AQUATIC TREADMILL RUNNING: EXERCISE TESTING, PRESCRIPTION, AND THE PHYSIOLOGICAL RESPONSE

by

NICHOLAS HELD

B.Sc. (Honours), The University of Ottawa, 2010
M.HK., The University of Ottawa, 2012

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the dissertation entitled:

Aquatic Treadmill Running: Exercise Testing, Prescription, and the Physiological Response

submitted by Nicholas Held in partial fulfillment of the requirements for
the degree of Doctor of Philosophy
in Experimental Medicine

Examining Committee:

Darren Warburton, Professor, Kinesiology/Experimental Medicine, UBC
Supervisor

Jack Taunton, Professor Emeritus, Family Practice, UBC
Supervisory Committee Member

Pat Camp, Associate Professor, Physical Therapy, UBC
University Examiner

Alex Scott, Associate Professor, Physical Therapy, UBC
University Examiner

Additional Supervisory Committee Members:

Matthew White, Associate Professor, Biomedical Physiology and Kinesiology, SFU
Supervisory Committee Member

Christopher MacLean, Director, Fortius Lab, Fortius Sport & Health
Supervisory Committee Member
Abstract

**Background:** Water immersion for exercise training, recovery, and rehabilitation has been a popular and effective modality for a variety of disciplines. Recent technological advancements have led to more sports teams, research facilities, and rehabilitation clinics using aquatic treadmills (ATM) as a modern form of aquatic exercise.

**Purpose:** The purpose of this investigation was to; 1) develop graded exercise testing criteria and evidence-based recommendations for ATM testing, 2) examine the cardiovascular response during maximal and submaximal ATM running, including ventilatory thresholds, 3) examine the hemodynamic response during submaximal ATM running, 4) determine the influence of small changes in water temperature on cardiovascular and hemodynamic responses during ATM running, and 5) explore the relationship between anthropometric measures and physiological alterations during ATM running.

**Methods:** Participants completed a series of interventions on a land treadmill (LTM) and a HydroWorx 2000 ATM in a crossover design. Participants completed maximal graded exercise tests with a verification phase on each treadmill to compare maximal and submaximal cardiorespiratory responses, as well as determine ventilatory thresholds (VT1&VT2). Three submaximal running protocols incorporating multiple water temperatures and distances from a resistance jet were completed to determine the influence of these variables on the cardiorespiratory and hemodynamic responses. Lastly, the relationship between anthropometric measures and physiological responses during ATM running was examined.

**Results:** Running between 0.61 metres and 0.76 metres from the resistance jet elicits the greatest cardiovascular response. The maximal and submaximal cardiorespiratory responses are similar
between LTM and ATM with the exception of a lower maximal heart rate during ATM running. The use of a verification phase to confirm the attainment of $\dot{V}O_2$max is appropriate. VT1 and VT2 occur at similar points in each environment. ATM running alters submaximal hemodynamic responses, specifically a lower cardiac output and stroke volume. A change in water temperature of only 4°C can alter the cardiovascular and hemodynamic responses during submaximal running. Anthropometric measures influence the ATM and LTM responses differently.

**Conclusions:** These results provide compelling insight into the use of ATM to aid practitioners globally in achieving their desired results and provide a recommended standard of practice to follow in further research.
Lay Summary

Aquatic therapy pools with underwater treadmills are becoming more popular for rehabilitation and exercise. These specialized pools can be found in universities, professional sports facilities, and private clinics. Exercising in the water includes many benefits, such as lower stress on the joints, less pain or discomfort, and an earlier return to activity after injury. The purpose of this thesis was to understand how the body responds to exercise in the water compared to on land, including new measures that have not been researched previously on underwater treadmills and some innovative approaches to exercise design. This thesis aimed to provide recommendations for future research based on differences in the design and results of previous studies. It is our hope that these recommendations will become common practice with the goal of fully understanding the body’s response to exercise on and underwater treadmill, and ultimately, the best health and recovery for users.
Preface

This thesis was written and developed including the research ideas, approach, and designs, by me, Nicholas James Held. All data collection and its analysis were conducted by me with the assistance of a certified exercise physiologist (CEP) during each performance test at Fortius Sport & Health. All projects were made possible by my supervisor Dr. Darren E.R. Warburton through his trust and support to conduct this project with all its responsibility. Dr. Warburton provided all necessary equipment required with the exception of the ParvoMedic metabolic cart and HyrdroWorx 2000 that was generously provided for use by Fortius Sport and Health. My entire committee of Dr. Jack Taunton, Dr. Christopher MacLean, and Dr. Matthew White all provided outstanding support and guidance throughout each investigation.

Chapter 3 A version of Chapter 3 is currently in review. Nicholas J. Held., Lauren K. Buschmann, Andrew S. Perrotta, Darren.E.R.Warburton. In Review. I was responsible for all major areas of concept formulation, writing the complete manuscript, and conducting the systematic review and meta-analysis. Both Lauren and Andrew acted as second reviewers during the systematic review and meta-analyses process. Dr. Warburton was the senior author on this manuscript and conducted the final review of the article prior to submission.

Chapter 4 A version of Chapter 4 has been published. Nicholas J. Held, Andrew S. Perrotta, Lauren K. Buschmann, Shannon S.D. Bredin, Darren E. R. Warburton. (2019). Health & Fitness Journal of Canada. 12(1): 17-33. I was responsible for all major areas of concept formulation, writing the complete manuscript, conducting the systematic review, and made all necessary edits after the peer review process. Both Andrew and Lauren acted as second reviewers during the systematic review process. Dr. Shannon Bredin provided her expertise and guidance throughout
the systematic review. Dr. Warburton was the senior author on this manuscript and conducted the final review of the article prior to submission.

**Chapter 5** A version of Chapter 5 has been published. Nicholas J. Held, Christopher L. MacLean, Darren ER. Warburton. (2018). Health and Fitness Journal of Canada. 11(4): 66-79. I was responsible for all major areas of concept formulation, for writing the complete manuscript, conducting the review of previous literature, and made all necessary edits after the peer review process. Dr. MacLean acted as a reviewer and provided biomechanical expertise in the development of the manuscript. Dr. Warburton was the senior author on this manuscript and conducted the final review of the article prior to submission.

**Chapters 6-10** Research examining the cardiorespiratory, thermoregulatory, and hemodynamic alterations during aquatic treadmill running and land treadmill running was conducted at Fortius Sport & Health located at 3713 Kensington Avenue, Burnaby, BC. This original research project was conducted during June and July 2017, with pilot testing from November 2016.

- The University of British Columbia’s Clinical Research Ethics Board (CREB) provided approval for the research project titled “Cardiovascular Reponses to Maximal Running on an Underwater Treadmill versus a Land-Based Treadmill in Elite Field Hockey Athletes”. The CREB identification number for this investigation is H15-01849.

- Each maximal graded exercise test and submaximal exercise trial involving gas analysis and impedance cardiography was conducted by me with the assistance of certified exercise physiologists (CEP) from Fortius Sport & Health.
• I was responsible for developing the research ideas and methodological approaches, as well as completing the data collection and statistical analysis. All statistical analyses and their modeling were processed using SPSS version 25.

• Fortius Sport & Health provided a ParvoMedics Metabolic cart for direct gas analysis during all aquatic treadmill and land treadmill trials.

• Fortius Sport & Health provided a HydroWorx 2000 aquatic treadmill to conduct all aquatic treadmill trials.

• Dr. Darren E.R. Warburton provided the Physioflow Enduro for impedance cardiography assessment of hemodynamic measures throughout all studies.

• Dr. Darren E.R Warburton provided the ingestible core temperature pills to analyze the pre- and post- core temperature changes following all land treadmill and aquatic treadmill trials.
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<tr>
<td>A-V̇O\textsubscript{2}\textsubscript{diff}</td>
<td>Arteriovenous Oxygen Difference (mL·100mL)</td>
</tr>
<tr>
<td>AD/M</td>
<td>Surface to Mass Ratio (cm\textsuperscript{2}·kg\textsuperscript{-1})</td>
</tr>
<tr>
<td>ATM</td>
<td>Aquatic Treadmill</td>
</tr>
<tr>
<td>BC</td>
<td>British Columbia</td>
</tr>
<tr>
<td>BD</td>
<td>Body Density</td>
</tr>
<tr>
<td>BF</td>
<td>Body Fat (%)</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>Cool</td>
<td>Cooler than thermoneutral water temperature (30°C)</td>
</tr>
<tr>
<td>DFJ</td>
<td>Distance from the jet experiment</td>
</tr>
<tr>
<td>EF</td>
<td>Ejection Fraction (%)</td>
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<tr>
<td>GXT</td>
<td>Graded Exercise Test</td>
</tr>
<tr>
<td>HR</td>
<td>Heart Rate</td>
</tr>
<tr>
<td>HR\textsubscript{max}</td>
<td>Maximum Heart Rate (beats·mins\textsuperscript{-1})</td>
</tr>
<tr>
<td>LTM</td>
<td>Land Treadmill</td>
</tr>
<tr>
<td>LVED</td>
<td>Left Ventricle End-Diastolic Volume (mL)</td>
</tr>
<tr>
<td>LVES</td>
<td>Left Ventricle End-Systolic Volume (mL)</td>
</tr>
<tr>
<td>Q</td>
<td>Cardiac Output (L·mins\textsuperscript{-1})</td>
</tr>
<tr>
<td>RER</td>
<td>Respiratory Exchange Ratio (VCO\textsubscript{2}/V̇O\textsubscript{2})</td>
</tr>
<tr>
<td>RR</td>
<td>Respiratory Rate (Breaths·mins\textsuperscript{-1})</td>
</tr>
<tr>
<td>SA</td>
<td>Surface Area (sqm)</td>
</tr>
<tr>
<td>SV</td>
<td>Stroke Volume (mL·beat\textsuperscript{-1})</td>
</tr>
<tr>
<td>Tc</td>
<td>Core Temperature (°C)</td>
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TV – Tidal Volume (mL)
$V_E$ – Ventilation (L·min$^{-1}$)
$VCO_2$ – Volume of Carbon Dioxide (L·min$^{-1}$)
$VO_2$ – Oxygen Consumption (L·min$^{-1}$)
$VO_{2\text{max}}$ – Maximal Oxygen Consumption (L·min$^{-1}$)
VT1 – Ventilatory Threshold One
VT2 – Ventilatory Threshold Two
Warm – Warmer than thermoneutral water temperature (34°C)
Glossary

Aquatic Treadmill  A pool containing an adjustable treadmill that includes resistance jets to increase the flow of water directed at participants.

Arteriovenous Oxygen Difference  The difference in the oxygen content of the blood between the arterial blood and the venous blood. It is an indication of how much oxygen is removed from the blood in capillaries as the blood circulates in the body.

Cardiac Output  The amount of blood, in litres, pumped per minute by the heart.

Contrast Water Immersion  A form of treatment where a limb or the entire body is immersed in warm water followed by the immediate immersion of the limb or body in cold water.

Deep Water Running  A form of exercise in water where individuals run in place or across a pool with the use of a flotation device without touching the floor of the pool.

Graded Exercise Test  The assessment of cardiorespiratory functional capacity for health and fitness reasons, or for clinical and diagnostic purposes. Such tests, primarily conducted on a motorized treadmill or stationary cycle ergometer, involve exercising at several workloads or exercise intensities/difficulties, during which cardiovascular and respiratory measurements are recorded.

Maximum Heart Rate  The highest heart rate achieved during maximal exercise testing.

Maximum Oxygen Consumption  $\dot{V}O_{2\text{max}}$ is the maximum rate of oxygen that can be consumed, transported throughout the cardiovascular system, and utilized at the substrate level during a maximal graded exercise test.

Passive Water Immersion  An individual that is immersed in the water at rest, without exercise.

Shallow Water Running  A form of exercise in water where individuals run while making ground contact in shallow water.

Stroke Volume  The amount of blood, in millilitres, pumped per heartbeat.
| **Ventilatory Threshold One** | Refers to the point during exercise at which ventilation starts to increase at a faster rate than $\dot{V}O_2$. This nonlinear increase in ventilation is thought to be the result of an imbalance in pyruvate production and its oxidation resulting in the increase in buffering of lactic acid build-up. |
| **Ventilatory Threshold Two** | Refers to the point during exercise at which ventilation starts to increase at a faster rate than $\dot{V}O_2$. This nonlinear increase in ventilation is thought to be the result of an increase in buffering of lactic acid build-up due to an increase in anaerobic glycolysis. |
| **Water Immersed Cycling** | A form of cycling in which a stationary bike is immersed in the water. Water depth is usually to the xiphoid process or clavicle. |
| **Water Calisthenics** | Exercises in water, such as jumping jacks, to develop strength and flexibility that are done without special equipment. |
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There are many people I would like to take the time to acknowledge for their support throughout this entire process. First, I would like to thank my academic supervisor Dr. Darren E.R. Warburton for his support throughout planning, implementing, and concluding this dissertation. Darren allowed me to personally and scientifically learn and evolve through fostering autonomy and perseverance.

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Although I was not fortunate enough to meet him, I would like to provide a special thank you to the late Dr. Dennis Dolny. Dr. Dolny is a pioneer in this field and has been the lead on numerous projects that helped shape my research. Without his dedication to understanding the effectiveness of aquatic treadmill exercise, this project may not have existed.
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Dedication

To my daughter Eleanor Jacqueline Held and son Noah Matthew Held. I hope that this inspires you both to accomplish the goals you set for yourself and encourages you to remain ambitious, persistent, and curious. At very least, I hope it provides a great colouring book for you.
Chapter 1: Introduction

1.1 Executive Summary

The use of water immersion in treating injuries, chronic pain, various musculoskeletal diseases, and sport and exercise training is well established. The literature includes both active and passive water immersion. Passive immersion often consists of cold water immersion, warm/hot water immersion, thermoneutral water immersion, and contrast water immersion (alternating cold and hot water immersion). Active aquatic exercise is often used while recovering from injury or as a means of cross training (Reilly, Dowzer & Cable, 2003). A few common forms of aquatic exercise include deep water running, shallow water running, water immersed cycling, and water calisthenics. Due to technological advancements, the use of aquatic treadmills (ATM) is a more recent form of aquatic exercise (Figure 1.1). However, ATM use in injury management and more specifically in training is less understood compared to other forms of aquatic exercise. Nonetheless, ATMs are becoming increasingly accessible with more pools throughout North America in professional sports facilities, universities, military facilities, senior living facilities, and healthcare facilities.

ATMs are frequently utilized in rehabilitation, conditioning, and recovery protocols as they can place great demand on the cardiovascular system and muscles while reducing the load on joints (Moening, Scheidt, Shepardson, & Davies, 1993). It has often been reported that hydrostatic pressure on the body during water immersion promotes an immediate increase in intrathoracic blood volume and a concomitant increase in venous return (Gabrielsen, Johansen, & Norsk, 1993; Risch, Koubenec, Beckmann, Lange, & Gauer, 1978; Khosla & DuBois, 1979), a response that leads to enlarged cardiac preload and stroke volume (Christie et al., 1990; Norsk, Bonde-Petersen, & Christensen, 1990). In addition, hydrostatic pressure has also been found to
influence lung mechanics (Moon, Cherry, Stolp, & Camporesi, 2009). These shifts in fluid may alter the cardiovascular response in underwater exercise compared exercise on land depending on the exercise mode and intensity.

Although research into deep water running, shallow water running, immersed cycling, and passive water immersion provides insight into the cardiorespiratory responses during ATM running, the responses may differ between modes. During deep water running and often during passive water immersion and water immersed cycling, individuals are immersed to the level of the neck/clavicle, whereas in ATM running studies the water is often set at chest level, specifically at the xiphoid process. Considering less body surface area is immersed during ATM running studies compared to other forms of aquatic exercise, the cardiorespiratory and thermoregulatory response may vary. Previous findings have suggested that deep water running is different from land running in terms of lower-extremity muscle recruitment and kinematics (Moening et al., 1993). Considering the different movement patterns and active muscles, metabolic requirements may be different between deep water running, shallow water running, ATM running, and land treadmill (LTM) running.

Shallow water running is more similar to land running than deep water running (Reilly et al., 2003; Frangolias, & Rhodes, 1996), however the increased frontal plane resistance of the water produces a different strategy of locomotion compared to land running (Moening et al., 1993; Kato, Onishi, & Kitagawa, 2001). ATM running eliminates whole body forward locomotion through the water due to the moving treadmill belt, which reduces the frontal resistance experienced during shallow water running. This may allow for a more natural gait and muscle recruitment pattern (Silvers, Rutledge, & Dolny, 2007).
Metabolic demand can be manipulated during ATM running by adjusting the depth of water immersion, the belt speed, the water temperature, and by further increasing the water resistance with pump driven water jets. In the current literature, there are discrepancies in the cardiorespiratory responses during ATM running compared to LTM running due to varying protocols, water immersion levels, running positions, and water temperatures utilized in various studies. Therefore, the aims of the dissertation were to, 1) better understand the varying responses to different protocols in order to standardize the procedures in future investigations, including running position, water temperature, and verifying \( V\dot{O}_2 \)max attainment during graded exercise tests, 2) compare the cardiorespiratory alterations during maximal and submaximal ATM running compared to LTM running, including hemodynamic alterations, core temperature changes, alterations to various water temperatures, and the occurrence of the first and second ventilatory thresholds, and 3) to examine any influence that anthropometric measures may have on the cardiovascular response to ATM running.

