2max}, values ranging from 43 $ml \cdot kg^{-1} \cdot min^{-1}$ [9] to 52.4 $ml \cdot kg^{-1} \cdot min^{-1}$ [10]. It is thought that a greater VO_{2max} is correlated to overall performance in the sport of AS, as reported by Sajber, Peric [11], Poole, Crepin [12], Yamamura, Zushi [13] and Chatard, Mujika [10]. This correlation between VO_{2max} and performance in AS is thought to be greater in solo swimmers as it is an important factor in fatigue during an AS routine [13, 14].

Despite AS making its Olympic debut in 1984 there is a scarcity of literature available on the physiological characteristics of AS athletes [4]. This leaves a large gap in the literature regarding the physical profiles and physiological responses of AS [4]. Previous research conducted in artistic swimming has utilized time-motion analysis [3], alveolar gases [15-17], heart rate (HR) [5, 15, 18-20], blood lactate (BLa) [21] and oxygen consumption (VO_2) [10, 22, 23] to quantify the external and internal load placed on the athlete; however, these measures seldom appear in the same study, and only provide limited insight of the physiology of AS.

Some authors have utilized a 400m front crawl , 400m swim of an unspecified stroke [10], arm cycle ergometry [16] and treadmill [24] to assess AS athletes. However, all above methods fail to consider the prolonged and repeated bouts of apnea during an AS routine [2]. The swim tests used by Bante, Bogdanis [22] and Chatard, Mujika [10] are likely to utilize discontinuous breathing, however the discontinuous breathing used in a 400m freestyle swim test is unlikely to mimic the long apneic periods observed in AS routines, which may last as long as 40 seconds (s). Interestingly, no available literature utilized a cycle ergometer test to determine VO_{2max} in AS athletes. The cycle ergometer whilst general in nature requires little familiarisation for athletes not accustomed to maximal land based exercise and also places demands on the lower limbs that are similar to the 'egg beater' kick, which can occupy up to 40% of an AS routine [25]. In addition, Jamnik et al. [12] found the relationship between cycling VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) and solo swim performance approached statistical significance ($r=0.41$, $p=0.06$) in 32 elite Canadian artistic swimmers. Therefore, the determination of VO_{2max} in AS athletes is important because it has been correlated to overall performance especially among soloist swimmers [4]; however, this is the only study to assess VO_{2max} in cycling and AS performance.

Like most other aquatic sports, AS is characterized by discontinuous breathing. However, very few aquatic sports sustain prolonged apneic periods, characterized as the time without breathing, which presents as a novelty to the sport of AS. In an AS routine, apneic periods may occupy half of a routine [3], with single bouts of apnea lasting as long as ~40 seconds [26, 27]. The prolonged and repeated apneic periods seen in AS routines are combined with intense, rapid muscle contractions which place additional physiological strain on the AS athletes, all while carbon dioxide (CO_2) accumulates and oxygen (O_2) stores deplete [5, 18, 28, 29]. To the knowledge of the authors there is no in-pool or laboratory test that reflects the cardiovascular and metabolic responses of a solo performance.

Moreover, the purpose of this study is to compare the VO_{2max} and establish the relationship between VO_{2max} obtained on the cycle ergometer and under-water swim test (UWST) in trained female artistic swimmers.

4.2 Methodology

Fifteen (n=15) trained provincial and national level artistic swimmers voluntarily participated in the study after written and informed consent was obtained. All athletes were informed of the experimental protocol, both verbally and in an information document. The study was approved by the Research Ethics Board at the Canadian Sport Institute Ontario (Toronto, Ontario, Canada) and Ontario Tech University (Oshawa, Ontario, Canada).

Experimental overview

The participants completed laboratory and pool-based assessments as part of their routine performance analysis. The laboratory testing included a maximal incremental exercise test to exhaustion to determine VO_{2max}. Within 24 hrs, a pool-based assessment was completed which comprised of an AS specific underwater swimming test (UWST) of

275 meters (m) in length, which is equivalent to the duration of an AS routine. All participants were familiar with the UWST, as they have completed at least one familiarization session prior to participating in this research study.

Cycle Ergometer Testing

A maximal incremental exercise test to exhaustion was performed on a cycle ergometer (Velotron, RaceMate Inc., Seattle, Washington USA). Each participant performed a 5 min warm up at 0.5 watts per kilogram (kg) of total body mass (w/kg). Participants then performed three, 3-minute submaximal stages at 50, 100 and 150 watts (W) followed by an increase of 15W every 30 seconds until volitional fatigue. During the test the resistance was electronically controlled with the athlete asked to maintain a consistent cadence of 70-75 rpm to serve as a termination criterion for VO_{2max}. Expired gases were continuously collected breath by breath by a system of calorimetry calibrated prior to every test (Moxus, Pittsburgh, Pennsylvania, AEI Technologies Inc.). The highest consecutive 15 sec average value for oxygen uptake (VO_2) was considered to be maximal oxygen VO_{2max}, which occurred at the onset of volitional fatigue. Backwards extrapolation of the oxygen recovery curve was not selected for the cycle ergometer test due to challenges in feasibility; Three Moxus metabolic carts were available versus a single CosMed K4b2.

Underwater Swim Test

The UWST was performed in a 25m pool and consisted of 50m, two lengths, of the freestyle stroke followed by 25m of underwater breaststroke. During the UWST participants were instructed to complete the total 275m in as rapidly as possible, without breathing during the 25m lengths of underwater breaststroke. The UWST test-retest reliability over a 6-week period, tested once per week in this athlete population, is r=0.93 based off the Pearson's r correlation coefficient. On average, each length of the UWST would occupy ~24 seconds resulting in ~24 seconds of apneic time per 25m of underwater breast stroke. VO_{2max} after the UWST was determined using backwards extrapolation of the oxygen recovery curve [30].

Blood Analysis

Capillary blood gas (BG) samples were collected from the fingertip following the standardized warm up and immediately after the completion of the VO_{2max} test and UWST. The following BG parameters were assessed for comparison between post-warm up and post-routine: the partial pressure of oxygen (pO_2), partial pressure of carbon dioxide (pCO_2), blood pH, and bicarbonate (HCO_3^-) (ABL80 FLEX CO-OX blood gas analyzer, Radiometer Medical ApS, Denmark). In addition to blood gases, blood lactate (BLa) was measured after the standardized warm up and 3 and 12 minutes after the routine to assess the rate of BLa clearance from the blood stream. BLa values were measured during passive recovery. Athletes were permitted to walk and gather their towel, water bottle and other personal belongings then sat on the pool deck until the 12 minute BLa sample was obtained.