Throughout this dissertation a few common mechanical characteristics of water will be referred to. These characteristics include buoyancy, hydrostatic pressure, and viscosity or drag resistance. Buoyancy is the upwards lift of the water which decreases the loading on the joints of the body. By definition, when a body is partially or totally immersed in a fluid, it is buoyed up by a force equal to the weight of the fluid that is displaced by the body (Torres-Ronda & i del Alcazar, 2014). Hydrostatic pressure is the pressure exerted by the water on the body during immersion. Hydrostatic pressure increases with water depth. The pressure is directly proportional to the density of the fluid, gravity, and the depth to which the body is immersed (Wilcock, Cronin & Hing., 2006). Lastly, viscosity is the magnitude of the internal friction associated with a given fluid, which is its resistance to flow (Torres-Ronda & i del Alcazar, 2014). In other
words, the viscosity or drag resistance of the water creates an opposing resistance as a body moves through water that is influenced by its velocity and surface area. This drag resistance continuously increases as velocity of movement increases.

Figure 1.1 The aquatic treadmill and metabolic cart at Fortius Sport and Health

1.1.1 Understanding the Responses to Variations in Protocols in order to Standardize the Criteria Used for Further Investigations, including Running Position, Water Temperature, and Verifying VO2max Attainment during ATM Graded Exercise Testing

Current literature investigating the cardiovascular alterations during ATM and LTM running includes a variety of different protocols that could influence the cardiovascular response.
These differences may be due to the inconsistencies in protocol design instead of the differing environments. Only a few studies report the running position of participants from the resistance jets. Of the studies reporting the distance from the resistance jet (Silvers, Rutledge & Dolny, 2007; Silvers & Dolny, 2008; Rutledge, Silvers, Browder & Dolny, 2007), it is common to have participants run one meter from the resistance jet, however a physiological rationale for this running position is not provided. It is possible that changes in running position could influence the cardiovascular response during submaximal and maximal ATM running. In addition, during ATM graded exercise testing, the distance from the resistance jet may further influence test duration, and/or stage progression, consequently influencing the overall results. Therefore, an intervention to determine the cardiovascular response to running at various distances from the resistance jet will help determine the running position that elicits the greatest metabolic response, as well as identify other positions that cause a significant reduction in metabolic demand. During a graded exercise test, any running position that produces a significantly lower metabolic response from the selected running position can be used as a termination criteria for the test, similar to a decrease in revolutions per minute during cycle testing (Poole, Wilkerson, & Jones, 2008; Day, Rossiter, Coats, Skasick, & Whipp, 2003).

During exercise testing it is important to verify that participants have provided a maximal effort when comparing different test modes, and whether the decision to stop the test was due to central fatigue mechanisms, peripheral fatigue, or something else. A potential problem arises when attempting to determine which participants terminated the test prematurely and possibly have not achieved a true \( \dot{V}O_2 \text{max} \). The primary criteria for achievement of \( \dot{V}O_2 \text{max} \) is the “\( \dot{V}O_2 \) plateau” as proposed by Taylor et al. (1955). Traditional secondary criteria include the attainment of arbitrary thresholds for maximal values of the respiratory exchange ratio and heart
rate during the graded exercise test, as well as post-test blood lactate concentration (Midgley et al., 2007b). It has been reported that these secondary criteria can be satisfied at a $\dot{V}O_2$ that is much lower than the participant’s eventual $VO_2\text{max}$ attained during the test, even as low as 73% $VO_2\text{max}$ (Poole et al., 2008). It has been suggested that the secondary criteria to verify $VO_2\text{max}$ attainment are invalid because they do not discern which participants achieve a plateau in $V_O_2$ at $VO_2\text{max}$ (Astorino, 2009). These secondary criteria become even more limited when considering their application to ATM graded exercise testing because maximal heart rate has repeatedly been found to be lower during water immersion exercise compared to land exercise. Further, respiratory exchange ratio at maximal exercise has been at times shown to be lower during ATM running (Greene et al., 2011). More recently verification stages have become increasingly popular to verify that a true $VO_2\text{max}$ has been achieved. However, a verification phase has never been completed during ATM running. Therefore, research including a verification phase during ATM graded exercise testing that assesses its effectiveness in confirming the attainment of $VO_2\text{max}$ is required.

Lastly, previous investigations have implemented a large variety of water temperatures (20.6°C – 35.6°C) during ATM research. For only a 6°C increase in water temperature (30.5°C versus 36.1°C), Gleim and Nicholas (1989) reported that heart rate increased at a fixed submaximal $\dot{V}O_2$. Further, for only an 8°C decrease in water temperature (25°C versus 33°C), $\dot{V}O_2$ has been reported to be 9% greater in 25°C water during water immersed cycling. Shimizu, Kosaka and Fujishima (1998) found statistically significant changes in heart rate when comparing 60 minutes of ATM walking at 25°C, 30°C, and 35°C while immersed to the middle of the chest. Based on previous findings, it is evident that water temperature can drastically
influence the cardiovascular response during ATM running and should be carefully considered when comparing responses to LTM exercise. Therefore, research into the influence of small changes in water temperature, which may be similar to daily fluctuations in an applied setting, on the cardiovascular response to ATM running in required.

In summary, developing ATM exercise criteria to standardize the running position, water temperature, and either altering the use of secondary criteria or implementing a verification phase would increase confidence that any alterations observed between the ATM and LTM cardiovascular response may be related to the exercise environment as opposed to variations in protocol design.

1.1.2 Examining the Cardiovascular Alterations during Maximal and Submaximal ATM Running Compared to LTM Running, including Hemodynamic Responses, Core Temperature Changes, Adaptations to Small Changes in Water Temperature, and the Occurrence of Ventilatory Thresholds

It is important to understand the cardiovascular response to ATM running to aid in exercise prescription, monitoring, and overall health of users. The hydrostatic pressure that is exerted on the body during upright water immersion stimulates an increase in central blood volume and concurrent alterations in cardiovascular function during exercise in water (Christie et al., 1990). When comparing aquatic and land exercise, conflicting results have been found for \( \dot{VO}_2 \) response. Studies that have used the same mode of exercise in and out of the water, such as cycling or ATM running, have shown similar values of \( \dot{VO}_{2\text{max}} \) between water and land (Christie et al., 1990; Connelly et al., 1990; Dressendorfer, Morlock, Baker & Hong, 1976; Sheldahl et al., 1987; Greene et al., 2011; Silvers et al., 2007; Schaal et al., 2012; Watson et al., 2012). Most
other studies that have shown lower cardiorespiratory responses in an aquatic environment have compared deep water running and LTM running (Butts, Tucker & Greening, 1991; Butts, Tucker & Smith, 1991; Frangolias & Rhodes, 1995; Mercer and Jensen, 1998; Svedenhag & Seger, 1992; Town & Bradley, 1991), or water aerobics exercise compared to LTM running (Alberton et al., 2013; Alberton et al., 2014). Differences in deep water running and LTM $\dot{V}O_{2\text{max}}$ could be related to differences in running style, gravitational effects, and hydrostatic responses (Frangolias & Rhodes, 1995). The similarities in $\dot{V}O_{2\text{max}}$ between the environments increase with the similarities in the exercise technique. It has been suggested that the movement pattern is primarily responsible for the lower $\dot{V}O_{2\text{max}}$ in the aquatic environment compared to the land environment (Alberton et al., 2014). ATM running allows for a more natural gait and muscle recruitment pattern compared to other forms of aquatic running that increases the specificity of muscles used between ATM and LTM running (Silvers, Rutledge, & Dolny, 2007; Kato, Onishi & Kitagawa, 2001). This provides a rationale for why $\dot{V}O_{2\text{max}}$ during ATM and LTM running may be similar while other forms of water exercise result in lower cardiorespiratory responses in the water (Silvers, Rutledge & Dolny, 2007; Schaal, Collins & Ashley, 2012; Greene, Greene, Carbuhn, Green & Crouse, 2011; Watson et al., 2012).

Discrepancies also exist in the literature for maximal heart rate during ATM and LTM running. Schaal et al. (2012) and Greene et al. (2011) reported lower maximal heart rates during ATM running, whereas Silvers et al. (2007) and Watson et al. (2012) reported no differences in maximal heart rate between ATM and LTM running. During submaximal running on an ATM it has been reported that heart rate is reduced compared to land when lower or no jet resistances are used (Rutledge et al., 2007; Porter et al., 2014; Greene et al., 2011), however heart rate is increased compared to LTM running using higher jet velocities (Porter et al., 2014; Watson et
al., 2012; Greene et al., 2011). It is possible that the use of water resistance jets in ATM running influences the maximal heart rate response making comparisons to other forms of aquatic exercise that do not include resistance jets, as well as between ATM designs, limited.

Respiratory exchange ratio has been shown to be similar (Silvers et al., 2007; Schaal et al., 2012) or lower (Greene et al., 2011) during maximal exercise on an ATM compared to a LTM, and either similar (Pohl & McNaughton, 2003; Garner et al., 2014; Schaal et al., 2012), higher (Watson et al., 2012), or lower (Watson et al., 2012) during submaximal ATM running compared to LTM running depending on speed and intensity. During maximal ATM running, ventilation has been reported to be higher (Silvers et al., 2007) or similar to LTM running (Greene et al., 2011). During submaximal ATM running, ventilation has been reported to be similar to LTM running (Rutledge et al., 2007; Brubaker et al., 2011). As with other measures, respiratory rate has been shown to be higher during peak ATM running (Silvers et al., 2007), and either similar (Brubaker et al., 2011), or lower (Rutledge et al., 2007) during submaximal running. Tidal volume has been reported to be similar during maximal ATM running (Silvers et al., 2007) and submaximal running (Rutledge et al., 2007). Depending on speed and intensity, tidal volume has also been reported to be lower during ATM running (Brubaker et al., 2011).

It is evident there have been inconsistencies in results reported in the literature and more research and standardized methods are needed to determine if cardiorespiratory differences are due to physiological response or variations in protocol design. Further, examining the submaximal and the maximal responses during a graded exercise testing in the same study to ensure the same participants are used, the water temperature is the same, the protocol is the same and continuous, and all other variables are as closely matched as possible is warranted and is a strength of our investigation.
To date, research into the hemodynamic responses during ATM and LTM running has not been completed. Previous research into exercise on a water immersed and land cycle ergometer (Sheldahl et al., 1984; Sheldahl et al., 1987; Christie et al., 1990) has reported greater left ventricular end-diastolic diameter during mild and moderate cycling exercise in water compared to land suggesting that cardiac preload remains elevated during exercise in water (Sheldahl et al., 1984). Further, right atrial pressure is increased during exercise in the water supporting enhanced venous return (Christie et al., 1990). Stroke volume appears to be greater during water immersion exercise at all intensities compared to land (Sheldahl et al., 1987; Christie et al., 1990). In addition, cardiac output was found to be significantly elevated during exercise in water at submaximal intensity between 40% and 80% $\dot{V}O_{2\text{max}}$ (Sheldahl et al., 1987; Christie et al., 1990). Left ventricle end-diastolic volume was 22-26% higher during water immersion exercise at 40 and 60% $\dot{V}O_{2\text{max}}$. These measures have been obtained during water immersed cycling and one can only speculate about ATM running at this point because no study has investigated cardiac output, stroke volume, and other hemodynamic measures during ATM running.

It is common during LTM graded exercise testing to incorporate three minute stages in order to obtain $\dot{V}O_{2\text{max}}$ values, as well as determine submaximal aerobic and anaerobic thresholds for exercise prescription. To date, only one previous study has examined lactate threshold points (Garner et al., 2014), however, no research has compared the occurrence of the two ventilatory thresholds (VT1 and VT2) during ATM compared to LTM running. Considering that the hydrostatic pressure of the water causes fluid shifts into the intravascular space, blood lactate measurements may be less accurate during aquatic exercise due to changes in concentration. In contrast, ventilation is not restricted by increased intrathoracic blood volume and hydrostatic
compression of the chest during immersion (Alberton et al., 2014). Taken together, the resistance of the water could induce greater peripheral fatigue which would preclude the attainment of VO\textsubscript{2max} and submaximal thresholds in what is typically a longer test with three minute stages. Examining the possibility of achieving all of these measures from one graded exercise test on an ATM has not been completed and would be extremely beneficial to enhance exercise prescription and adaptation during regular ATM exercise. Due to the impact of water immersion on the cardiovascular and respiratory system, a better understanding of protocol criteria as well as the cardiovascular and respiratory responses during ATM running will aid practitioners in effectively incorporating ATMs into rehabilitation and exercise training programs. Additionally, more specific evidence-based exercise criteria that is designed specifically for ATM research is critical for understanding the health, rehabilitation, and performance adaptations during and following ATM exercise.

1.1.3 Observing the Influence of Anthropometric Measures on the Cardiovascular Response to ATM running

It is common in the ATM literature for anthropometric measures (e.g. height, weight, body mass index) to be collected for the purpose of describing the research participants. However, no investigation has examined the relationship between anthropometric measures and the physiological response. Specifically, these measures may relate to the achievement of VO\textsubscript{2max}, the change in core temperature, and the influence of the resistance jets on the cardiorespiratory response. The relationship between an individual’s body composition and thermal response has often been reported during water immersion and several investigators have demonstrated the insulating effects of body fat during exercise in cold water (Holmer & Bergh,
McArdle et al. (1976) noted that in 25°C water the three leanest participants complained of cold discomfort and were noticeably shivering during submaximal work. However, the participants with the largest percentage of body fat showed no difference in \( \dot{V}O_2 \) in 25°C water compared to 33°C water, and air at 25°C. At maximal exercise, participants did not complain of cold discomfort and the participants with a higher percentage of body fat were sweating at the face in 33°C and 25°C water (McArdle et al., 1976).

In a second cycling investigation, body temperature was measured in individuals of varying body composition at multiple water temperatures and in air at 22°C (Craig & Dvorak, 1969). Body temperature decreased in the leaner individuals in 22°C, 25°C, 30°C, and 32°C water by a greater extent compared to the corpulent individuals. Interestingly, the individuals with the highest average skinfold thickness expressed a strong desire to avoid exercising in 32°C and 34°C water. Although these findings are from limited studies with small sample sizes, it appears that for each individual with a given skinfold thickness a water temperature exists at which heat derived by muscular work is not balanced by the heat losses induced by an elevated convective heat-transfer coefficient (Holmer & Bergh, 1974). This water temperature is influenced by the clothing worn (Keatinge, 1969), flowing water (Nadel et al., 1974), and body movement during exercise (Keatinge, 1969). Therefore, the influence of anthropometrics during ATM running is critical to understand the thermal and metabolic response between investigations and water temperatures.

Specific to ATM running, data on the influence of anthropometrics is scarce. Anthropometric measures are more commonly collected for the purpose of participant
description or adaptation over a training program, and are at times mentioned as a possible rationale for various physiological outcomes, however, it is less common for anthropometrics to be part of the statistical analyses of ATM running. Rutledge et al. (2007) noted that in all of their trials men tended to have a higher $\dot{V}O_2$ (reported in mL kg$^{-1}$ min$^{-1}$) than women which the authors suggested might be attributed to the fact that females in the study had a greater average body-fat percentage compared to men. It was stated that the lower body density would increase the buoyancy of the females and could decrease the metabolic cost (Rutledge et al., 2007). Additionally, men were taller and heavier in the Rutledge study which would lead to a larger frontal area and could increase drag force, specifically when the legs swing forward during the stride cycle (Rutledge et al., 2007). Porter et al. (2014) also collected anthropometric measures on participants and suggested that larger body mass index scores could increase buoyancy and therefore a lower $\dot{V}O_2$ during walking on an ATM (Porter, Alkurdi, & Dolny, 2011). As suggested by Porter et al. (2014) measures of adiposity should be taken into consideration when attempting to predict metabolic cost during ATM exercise.

Therefore, in order to create better evidence-based criteria, as well as to understand how the cardiorespiratory system responds to ATM running, it is imperative that the relationship between anthropometric measures and the physiological response is examined. This includes both an understanding of the thermal and metabolic responses that can be manipulated by protocol design, such as water temperature, jet resistance used, and the buoyancy and resistance properties of water.
1.2 Hypotheses

The purposes of the following original investigations were to: 1) compare the various alterations to the cardiorespiratory responses to maximal ATM compared to LTM running, 2) compare the occurrence of ventilatory threshold one and two during ATM and LTM running, 3) determine the influence of running at different distances from the resistance jet on the cardiovascular response in order to understand the optimal running position and establish a test termination position, 4) examine the use of a verification phase during ATM running to confirm attainment of $\dot{V}O_2$max, 5) compare the influence of water temperature during submaximal running at the upper and lower end of thermoneutral water temperature for exercise, as well as during maximal running at a thermoneutral water temperature, and 6) assess the relationships between individual anthropometric measures and the physiological response during ATM running.

1.2.1 Cardiorespiratory Responses to Maximal ATM Running

This component of the dissertation investigated the cardiorespiratory alterations that occur during maximal ATM running as compared to LTM running. Our hypotheses were based on previous literature into ATM running as well as pilot work completed prior to our investigation. During maximal ATM running, we hypothesized that cardiorespiratory responses would be similar between ATM and LTM running, however, maximal heart rate would be lower during ATM running. With the exception of heart rate, we hypothesized that all other measures of cardiovascular and respiratory measures would be similar. Previous literature into ATM running has shown similar responses to maximal running compared to LTM running, however, the lower heart rate is unclear. Considering the reduced catecholamine release (Robinson et al., 1966; Connelly et al., 1990) and the lower resistance jets incorporated in our study, we
hypothesized that the maximal heart rate would be lower during ATM running. In addition, we completed pilot testing using four different protocols to ensure all stages were metabolically similar between ATM and LTM protocols. In the pilot collection, we found maximal heart rate to be statistically lower during ATM compared to LTM running. Further, we hypothesized that core body temperature would increase similarly during ATM and LTM running with no significant difference in peak core temperature. Considering no studies to date have measured core temperature during ATM running, our hypothesis is based on water-immersed cycling recommendations. Therefore, although we expect the peak core temperatures to mimic each other, it is possible that the responses may differ due to water immersion depth, the amount of surface area exposed to ambient air, running posture, and the increased muscle requirements of running compared to cycling.

1.2.2 Cardiorespiratory and Hemodynamic Responses to Submaximal ATM Running

This component of the dissertation examined the cardiorespiratory alterations that occur during submaximal ATM running as compared to LTM running. Our hypotheses were based on previous literature into ATM running as well as pilot work completed prior to our investigation. During submaximal exercise, we hypothesized that heart rate would be similar during ATM and LTM running in thermoneutral water temperatures during lower intensity running, however, during higher intensity running (>60% VO2max) heart rate values would be lower during ATM running. We hypothesized that all other cardiorespiratory responses would be similar during submaximal running on the ATM and LTM. Previous investigations have reported similar submaximal cardiorespiratory responses between water-immersed and land-based exercise,
however, heart rate has shown to be lower during water-based exercise at intensities over 60% VO$_{2\text{max}}$ (Christie et al., 1990).

A second focus of this component was to compare the hemodynamic changes that occur during ATM compared to LTM running. Given that our investigation is the first to examine these alterations in ATM running, our hypotheses were based on previous literature incorporating other forms of aquatic exercise, such as water-immersed cycling. We hypothesized that for a matched metabolic demand, stroke volume, cardiac output, and left ventricle end-diastolic volume would be greater during ATM running compared to LTM running. It is possible that the responses may differ compared to the responses found in water-immersed cycling due to water immersion depth, the amount of surface area exposed to ambient air, running posture, and the increased muscle requirements of running compared to cycling.

### 1.2.3 Exercise Criteria

The third component of the thesis focused on the cardiovascular response to running at various distances from the resistance jet. Our investigation was the first to examine the influence of the running position from the water jets on the cardiorespiratory and hemodynamic response, the use of a verification phase during ATM testing, and the occurrence of the two ventilator thresholds. Therefore, our hypotheses are based in part on findings of previous literature and partly based on pilot testing. We hypothesized that running at 1.37 metres from the resistance jet would elicit the greatest metabolic demand. In addition, we hypothesized that running at 0.61 metres, 0.76 metres, 0.91 metres, 1.07 metres, 1.52 metres, 1.68 metres, and 1.83 metres would produce a statistically lower metabolic demand compared to 1.37 metres, and that 1.22 metres from the resistance jet would be lower, yet not statistically different from 1.37 metres. Therefore,
1.52 metres could act as a test termination distance during ATM graded exercise testing. Prior to data collection, a pilot study was conducted on four participants to determine their cardiovascular responses to running at each distance selected from the resistance jet to help inform our hypothesis.

Secondly, we hypothesized that a verification stage would provide a better confirmation on the attainment of \( \dot{V}O_{2\max} \) compared to the commonly used secondary criteria during ATM running. Although a verification phase has never been conducted on an ATM, previously literature during LTM running suggests that verification phase testing is a robust measure to confirm the attainment of \( \dot{V}O_{2\max} \). Therefore, we believe this will extend to ATM testing as well.

Lastly, we hypothesized that the first and second ventilatory thresholds would occur at statistically similar points between ATM and LTM running. Previous research has suggested that lactate thresholds occur at different points during ATM and LTM running (Garner et al., 2014). However, ventilatory measures during water exercise have been found to be similar to land-based measures at a variety of intensities and water temperatures (McArdle et al., 1972). It appears that ventilatory measures during water-based exercise tend to be more robust than lactate measures, and ultimately, a better option for water-based exercise. Based on this, we anticipate that the first and second ventilatory threshold will occur at similar points during ATM and LTM running.

### 1.2.4 Submaximal ATM Running in Multiple Water Temperatures Compared to Land

A fourth component of this thesis aimed to understand how small changes in water temperature influence the cardiovascular response. Based on previous literature incorporating other types of aquatic exercise, we hypothesized that running in 30°C water would cause a
reduction in core temperature change compared to 34°C water for a given running intensity. We hypothesized that stroke volume would be lower and heart rate would be higher during ATM running in 34°C water compared to 30°C water with a similar cardiac output. Previous literature has reported that during water immersed cycling at a similar cardiac output, heart rate is higher in 34.5°C water compared to 30°C water (Park, Choi, & Park, 1999). Lastly, we hypothesized that the cardiorespiratory and hemodynamic responses to running on the ATM in 32°C water would be most similar to those on the LTM. Although core temperature has never been measured during ATM running, based on water-immersed cycling studies, it is suggested that 31-33°C water temperature is thermoneutral during exercise. During graded exercise in air and water of various temperatures while cycling, \( \dot{V}O_2 \) was almost identical between 33°C water and air at 25-27°C (McArdle et al., 1976).

1.2.5 The Influence of Anthropometric Measures during ATM Running

A fifth component of this dissertation aimed to understand the relationship between individual anthropometrics and the thermal and metabolic response during ATM running. Since our investigation was the first to examine this relationship during ATM running, our hypotheses were based on previous literature incorporating other types of aquatic exercise. We hypothesized that variations in anthropometrics between individuals would influence \( \dot{V}O_2_{\text{max}} \) during ATM and LTM running, the peak core temperature achieved, and the change in \( \dot{V}O_2 \) in relation to the resistance jets. Specifically, we hypothesized that the participants with higher body fat would be impacted greater by buoyancy and have a lower ATM \( \dot{V}O_2_{\text{max}} \) compared to LTM running. Similarly, we hypothesized that participants with a greater body surface area would have less of a decrease in metabolic demand as they move away from the resistance jets due to the amount
surface area that remains in contact with the resistance jet stream. In regard to core temperature change, we hypothesized that the participants with higher percentages of body fat would have greater increases in core temperature. Finally, we hypothesized that the influence of anthropometrics on core temperature would be similar during ATM running compared to LTM running.
Chapter 2: Literature Review

2.1 Cardiorespiratory Response to Water Immersion

Conflicting results have been reported for a variety of cardiorespiratory responses to ATM and LTM exercise. For $\dot{V}O_2$ responses, it has been suggested that the differences in $\dot{V}O_{2\text{max}}$ between ATM and LTM running are related to factors that limit $\dot{V}O_{2\text{max}}$ in the water environment, such as the exercise mode, reduced vital capacity, total lung capacity, and pulmonary elasticity, which could increase the $\dot{V}O_2$ of the ventilatory muscles and reduce the availability of $O_2$ for other muscles (Frangolias and Rhodes, 1995). However, studies that have compared the same exercise mode on land versus thermoneutral water immersion have found similar values for $\dot{V}O_{2\text{max}}$ in water and land (Christie et al., 1990; Connelly et al., 1990; Dressendorfer, Morlock, Baker & Hong, 1976; Sheldahl et al., 1987; Silvers, Rutledge & Dolny, 2007; Greene et al., 2011; Watson et al., 2012; Schaal, Collins & Ashley, 2012). Studies that have reported lower $\dot{V}O_{2\text{max}}$ values in aquatic environments have compared deep water running and LTM running (Butts, Tucker & Greening, 1991; Butts, Tucker & Smith, 1991; Frangolias & Rhodes, 1995; Mercer and Jensen, 1998; Svedenhag & Seger, 1992; Town & Bradley, 1991), shallow water running to LTM running (Town & Bradley, 1991), or water calisthenics compared to land calisthenics (Alberton et al., 2013; Alberton et al., 2014).

Town and Bradley (1991) found the highest $\dot{V}O_2$ values for LTM running, however, shallow water running produced $\dot{V}O_2$ responses more similar to LTM than deep water running. According to the authors, the shallow water running technique better simulated land-based running. Differences between deep water running and LTM $\dot{V}O_{2\text{max}}$ could be related to differences in running style, gravitational effects, and hydrostatic responses (Frangolias & Rhodes, 1995). The similarities in $\dot{V}O_{2\text{max}}$ between the environments increase with the
similarities in the exercise technique. It has been suggested that the movement pattern is primarily responsible for limitations to \( \dot{V}O_2 \text{max} \) rather than solely the aquatic environment (Alberton et al., 2014).

Deep water running is different from land running in terms of lower-extremity muscle recruitment and kinematics (Moening et al., 1993). Considering the different movement patterns and active muscles, metabolic requirements may differ between deep water running, shallow water running, and LTM running. Shallow water running without a moving treadmill is more similar to land running than deep water running (Reilly et al., 2003; Moening et al., 1993), however the increased frontal plane resistance of the water in shallow water running produces a different strategy of locomotion compared to land running (Moening et al., 1993; Kato, Onishi, & Kitagawa, 2001). ATM running eliminates forward locomotion through the water due to the treadmill belt which mitigates the increased frontal resistance in shallow water running. This may allow for a more natural gait and muscle recruitment pattern in ATM running (Silvers, Rutledge, & Dolny, 2007; Kato, Onishi & Kitagawa, 2001) that is more similar to LTM running.

Research comparing ATM and LTM running supports this idea as similar \( \dot{V}O_2 \text{max} \) values are consistently reported (Silvers, Rutledge & Dolny, 2007; Schaal, Collins & Ashley, 2012; Greene et al., 2011; Watson et al., 2012).

It is commonly reported that maximal heart rate is lower during deep water running (Butts et al., 1991; Svedenhag & Seger, 1992; Town & Bradley, 1991) and water immersion cycling (Christie et al., 1990; Connelly et al., 1990; Dressendorfer et al., 1976; Sheldahl et al., 1987) when compared to land in thermoneutral conditions. The lower maximal heart rate response during water immersion is partially attributed to the central shift in blood volume (Arborelius, Balldrin, Liga & Lundgren, 1972) that results from the hydrostatic pressure of the
water exerted on the body which facilitates venous return, greater preload, and increased stroke volume (Arborelius et al., 1972; Christie et al., 1990; Connelly et al., 1990). Additionally, heart rates during water immersed and land cycling have reported to be similar during mild to moderate exercise, however, heart rate at higher intensities is significantly lower in the water environment (Christie et al., 1990; Sheldahl et al., 1987). Christie et al. (1990) reported similar heart rates between land and water cycling at 40% and 60% \( \dot{V}O_2 \text{max} \), with significantly lower water heart rates at 83% and 100% \( \dot{V}O_2 \text{max} \).

A second possible explanation for the lower heart rate during water immersion exercise is that sympathetic neural outflow is reduced in water (Christie et al., 1990). A reduction in sympathetic neural outflow should have a greater impact on heart rate at workloads above 50% \( \dot{V}O_2 \text{max} \), as Robinson et al. (1966) showed that the rise in heart rate with work above this intensity is primarily dependent on increased sympathetic neural outflow. However, at lighter work intensities, parasympathetic neural withdrawal primarily contributes to the rise in heart rate (Robinson et al., 1966). In addition, previous studies have shown plasma norepinephrine to be reduced during passive water immersion (Krishna, Danovitch, & Sowers, 1983; O’Hare et al., 1986), and both norepinephrine and epinephrine were reduced during high-intensity water immersion cycling (Connelly et al., 1990).

Interestingly, Silvers et al. (2007) and Watson et al. (2012) reported no difference in maximal heart rate between ATM and LTM running. The study by Watson et al. (2012) compared four aquatic treadmill graded exercise protocols to a land Bruce protocol. The increments in treadmill speed throughout both tests were the same, however, increasing intensities of resistance jets were used. With higher resistance jet intensities (66% of capacity and full capacity) \( \dot{V}O_2 \text{max} \) values and maximal heart rates were not different compared to land. It
is possible that the use of water resistance jets in ATM studies that were not previously used in water immersion cycling or deep water running may influence the maximal cardiovascular response.

Reduced vital capacity, total lung capacity, and lung compliance have been reported during passive water immersion exercise (Agostoni, Gurtner, Torri & Rahn, 1966; Farhi & Linnarsson, 1977; Hong, Cerretelli, Cruz & Rahn, 1969). A tendency for breathing frequency to be higher and tidal volume to be lower has been reported during submaximal and maximal water immersion exercise (Sheldahl et al., 1987). Coast et al. (1993) have reported an increase in the work of breathing, and therefore the energy requirement of the ventilatory muscles, when a higher breathing frequency versus tidal volume pattern is used to produce an equivalent submaximal ventilation. This would seem to suggest that the cost of breathing may also be increased in water immersion exercise. In this case, a larger portion of the $\dot{V}O_2$ would be consumed by the ventilatory muscles and may function to limit the $O_2$ available to the leg muscles. Given the hydrostatic pressure and fluid resistance of the water, ATM running with immersion to the xiphoid process would require the arms and respiratory muscles be working through the resistance of the water. Therefore, the increase in exercising muscle could also limit the amount of oxygen available for the legs as more is consumed by the arms and respiratory muscles compared to LTM running.

At rest, during head-out water immersion, several studies have reported a greater heart preload compared to land in the supine position (Arborelius et al., 1972; Echt, Lange & Gauer, 1974; Epstein, 1976; Lin, 1984; Risch, Koubene, Beckmann, Lange & Gauer, 1978), increases in right atrial pressure (Arborelius et al., 1972; Echt et al., 1974; Risch et al., 1978), an increase in cardiac output and stroke volume (Arborelius et al., 1972; Farhi & Linnarsson, 1977; Gauer &
Henry, 1976; Lin, 1984), and an increase in cardiac volume (Gauer & Henry, 1976; Lange, Lange, Echt & Gauer, 1974; Risch et al., 1978). Systemic blood pressure has been found to remain unchanged or to slightly increase (Arborelius et al., 1972; Epstein, Preston & Weitzman, 1981; Gauer & Henry, 1976).

There are a few studies that have compared cardiac responses during active exercise on a water immersed and land cycle ergometer (Sheldahl et al., 1984; Sheldahl et al., 1987; Christie et al., 1990). These studies suggest that left ventricular end-diastolic diameter was greater during mild and moderate cycling exercise in water compared to land, suggesting that cardiac preload is elevated during exercise in water, at least to a moderate level of exertion (Sheldahl et al., 1984). Cardiac output was found to be significantly elevated during exercise in water at submaximal intensities up to 80% VO₂max (Sheldahl et al., 1987; Christie et al., 1990). Although participants in the study by Christie et al. (1990) exercised to VO₂max, cardiac flows were not possible at maximal intensity using the thermodilution method, however, Doppler measurements indicated that cardiac index remained significantly elevated in water compared to land at peak effort.

Stroke volume appears to be greater during water immersion exercise at all intensities compared to land (Sheldahl et al., 1987; Christie et al., 1990). The elevated stroke volume in water can be attributed to enhanced preload (the Frank-Starling mechanism) rather than to increased left ventricular emptying as left ventricle end-systolic volumes are greater in water (Christie et al., 1990). Interestingly, although stroke index significantly increased from rest to exercise at approximately 40% VO₂max on land, there was no significant difference in water. It has been suggested that the central shift in venous blood volume at rest in water immersion reduces the amount of venous blood available to be shifted centrally with exercise via the muscle pump action and/or venoconstriction (Christie et al., 1990). Additionally, left ventricular end-diastolic
volume at rest during water immersion may be near maximal, resulting in limited ability to increase stroke volume with exercise through a further increase in left ventricle end-systolic volume (Christie et al., 1990). Although the increase is non-significant, it appears that the greatest stroke volume during water immersion cycling occurs at approximately 40% $\dot{VO}_2_{max}$.

To date, no ATM running studies have investigated cardiac output, stroke volume, and other hemodynamic measures. It is possible that results would be different with ATM running based on postural changes, the proportion of the body immersed in water, and possibly the amount of resistance jet used during running. It has been previously postulated that with added jet resistance directed toward the trunk of the body, differences in cardiac return may occur and that to fully appreciate the effect of jet resistance on cardiac output, a future investigation would be required (Garner et al., 2014). Further, during passive water immersion, heart rate has been reported to be similar between neck and chest immersion, however, cardiac output, stroke volume, and central venous pressure are lower during chest immersion compared to neck immersion (Lollgen, Nieding, Koppenhagen, Kersting, & Just, 1981; Larsen et al., 1994). These results suggest that a change in depth from neck immersion in cycling to chest immersion in ATM running may lead to an altered exercise response. In summary, although the previous literature on immersed cycling provides a glimpse into the possible alterations during ATM running, due to a variety of changes between the two forms of exercise data, specific to ATM running is required.

### 2.2 Thermal Regulation during Aquatic Exercise

During dynamic exercise the increase in cardiac output must be partitioned between the contracting muscles to meet the oxygen delivery requirements and the skin to meet the heat transfer requirements of the temperature regulatory system (Nadel, Cafarelli, Roberts & Wenger,
Heat can be exchanged with the environment through a variety of different avenues including conduction, convection, radiation, metabolism, and evaporation. Skin temperature is important in heat exchange and thermoregulation as most heat is exchanged between the body and the environment at the skin surface (Wenger, 1997). Skin temperature is affected by thermoregulatory responses such as skin blood flow, sweat secretion, and by environmental factors including air temperature, water temperature, air and water movement, and thermal radiation (Wenger, 1997). When exercising in a cool environment, the vasodilatory threshold is high and the demand for skin blood flow is low (Nadel et al., 1979). However, when exercising at higher intensities in the heat, both the skin and the muscle demands for blood flow are high which presents a problem for the body to provide sufficient circulation to both of these vascular beds (Nadel et al., 1979). If uncompensated, the reduction in central blood volume would lead to progressive reductions in cardiac filling pressure and stroke volume, resulting in an increased heart rate, and possibly circulatory collapse (Nadel et al., 1979). A balance is maintained to selectively direct a portion of the blood away from the contracting muscles to the skin to prevent an excessive rise in internal body temperature while maintaining adequate flow to the muscles to meet the demand for oxygen.