4.3 Statistical Analysis

Descriptive data in this study are presented as mean, standard deviation (±SD) and range. Paired sample t tests were performed to identify any differences in VO_{2max}, and blood gas responses to the VO_{2max} test and UWST. All statistics were performed using

IBM SPSS version 24. Effect sizes (ES) were calculated to supplement important findings as the ratio of the mean difference to the pooled SD of the difference. The magnitude of the ES was classed as trivial (< 0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), and very large (≥ 2.0) based on previous published guidelines (Batterham & Hopkins, 2006). Lastly, intraclass correlation coefficient (ICC) was performed to determine the level of agreement between the VO_{2max} obtained on the cycle ergometer and the UWST.

4.4 Results

Cardiorespiratory and Blood Gas Responses to the Cycle Ergometer Max Test

Mean VO_{2max} achieved on the cycle ergometer was 44.4 ± 6.7 $ml \cdot kg^{-1} \cdot min^{-1}$ (range: 31.7-55.4). There was a significant decrease in blood pH (-2.0% ± 0.5; t=14.18, df= 14, p<0.01, ES: 4.7; Table 1), and a decrease in HCO_3^- by 38.0% ± 6.7 (t=19.36, df=14, p<0.01, ES: 6.0). There was a increase in pO_2 (51.2% ± 30.4)(t=-5.7, df= 14, p<0.01, ES: 2.3) when comparing the pre and post-VO_{2max} BG values.

Cardiorespiratory and Blood Gas Responses to the UWST

The UWST yielded a VO_{2max} value of 45.0 ± 7.9 $ml \cdot kg^{-1} \cdot min^{-1}$ (range: 28.1-60.7 $ml \cdot kg^{-1} \cdot min^{-1}$). Average time to complete the 275 meter UWST was 266.5 ± 19.6 seconds (s). HR_{peak} and HR_{avg} values were 176.6 ± 17.4 bpm and 141.9 ± 16.2 bpm, respectively. Blood lactate response at three minutes after the UWST was 7.5 ± 2.8 mmol/L and at twelve minutes after the UWST was 5.2 ± 1.8 mmol/L. There was a significant decrease in blood pH (-2.0 ± 0.7%; t=9.45, df=12, p<0.01, ES: 3.9; Table 2), and HCO_3^- (38.0 ± 6.7%; t=6.70, df= 12, p<0.01, ES: 2.5).

Relationship Between UWST and Cycle Ergometer

VO_{2max} achieved with the UWST (45.0 ± 7.9 $ml \cdot kg^{-1} \cdot min^{-1}$) and cycle ergometer test (44.4 ± 6.7 $ml \cdot kg^{-1} \cdot min^{-1}$) was not significantly different from each other (t=-0.59, df=13, p=0.56, d=0.21). HR_{peak} was significantly lower during the UWST (162.5 ± 18.4 bpm) (t=7.81, df=12, p<0.00, ES=2.1) when compared to the cycle test (194.6 ± 11.6 bpm). In addition to the bradycardic response playing a role with the lower HR during the UWST, differences in cardiac output are likely different during the two exercise challenge tests. During the UWST there is likely to be a greater a-v_{O2} difference when compared to the cycle ergometer test. The UWST time and peak work capacity (PWC) (Watts) during the cycle ergometer test was not significantly correlated to each other (r=-0.25, p=0.39). There was a slight negative relationship between the VO_{2max} achieved during the UWST and the duration of the UWST (r=-0.39, p=0.17), and the VO_{2max} obtained on the cycle ergometer revealed a significant negative correlation to UWST time (r=-0.58, p=0.03).

BG responses

There was no significant difference in resting BG responses before the cycle ergometer max test and the UWST (pH, p=0.07; pO_2, p=0.24; pCO_2, p=0.3; $HCO3^-$, p=0.4). Meanwhile, after the UWST blood HCO_3^- was significantly higher than after the cycle ergometer max test (p=0.02).

Intraclass Correlation Coefficient

When examining the ICC between the VO_{2max} values obtained on the cycle ergometer and UWST, the ICC approached statistical significance (r=0.66, p=0.06, ES=0.09). It remains unknown if a larger sample size would permit for statistical significance or if the ICC would remain statistically insignificant.

4.5 Discussion

To the knowledge of the authors this is the first study to compare VO_{2max} values obtained during a cycle ergometer test and UWST designed to mimic the duration of a team routine while including periods of apnea with vigorous movements. The UWST began with 50m of freestyle with unregulated breathing followed by 25m of underwater breast stroke, where participants were instructed to avoid breathing. This pattern was repeated for a total of 11 lengths with the participants in this study finishing with the freestyle stroke, with each length lasting ~25s. There are a total of 75m of underwater breast stroke, which corresponds to ~75s of apneic time, or ~28% of the total UWST duration. This ~28% of apneic time is less than that reported by Alentejano, Marshall [3], who reported apneic times of a ~59% during a 3:30 solo routine for a total apneic duration of ~124s. However, the average apneic time reported by Alentejano, Marshall [3] was only 6.8s, compared to the ~25s in this study. Chatard, Mujika [10] utilized the 400m freestyle swim to assess VO_{2max} across a 5-week training programme which yielded greater VO_{2max} values than those in this study, 52.4 $ml \cdot kg^{-1} \cdot min^{-1}$ versus 44.3 $ml \cdot kg^{-1} \cdot min^{-1}$, however did not provide a laboratory based VO_{2max} measure for comparison. A potential reason for the discrepancy of VO_{2max} values could be the duration of the tests, 400m by Chatard et al., [10] and 275m in this study. Additionally, Chatard et al. [10], did not include apneic periods in their 400m swim test, which could also explain the differences in VO_{2max} values obtained in these two studies. Bante, Bogdanis [22], presented a lower VO_{2max} after a 400m front crawl swim test (35.4 ± 2.5

ml/kg/min for AS athletes over 18 years, and 35.6 ± 2.1 $ml \cdot kg^{-1} \cdot min^{-1}$ for AS athletes under 15 years), and lower VO_{2max} (28.6 ± 2.3 $ml \cdot kg^{-1} \cdot min^{-1}$ for AS athletes over 18 years and 32.3 ± 2.2 $ml \cdot kg^{-1} \cdot min^{-1}$ for AS athletes under 15 years) after a simulated solo routine based off the following four elements: Ariana, Eiffel tower, Subalina and Swordfish straight leg. The differences observed between the routine VO_{2max} in this study and Bante, Bogdanis [22] likely stems from the difference in routine requirements. Bante, Bogdanis [22] had participants perform four elements for the routine, whereas the participants in this routine performed a modified team routine. Firstly, the routine duration is likely to be substantially longer in the routine performed in this study than that of Bante, Bogdanis [22]. Secondly, the modified team routine contains more than four individual elements, and included locomotion such as sculling and the eggbeater kick. Lastly, [22] found a significant difference between the VO_{2max} obtained after the simulated routine and the 400m front crawl VO_{2max} test, whereas no significant difference was shown in this study. Lastly, pacing and stroke mechanics may have been a factor in the different VO_{2max} values obtained in all three studies. However, direct comparison of VO_2 data during a routine is limited to backwards extrapolation of the oxygen recovery curve, as the real time collection of expired gases is not possible [22]. No available literature has provided a means of comparison between a laboratory and pool-based measure of VO_2 in AS athletes, thus making comparison between VO_2 values challenging between studies due to variances in test methodology.

When comparing the BG values of this study to other aquatic sports, such as sprint swimming, pre and post-swim blood pH are similar after 8 x 25m all out efforts [31]. Siegler and Gleadall-Siddall [31] reported a pre-swim pH of 7.41 ± 0.01 in 14 university aged participants, which fell to 7.20 ± 0.02. The pH values reported by Siegler and Gleadall-Siddall [31] is similar to that reported in this study both before and after the UWST. When comparing HCO_3^- values between this study and the placebo trials of Siegler and Gleadall-Siddall [31] are not dissimilar. Siegler and Gleadall-Siddall [31] reported pre and post-swim values of 24.9 ± 0.4 mmol/L and 13.8 ± 0.6 mmol/L, respectively. The greater reduction in HCO_3^- observed by Siegler and Gleadall-Siddall [31] may be explained by the highly anaerobic nature of the 8 x 25m sprints when compared to the 275m UWST used in this study.

The significant difference observed in HR_{peak} during the VO_{2max} test and UWST may stem from the bradycardic response [5]. The bradycardic response is thought to be a survival mechanism which reduces cardiac output and elicits peripheral vasoconstriction to preserve oxygen for the tissues which cannot produce energy anaerobically, such as the brain and the heart [32, 33]. The bradycardic response occurs in marine mammals and birds, and the magnitude of the response is made greater by facial immersion, especially in cold water [34].

4.6 Conclusion

The purpose of this study was to compare the cardiorespiratory and acid-base responses between a maximal cycle ergometer test and an under-water swim test (UWST) in trained female artistic swimmers. The VO_{2max} obtained using both modalities did not differ significantly from each other, which indicates similar oxygen cost and effort required for both the VO_{2max} test and UWST. Additionally, BG values were largely indifferent from each other which suggests the changes in acid-base balance are not dissimilar from each other. Future directions for this research would be to include changes in acid-base balance and metabolic responses during a simulated routine to determine if the UWST resembles the metabolic demands of an AS routine.

4.7 References

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Chapter 5

The relationship between physical and physiological characteristics and simulated solo artistic swim performance

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Submitted to the International Journal of Sports Medicine

5.1 Introduction

Artistic swimming (AS), formerly known as synchronized swimming, is a unique aesthetic sport based on both technical merit and artistry [2]. The positioning and movements of athletes in an AS competition are choreographed to music and costume themes to form a full AS routine, which range in the number of athletes (1 to 10: solo, duet, team combo, and highlight routine) [2, 10, 35]. An AS routine is composed of 'elements' which are sport specific body positions and movement patterns, each of which require different physical demands with the combination of movements, along with choreography, influencing the physiological demands of a routine[5, 36]. Additionally, routines may have mandatory elements seen in all technical routines or no mandatory elements in free routines [7]. Despite these differences in routine requirements and number of athletes competing at any one time, all disciplines of AS share a common demand: repeated apneic exposures, which in combination with vigorous movements imposed by the specific elements, represent a considerable respiratory and metabolic challenge for athletes [36]. For example, Homma [27] reported that the time spent underwater (UW) in international competitions was highest in solo (62%), duets (56%), and teams (51%) with UW bouts lasting ~40 seconds (s) in length [3, 10, 26, 27]. Therefore the physiological assessment of artistic swimmers should consider the specific demands including repeated breath hold and vigorous exercise[36].

The significance of maximal oxygen uptake (VO_{2max}) in endurance based sports has been widely reported [37]. However, the importance of VO_{2max} in AS is controversial, with the majority of studies conducted in AS have examined VO_{2max} in mixed cohorts and have used a variety of exercise challenge tests to induce a maximal response [14-18].

Furthermore, sport specific physiological correlates to performance where underwater exposures are combined with exertion are not yet known in the sport of AS. The relationship between VO_2max and AS performance has not been directly determined in high level athletes.

Therefore in light of the scarcity of studies examining the relationship between VO_{2max} and performance in AS[3], the purpose of this investigation was to examine the relationship between cycling VO_{2ma}, and swimming velocity during an underwater swim test (UWST) as well as the performance score of the 'figures session' during a simulated AS solo routine.

5.2 Methodology

Subjects

Twelve (n=12) trained provincial and national level artistic swimmers voluntarily participated in the study after written and informed consent was obtained (Table 1). All athletes were informed of the experimental protocol, both verbally and in an information document. The study was approved by the Research Ethics Board at the Canadian Sport Institute Ontario (Toronto, Ontario, Canada) and Ontario Tech University (Oshawa, Ontario, Canada).