It has been suggested that cardiac output is increased during exercise in the heat compared to cool conditions in order to meet the increased circulatory requirements and prolong exercise (Brouha, 1960). During exercise at 40% \( \dot{V}O_{2\text{max}} \) in a 36°C environment, cardiac output is increased above that of a 20°C and 26°C environment (Nadel et al., 1979). However, with increasing intensity at 70%\( \dot{V}O_{2\text{max}} \) in a 36 °C environment, it becomes increasingly challenging to augment cardiac output as heart rate approaches its maximum and stroke volume is limited
due to the reduced cardiac filling pressure through venous pooling and loss of volume from the vascular space (Nadel et al., 1979).

The hydrostatic pressure that is exerted on the body during upright water immersion promotes an increase in central blood volume and concomitant alterations in cardiovascular function during exercise in water (Christie et al., 1990). Considering an increase in cardiac output, stroke volume, central blood volume, and venous return has been shown during aquatic exercise it is expected that the thermoregulatory response would be different compared to land exercise. The increase in blood volume due to fluid shifts into the intravascular compartment from the hydrostatic pressure of the water may allow for an increase in blood flow for heat exchange while still meeting muscular oxygen demand. In addition, based on altered avenues of heat exchange, the body responds differently to water immersion as to land. The coefficient of transport of alternate heat for a body at rest in still water is 230 watts·m⁻²·°C (Nadel, Holmér, Bergh, Astrand, & Stolwijk, 1974) compared to 9 watts·m⁻²·°C (Costill, Cote, Miller, Miller, & Wynder, 1975) in still air. The critical temperature, which is defined as the lowest air or water temperature that does not cause an increase in metabolic rate or shivering over three hours, is higher in water (28°C - 33°C) than in air (21°C - 27°C) (Alexiou, 2014). In addition, overall critical water temperature decreases linearly as skin fold thickness increases providing a rationale for a large temperature range based on individual composition (Park et al., 1983).

Although the thermoregulatory response to exercise in air at a variety of temperatures are well documented, the response during water immersion in less understood. Therefore, differences could exist when comparing the various avenues of heat exchange during exercise in air and water. Although much of the literature involves swimming, water immersed cycling, and
other forms of aquatic exercise, special attention will be given here to implications of water temperature during ATM running.

2.2.1 Avenues of Heat Exchange during Exercise

During exercise, metabolic heat and muscle blood flow are increased (Mitchell, 1977). Excess heat generated by the active muscles during exercise may be dissipated by increased blood flow through dilated vessels of the skin (Berger, 1982; Franklin, Green, & Cable, 1993; Kellogg et al., 1993). Ultimately, the heat is transferred to the surrounding environment by four different pathways: conduction, convection, radiation, and evaporation (Mitchell, 1977; Berger, 1982; Brooks, Fahey & White, 1984). Human beings regulate their internal body temperatures within a narrow band near 37°C despite wide variations in environmental temperature (Wenger, 1997). It has been suggested that temperature regulation is impaired if the core temperature rises above approximately 40°C or drops below approximately 34°C (Wenger, 1997). Although heat is gained throughout the body, it is lost only from tissues that are in contact with the environment (Wenger, 1997). The various avenues of heat exchange are described below.

Metabolic Heat

Metabolism at rest or during exercise can increase heart within the body. Metabolic energy is required for active transport via membrane pumps, for muscular work, and for chemical reactions such as the formation of glycogen from glucose (Wenger, 1997). Most of the energy used in these processes is transformed into heat in the body (Wenger, 1997). It is important to consider metabolic heat during ATM running as more muscles are working through a resistance that is 800 times denser than air (di Prampero, 1986). The muscles that may be more active during ATM running as compared to LTM running include the legs, arms, and respiratory muscles due to the fluid resistance and hydrostatic pressure. Heat as a by-product of muscular
contraction can be almost immediate. As suggested by Wenger (1997), even during mild exercise, the muscles are the main source of metabolic heat and during heavy exercise they may account for up to 90% of metabolic heat. Exercising muscles may be nearly 1°C warmer than the core because of their metabolic rate and blood is warmed as it perfuses these muscles. In turn, the blood warms the rest of the body and raises the core temperature (Wenger, 1997). Other forms of metabolic heat can be released from the conversion of ADP to ATP, as well as when ATP is hydrolyzed during muscle contraction, and also when some mechanical work is converted by friction into heat within the body (Wenger, 1997). It has been established that no more than one quarter of the metabolic energy released during exercise is converted into mechanical work outside the body and the remaining three quarters is converted into heat within the body (Astrand & Rodahl, 1977).

**Convection and Conduction**

Heat within the body is transported by two means, conduction through the tissues and convection by flowing blood carrying heat from warmer tissues to cooler tissues (Wenger, 1997). Convective heat exchange between the skin and the environment is proportional to the difference between skin and ambient air temperature or water temperature during immersion (Wenger, 1997). Water immersion increases the convective heat transfer coefficient about 200 times compared to still air (Pugh et al., 1960). Both of these pathways are of importance during ATM running depending on water temperature as a majority of the body (i.e. up to the xiphoid process) is immersed and in direct contact with the skin.

Heat flow by conduction is proportional to the thermal conductivity of the tissues, the change of temperature with distance in the direction of heat flow, and the area through which the heat flows (Wenger, 1997). Conductivity varies depending on tissue with rates for epidermis,
dermis, fat, and muscle of 0.00005 kcal/(s·m·°C), 0.00009 kcal/(s·m·°C), 0.00004 kcal/(s·m·°C),
0.00011 kcal/(s·m·°C), respectively (Wenger, 1997). Heat flow by convection depends on the
rate of blood flow and the temperature difference between the tissue and the blood supplying the
tissue (Wenger, 1997). In a cool individual, skin blood flow is low, so that the core to skin heat
transfer is dominated by conduction. However, in a warm individual the skin blood flow is high,
so that heat flow from the core to the skin is dominated by convection (Wenger, 1997).

**Evaporation**

When the air environment is hotter than the skin, evaporation is the body’s only way to
lose heat and must dissipate not only metabolic heat, but also any heat gained from the
environment through radiation, conduction and convection. (Wegner, 1997). To achieve heat
balance at higher ambient temperatures individuals increasingly depend on evaporation of sweat,
which in humans can dissipate a large amount of heat. There are two types of sweat glands,
eccrine and apocrine. Apocrine glands are found mostly in the axilla, inguinal region, perianal
skin, and mammary areolae, and less consistently on other parts of the trunk and the face (Hurley & Shelley, 1960). Eccrine sweat glands are widely distributed including two to three million
functionally active eccrine glands and are the more important type in human thermoregulation
(Kuno, 1956). Evaporative heat loss from the skin is proportional to the difference between the
water vapour pressure at the skin surface and the water vapour pressure in the ambient air
(Wenger, 1997). If secretion exceeds evaporation, sweat accumulates on the skin and spreads out
to wet more of the space between neighbouring sweat glands, thus increasing wettedness and
evaporation. Whereas if evaporation exceeds secretion the reverse occurs. If sweat rate exceeds
maximal evaporation the excess sweat drips from the body because it cannot evaporate (Wenger,
1997).
Previous reports have indicated that sweating is suppressed during water immersion and thus may limit heat exchange at higher exercise intensities, especially in warmer water temperatures (Pendergast & Lundgren, 2009).

**Radiation**

Every surface emits energy as electromagnetic radiation with a power output that depends on its’ area, its’ temperature, and its’ emissivity. Thermal radiation has characteristic distribution of energy as a function of wavelength, which depends on the temperature of the surface (Wenger, 1997). At ordinary tissue and environmental temperatures virtually all of the emitted energy is at wavelengths longer than three microns. As surface temperature increases the average wavelength of its thermal radiation decreases (Wenger, 1997). If two surfaces exchange heat by thermal radiation, radiation travels in both directions, but as each surface emits radiation with an intensity that depends on its temperature, the net flow is from the warmer to the cooler body (Wenger, 1997). Some parts of the body surface exchange heat by radiation with other parts of the body surface, so that the body exchanges heat with the environment as if it has an effective area smaller than its actual surface area (Wenger, 1997).

Based on the above avenues of heat exchange and the interaction with the environment, it is evident that water and air of similar temperature would produce different metabolic and thermal responses during exercise. In addition, the characteristics of various forms of aquatic exercise are quite different. For example, during water immersed cycling it is common for an individual to be immersed to the clavicle resulting in a majority of heat exchange by convection and conduction with an impairment in evaporation. However, during ATM running it is more common to have an individual immersed at a level between the hips and xiphoid process. Therefore, a greater surface area is exposed to the room air environment possibly facilitating
more effective evaporation during ATM running as compared to water immersed cycling. In addition, various modes of aquatic exercise could contribute alter convective heat transfer during water immersion (McArdle et al., 1992). Given the above methods of heat gain and loss it becomes apparent that water immersion could greatly influence heat storage and is an important consideration during ATM running.

2.2.2 Thermoregulatory Response during Exercise in Air and Water

Vigorous exercise can increase oxygen consumption and metabolic heat within the body 10-fold or more (Wenger, 1997). Unless exercise is very brief, it is quickly accompanied by increases in the heat-dissipating responses of skin blood flow and sweating to counter the increase in metabolic heat (Wenger, 1997). Receptors in the body core and the skin transmit information about their temperature to the brain stem, and specifically the hypothalamus, medulla and spinal cord, where much of the integration of temperature information occurs (Boulant, 2011). The anterior preoptic area of the hypothalamus contains many neurons which increase their firing rate in response to warming or cooling (Wegner, 1997). The sensitivity of the thermoregulatory responses to core temperature allows the thermoregulatory system to adjust heat gain and heat loss to resist disturbances in core temperature so that environmentally induced changes in body heat occur almost entirely in the peripheral tissues (Wegner, 1997). As mentioned earlier, during exercise in the heat, both the skin and the muscle demands for blood flow are high and the body is presented with the problem of providing sufficient circulation to both of these vascular beds (Nadel et al., 1979). Although achieving a balance is the goal, circulatory regulation has precedence over temperature regulation (Nadel et al., 1979). The body attempts to compensate for a loss of plasma from intravascular volume by utilizing the muscle pump to squeeze a part of the cutaneous venous volume back toward the heart and perfusion of
inactive tissues is reduced in proportion to the increase demand from the skin (Rowell, Blackmon, Martin, Mazzarella & Bruce, 1965).

In hot conditions the body controls dry (convective, conduction and radiative) heat loss by varying blood flow and skin temperature. Once sweating begins, skin blood flow continues to increase as an individual becomes warmer, but now the tendency of an increase in skin blood flow to the skin is approximately balanced by the tendency of an increase in sweating to cool the skin. (Wenger, 1997). Therefore, after sweating has begun, further increases in skin blood flow usually cause little change in skin temperature or dry heat exchange, and serve primarily to deliver heat to the skin that is being moved by evaporation of sweat. Skin blood flow and sweating thus work in tandem to dissipate heat under such conditions (Wenger, 1997).

Immersion in warm water causes an immediate drop in temperature gradient, or reversed gradient in hot water, across the skin and an inability to evaporate sweat causing a rapid increase in skin and core temperature (Pendergast & Lundgren, 2009). The primary cardiovascular burden of heat stress on land results from impairment of venous return (Rowell, 1983; Hardy, 1970; Rowell, 1977). One concern as skin blood flow increases is that blood pools in the large dilated cutaneous vascular bed, thus reducing central blood volume, cardiac filling, and stroke volume (Wegner, 1997). In order to maintain cardiac output in the event of decreased stroke volume, there is an increase in heart rate to meet the demands of exercise. The displacement of blood volume into cutaneous veins can be counteracted by water immersion (Nielsen, Rowell & Bonde-Petersen, 1984). Prevention of hydrostatic influences on peripheral venous volume will permit the maintenance of a higher cardiac output and skin blood flow, and counteract a fall in stroke volume (Nielsen et al., 1984). Therefore, it has been suggested that there may be an
enhanced ability of the circulatory system to handle heat stress in a low gravity environment until circulation is compromised by loss of plasma volume (Nielsen et al., 1984).

Thermoneutral water temperature, where there is little effect on resting metabolism during immersion, occurs at 34-35°C (Pendergast & Lundgren, 2009). With decreasing temperature and longer durations, metabolism increases in proportion to the reduction in skin and core temperatures (Pendergast, 1988). In water above the thermoneutral temperature, significant risk of hyperthermia exists as the ability to eliminate heat from the body in this environment is limited (Pendergast & Lundgren, 2009). Craig and Dvorak (1968) provided an estimation of the water temperature which could be considered neutral when individuals are exercising. With a light load it was suggested the water temperature necessary to prevent a change in core temperature would be 34°C for an individual with a metabolic heat of approximately 2.5 times resting. Similarly, with a heavy load the suggested water temperature would be 29°C. It is important to note that the work by Craig and Dvorak used the term thermoneutral to describe a water temperature that prevents a change in core temperature. It is common to use this definition during passive water immersion, however, during aquatic exercise the term thermoneutral more commonly refers to an increase in core temperature similar to land exercise in a temperate environment for a given range of intensities.

Christie et al. (1990) compared land and water exercise on cycle ergometers in 32.5°C water and 22.7°C air. These authors reported that at 40%, 60%, 80%, and 100% \( \dot{V}O_{2\text{max}} \) pulmonary arterial blood temperature and \( \dot{V}O_2 \) increased similarly with no differences in temperature between land and water. Also, it has been shown that muscle temperature,
epinephrine, and glycogen levels increase while exercise time is significantly shorter in hot than in thermoneutral or cold water (Parkin, Carey, Zhao & Febbraio, 1999).

2.2.3 Metabolic Responses to Exercise in Air and Water of Varying Temperatures

Multiple investigations have compared the metabolic and cardiovascular responses to exercise in land and water at similar temperatures (McArdle, Magel, Lesmes, & Pechar, 1976; Craig & Dvorak, 1969; Young et al., 1995; Holmer & Bergh, 1974; Gleim & Nicholas, 1989). During immersion in cold water, it is likely that a smaller fraction of cardiac output is shunted to the skin for the purpose of heat dissipation (Rennie, Di Prampero & Cerretelli, 1971). The increase in peripheral vasoconstriction and the hydrostatic pressure on the immersed body increases central blood volume and possibly results in a larger stroke volume (Echt, Lange & Gauer, 1974; Lange, Lange, Echt & Gauer, 1974). In turn, the increases in stroke volume would balance any decrease in heart rate to maintain cardiac output at similar levels of $\dot{V}O_2$ in water of different temperatures (McArdle et al., 1976).

During ATM running in waist deep water it has been reported that 36.1°C water increases heart rate for a given $\dot{V}O_2$ compared to 30.5°C water and land temperature of 24-26.5°C (Gleim & Nicholas, 1989). During graded exercise in air and water of various temperatures while cycling, $\dot{V}O_2$ with increasing workload was almost identical between 33°C water and air at 25-27°C (McArdle et al., 1976). However, during submaximal work in 25°C and 18°C water $\dot{V}O_2$ was higher than in 33°C (9.0% and 25.3%, respectively). Similar to the findings by Gleim and Nicholas (1989), at a given submaximal $\dot{V}O_2$, heart rate in 18°C water was five beats per minute lower than in 25°C water and 15 beats per minute lower than in 33°C water or air (McArdle et al., 1976). In addition, stroke volume was larger in 18°C and 25°C water as well with the largest
stroke volumes being observed in 18°C water. At a \( \dot{V}O_2 \) of 2.4 L/min the heart rate averaged 19% lower and stroke volume was 14% higher in cold water of 18°C compared to similar \( \dot{V}O_2 \) in air and thermoneutral water of 33°C (McArdle et al., 1976). In agreement, Avellini, Shapiro, Fortney and Pandolf (1982) noted the heart rate to \( \dot{V}O_2 \) curve shifted to the right with higher heart rates (~10 beats per minute) at 75% \( \dot{V}O_{2\text{max}} \) in 32°C compared to 20°C.

Metabolic comparisons between running on land in 20-22°C air and swimming at 18°C, 26°C and 34°C have also been reported (Holmer & Bergh, 1974). These authors reported that at a given submaximal swimming speed, \( \dot{V}O_2 \) was higher in 18°C compared to warm water with the elevation in \( \dot{V}O_2 \) being proportional to the decrease in core temperature below 37°C (Holmer & Bergh, 1974). In agreement with other investigations heart rate was lower in 18°C water compared to 26°C and 34°C. Young et al. (1995) also reported that for water immersed cycling, heart rate was higher during exercise in hot water (35°C) as compared to cold water (18°C). In addition, cardiac output was maintained regardless of temperature due to larger increases in stroke volume in cold water.

Therefore, it appears that cardiac output is maintained throughout a range of water temperatures. Heart rate tends to increase in order to offset reductions in stroke volume as blood is directed to the skin for heat exchange. For higher water temperatures (i.e. >34°C) with increasing intensity and duration of exercise, maximal heart rate may be obtained and limit the ability to maintain cardiac output to meet the muscular and thermoregulatory demand.

2.2.4 Thermal Responses to Exercise in Water of Varying Temperatures

The change is core temperature during cold water immersion is related to exercise intensity (McArdle, Toner, Magel, Spina & Pandolf, 1992). Exercise can increase overall heat
loss as it has been indicated that in cold water moderate exercise facilitates overall heat
conductance (Veicsteinas, Ferretti & Rennie, 1982). In cold water of 5°C – 20°C, it has been
reported that swimming will cause a greater decrease in core temperature compared to being
inactive other than involuntary shivering (Carlson, Hsieh, Fullington & Elsner, 1958; Keatinge,
1961; Pugh, 1965). Heat loss is increased from highly perfused, active limbs causing core
temperature to fall at an even greater rate compared to still conditions (Cannon and Keatinge,

Core temperature has been reported to increase higher during exercise in hot water at
35°C compared to cold water at 18°C (Young et al., 1995). During 20 minutes of submaximal
swimming core temperature rose by 0.6°C in 34°C water while core temperature decreased in a
majority of participants in 18°C water (Holmer & Bergh, 1974). During arm-leg cycling in men
in 28°C water at 0.8 L·min⁻¹ for 60 minutes core temperature decreased 0.79°C even with a two-
fold increase in energy expenditure. During exercise at 1.29 L·min⁻¹ core temperature dropped
0.54°C, whereas core temperature was essentially unchanged with exercise at a \( \dot{V}O_2 \) of 1.7
L·min⁻¹. In 20°C water immersion, core temperature was also decreased and even the highest
intensity of exercise (1.7 L·min⁻¹) did not maintain core temperature from baseline (McArdle et
al., 1992). Fujishima et al. (2001) reported no change in rectal temperature while swimming for
120 minutes in 33°C water at an intensity equivalent to 50% treadmill \( \dot{V}O_2_{max} \) with reduction in
rectal and skin temperature at 23°C and 28°C. Craig and Dvorak (1968) noted that with low
work load during water immersed cycling (0.7 L·min⁻¹) there was a decrease in ear temperature
when the water was less than 32°C. With a heavier workload (0.92 L·min⁻¹) the ear temperature
decreased only in the 24°C water as compared to a range of temperatures up to 35°C. Similarly,
changes in rectal temperature during the low workload continuously declined when the water was less than 32°C. At the higher workload (0.92 L·min⁻¹) rectal temperature increased when the water temperature was 28–32°C. In addition, the increment in skin temperature was independent of the work load but linearly related to the water temperature. During immersion in 35°C water, skin temperature increased compared to pre-immersion and after 60 minutes of exercise at 60% \( \dot{V}O_2 \text{max} \) skin temperature averaged 0.2-0.4°C above the water temperature (Young et al., 1995). During the first 20 minutes of immersion in 18°C water skin temperature declined and remained stable for the remainder of exercise, averaging 1.4°C above water temperature by minute 60 (Young et al., 1995).

It can be suggested that an appropriate water temperature is largely based on exercise intensity and these studies align with the suggested water temperature range of 31-33°C to maintain similar rises in core temperature compared to temperate environments in air. However, factors other than exercise intensity could influence the thermal response.

2.2.5 Type of Aquatic Exercise and the Thermal Response

Another important factor concerning thermoregulation during aquatic exercise is the type of activity. The use of swimming or combined arm and leg exercise maximizes the surface area between the contracting musculature and the water (Toner, Sawka & Pandolf, 1984). If a given amount of metabolic heat is dissipated over a smaller surface area with cool water, such as with leg exercise only, a relatively smaller absolute heat flux would be predicted (Toner et al., 1984). Another factor that may be important for heat loss in cool water is the surface area-to-mass ratio of the limbs performing the exercise (Toner et al., 1984). For a given \( \dot{V}O_2 \), the larger the surface area-to-mass ratio the larger the expected heat flux to cool water. During high intensity exercise
in 20°C water, core temperature remained constant during leg exercise and decreased during arms and leg exercise. During high intensity exercise in 26°C and 33°C water core temperature increased steadily in leg exercise, as well as arm and leg exercise. However, the final core temperature was lower for arm and leg exercise compared to leg exercise only across all water temperatures (Toner et al., 1984). In addition, no differences were noted in skin temperature between arm and leg exercise versus legs only exercise in all water conditions (i.e. 20-33°C). Toner et al. (1984) suggested that different exercise modes that alter the interaction of the contracting skeletal muscle mass with water and also change the surface area-to-mass ratio of the performing limbs could influence thermoregulatory responses during water immersion exercise. As such, ATM running would be expected to provide an altered thermoregulatory response compared to water-immersed cycling.

The points discussed above should all be considered during ATM running as the mechanics are different than cycling and the active musculature is likely higher than running on land and cycling due to the increased resistance of moving the upper body through the water. Therefore, the temperatures that have been determined to be thermoneutral or metabolically similar to temperate air derived off of water immersed cycling may not be transferable to ATM running.

2.2.6 Thermoneutral Temperature during Graded Exercise Tests on an Aquatic Treadmill

As identified above exercise intensity influences the metabolic and thermal response to exercise. A challenge is determining an appropriate water temperature when implementing a graded exercise test that incorporates exercise at a variety of intensities. As mentioned previously, central blood volume is increased through the redistribution of venous blood which
in turn leads to a readjustment of the cardiovascular system. Consequently, increases in central venous pressure, cardiac output and stroke volume may lower heart rate (Watenpaugh, Pump, Bie & Norsk, 2000). Additionally, the change in thermal conditions offered by the water seems to contribute to the reduction in heart rate due to the heat exchange between the body and the environment, which is facilitated during water immersion as stroke volume can be better maintained (McArdle et al., 1976; Sramek, Simeckova, Jansky, Savlikova & Vyrbiiral, 2000). Accordingly, the need to distribute blood from the central region to the extremities decreases, concentrating the plasma volume in the central region of the body. The magnitude of these alterations is directly related to water temperature (Craig & Dvorak, 1966; Craig & Dvorak, 1969; McArdle et al., 1976; Park, Choi, & Park, 1999; Sramek et al., 2000).

It is important to consider how temperature influences the cardiovascular response when comparing water exercise to land exercise. Thermoneutral water immersion during dynamic exercise does not mean that the core temperature does not change, it means that with increasing exercise intensity the core temperature change and metabolic response mimics land in a temperate environment. In other words, a temperature is selected in an attempt to avoid a superimposed metabolic response. Previous studies suggest that the thermoneutral range for dynamic exercise is between 30-35°C (Sheldahl et al., 1987; Christie et al., 1990; McArdle et al., 1976). McArdle et al. (1976) compared 18°C, 25°C and 33°C water immersed cycling exercise with cycling on land in air of 25-27°C in graded exercise to maximal exertion. \( \dot{V}O_2 \) was almost identical between 33°C and air, whereas for a given workload 25°C produced a 9% greater \( \dot{V}O_2 \) and 18°C a 25.3 % increase in \( \dot{V}O_2 \). Similarly, for a given submaximal \( \dot{V}O_2 \), immersion in 18°C water averaged five beats per minute lower than 25°C water, and 15 beats per minute lower than
in 33°C and air. Christie et al. (1990) cycled to maximal effort in 32.5°C water and air at 22.7°C. These authors determined that pulmonary arterial blood temperatures did not differ between land and water at 41%, 60%, 83%, and 100% \( \dot{V}O_2\text{max} \).

These two studies suggest that throughout exercise up to maximal intensity, a water temperature of 32.5-33°C is optimal for maintaining thermoneutrality compared to land, especially when the comparative outcome measures are \( \dot{V}O_2 \) and heart rate. When considering this temperature range, there are two important considerations: 1) these temperatures were determined using water immersed cycling; and 2) participants were immersed to the level of the neck. During ATM running, it is common for participants to be immersed to the xiphoid process. At higher intensity of exercise, it is likely that evaporation will be more effective in an attempt to exchange heat with the environment as less of the body is immersed in the water. In addition, the active muscle recruitment will be different during ATM running versus cycling. Therefore, it is unknown whether it is appropriate to equate the cycling ranges of thermoneutral water exercise to ATM running. Shimizu, Kosaka and Fujishima (1998) compared water temperatures of 25°C, 30°C, and 35°C to air at 25°C during 60 minutes of ATM walking at the xiphoid process. These authors reported no difference in rectal temperature throughout the exercise between the three water temperatures. However, rectal temperature was significantly lower during walking in water at 25°C compared to air at 25°C. In addition, there was a significant difference in mean skin temperature between all water temperatures with 35°C being the highest, followed by 30°C and 25°C, as well as a significant difference between land and water at 25°C.

Recent scientific literature on ATM running has used a variety of water temperatures to compare cardiovascular responses during ATM and LTM running, including 25.8°C (Schaal et
al., 2012); 28°C (Silvers et al., 2007; Rutledge et al., 2007; Brubaker et al., 2011); 29.5°C (Silvers et al., 2014); 30°C (Porter et al., 2014; Garner et al., 2014); 32°C (Rife et al., 2010); and 33°C (Pohl & McNaughton, 2003). In addition, Greene et al. (2011) reported using a range of 32-34°C, and Watson et al. (2012) used a range of 33-35°C. With a large range of water temperatures included in these studies, it is likely that water temperature could influence the comparison of cardiovascular responses. Gleim & Nicholas (1989) demonstrated significantly different \( \dot{V}\text{O}_2\)-HR slopes when running on a land treadmill at 24-26.5°C, as compared to an ATM at 30.5°C and 36.1°C. For a given \( \dot{V}\text{O}_2\), heart rate is greater at 36.1°C compared to 30.5°C and land. In addition, 30.5°C is significantly greater than land. The difference is greatest when exercising at a heart rate above 140 beats per minute. Therefore, there is reason to believe that the variety of temperatures currently used in the ATM literature could influence the cardiovascular response during exercise. Further investigation into core temperature change during graded exercise and submaximal running at various water temperatures is warranted to ensure the typical temperature range used in cycling is appropriate for ATM running.

It appears that the suggested range of 31-33°C may be appropriate for thermoneutrality during aquatic exercise. However, there are a variety of considerations that must be taken into account including exercise intensity, immersion level, body composition, and the type of exercise. During ATM running, the level of water immersion and the mode of exercise are quite different than cycling and swimming with the ability to influence heat exchange. Therefore, more investigations incorporating ATM running in order to determine adequate temperature ranges to avoid a superimposed metabolic response are warranted. As is evident from the literature, research often incorporates large temperature ranges to compare the cardiovascular
response. Exploring a smaller range of water temperatures is necessary to understand the cardiovascular alterations that occur during ATM running using a water temperature range that could represent day-to-day variations in an applied setting. Further, body composition should be given greater attention in future investigations during ATM running. Lastly, a range of water temperatures above or below thermoneutral water temperature can be used in order to alter the metabolic and thermal response in order to possibly influence chronic adaptations to ATM running.

2.3 Standardized Criteria for ATM Running Prescription and Testing

$\dot{V}O_{2\text{max}}$ has been regarded as the gold standard measure of cardiorespiratory fitness (Shephard et al., 1968; Midley & Carroll, 2009), ever since the work of Hill and Lupton (1923). The determination of $\dot{V}O_{2\text{max}}$ has become one of the most widely used test procedures in exercise physiology laboratories (Howley et al., 1995). The attainment of $\dot{V}O_{2\text{max}}$ typically requires participants to continue an incremental exercise test until they reach their limit of tolerance (Wagner, 2000). A potential problem arises when attempting to determine if participants terminated the test early and possibly have not elicited a true $\dot{V}O_{2\text{max}}$. It has been suggested that the limits of cardiac function and muscle vasoconstriction contribute to the inability of the circulatory system to meet the increasing oxygen demand of skeletal muscles and other tissues during incremental exercise to maximal exertion (Midgley & Carroll, 2009). Additionally, it has been suggested that the participant’s motivation to continue to a maximal effort may be another limiting factor during testing due to the relatively high level of discomfort (Wyndham et al., 1959).
Criteria have been suggested in order to determine whether an individual has achieved a true \( \dot{V}O_2_{\text{max}} \). The primary criteria for achievement of \( \dot{V}O_2_{\text{max}} \) is the \( \dot{V}O_2 \) plateau as proposed by Taylor et al. (1955) who observed that in response to multiple bouts of exercise, each with a higher workload than the previous bout, an upper limit of oxygen uptake per unit of time was reached, despite typically being able to exercise at even higher workloads. It has been reported that an increase of less than 150 milliliters per minute with an increase in intensity suggests that \( \dot{V}O_2 \) has leveled off and that there is a small chance of making an error in deciding if \( \dot{V}O_2_{\text{max}} \) has been achieved (Taylor, Buskirk & Henschel, 1955). However, the absence of a \( \dot{V}O_2 \) plateau does not necessarily suggest that a maximum effort has not been given or a true \( \dot{V}O_2_{\text{max}} \) was not elicited (Midgley & Carroll, 2009). One persuasive piece of evidence highlighting the limitation of \( \dot{V}O_2 \) plateau criterion is that individuals who perform two identical continuous incremental tests can demonstrate a \( \dot{V}O_2 \) plateau in only one of the tests, despite negligible differences in \( \dot{V}O_2_{\text{max}} \) during the two tests (Katch et al., 1982; Midgley et al., 2006).

In addition to the \( \dot{V}O_2 \) plateau, secondary criteria are often used to help determine if a true \( \dot{V}O_2_{\text{max}} \) has been achieved. Traditional secondary criteria include the attainment of arbitrary thresholds for maximal values of the respiratory exchange ratio and heart rate during the graded exercise test, as well as post-test blood lactate concentration (Midgley et al., 2007b). The values most commonly used for attainment of these secondary criteria are a respiratory exchange ratio of 1.10, a peak heart rate within ten beats per minute of the age-predicted maximum heart rate, and a post-test blood lactate level of at least eight millimoles (Howley, Bassett & Welch, 1995). Other commonly used criteria include respiratory exchange ratio of 1.00 or 1.15, a heart rate of less than 5% of the age-predicted maximum, and blood lactate of 8–10 millimoles (Astrand & Rodahl, 1986; Horton, Grunwald, Lavelly & Donahoo, 2006; McArdle, Katch & Katch, 1996;
Poole, Gaesser, Hogan, Knight & Wagner, 1992; Poole et al., 1991; Powers & Howley, 1997; Robergs & Roberts, 1997; Smith & Jones, 2001). These secondary criteria can be satisfied at a $\dot{V}O_2$ that is much lower than the individual’s eventual $\dot{V}O_{2\text{max}}$ attained during the test, even as low as 73% $\dot{V}O_{2\text{max}}$ (Poole et al., 2008). Therefore, these criteria are limited due to their lack of specificity in identifying those who have not exercised to their limit of tolerance. In contrast, due to considerable between-subject variation in physiological response individuals may not satisfy one criteria even when a maximal effort is given (Midgley & Carroll, 2009). It has been suggested that the secondary criteria to verify $\dot{V}O_{2\text{max}}$ attainment should be limited in their use as they do not discern between individuals who do and do not reveal a plateau in $\dot{V}O_2$ at $\dot{V}O_{2\text{max}}$ (Astorino, 2009).

These secondary criteria may become even more limited when considering their application to ATM graded exercise tests. As mentioned previously, maximal heart rate has repeatedly been found to be lower during water immersion exercise compared to land. Respiratory exchange ratio at maximal exercise has shown to be no different (Silvers et al., 2007; Schaal et al., 2012; Watson et al., 2012), or lower (Greene et al., 2011) during ATM running. Silvers et al. (2007) reported no difference in peak blood lactate during ATM and LTM running and Watson et al. (2012) reported no significant difference in maximum blood lactate during ATM and LTM running (13.6 ± 1.13 vs 15.80 ± 5.64, respectively), however significance criterion may have been too restrictive as alpha was set at $p<0.001$ and the ATM lactate values was over 2.0 mmol/L lower. In a reliability study for maximal graded exercise tests on an ATM, Silvers and Dolny (2008) suggested that 75% of participants achieved a plateau, and 47%, 85%, and 95% of participants achieved a maximal heart rate of within five beats of age-predicted maximum heart rate, a respiratory exchange ratio of 1.10, and a blood lactate of nine millimoles.
per litre, respectively. These results are in agreement with previous findings as age-predicted maximum heart rate from a land-based calculation would be challenging to achieve, and the possible lower respiratory exchange ratio and blood lactate would make satisfying these criteria incomparable with LTM running regardless of whether a true $\dot{V}O_{2\text{max}}$ was achieved. These results support the recommendation to develop altered criteria that are appropriate for ATM graded exercise tests.

More recently verification phases have become increasingly popular to verify that a true $\dot{V}O_{2\text{max}}$ has been achieved. The verification phase was originally proposed by Thoden, MacDougall and Wilson (1982) and was termed the “exhaustive phase”, later changing the name to verification phase (Thoden, 1991). Originally, it was suggested that after completing a graded exercise test the participant recovers for 15 minutes prior to completing a constant bout of exercise at the intensity equivalent to the last completed stage to the limit of tolerance (Thoden et al., 1982). The original verification stage guidelines were later updated and a recovery of 5 to 15 minutes, in order to obtain a heart rate of 100 beats per minute, was completed prior to implementing a constant workload at an intensity that is one stage higher than the last completed stage during the graded exercise test (Thoden, 1991). If a graded exercise test lasts less than eight minutes, it has been recommended to complete the verification phase at the same intensity of the last completed stage. Since the original proposed protocol, investigations have compared various verification phase intensities and recovery periods.

In a study by Rossiter, Kowalchuk and Whipp (2006) participants cycled at 105% of the peak power output achieved in the ramp protocol following five minutes of active recovery at 20 watts. It was concluded that the insignificant difference between the maximal $\dot{V}O_2$ values in the two test phases satisfied the primary criterion for achieving $\dot{V}O_{2\text{max}}$, even though the individual
test phases did not exhibit a plateau (Rossiter et al., 2006). On a separate occasion, the participants completed the same verification phase, except at 95% peak power output. It was determined that both intensities are equally effective at verifying $\dot{V}O_{2\text{max}}$, however, only the supramaximal verification phase can be recommended since the submaximal phase does not conform to the original concept of $\dot{V}O_{2\text{max}}$. Regardless of the protocol, the verification phase should incorporate a workload higher than that in the graded exercise test to conform to the original concept of $\dot{V}O_{2\text{max}}$ (Hill & Lupton, 1923). One risk of completing the verification phase at a higher intensity is that the duration of the verification phase may be shorter which may bring into question the efficacy of eliciting $\dot{V}O_{2\text{max}}$, especially in untrained participants with slow $\dot{V}O_2$ kinetics (Caputo et al., 2003). However, subsequent research by Rossiter et al. (2006) supported the premise that generally, two minutes of supramaximal exercise can be sufficient to elicit $\dot{V}O_{2\text{max}}$. A supramaximal verification phase was used to verify three different test protocols (Midgley, McNaughton & Carroll, 2007). These protocols included one continuous and two discontinuous protocols with mean durations of 10 minutes to 30 minutes. Although the graded exercise tests were distinctly different, the mean maximal $\dot{V}O_2$ values during the verification phases were almost identical (Midgley et al., 2007). This study helped suggest that the verification phase is independent of the incremental test protocol (Midgley & Carroll, 2009).