Maximal incremental exercise testing

A maximal incremental exercise test to exhaustion was performed on a cycle ergometer (Velotron, RaceMate Inc., Seattle, Washington USA) to determine VO_{2max}. A cycle ergometer test was chosen as it places demands on the lower limbs which are used in the ‘egg beater’ kick, which can occupy up to 40% of an AS routine (Homma 1997), and Poole et al., (1980) found cycling $VO2_{max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) approached statistical significance to solo performance scores ($r=0.41$, $p=0.06$) in 32 elite Canadian artistic swimmers. Each participant performed a 5 min warm up at 0.5 watts per kilogram (kg) of total body mass (w/kg). Participants then performed three, 3-minute submaximal stages at 50, 100 and 150 watts (W) followed by an increase of 15W every 30 seconds until volitional fatigue. During the test the resistance was electronically controlled and modified by the researcher with the athlete asked to maintain a consistent cadence of 70-75 rpm. Expired gases were continuously collected breath by breath by a system of calorimetry calibrated prior to every test (Moxus, Pittsburgh, Pennsylvania, AEI Technologies Inc.). The highest consecutive 15 sec average value for oxygen uptake (VO_2) was considered to be maximal oxygen VO_{2max}, which occurred at the onset of volitional fatigue.

Underwater swim test (UWST)

The pool-based performance testing was performed on another day with 24 hrs separating the maximal exercise testing. The pool-based testing consisted of AS specific 275m UWST occurring in a 25m pool. Before and after the UWST was performed participants completed a ‘body boost’ and ‘barracuda’ (performed in a randomised order), two core movements required for many AS elements [38]. After a standardized warm-up consisting of 600m (about 10 min) of easy swimming, sculling and elements, participants performed a baseline body boost and barracuda with the aim to achieve the greatest vertical height out of water. A body boost requires participants to immerse themselves below the water level and breach the water head first aiming to lift their torso high out of the water. The barracuda is similar to the body boost; however, participants will breach the water feet first and lift their torso out of the water. Immediately after completing the initial body boost and barracuda, participants performed the UWST, with the goal being to complete the 275m distance in the least amount of time possible. Participants began the UWST from a push off start, then completed 50m of freestyle stroke followed by 25m of underwater breaststroke (BS) where the participants were discouraged from breathing during the 25m. This format of 50m freestyle and 25 underwater BS was completed until 275 m was achieved. The test-retest reliability of the UWST was shown to be r=0.93. Immediately after completing the UWST participants performed a second body boost and barracuda to assess the change in jump height after performing a vigorous test aimed to mimic some demands of an AS routine.

Prior to the warm up the greater trochanter and lateral malleoli of the left leg was marked with easily visible reflective material. In addition, the length between these two anatomical points was measured and used to establish height out of the water in subject video analysis. The boost and barracuda both were recorded using a video camera (DSC-RX10M4, Sony) positioned exactly 5 m from the participant performing the boost and barracuda. The body boost was measured from the greater trochanter to the water level, and barracuda measured from the malleoli of the ankle to the surface of the water. These landmarks were selected because they would be easily visible while performing the body boost and barracuda. The distance between the two anatomical points was determined using sport performance video analysis software (Kinovea, open source project).

A capillary blood sample (3 µL) was obtained three minutes after concluding the UWST on the index finger using a small incision under aseptic conditions. The blood sample was analysed for blood lactate concentration (mM) using a portable analyser (EDGE Lactate Analyser, Transatlantic Science, USA). Heart rate (HR) ($b \cdot min^{-1}$) was measured using a Polar (Equine Heathcheck, Polar Electro, Kempele, Finland) chest strap which was placed against the athlete's chest immediately after completing the UWST.

Simulated 'solo routine' performance

On a separate day, all athletes completed a standardised solo routine with all elements in the solo scored by FINA accredited judges. The group elements were scored by three FINA judges, with the mean values being calculated. The solo elements were scored by five FINA judges, with the average score being calculated. All element scores are based on a 10-point scale, and are displayed as mean ± SD (range). The following elements were scored by three FINA judges and are performed during non-solo routines, such as duets, highlights and combo routines: thrust one, vertical twist spin, cyclone, ballet leg, manta ray, rocket split, Ariana and flying fish.

5.3 Statistical analysis

Descriptive data in this study are presented as mean, standard deviation (±SD) and range. Pearson r correlation coefficients were used to determine the relationship between laboratory testing, the UWST and performance scores during a simulated solo routine. Pearson r correlations were performed at the 95% confidence intervals (CI_{95}) with an α value of 0.05. Paired sample t tests were performed to identify any differences in the body boost and barracuda. All statistics were performed using IBM SPSS version 24.

Effect sizes (ES) were calculated to supplement important findings as the ratio of the mean difference to the pooled SD of the difference. The magnitude of the ES was classed as trivial (< 0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), and very large (≥ 2.0) based on previous published guidelines (Batterham & Hopkins, 2006).

5.4 Results

The VO_{2max} was found to be 48±4 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (range: 41.4-53.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). The average completion time for the UWST was 176.9±16.3s (range: 138-210s) with a HR_{peak} of 169.4±16.5 $b{\cdot}min^{-1}$ (range: 122-187 $b{\cdot}min^{-1}$) and BLa of 6.8±1.9 $mmol{\cdot}L^{-1}$ (range: 4.2-11.7 $mmol{\cdot}L^{-1}$) (Table 2). The body boost before the UWST (BB_{pre}) as significantly higher than the body boost after the UWST (BB_{post}) (t=2.47, df=9, CI_{95}: 0.24-5.40, p=<0.04, Table 2), however B_{pre} and B_{post} did not differ significantly from each other (t=1.00, df=9, CI_{95}: -1.96-5.01, p=0.34, Table 2).

The following elements were scored by three FINA accredited judges on a 10-point scale. Thrust one 7.5±0.4 (range: 6.7-8.1), vertical twist spin 7.4±0.3 (range: 6.7-8.0), cyclone 7.4±0.3 (range: 6.8-7.8), ballet leg 7.3±0.3 (range: 6.6-8.0), manta ray 7.3±0.3 (range: 6.5-7.8), solo section 7.3±0.3 (range: 6.4-7.8), rocket split 7.4±0.3 (range: 6.6-8.0), Ariana 7.3 ± 0.4 (range: 6.7-8.5), flying fish 7.2±0.4 (range: 6.2-7.8), overall execution 7.4±0.4 (range: 6.5-7.9). During the same data collection period the following elements were scored by five FINA accredited judges on a 10-point scale. Thrust one 7.3±0.4 (range: 6.8-7.9), vertical twist spin 7.4±0.4 (range: 6.6-8.2), cyclone 7.3±0.4 (range: 6.8-8.1), manta ray 7.3±0.4 (range: 6.8-8.2) and rocket split 7.4±0.3 (range: 6.8-8.0).