Foster et al. (2007) examined shorter recovery periods using recovery phases of one minute in non-athletes and three minutes for runners, which was shorter than the traditionally used five and 10-minute recovery periods (Midgley, McNaughton & Carroll, 2006; Midgley et al., 2007; Rossiter et al., 2006). The difference in mean maximal $\dot{V}O_2$ values attained during the graded exercise test and the verification phase were negligible and suggested that short recovery phases do not detract from the efficacy of the verification phase (Foster et al., 2007).
In addition to corresponding maximal $\dot{V}O_2$ values in the graded exercise test and the verification phase, it has been suggested that maximal heart rate values for the graded exercise test and verification phases that agree within two beats per minute of each other provide a high degree of confidence that maximal effort has been given (Midgley et al., 2006). Maximal heart rate verification is advantageous because it is not affected by the inaccuracy associated with age-predicted maximal heart rate (Londeree & Moeschberger, 1984). However, the verification phase may be too short for some participants to obtain their maximal heart rate, so it has been suggested that further validation is required before maximal heart rate verification can be recommended as a valid $\dot{V}O_2_{max}$ criterion (Midgley & Carroll, 2009).

Therefore, it appears that the verification phase is a robust test to use in order to confirm a true $\dot{V}O_2_{max}$ has been achieved. Current research suggests that the verification phase is well tolerated in athletic and apparently healthy sedentary populations (Midgley & Carroll, 2009). To date, a verification phase has not been completed in any ATM graded exercise tests to confirm $\dot{V}O_2_{max}$.

In addition to the previously discussed criteria, there are other factors that can influence the determination of a true $\dot{V}O_2_{max}$. Three main factors include sampling rate, stage and test duration, and revolutions per minute when completing a test on a cycle ergometer. The choice of $\dot{V}O_2$ sampling rate can have a profound effect on the $\dot{V}O_2$ values obtained (Myers, Walsh, Sullivan & Froelicher, 1990; Astorino, 2009). It has been demonstrated that small sampling intervals (i.e. 5-10 seconds) result in unacceptable variability, whereas intervals that are too large (i.e. 60 seconds) may be too imprecise for accurately determining quickly changing $\dot{V}O_2$ responses during a graded exercise test (Myers et al., 1990). $\dot{V}O_2$ plateau occurrence was higher using breath-by-breath (81%), 15-second time averaging (91%) and 30-second time averaging.
(89%) compared to 60-second time averaging (59%) (Astorino, 2009). It has been suggested that a 30-second sampling rate appears to provide the best compromise between precision and reliability for $\dot{V}O_{2\text{max}}$ determination (Midgley et al., 2007), as it reduces noise caused by large breath-by-breath fluctuations (Myers et al., 1990; Potter, Childs, Houghton & Armstrong, 1999), as well as minimizes the influence of longer averages (i.e. 60-seconds) that may be excessively smoothed and may result in artificially depressed $\dot{V}O_{2\text{max}}$ values (Johnson, Carlson, Vanderlaan & Langholz, 1998). Similarly, a 30-second time interval may better reflect the physiological response and help to avoid artificially elevated $\dot{V}O_{2\text{max}}$ values (Midgley, McNaughton & Carroll, 2007). Therefore, a 30-second sampling rate appears to be optimal for $\dot{V}O_{2\text{max}}$ determination (Midgley, McNaughton & Caroll, 2007; Bassett & Howley, 1997; Hill, Stephens, Blumoff-Ross, Poole & Smith, 2003).

Numerous studies investigating various stage durations have been conducted in order to determine the influence on $\dot{V}O_{2\text{max}}$ (Smith, Skelton, Kremer, Pascoe & Gladden, 1998; Froelicher, Brammell, Davis, Noguera, Stewart & Lancaster, 1974; Whipp, Davis, Torres, & Wasserman, 1981; Buchfuhrer, Hansen, Robinson, Sue, Wasserman & Whipp, 1983; Stockhausen, Grathwohl, Bürklin, Spranz & Keul, 1997; Yoshida, 1986; Kim, Ichimaru, Kakimura & Ishii, 1988; Coen, Urhausen & Kindermann, 2001; Bentley & McNaughton, 2003; Amann, Subudhi & Foster, 2004; Bishop, Jenkins & Mackinnon, 1998; McNaughton, Roberts & Bentley, 2005; Pierce, Hahn, Davie & Lawton, 1999). It has been supported that stage durations of 60-seconds and three minutes produced no difference in measured $\dot{V}O_{2\text{max}}$ (Pierce et al., 1999; Bishop et al., 1998). It has also been recommended that incremental exercise protocols compromising of stages of three minutes in duration may induce more valid blood lactate and respiratory responses (Bentley, Newell & Bishop, 2007). Additionally, incremental exercise
protocols comprising three minute stages can be used to measure maximal cardiorespiratory values and can be coupled to measure valid submaximal variables, such as aerobic and anaerobic thresholds (Bentley, Newell & Bishop, 2007). Therefore, the use of three minute stages offers the opportunity to determine maximal \( \dot{VO}_2 \) values, as well as determine the two ventilatory threshold points by analysis of respiratory exchange data that can be used for prescribing exercise intensity in training (Bentley, Newell & Bishop, 2007).

A key component of completing a graded exercise test is ensuring that each stage has an increased work rate. During treadmill running, intensity can be increased with the speed of the belt or incline, whereas during cycling and ATM running an external resistance is required. Due to the external resistance, it is important to ensure that the work rate is increased and not only the resistance. During cycling, it is required that a certain cadence is maintained even with an increased resistance, such as 50 or 60 revolutions per minutes (Foster, Kuffel, Bradley, Battista, Wright, Porcari, Lucia & deKoning, 2007; Poole, Wilkerson & Jones, 2008). If the participant drops below this cadence, the test may be terminated. During ATM running, there are currently no criteria to determine whether work rate is increased concurrently with the increase in resistance. One proposed method is to determine the position at which the running distance from the resistance jet produces the greatest metabolic demand and subsequently determine the distance from this point that is a significantly lower metabolic requirement. Currently, a few studies (Silvers, Rutledge & Dolny, 2007; Silvers & Dolny, 2008; Rutledge, Silvers, Browder & Dolny, 2007) include the running position in the methods (i.e. one meter from the resistant jet), however, there is no scientific rationale for this position.

To this point, no studies have determined the occurrence of ventilatory thresholds during ATM running and how these points may differ compared to LTM running. Considering that the
hydrostatic pressure of the water causes fluid shifts into the intravascular space, blood lactate measurements may be less relevant during aquatic exercise due to changes in concentration. In contrast ventilation is not restricted by increased intrathoracic blood volume and hydrostatic compression of the chest during water immersion (Alberton et al., 2014). Previous literature has shown a significantly lower blood lactate in water exercise over 80% VO₂max compare to land (Connelly et al., 1990), however ventilation appears to remain similar to land at multiple intensities and water temperatures (McArdle, Magel, Lesmes & Pechar, 1976).

Ventilatory thresholds can be determined using the ventilatory equivalents method where the first and second ventilatory thresholds are determined through the curves of the $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/VCO_2$, respectively (Davis, 1985). During initial increments of the exercise test both the ventilatory equivalents for oxygen ($\dot{V}_E/\dot{V}O_2$) and carbon dioxide ($\dot{V}_E/VCO_2$) decrease due to changes in the physiological dead space and tidal volume ratio. As arterial lactate values begin to increase at the anaerobic threshold, blood bicarbonate concentrations decrease and the non-metabolic CO₂ produced from the buffering of the developing metabolic acidosis cause ventilation and VCO₂ to increase out of proportion to $\dot{V}O_2$. As a result, $\dot{V}_E/\dot{V}O_2$ reaches a minimum value at the anaerobic threshold, increasing progressively thereafter with further increments in intensity (McLellan, 1987). The ventilatory threshold is the stage or exercise intensity corresponding to a systematic increase in the ventilatory equivalent of oxygen ($\dot{V}_E/\dot{V}O_2$) without a concomitant increase in the ventilatory equivalent of carbon dioxide ($\dot{V}_E/VCO_2$) (Wasserman & McIlroy, 1964).

It has been demonstrated that the ventilatory equivalents method of determining ventilatory threshold is highly correlated with lactate thresholds in endurance athletes, active adults, and sedentary adults ($r^2 = 0.92, 0.90, 0.78$, respectively) (Gaskill, Ruby, Walker, Sanchez,
Further, paired t-tests determined that there was no difference between lactate threshold and ventilatory threshold in any of these populations (Gaskill et al., 2001) and the first and second ventilatory thresholds identified through the ventilatory equivalents method are similar with one-minute, three-minute, and five-minute stages (McLellan, 1985). It has been proposed that assessing the anaerobic threshold using ventilatory markers rather than lactate analyses may be superior as 1) ventilation may be a more sensitive indication of hydrogen ion concentration than blood lactate concentration, 2) ventilation is not only influenced by the central and peripheral chemoreflex control, but also by central and/or peripheral neurogenic control, which can be linked to muscular fatigue, and 3) following an increase in work rate, gas exchange and ventilatory response stabilize after only 30 to 40 seconds (Ward, 2000), whereas lactate equilibrium may take 10 minutes (Rusko et al., 1986; Amann, Subudhi & Foster, 2006).

Ventilatory thresholds have been compared during land and water exercise (Frangolias & Rhodes, 1995; Alberton et al., 2013; Alberton et al., 2014), however, no studies have compared the occurrence of the ventilatory thresholds during ATM running. Studies using deep water running and water calisthenics have reported a lower (Alberton et al., 2013; Frangolias & Rhodes, 1995) or similar (Alberton et al., 2014) \( \dot{V}O_2 \) at the first ventilatory threshold in water. The second ventilatory threshold occurs at a lower \( \dot{V}O_2 \) in water (Alberton et al., 2014; Alberton et al., 2013). Of interest, when considering the percent of \( \dot{V}O_{2\text{max}} \) at the second ventilatory threshold, there appears to be no difference between air and water (Alberton et al., 2013; Alberton et al., 2014). Comparing percent of \( \dot{V}O_{2\text{max}} \) at the first ventilatory threshold, it has been reported that there is either no difference between air and water (Alberton et al., 2013; Frangolias & Rhodes, 1995) or that the first ventilatory threshold occurs at a higher percentage of \( \dot{V}O_{2\text{max}} \) in water (Alberton et al., 2014). During ATM running \( \dot{V}O_{2\text{max}} \) has repeatedly been shown to be
comparable to LTM running (Silvers, et al., 2007; Greene et al., 2011; Watson et al., 2012; Schaal et al., 2012). Therefore, one may expect that the ventilatory thresholds will occur at the same \( \dot{V}O_2 \) and percent of \( \dot{V}O_{2\max} \) in air and water.

In addition, it appears that there is no difference between the percent of maximal heart rate at the first and second ventilatory threshold on land and in water (Alberton et al., 2014). However, a maximal exercise test must be completed in the water to obtain maximal heart rate values as research has often shown heart rate to be lower at maximal exercise in water (Greene et al., 2011; Schaal et al., 2012; Christie et al., 1990). Additionally, ratings of perceived exertion appear to be the same at the first and second ventilatory threshold (Alberton et al., 2013; Frangolias & Rhodes, 1995).

During ATM compared to LTM running, Garner et al. (2014) found that the lactate threshold point occurred at a lower heart rate and \( \dot{V}O_2 \) during ATM running. During the study, the lactate-\( \dot{V}O_2 \) curve was shifted up and to the left during ATM running, demonstrating that lactate levels of two and four millimoles per litre were achieved at a lower \( \dot{V}O_2 \) during ATM running (Garner et al., 2014). It has been previously suggested that the point of occurrence of the onset of blood lactate accumulation and even the lactate threshold in the ATM environment may depend upon the water jet percentage selected (Garner et al., 2014; Watson et al., 2012).

Therefore, it appears that lactate is not a very robust measure for the prescription of exercise during ATM training. In contrast, the ventilation to \( \dot{V}O_2 \) curve has been shown to be similar during land and aquatic graded exercise tests, even at various water temperatures (McArdle et al., 1976). Determining of the occurrence of the ventilatory thresholds may be more appropriate for ATM running as compared to lactate thresholds in order to guide exercise prescription and monitor adaptations.
2.4 Anthropometrical Considerations during Aquatic Exercise

Heat storage is a change in the body’s heat content and the rate of heat storage is the difference between heat gain and heat loss taking into consideration all of the avenues listed previously. The body’s mean specific heat depends on its composition, especially the proportion of fat (Wenger, 1997). The relationship between an individual’s body composition and thermal response has often been reported during water immersion and several investigators have demonstrated the insulating benefits of body fat during exercise in cold water (Holmer & Bergh, 1974; Nadel, Holmer, Bergh, Astrand & Stolwijk, 1974). The most important factor for a nude person in reducing body cooling in cold water is the thickness of cutaneous fat (Keatinge, 1969; Nadel et al., 1974; Pugh & Edholm, 1955). McArdle et al. (1976) noticed that in 25°C water, the three leanest participants complained of cold discomfort and were noticeably shivering during submaximal work. However, the two participants with the largest percentage of body fat showed no difference in $\dot{V}O_2$ in 25°C water compared 33°C water and air at 25°C. In addition, these individuals did not appear to have any discomfort in the cooler water. In 18°C water all participants except one were uncontrollably shivering at rest and with submaximal work (McArdle et al., 1976). At maximal exercise, no participants complained of cold discomfort and the participants with a higher percentage of body fat were sweating at the face in 33°C and 25°C water (McArdle et al., 1976).

In a second cycling investigation, body temperature was measured in two individuals of varying composition at multiple water temperatures and land at 22°C (Craig & Dvorak, 1969). The individual with a smaller average skin fold thickness (9.3mm vs. 21.7mm) increased body temperature in air by 0.1°C and 0.3°C in two trials, however, body temperature decreased in
22°C, 25°C, 30°C and 32°C water by -2.7°C, -1.6°C, - 0.9°C and – 0.4°C, respectively. Body temperature only increased at 34°C water immersion by 0.4°C. The individual with the higher skin fold thickness had body temperature increases of 0.5°C and 0.6°C in air, and decreases in body temperature in 22°C, 25°C and 30°C of -2.1°C, - 1.7°C and -0.5°C, respectively.

Interestingly, this individual expressed a strong desire to avoid exercising in 32°C and 34°C water. Previous literature suggests that for each individual with a given skinfold thickness, a water temperature exists in which heat derived by muscular work is not balanced by the heat losses induced by an elevated convective heat-transfer coefficient (Holmer & Bergh, 1974). This water temperature is influenced by the clothing worn (Keatinge, 1969), flowing water (Nadel et al., 1974), and body movement during exercise (Keatinge, 1969). Therefore, the influence of anthropometrics during ATM running is critical to understand the thermal and metabolic response between investigations and water temperatures, however, these data are often not reported.

Specific to ATM running, data on the influence of anthropometrics is scarce. Anthropometric measures are more commonly collected for the purpose of participant description or adaptation over a training program, and are at times mentioned as a possible rationale for various physiological outcomes, however, it is less common for anthropometrics to be part of the statistical analyses during ATM running. Rutledge et al. (2007) noted that in all of their trials, men tended to have a higher \( \dot{V}O_2 \) (reported in mL·kg·min\(^{-1}\)) than women which the authors suggested might be attributed to the fact that females in the study had a greater average body-fat percentage compared to men. It was stated that the lower body density would increase buoyancy in the females and could decrease their metabolic cost (Rutledge et al., 2007).
Additionally, men were taller and heavier in this study which would lead to a larger frontal area and could increase drag force, specifically when the legs swing forward during the stride cycle in water (Rutledge et al., 2007). Porter et al. (2014) also collected anthropometric measures on participants. During walking on an aquatic treadmill, it has been reported that body mass index scores could account for buoyancy and therefore a lower $\dot{V}O_2$ (Porter, Alkurdi, & Dolny, 2011). As suggested by Porter et al. (2014) measures of adiposity should be taken into consideration when attempting to predict metabolic cost during ATM exercise.

As with other responses, ATM running differs from water immersed cycling in many ways that are influenced by anthropometric measures. For example, more of the body surface area is exposed to ambient air during ATM running which could influence the thermal response, the depth of immersion and the buoyancy properties of the water could influence the metabolic response, and the resistance jets could affect larger individuals more with increased surface area. Taking these factors into consideration, an increased understanding of how individual body composition influences the physiological response specific to ATM running is necessary to fully compare results of future studies and prescribe individualized exercise training.
Chapter 3: The Cardiorespiratory Response to Aquatic Treadmill Running: A Systematic Review and Meta-Analyses

3.1 Introduction

The use of water immersion, either passive or active, for injury rehabilitation, chronic pain, various musculoskeletal diseases, and sports training is well established (Hall et al., 2008; Lee & Yi, 2019; Held et al., 2019). The prescription of aquatic exercise has become frequently incorporated into physical rehabilitation programs as a means for enhancing exercise participation in individuals at risk for falling (Waller et al., 2016) and in individuals with musculoskeletal impairment (Binkley & Rudd, 2019; De Mattos et al., 2016). Commonly utilized forms of aquatic exercise may include; deep water running, shallow water running, water immersed cycling, and water calisthenics. However, the use of aquatic treadmills (ATM) in injury management, and more specifically in exercise prescription, is less understood. ATMs are becoming increasingly accessible and frequently utilized in rehabilitation, conditioning, and recovery protocols as evidenced by increases in the number of specialized therapy pools in North America. ATMs can place great demand on the cardiovascular and musculoskeletal systems while mitigating the weight bearing effect of repeated exercise movements (Moening, Scheidt, Shepardson, & Davies, 1993). The reduction in weight-bearing exercises when immersed has shown to be dependent on the level of submersion, whereby immersion up to the anterior superior iliac spine, xiphoid process, and the seventh cervical vertebra have elicited reductions in limb loading by 57%, 71%, and 85%, respectively (Harrison, Hillman, & Bulstrode, 1992). Although the efficacy for prescription of aquatic exercise during physical rehabilitation is well
established, the cardiorespiratory response while performing walking or running exercise when immersed as compared to performing these exercise on land remains less understood.

It is well documented that hydrostatic pressure on the body during water immersion promotes an immediate increase in intrathoracic blood volume and a concomitant improvement in venous return (Gabrielsen, Johansen, & Norsk, 1993; Risch, Koubene, Beckmann, Lange, & Gauer, 1978; Khosla & DuBois, 1979). These transient responses have shown to augment both cardiac preload and stroke volume while promoting a reduction in heart rate (Christie et al., 1990; Norsk, Bonde-Petersen, & Christensen, 1990). In addition, hydrostatic pressure has also been found to influence respiratory performance as observed through lung mechanics (Moon, Cherry, Stolp, & Camporesi, 2009). These fluid shifts may alter the cardiovascular response to exercise compared to land depending on exercise mode and intensity.

Metabolic demand can be influenced during ATM running by adjusting the level of water immersion, belt speed, water temperature, and by further increasing the water resistance with pump driven water jets. In the current literature, there are discrepancies in the cardiorespiratory responses during ATM running compared to land treadmill (LTM) running due to a variety of protocols, water immersion levels, running positions, and water temperatures utilized in various studies. A better understanding of the cardiovascular and respiratory responses to ATM running is necessary to better incorporate ATMs into exercise protocols whether in rehabilitation settings or high-performance sport. Therefore, the purpose of this review was to compare the cardiovascular and respiratory responses while running on an ATM to LTM in healthy individuals during both maximal and submaximal exercise. Furthermore, a second aim was to complete a meta-analysis in order to compare the cardiorespiratory responses between running on an ATM and LTM for a matched metabolic demand with chest level immersion.
Cardiovascular measures included heart rate, \( \dot{\text{VO}}_2 \), blood lactate, respiratory exchange ratio, and ratings of perceived exertion. Respiratory measures included ventilation, respiratory rate, and tidal volume.

### 3.2 Methods

#### Review Protocol

This review was designed using the guidelines set forth by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to enhance its transparency while limiting the risk of publication and selection bias (Liberati et al., 2009).

#### Inclusion and exclusion criteria

A thorough, systematic approach was used to compare the cardiorespiratory responses of running on an ATM versus a LTM. Studies were eligible for inclusion if they examined cardiorespiratory measures during ATM running in healthy human participants. Studies were excluded if the investigations included the following; 1) those utilizing equipment other than shoes to increase drag or resistance, 2) studies without human participants, 3) studies completed without the use of an ATM with a motor-driven belt, 4) case studies, 5) review studies, and 6) studies not collecting cardiorespiratory measurements during exercise trials.

#### Data Sources

An electronic search was conducted that included all publications years up to and including December 2019. Databases used to conduct a systematic literature search included MEDLINE (1966 – present), SPORTDiscus (1930 – present) and EMBASE (1947 – present).
Search Strategy

Broad, inclusive subject headings and key words were used as search terms to identify appropriate studies. Key search terms were produced from reviewing previous literature and using a number of synonyms for Exercise (exercise test, exercise tolerance, exercise therapy), were grouped and searched within the article title and abstract, and keywords using the search conjunction ‘OR’. Combinations of the following terms were used as search terms: ‘exercise”, ‘water treadmill’ ‘underwater treadmill’ ‘hydrotherapy’ ‘aqua* treadmill. Details of the search strategy are provided in Table 3.1.
Table 3.1 Details of the search strategy

MEDLINE (via OVID)

<table>
<thead>
<tr>
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<th>Search history</th>
<th>Results</th>
</tr>
</thead>
<tbody>
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<td>210923</td>
</tr>
<tr>
<td>2</td>
<td>Water treadmill</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>Underwater treadmill</td>
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<td>4</td>
<td>Hydrotherapy (exploded)</td>
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<tr>
<td>5</td>
<td>Aqua* treadmill</td>
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</tr>
<tr>
<td>6</td>
<td>2 or 3 or 4 or 5</td>
<td>18554</td>
</tr>
<tr>
<td>7</td>
<td>1 AND 6</td>
<td>413</td>
</tr>
<tr>
<td>8</td>
<td>Limits of English language, Humans, Journal Article</td>
<td>283</td>
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</table>

EMBASE (via OVID)

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<tr>
<td>2</td>
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<td>3</td>
<td>Underwater treadmill</td>
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<tr>
<td>4</td>
<td>Hydrotherapy (exploded)</td>
<td>3785</td>
</tr>
<tr>
<td>5</td>
<td>Aqua* treadmill</td>
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<td>1 AND 6</td>
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<td>Limits of English language, Humans, Journal Article</td>
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</table>

SPORTDiscus (via EBSCO)

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<th>Results</th>
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<td>107577</td>
</tr>
<tr>
<td>2</td>
<td>Water treadmill</td>
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</tr>
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<td>3</td>
<td>Underwater Treadmill</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>Hydrotherapy</td>
<td>258</td>
</tr>
<tr>
<td>5</td>
<td>Aqua* treadmill</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>2 or 3 or 4 or 5</td>
<td>311</td>
</tr>
<tr>
<td>7</td>
<td>1 AND 6</td>
<td>311</td>
</tr>
</tbody>
</table>

* is the truncation character.

Search Limits

The criteria for study inclusion was limited to the following; 1) original investigations and 2) published in English with full-text available. If full-texts were not available, an attempt to contact the author was made via email.
Study selection

Two separate reviewers screened all studies that were identified through the search strategy using a comprehensive multi-step process. At each level of the process, discrepancies were recorded and reassessed by consensus. The number of articles that were excluded at each step of screening was also recorded (Figure 3.1). The combined articles from the three electronic databases were reviewed and duplicates were excluded. Titles and abstracts were then screened for inclusion with a 95.01% agreement between reviewers. Once all of the studies were identified following the abstract screening, full-text were obtained. If a full-text article was not available, an attempt was made to contact the author via email. Full-text articles were screened in full by two reviewers for inclusion with a 100% agreement between reviewers. A reason for an excluded article during full-text was noted (Figure 3.1). A thorough review of the references of the included papers was completed by two reviewers to identify additional studies that were eligible for inclusion.
Figure 3.1 PRISMA diagram
Data Collection Process

All search results were downloaded and organized using an online bibliographic management program (RefWorks, Bethesda, MD, USA).

Data Extraction

Data was extracted from the included studies using a standardized extraction form and was confirmed by two reviewers. The focus of the extraction was primarily on the comparison of cardiorespiratory responses during running on an ATM and a LTM. Consensus was reached through discussion as necessary. Data extraction included the study design, the purpose, the sample size, and participant characteristics (Table 3.2), as well as the cardiorespiratory responses to running on an ATM and a LTM including heart rate, $\dot{V}O_2$, blood lactate, rating of perceived exertion, respiratory exchange ratio, ventilation, tidal volume, and respiratory rate when measured.
<table>
<thead>
<tr>
<th>Publication</th>
<th>Study Design</th>
<th>Purpose</th>
<th>Population</th>
<th>Sample Size</th>
<th>Age, years (mean ± SD[Range])</th>
<th>VO_{2max} (mL·kg^{-1}·min^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silvers et al., 2007</td>
<td>Randomized cross-over</td>
<td>To evaluate the peak cardiorespiratory responses to maximal-effort exercise during ATM and LTM running.</td>
<td>Recreationally competitive runners</td>
<td>N=23</td>
<td>Male: 24.8 ± 3.8 [19-33]</td>
<td>52.8 ± 7.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Female: 22.1 ± 2.3 [19-26]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rutledge et al., 2007</td>
<td>Randomized cross-over</td>
<td>1. To determine the effect of varying ATM speeds and jet resistances.</td>
<td>University of Idaho undergraduate exercise class students and members from the varsity track and field team.</td>
<td>N=15</td>
<td>Male: 24.63 ± 4.57</td>
<td>Male: 59.08 ± 1.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. To determine the running speed on a LTM that elicited comparable metabolic costs.</td>
<td></td>
<td>Female: 19.38 ± 1.19 [19-26]</td>
<td>Female: 44.17 ± 5.59</td>
<td>Female: 53.24 ± 8.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total: 22 ± 4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porter et al., 2014</td>
<td>Randomized cross-over</td>
<td>To compare running on a LTM at specific inclines with an ATM at equivalent running speeds with selected jet resistances.</td>
<td>Well-trained runners</td>
<td>N=17</td>
<td>* 1 participant was unable to complete the study due to illness, however the gender was not reported on</td>
<td>26 ± 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(9 male; 8 female)</td>
<td></td>
<td>53.53 ± 8.33</td>
</tr>
<tr>
<td>Publication</td>
<td>Study Design</td>
<td>Purpose</td>
<td>Population</td>
<td>Sample Size</td>
<td>Age, years (mean ± SD[Range])</td>
<td>( \dot{\text{VO}}_{2\text{max}} ) (mL·kg(^{-1})·min(^{-1}))</td>
</tr>
<tr>
<td>-----------------------------</td>
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<td>-------------------------------------------------------------------------</td>
<td>------------------------------------------------------</td>
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<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Pohl &amp; McNaughton, 2003</td>
<td>Cross-over</td>
<td>To compare the physiological responses of ATM and LTM exercise at two different depths of water</td>
<td>Recreational active students</td>
<td>N=6</td>
<td>23.2 ± 2.9</td>
<td>Not reported</td>
</tr>
<tr>
<td>Garner et al., 2014</td>
<td>Randomized cross-over</td>
<td>To compare the lactate threshold while running on an ATM versus LTM</td>
<td>Recreational active runners.</td>
<td>N=15</td>
<td>Male: 27.1 ± 3.4</td>
<td>Male: 53.3 ± 6.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Female: 23.9 ± 5.4</td>
<td>Female: 45.2 ± 5.9</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total: 25.6 ± 4.6</td>
<td>Total: 49.5 ± 7.1</td>
</tr>
<tr>
<td>Brubaker et al., 2011</td>
<td>Randomized cross-over</td>
<td>To determine the cardiorespiratory responses of ATM versus LTM exercise.</td>
<td>College athletes</td>
<td>N=11</td>
<td>20.8 ± 0.6</td>
<td>Not reported</td>
</tr>
<tr>
<td>Silvers et al., 2014</td>
<td>Exploratory, cross-over</td>
<td>To compare normalized, absolute duration, and total lower-extremity muscle activity during ATM and LTM running at the same speeds.</td>
<td>Recreational male runners</td>
<td>N=12</td>
<td>25.8 ± 5</td>
<td>Not reported</td>
</tr>
<tr>
<td>Publication</td>
<td>Study Design</td>
<td>Purpose</td>
<td>Population</td>
<td>Sample Size</td>
<td>Age, years (mean ± SD[Range])</td>
<td>( \dot{V}O_2^{\text{max}} ) (mL·kg(^{-1})·min(^{-1}))</td>
</tr>
<tr>
<td>--------------------------------</td>
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<td>--------------------------------------------------------------------------</td>
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<tr>
<td>Schaal, Collins &amp; Ashley, 2012</td>
<td>Cross-over</td>
<td>To compare cardiorespiratory responses between ATM and LTM running.</td>
<td>Experienced triathletes</td>
<td>N=14</td>
<td>35.1 ± 9.8 [20-46]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Rife et al., 2010</td>
<td>Randomized, cross-over</td>
<td>To establish ATM running parameters with and without shoes needed to obtain known LTM cardiorespiratory responses.</td>
<td>Trained runners</td>
<td>N=18</td>
<td>Male: 23.0 ± 3.2 Female: 21.6 ± 1.1 Total: 22.3 ± 2.4</td>
<td>Male: 59.6 ± 4.6 Female: 50.9 ± 2.9 Total: 55.3 ± 5.8</td>
</tr>
<tr>
<td>Watson et al., 2012</td>
<td>Cross-over</td>
<td>To determine the response of four graded exercise tests performed on an ATM compared to a LTM.</td>
<td>NCAA Division I ice hockey players</td>
<td>N= 12</td>
<td>20.92 ± 1.5 [18-22]</td>
<td>55.7 ± 5.92</td>
</tr>
<tr>
<td>Greene et al., 2011</td>
<td>Randomized, cross-over</td>
<td>1. To compare the cardiorespiratory responses to submaximal and maximal exercise on an ATM and LTM at different jet intensities. 2. To develop an equation to estimate ( \dot{V}O_2 ) during ATM exercise.</td>
<td>Healthy participants</td>
<td>1. N=49</td>
<td>Male: 42 ± 14 Female: 40 ± 14 Total: 41 ± 14</td>
<td>1. Male: 33.02 ± 8.63 Female: 27.55 ± 7.90 Total: 30.09 ± 8.59</td>
</tr>
<tr>
<td>Publication</td>
<td>Study Design</td>
<td>Purpose</td>
<td>Population</td>
<td>Sample Size</td>
<td>Age, years (mean ± SD[Range])</td>
<td>$\dot{V}O_{2\text{max}}$ (mL·kg$^{-1}$·min$^{-1}$)</td>
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</tr>
<tr>
<td>Gleim &amp; Nicholas, 1989</td>
<td>Randomized, cross-over</td>
<td>To determine how water depth and temperature changes the linear relationship of oxygen uptake and heart rate.</td>
<td>Physically active participants</td>
<td>Depth: N=11 (6 male; 5 female)</td>
<td>27.5 ± 1.8</td>
<td>Not reported</td>
</tr>
</tbody>
</table>
Level of evidence

A modified Downs and Black scoring system (Downs & Black, 1998) was used to score the quality of the included studies. The questions from the original Downs and Black scoring system that were considered relevant to the topic of this systematic review were included to measure the level of evidence. The questions were predetermined, prior to any scoring of studies, by the reviewers. The scoring of the studies was completed independently by two reviewers and consensus was reached through discussion as necessary. The outcome of the modified Downs and Black scoring system is provided (Table 3.3).
Table 3.3 Modified Downs and Black scoring system

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<td>Rife, 2010</td>
<td>1 1 1 1 1 0 1 1 0 1 1 1 1 1 1 1 1 1 5 19</td>
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<td>Schaal, 2012</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 0 5 19</td>
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<td>Silvers, 2007</td>
<td>1 1 1 1 1 0 1 1 1 1 1 1 1 1 0 0 1 5 18</td>
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<td>Watson et al., 2012</td>
<td>1 1 1 1 1 0 1 1 1 1 1 1 1 0 1 1 1 0 5 18</td>
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<td>Greene, 2011</td>
<td>1 1 1 1 1 0 1 1 1 1 1 1 1 0 1 0 0 1 5 17</td>
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<tr>
<td>8</td>
<td>Pohl, 2003</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 1 16</td>
</tr>
<tr>
<td>9</td>
<td>Porter, 2014</td>
<td>1 1 1 1 1 0 1 1 0 1 1 1 0 1 0 0 0 1 5 16</td>
</tr>
<tr>
<td>10</td>
<td>Rutledge, 2007</td>
<td>1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0 1 16</td>
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<tr>
<td>11</td>
<td>Gleim &amp; Nicholas, 1989</td>
<td>1 1 1 1 1 0 1 1 0 1 1 1 1 1 0 1 1 3 16</td>
</tr>
<tr>
<td>12</td>
<td>Silvers, 2014</td>
<td>1 1 1 1 1 0 1 1 0 1 0 0 1 1 0 0 1 5 15</td>
</tr>
</tbody>
</table>
Summary of Measures

The primary focus of this review was to examine the cardiorespiratory response between ATM and LTM running. Variables included in the meta-analysis were the following; 1) heart rate, 2) \( \dot{V}O_2 \), 3) blood lactate, 4) respiratory exchange ratio, 5) respiratory rate, 6) ventilation, and 7) tidal volume.

Data Synthesis

Group data are displayed as means (±SD). All calculations for the meta-analysis were conducted using an open source software program (Open Meta-Analyst, Center for Evidence-Based Medicine, Brown University School of Public Health, USA). The standardized mean difference, adjusted for small sample size bias (Hedges’ adjusted g) were calculated with a 95% confidence interval using data extracted from the systematically identified manuscripts to compare the differences between cardiorespiratory variables while running on an ATM versus a LTM (Hedges & Olkin, 1985). Effect size thresholds were interpreted as the following; small \( \geq 0.2 \), medium \( \geq 0.5 \), and large \( \geq 0.8 \) (Cohen, 1988).