VO_{2max} was positively correlated to the following group elements: thrust one~~,~~ vertical twist spin, cyclone, ballet leg, solo section and rocket. VO_{2max} was also significantly correlated to the overall performance score of the nine group elements and thrust one performed during the solo routine (Figure 1).

There was a decrease in body boost but not barracuda height after the UWST. The UWST time and HR revealed significant negative correlations to overall performance score in the group elements ($r=-0.59$, $ES= 14.74$; $r=-0.69$, $ES=13.85$, respectively, $p<0.05$). The BLa after the UWST (7.2 ± 1.9 $mmol \cdot L^{-1}$) was positively correlated with the ΔBB after the UWST ($r=-0.76$, $p<0.01$, $ES=1.16$).

None of the elements included in this study were significantly correlated to the BLa obtained after the UWST. The BLa obtained three minutes after the simulated competition (8.7 ± 2.1 $mmol \cdot L^{-1}$) revealed significant negative correlations to all solo elements during the simulated competition: thrust one, vertical twist spin, cyclone, manta ray, and rocket (Table 3). The BLa obtained three minutes after the UWST revealed significant negative correlations to all group elements during the simulated competition: thrust one, vertical twist spin, cyclone, ballet leg, manta ray, solo section, rocket, Ariana, flying fish, and overall execution (Figure 2).

5.5 Discussion

This is the first study to examine the relationship between VO_{2max}, an AS specific UWST, and technical scores of individual AS elements in highly trained female artistic swimmers. The results of this study demonstrate 1) a positive correlation between VO_{2max} and overall execution score of the nine group elements performed, 2) a negative correlation between BLa obtained after the UWST and element score during a simulated competition and, 3) a positive correlation between UWST time and seven of the nine group elements and three of five solo elements

To the knowledge of the authors this is the only study that compared VO_{2max} obtained on a cycle ergometer to AS performance. The VO_{2max} presented in this study (48 ± 4 $ml \cdot kg^{-1} \cdot min^{-1}$) is similar to that of Bante et al. [12] [42.8 ± 3.1 $ml \cdot kg^{-1} \cdot min^{-1}$ in senior athletes (age: 22.6 ± 0.2 years) and 37.6 ± 4.1 $mL \cdot kg \cdot min^{-1}$ in junior athletes (age: 13.8 ± 0.9 years)] and Chatard et al.[10] (52.4 ± 4.9 $mL \cdot kg \cdot min^{-1}$ before a 5-week training intervention, 50.1 ± 3.6 $ml \cdot kg^{-1} \cdot min^{-1}$ after a 5-week training intervention). During whole body exercise, such as treadmill running and swimming, a greater amount of skeletal muscle mass is engaged when compared to cycling [39]. The variances in methodology may account for some of the discrepancy between the VO_{2max} obtained in this study and varying levels of aerobic fitness across the three populations. Roby et al.[9] found a mean VO_{2max} of 43 $ml \cdot kg^{-1} \cdot min^{-1}$ when measured in tethered swimming which did not differ to a group of untrained individuals. It was therefore suggested that aerobic capacity was not a factor in AS performance. In contrast, Poole, Crepin, and Sevigny [12] correlated cycling VO_{2max} with scores during a solo routine ($r=0.41$, $p=0.06$) with the authors concluding that aerobic capacity was an important factor during an AS routine. Yamamura et al. [13] confirmed this finding and found performance scores in a group of well trained AS correlated with relative VO_{2max} (50.8±2.8 $ml \cdot kg^{-1} \cdot min^{-1}$) when tested in a swimming flume ($r=0.71$, $p<0.05$). Most recently, Sajber et al.[11] used a variation of the land based multi-stage shuttle test (MSST) in a 25m pool and found the total duration of the MSST strongly correlated with AS performance score at a national championship ($r=-0.81$), indicating the longer the swim time the higher the score. Whilst it is difficult to compare the results of this study to previous work, the results of the present study confirm the importance of VO_{2max} in AS.

Unlike the literature supporting the relationship between VO_{2max} and performance, this is the first study to examine the relationship between BLa and performance in AS. In this study, the BLa response observed after the UWST (7.2 ± 1.9 $mmol·L^{-1}$) and after the simulated solo (8.7 ± 2.1 $mmol·L^{-1}$) are similar to that observed by Rodríguez-Zamora et al. [5] (7.3 ± 2.0 $mmol·L^{-1}$). These findings suggest the anaerobic demands of the UWST performed in this study require similar anaerobic energy contributions to a simulated solo routine. Additionally, the mean BLa values obtained in this study are similar to those observed by Rodríguez-Zamora et al. [5] during technical solo, free solo, technical duet, free duet, technical team and free team routines.

Moreover, in this study there was no significant correlation between UWST time and the performance in the 'figures session'. This may be attributed to the role stroke mechanics play on overall swim speed [40]. In the freestyle stroke any increase in velocity is matched by an increase in body drag by a factor of 1.83 times [40]. Increases in stroke frequency and distance per stroke from an increase in upper body strength, power and endurance may not exceed the increase in body drag [40]. Thus, the role of stroke mechanics may be of greater importance in competitive swimming than overall fitness [41-43]. Similar to the technical aspect of AS, the technical skill of an AS athlete and competitive swimming athlete play a significant role on performance. However, the impact of stroke mechanics and physiology have been quantified in competitive swimming [8, 40]. In AS this relationship is still under investigation [4].

Lastly, there was no relationship between the BB and B and AS performance. These findings are contrary to those found by Peric et al. [11], and may be due to differences in the methodology between this study and that of Peric et al. [11]. It is within the realm of possibility that different anthropometrical landmarks were chosen as points of measure. In this study it was chosen to measure the from the acromion process during the BB, and malleoli of the ankle rather than the toes during the B as variances in hand and foot size would not have to be accounted for thereby increasing the validity of the analysis.

5.6 Conclusion

This study demonstrates that VO_{2max} is cycling and the blood lactate response to exercise are important and linked parameters that influence AS performance. The positive correlation between VO_{2max} and element scores during a simulated solo routine, and the negative correlations between BLa and element scores suggest coaches and sport scientists working with AS may elect to prescribe training to improve VO_{2max} and metabolic efficiency, the rate at which ATP can be synthesized from energy substrates such as carbohydrates. These training methods may include high intensity training with the goals of improving aerobic capacity. However further research is required to examine different dryland training interventions as well as the reliability and validity of testing methods including the UWST used in this study.

5.7 References

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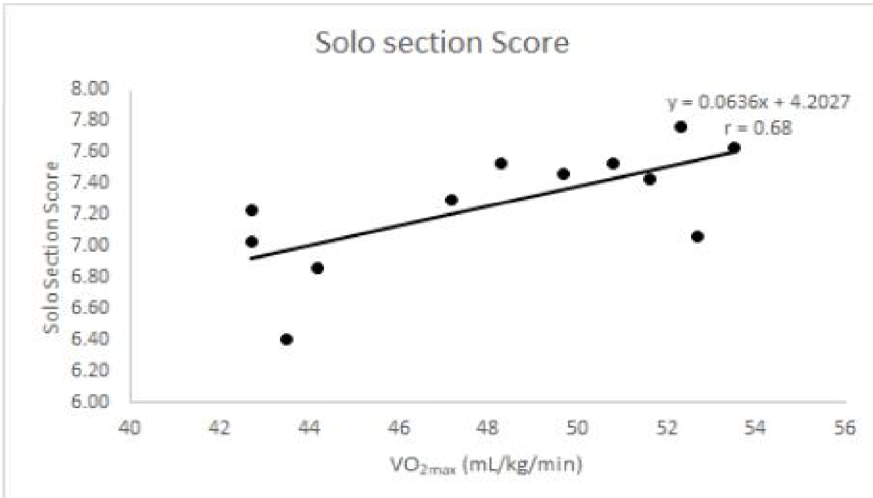
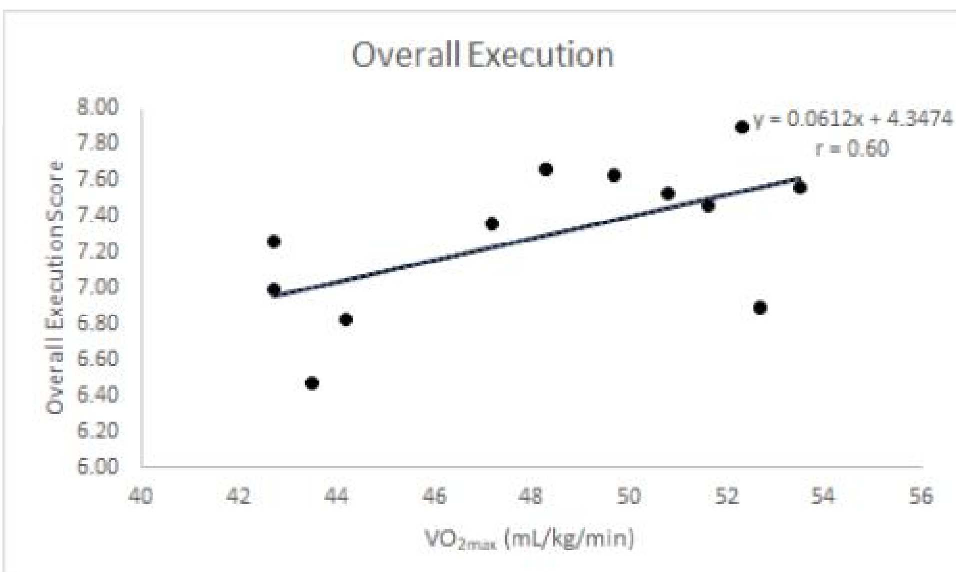
Figures & Tables

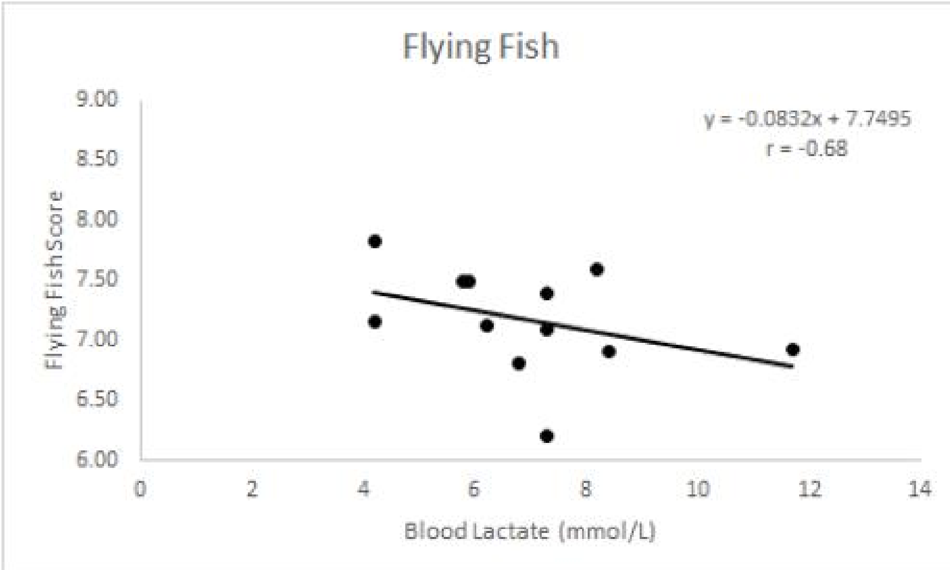
5.8. Figure 1a. Correlation between maximum oxygen uptake (VO_{2max}) and solo section score during a simulated competition. r=0.68, d=13.10, p=0.01.



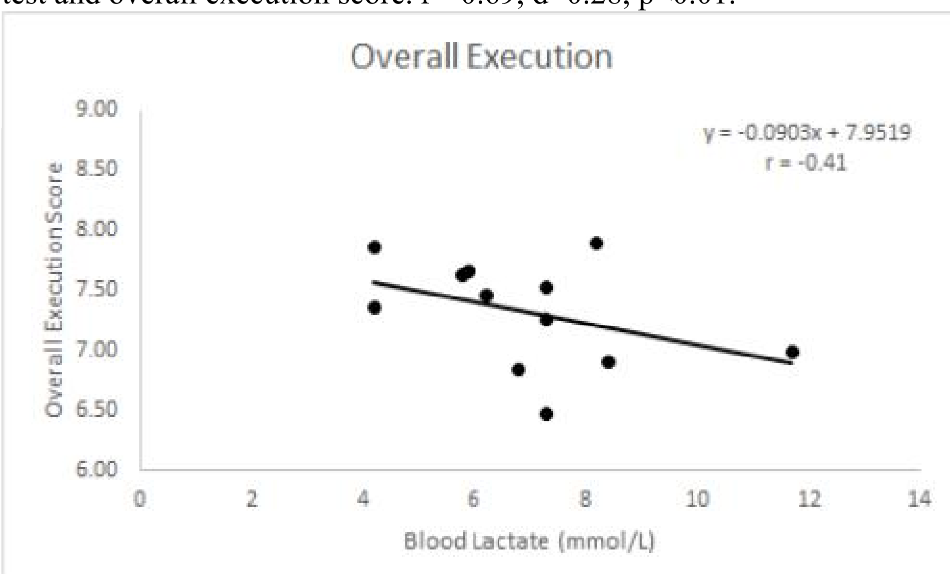
5.9. Figure 1b. Correlation between maximum oxygen uptake (VO_{2max}) and overall execution score during a simulated competition. r=0.60, d=13.10, p=2.02.



5.10 Figure 2a. Correlation between blood lactate obtained after the underwater swim test and flying fish score. r=-0.69, d=0.28, p<0.01.



5.11. Figure 2b. Correlation between blood lactate obtained after the underwater swim test and overall execution score. r=-0.69, d=0.28, p<0.01.



5.12 Table 1. Results of group elements

Thrust one	7.5±0.4 (6.7-8.1)
Vertical twist spin	7.4±0.3 (6.7-8.0)
Cyclone	7.4±0.3 (6.8-7.8)
Ballet leg	7.3±0.3 (6.6-8.0)
Manta ray	7.3±0.3 (6.5-7.8)
Solo section	7.3±0.3 (6.4-7.8)
Rocket split	7.4±0.3 (6.6-8.0)
Ariana	7.3 ± 0.4 (6.7-8.5)
Flying fish	7.2±0.4 (6.2-7.8)
Overall execution	7.4±0.4 (6.5-7.9)

Values are mean ± SD (range).

5.13 Table 2. Results of solo elements

Thrust one	7.3±0.4 (6.8-7.9)
Vertical twist spin	7.4±0.4 (6.6-8.2)
Cyclone	7.3±0.4 (6.8-8.1)
Manta ray	7.3±0.4 (6.8-8.2)
Rocket split	7.4±0.3 (6.8-8.0).

Values are mean ± SD (range).

5.14 Table 3. Group element correlates to blood lactate obtained post simulated competition. The UWST was significantly correlated to the following solo elements: vertical twist spin (r=-0.69, p=0.01), cyclone (r=-0.66, p=0.02), and rocket (r=-0.66, p=0.02).

	Vertical twist spin	Cyclone	Ballet leg	Solo section	Rocket	Ariana	Overall execution
UWST time	r=-0.60 p=0.4	r=-0.59 p=0.4	r=-0.67 p=0.02	r=-0.63 p=0.03	r=-0.73 p<0.01	r-0.66 p=0.02	r=-0.59 p=0.04

UWST: Underwater swim test

5.15 Table 4. Solo element correlates to blood lactate obtained post simulated competition

	Vertical twist spin	Cyclone	Rocket
UWST time	r=-0.69 p=0.01	r=-0.66 p=0.02	r=-0.66 p=0.02

UWST: Underwater swim test

5.16 Table 5. Group element correlates to peak heart rate after the underwater swim test

	Thrust one	Vertical twist spin	Cyclone	Ballet leg	Manta ray
HR_{peak}	r-0.67 p=0.02	r=-0.64, p=0.03	r=-0.69 p=0.01	r=-0.79 p<0.01	r=-0.73 p<0.01
	Solo section	Rocket	Ariana	Flying fish	Overall execution
HR_{Peak}	r=-0.67 p=0.02	r=-0.75 p<0.01	r=-0.93 p<0.01	r=-0.72 p<0.01	r=-0.69 r=0.01

HR_{peak}: Peak heart rate

5.17 Table 6. Solo element correlates to peak heart rate after the underwater swim test

	Thrust one	Vertical twist spin	Cyclone	Manta ray	rocket
HR_{peak}	r=-0.85 p<0.01	r=-0.79 p<0.01	r=-0.85 p<0.01	r=-0.78 p<0.01	r-0.91 p<0.01

HR_{peak}: Peak heart rate

Chapter 6

Thesis Discussion

6.1 Physical and Physical Performance Characteristics of AS Athletes

When comparing female AS athletes to other athletic populations, AS athletes have a tendency to have long, lean limbs, lower body mass and shorter in stature [11, 24, 44]. Although not a criteria that can be ranked by FINA judges, there is thought to be a favouritism for homogeneity amongst AS teammates competing in the same routine, and a desire for long, lean limbs [11]. AS athletes have a bias towards relatively shorter and lighter athletes with Ponciano, Miranda [4] reporting values of 160.1-173.0cm and 44.8-66.5kg, respectively. Despite these physical characteristics playing some role on performance in AS, this thesis will focus on the physiological correlates to performance in AS athletes.

Due to the scarcity of literature available on the sport of AS, especially literature available on the most recent technical regulations, it is difficult to determine all physiological characteristics of AS athletes. To date no author has generated a physiological profile of AS athletes, nor determined which physiological parameters have a bearing on performance. Despite this there is a commonality among the available literature: AS athletes generally have a high VO_{2max}, and it has been correlated to overall performance scores [9, 12, 13].

Perhaps the greatest bearing on performance in AS is the technical abilities of the athletes which compete in the sport. These technical abilities include the execution of the element, synchronization in duet, combination and team routines, artistic impression, the difficulty of the routine, and the overall execution of the elements [6]. These technical abilities must be performed in a variety of body positions and may include breath holding (BH) and facial immersion (FI). In this scenario these technical abilities refer to how well

AS athletes execute elements and move through the pool throughout their routine. Moreover, the difficulty of these elements increases as the athlete performs them during of after bouts of prolonged apnea [3]. While performing these elements, many of which involve strenuous movements, and BH a degree of metabolic acidification may occur due to the restrictive breathing pattern observed in AS and other aquatic sports [2].

6.2 Physiological Demands, Responses and Adaptations of AS athletes

Physiological Demands

Perhaps the most prominent and consistent demand of AS athletes is the ability to perform vigorous movements on and below the surface of the water in a variety of body positions. These movements are often explosive and dynamic, especially during the team and highlight routines which include aerobatic manoeuvres [45, 46]. These explosive movements are primarily driven by anaerobic metabolism, since the demand for energy is immediate and short in nature, however only one study to date has examined maximal anaerobic power using the WANT in AS athletes, and they ranked poorly falling in the 10^{th} and 20^{th} percentiles [47, 48]. Adding to the physiological difficulty of AS routines is the need for choreography to costume themes and music, and coordination of movements with teammates. Lastly, AS athletes must perform all movements with artistry and grace, with up to 40% of a routine score being allocated to artistic impression [7]. This combination of movements (dynamic, vigorous and explosive in nature), breath holding and artistry place highly unique physiological demands on AS athletes and their bodily systems.

Physiological Responses

Based on the demands of AS routines AS athletes have developed some unique physiological responses, such as a degree of metabolic acidification and the bradycardic response. Metabolic acidification occurs as a result of increased ATP hydrolysis to satisfy the energy demands required to complete the movements performed during an AS routine [49, 50]. This increased rate of ATP hydrolysis requires increased shuttling of H^+ through the sodium-potassium ATPase pump to resynthesize ADP to ATP. Under normal resting physiological conditions blood pH is generally between 7.35-7.35 [49, 50], and as shown in chapter four of this thesis blood pH fell to 7.20. This reduction in pH corresponds to an increase in H^+ accumulation in the bloodstream and an increase in the acidity of the blood. The human body has three methods of maintaining pH 1) the bicarbonate buffering system, 2) respiration and 3) ion excretion by the kidneys [49]. The bicarbonate buffering system and respiration are equipped to manage acute changes in blood pH, whereas ion secretion by the kidneys is generally a means of long-term acid-base balance [49]. The bicarbonate buffering system uses bicarbonate (HCO_3^-) to bond to H^+ to form CO_2 and water, which are normally expelled during the exhalation phase of breathing [49]. However, this ability to expel CO_2 is impaired in AS due to the discontinuous breathing found in aquatic sports, combined with the prolonged and repeated bouts of apnea that are unique to AS [45]. This allows CO_2 and H^+ to accumulate in the bloodstream, which subsequently decreases blood pH and increases the degree of blood acidity. These changes in blood pH can impair anaerobic energy production by impairing the efficiency of glycolytic enzymes [49]. This may result in a mismatch between the energy demanded by the AS routine and the body's ability to produce energy.

Further exacerbating the potential mismatch between energy demands and energy produced is the bradycardic response. The bradycardic response is thought to be a protective mechanism, which can prolong BH time [32, 33]. The protective mechanisms of the bradycardic response are reductions in cardiac output and peripheral vasoconstriction [32, 33]. These two mechanisms serve to protect tissues which cannot produce energy anaerobically, such as the brain and the heart, from hypoxia induced damage [51]. The bradycardic response is thought to be a survival adaptation found in marine mammals and birds [34], which prolong BH times especially while the face is immersed in cold water. Due to the reduction in HR seen during the bradycardic response as a means of reduced cardiac output the use of HR is not accurate for gauging the intensity of an AS routine or AS training session [18].

Training Adaptations

Perhaps the most novel adaptation found in AS athletes is the bradycardic response. As previously described, it is thought to be a protective mechanism which can prolong BH times in mammals [32, 33]. It is currently unknown how long it takes for this adaptation to occur, or if training age or chronological age is more important to developing this adaptation.

Additionally, AS athletes have demonstrated a blunted chemosensitivity and hypoxic ventilatory response as a result of the prolonged and repeated apneic exposures consequent to AS routines [52, 53]. Blunted chemosensitivity is advantageous to AS athletes as their carotid bodies are less sensitive to changes in CO_2 and hypoxia becomes the driving force for respiration rather than the accumulation of CO_2 in the bloodstream [53].

6.3 Acute Physiological Responses to a Simulated Artistic Swimming Routine

During a simulated AS routine, the bradycardic response is shown by decreases in HR when the athlete's face drops below the surface of the water [5]. The reduction in HR is a function of the reduction in cardiac output caused by the bradycardic response. As soon as the athlete's face breaches the surface of the water an increase of HR can be observed when HR data is paired with video footage and time synched to determine when the athlete's face was indeed above the surface of the water [5]. Additionally, it remains unknown how rapidly the HR rises and falls in response to FI and the face being above the surface of the water as no study has combined time motion analysis and HR data.

Lastly, changes in acid-base balance can be observed after an AS routine. Significant changes in pH, pO_2, pCO_2 and HCO_3^- were observed in chapter four. The significant reductions in blood pH and HCO_3^- is indicative of H^+ accumulation from the increased rate of ATP hydrolysis and apneic nature of AS. Increases in pO_2 and pCO_2 may indicate a shift in the hemoglobin dissociation curve, which again, indicates a degree of metabolic acidosis among the circulating blood. Perhaps most interestingly, is the large reduction in HCO_3^- available to buffer against further metabolic acidification. The routines analyzed in chapter four were relatively short, all less than three minutes, and it would be interesting to examine how these BG parameters change when the same athlete performs routines of vary lengths and demands, such as a free routine versus a technical routine.

6.4 Future Directions

AS is a poorly researched sport with many avenues of future research available for students and sport scientists. Physiological profiles of AS athletes are yet to be available, only one study has performed a training intervention but did not provide a performance metric to determine if the intervention would be beneficial during competition. There are currently no two studies which utilize the same methodology, which makes comparison challenging as differences in study design must be accounted for. Additionally, no studies have used ergogenic aids, such as sodium bicarbonate, nor has hypoxic training been utilized in this population. Moreover, due to the infancy of research in this fascinating and complex sport, there are many areas for future research.

6.5 Conclusion

In conclusion, this thesis aimed to mitigate the large gaps in the literature by providing a physiological overview of AS, and two novel studies. The research in this thesis helped elucidate the physiological characteristics of trained AS athletes. Additionally, two novel studies were produced which presented the use of the UWST to assess VO_{2max} in AS athletes as the modality of swimming, which may be more appropriate than that of cycling. Lastly, greater detail was added to the physiological responses to a simulated AS routine by investigating blood gas responses.

6.6 References

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