The trials selected from each manuscript were matched for a given \( \dot{V}O_2 \) in order to ensure there was one constant variable with varying speeds, jet resistances, and inclines between ATM and LTM running. As each manuscript contains comparisons for multiple speeds and resistances between ATM and LTM, each different trial was treated separately for comparison. Forest plots were constructed into subgroups of cardiovascular and respiratory responses to submaximal ATM running and cardiorespiratory responses to maximal ATM running.
Table 3.4 Summary of aquatic treadmill running protocols

<table>
<thead>
<tr>
<th>Publication</th>
<th>Maximal or Sub-Maximal</th>
<th>Depth</th>
<th>Temperature (°C) (mean ± SD[Range])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silvers et al., 2007</td>
<td>Maximal</td>
<td>Xiphoid</td>
<td>28</td>
</tr>
<tr>
<td>Rutledge et al., 2007</td>
<td>Sub-maximal</td>
<td>Xiphoid</td>
<td>28</td>
</tr>
<tr>
<td>Silvers et al., 2014</td>
<td>Sub-maximal</td>
<td>Xiphoid</td>
<td>29.5 ± 0.2</td>
</tr>
<tr>
<td>Garner et al., 2014</td>
<td>Maximal and sub-maximal</td>
<td>Xiphoid</td>
<td>30</td>
</tr>
<tr>
<td>Porter et al., 2014</td>
<td>Sub-maximal</td>
<td>Xiphoid</td>
<td>30</td>
</tr>
<tr>
<td>Rife et al., 2010</td>
<td>Sub-maximal</td>
<td>Chest</td>
<td>32.2 ± 2</td>
</tr>
<tr>
<td>Watson et al., 2012</td>
<td>Maximal and sub-maximal</td>
<td>Xiphoid</td>
<td>33-35</td>
</tr>
<tr>
<td>Schaal et al., 2012</td>
<td>Maximal and sub-maximal</td>
<td>Xiphoid</td>
<td>25.8 [20.6-35.6]</td>
</tr>
<tr>
<td>Greene et al., 2011</td>
<td>Maximal and sub-maximal</td>
<td>4th intercostal</td>
<td>32-34</td>
</tr>
<tr>
<td>Pohl &amp; McNaughton, 2003</td>
<td>Sub-maximal</td>
<td>1) thigh-deep 2) waist-deep</td>
<td>33</td>
</tr>
<tr>
<td>Gleim &amp; Nicholas, 1989</td>
<td>Sub-maximal</td>
<td>1) lateral malleolous 2) patella 3) mid thigh 4) umbilicus</td>
<td>30.5 and 36.1</td>
</tr>
<tr>
<td>Brubaker et al., 2011</td>
<td>Sub-maximal</td>
<td>Xiphoid</td>
<td>28</td>
</tr>
</tbody>
</table>

3.3 Results

Cardiovascular Response

Heart rate

A total of 11 studies recorded heart rate during ATM running. For maximal graded exercise tests, Silvers et al. (2007) found no difference in maximal heart rate, whereas both Schaal, Collins and Ashley (2012), and Greene, Greene, Carbuhn, Green and Crouse (2011) found that ATM maximum heart rate while running barefoot was lower than LTM running. Interestingly, Schaal et al. (2012) found no difference in maximal heart rate while running on an LTM and an ATM with AQx hydrodynamic training shoes. Watson et al. (2012) compared four
different ATM graded exercise tests with a standard Bruce protocol completed on a LTM. Each ATM protocol followed the same progression in speeds, however the amount of water jet resistance added to each graded exercise test was increased from no jet, to 1/3 open, to 2/3 open, and to full jet for ATM tests 1-4, respectively. During the first ATM graded exercise test with no jet, ATM heart rate was lower than LTM in all stages. During the second ATM graded exercise test with 1/3 jet, heart rate was lower on the ATM for all speeds except for 1.34 m·s\(^{-1}\). The ATM graded exercise test with 2/3 jet and full jet were more similar to land with comparable heart rates at 1.34 m·s\(^{-1}\) with 2/3 jet and full jet, as well as at 2.01 m·s\(^{-1}\) with 2/3 jet and full jet. To summarize, it was found that heart rate values were similar between ATM and LTM running when \(\dot{V}O_2\) was equivalent.

During submaximal running, three studies found heart rate to be lower on an ATM versus a LTM (Rutledge, Silvers, Browder, & Dolny, 2007; Porter et al., 2014; Brubaker, Ozemek, Gonzalez, Wiley, & Collins, 2011). Schaal et al. (2012) reported no difference in average heart rate, and two studies found heart rate to be higher during ATM running versus LTM running (Pohl & McNaughton, 2003; Gleim & Nicholas, 1989). Pohl and McNaughton (2003) found heart rate to be higher during ATM compared to LTM running at the same speed at thigh and waist levels of immersion, whereas Gleim and Nicholas (1989) found heart rate was higher during various ATM running speeds for depths at and below the umbilicus. This exemplifies the importance of water depth and the effect on heart rate. The findings from Greene et al. (2011) demonstrate that alterations in heart rate during ATM compared to LTM also depend on the relationship between speed and water jet resistance. These findings suggest that heart rate is lower during ATM running compared to LTM running without the use of resistance jets and with the resistance jet set at 25% of capacity for speeds greater than 1.34 m·s\(^{-1}\). Heart rate was found
to be higher during ATM running with jets of 75% and 100% at all velocities compared to LTM running. ATM running with a jet resistance of 50% produced a greater heart rate response than LTM running at 0.89 m·s⁻¹ and 1.34 m·s⁻¹, however heart rate was lower than LTM at 2.23 m·s⁻¹ and 2.68 m·s⁻¹.

Water immersion to both knee and thigh depths produced higher heart rate responses compared to the ankle and waist depth at speeds greater than 1.12 m·s⁻¹. The heart rate response during waist deep water immersion was higher than all other depths and land for a given VO₂ (Gleim & Nicholas, 1989). Rutledge et al. (2007) tested three different running speeds with 0%, 50% and 75% jet at each speed on an ATM and found speeds on a LTM to match the VO₂ response. For a given VO₂, heart rate was lower during ATM running compared to LTM running except for the trials without the use of jets. It should be noted that there was a discrepancy between the written results and the table in this study, so the certainty of the results is unclear.

The speed required to match VO₂ was faster on the LTM compared to the ATM, but was comparable during ATM running without the resistance jet. Brubaker et al. (2011) compared speeds of 0.64 m·s⁻¹, 2.03 m·s⁻¹ and 2.67 m·s⁻¹ on an ATM and LTM. The results suggested that heart rate was lower during ATM running at 2.03 m·s⁻¹, but was comparable at 0.64 m·s⁻¹ and 2.67 m·s⁻¹. It should be noted that a discrepancy was found between the written results and the provided table. Therefore, certainty in the results remains unclear. Porter et al. (2014) added LTM incline to attempt to account for resistance jets on an ATM for identical speeds. During a slow running speed (2.32 ± 0.27 m·s⁻¹), heart rate during ATM running with jets of 0-60% was lower compared to LTM running with an incline of 0-6%, however heart rate was higher while running on an ATM at 100% compared to LTM with an incline of 10%. While running at a medium speed (2.68 ± 0.32 m·s⁻¹), heart rate was lower during ATM running with jets of 0-40%
compared to LTM running with an incline of 0-4%. Lastly, running at a fast speed (3.04 ± 0.36 m·s⁻¹) produced a lower heart rate during ATM running with jets of 0-60% compared to LTM running with an incline of 0-6%.

In the only published study to compare lactate threshold between an ATM and LTM graded exercise test, Garner, Wagner, Bressel and Dolny (2014) found lactate threshold occurred at a lower heart rate on an ATM compared to a LTM. Finally, Gleim and Nicholas (1989) compared heart rate at various temperatures of water to LTM running. These findings suggest that running on an ATM at waist depth in 30.5°C and 36.1°C for a given \( \dot{V}O_2 \) produced a higher heart rate compared to running at the same speeds on a LTM. However, at the lower depths of water immersion, there was no difference between ATM and LTM. Taken together, these studies suggest that speed and water jet resistance as well as immersion depth and temperature alter the heart rate response while running on an ATM compared to a LTM.

*Metabolic Demand (\( \dot{V}O_2 \))*

All studies examined \( \dot{V}O_2 \) during ATM running. During maximal running, four studies (Silvers et al., 2007; Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012) showed no difference between peak \( \dot{V}O_2 \) during an ATM and LTM graded exercise test. Watson et al. (2012) compared four different ATM graded exercise tests to a standard Bruce protocol on a LTM. Each ATM protocol followed the same progression in speeds, however the amount of water jet resistance added to each graded exercise test was increased from no jet, to 1/3 open, to 2/3 open and to full jet for ATM tests 1-4, respectively. During the first ATM graded exercise test with no jet, \( \dot{V}O_2 \) was lower on the ATM compared to the LTM at all speeds. The second ATM graded exercise test with 1/3 jets produced a lower \( \dot{V}O_2 \) on the ATM compared to the LTM at all speed except 1.34 m·s⁻¹. The ATM graded exercise test with 2/3 jet and full jet were more
similar to land, with comparable results at 1.34 m·s\(^{-1}\) with 2/3 jet and full jet, as well 2.01 m·s\(^{-1}\) with 2/3 jet and full jet.

During submaximal running, Rutledge et al. (2007) matched \(\text{VO}_2\) for nine different trials that included various speeds and jet resistances. Their findings for a matched \(\text{VO}_2\) demonstrated that LTM speed was similar to ATM speed without the use of the resistance jets, however, with the addition of resistance jets a higher LTM speed was required. Rife et al. (2010) based \(\text{VO}_2\) on heart rate and found that for a given heart rate, \(\text{VO}_2\) was greater on an ATM than LTM and that there was no difference wearing and not wearing AQx hydrodynamic training shoes on an ATM.

Many studies reported \(\text{VO}_2\) to be lower during ATM running compared to LTM running for at least part of the trials (Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012; Porter et al., 2014; Brubaker et al., 2011; Silvers, Bressel, Dickin, Killgore, & Dolny, 2014). In contrast, other studies found ATM \(\text{VO}_2\) to be greater than LTM \(\text{VO}_2\) for some or all trials (Greene et al., 2011; Watson et al., 2012; Porter et al., 2014; Pohl & McNaughton, 2003; Gleim & Nicholas, 1989; Rife, Myrer, Vehrs, Feland, Hunter, & Fellingham, 2010). Porter et al. (2014) found ATM running at 2.32 ± 0.27 m·s\(^{-1}\) produced lower \(\text{VO}_2\) measurements compared to LTM running for jet resistances of 0-60% and inclines of 0-6%, respectively. For the same speed, \(\text{VO}_2\) was higher during ATM running with 100% jet compared to LTM running with 10% incline. At 2.68 ± 0.32 m·s\(^{-1}\), \(\text{VO}_2\) was lower during ATM running with 0-40% compared to LTM running with 0-4% grade and higher at 100% jet and 10% incline, respectively. Finally, at 3.04 ± 0.36 m·s\(^{-1}\), \(\text{VO}_2\) during ATM running with a jet of 20% and 40% was less than \(\text{VO}_2\) during LTM with an incline of 2% and 4%, respectively.

Brubaker et al. (2011) reported \(\text{VO}_2\) to be lower during ATM running than LTM at 2.03 m·s\(^{-1}\) and 2.67 m·s\(^{-1}\) with 0% jet and grade, during xiphoid process level immersion. Greene et al.
(2011), which compared jet resistances at the same velocities between LTM and ATM running, found \(\dot{V}O_2\) during ATM running with a jet of 0 and 25% was lower than LTM at all velocities other than 1.34 m\(\cdot\)s\(^{-1}\). At 50% jet, ATM running resulted in a higher \(\dot{V}O_2\) than LTM at 1.34 m\(\cdot\)s\(^{-1}\) and lower \(\dot{V}O_2\) than LTM at speeds greater than 1.79 m\(\cdot\)s\(^{-1}\). During 75% jet, ATM running produced higher \(\dot{V}O_2\) than LTM running at speeds slower than 2.23 m\(\cdot\)s\(^{-1}\). ATM running with 100% jet \(\dot{V}O_2\) was higher than LTM running at all speeds.

Pohl and McNaughton (2003) found \(\dot{V}O_2\) to be higher during ATM than LTM running at 1.95 m\(\cdot\)s\(^{-1}\) with immersion level to the waist and thigh. Investigating water depth, Gleim and Nicholas (1989) found \(\dot{V}O_2\) to be higher during ATM running than LTM at speeds greater than 0.67 m\(\cdot\)s\(^{-1}\) with immersion levels to the ankle, knee and thigh. For waist depth immersion, ATM was higher than LTM at speeds between 0.89 and 2.01 m\(\cdot\)s\(^{-1}\). In addition to depth, Gleim and Nicholas (1989) investigated water temperature and reported for a given heart rate, hot water produced a lower \(\dot{V}O_2\) than warm water. Both water trials of 30.5\(^\circ\)C and 36.1\(^\circ\)C at waist depth immersion had a lower \(\dot{V}O_2\) than LTM.

Garner et al. (2014) found that lactate threshold point occurred at a lower \(\dot{V}O_2\) on the ATM compared to LTM. Silvers et al. (2014) collected \(\dot{V}O_2\), and provided descriptive statistics, however significance was not reported. Effect sizes (Cohen, 1988) were calculated using the pooled LTM standard deviations (Hopkins, Marshall, Batterham, & Hanin, 2009) in order to report the standardized difference of the means. \(\dot{V}O_2\) was lower while running on an ATM compared to an LTM at all speeds with a moderate effect size. Schaal et al. (2012) also studied running on an ATM with and without AQx shoes compared to LTM running. The findings suggest that both ATM conditions had a lower \(\dot{V}O_2\) than LTM running. However, the authors note that although an attempt was made to maintain running intensity at 70% of \(\dot{V}O_{2\text{max}}\), as
calculated from a LTM and an ATM graded exercise test, the ATM trial without AQx shoes, with AQx shoes, and on the LTM was completed at 70.3 ± 8.5%, 73.4 ± 7.0% and 76.9 ± 25.5%, respectively. This brings into question the veracity of the other measured variables being compared in this study specifically, as well as in other studies in which metabolic demand was not matched. Furthermore, this confirms the importance of the rationale in this paper to complete the meta-analyses on only matched trials. Based on the above findings it is apparent that there is a multitude of factors that can influence the \( \dot{V}O_2 \) response during ATM running, including treadmill speeds, jet resistance, water temperature, and depth of immersion. Considering all of the variations in protocol designs, it appears to be critical to match metabolic demand in order to determine a more accurate comparison of responses as compared to similar treadmill speeds.

**Blood Lactate**

Three studies included in this review examined the blood lactate response to exercise (Silvers et al., 2007; Watson et al., 2012; Garner et al., 2014). Silvers et al. (2007) found no difference in peak lactate during graded exercise tests on an ATM and LTM. Watson et al. (2012) reported no difference in peak blood lactate during maximal exercise, however, found that blood lactate was lower during ATM compared to LTM running during stage one at 0.67 m·s\(^{-1}\) with no jets and the jet 1/3, 2/3, and fully open. ATM blood lactate was also lower during stage four at 2.68 m·s\(^{-1}\) with no jet, as well as with the jet 1/3 and 2/3 open. Blood lactate was also lower during ATM running compared to land during stage five at 3.35 m·s\(^{-1}\) with no jet and the jet 1/3 open. These stages were compared to stages one to five in a standard Bruce protocol (Bruce et al., 1949) and blood lactate levels differed compared to land irrespective of \( \dot{V}O_2 \). Garner et al. (2014) compared the point of the lactate threshold on an ATM and LTM and found
that there was no difference in blood lactate concentration or running speed at the lactate threshold point.

*Respiratory Exchange Ratio*

Six studies in this review examined respiratory exchange ratio (Silvers et al., 2007; Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012; Pohl & McNaughton, 2003; Garner et al., 2014). Three studies (Silvers et al., 2007; Schaal et al., 2012; Watson et al., 2012) found no difference in peak respiratory exchange ratio between ATM and LTM running, whereas Greene et al. (2011) found respiratory exchange ratio to be lower on the ATM at peak compared to LTM. During submaximal running, Pohl and McNaughton (2003) found no difference in respiratory exchange ratio between ATM running and LTM running at 1.95 m·s⁻¹ with water immersion at thigh and waist levels. Similarly, Schaal et al. (2012) found no difference in respiratory exchange ratio between ATM and LTM with and without AQx shoes with xiphoid level immersion compared to LTM running. Watson et al. (2012) reported that respiratory exchange ratio was lower during ATM running compared with a LTM Bruce protocol at 1.67 m·s⁻¹ and 2.08 m·s⁻¹ with no resistance jet and with the resistance jet at 1/3 capacity. Respiratory exchange ratio was greater during ATM running at 0.83 m·s⁻¹ with the resistance jet set at 2/3 capacity, as well as at 1.25 m·s⁻¹ with the resistant jet at full capacity. The relationship between the respiratory exchange ratio during ATM and LTM was altered from land irrespective of VO₂.

*Rating of Perceived Exertion*

Rating of perceived exertion was measured in seven of the included studies (Silvers et al., 2012; Schaal et al., 2012; Greene et al., 2011; Rutledge et al., 2007; Porter et al., 2014; Brubaker et al., 2011; Garner et al., 2014). Silvers et al. (2007), Greene et al. (2011), and Schaal et al. (2012) each reported no difference in rating of perceived exertion during maximal exercise on an
ATM versus LTM. Additionally, Schaal et al. (2012) found no difference in rating of perceived exertion between ATM with and without AQx shoes and LTM running for maximal and submaximal running. Rutledge et al. (2007) found the rating of perceived exertion to be lower during ATM compared to LTM running for speeds of 2.9 m·s⁻¹ with 75% jet and 3.35 m·s⁻¹ with 50% jet. Porter et al. (2014) reported the rating of perceived exertion was similar between ATM and LTM at any speed with 0-40% jet resistance and 0-4% incline. However, rating of perceived exertion was higher during ATM than LTM running at 2.32 ± 0.27 m·s⁻¹ with jet resistance at 60% compared to an incline of 6%, and for all speeds with a jet resistance of 80% and 100%, compared to 8% and 10% incline on a LTM. This suggests that perceived effort is greater with higher jet resistance as compared to incline irrespective of heart rate and $\dot{V}O_2$.

Garner et al. (2014) found that the lactate threshold occurred at the same rating of perceived exertion between ATM and LTM running. Brubaker et al. (2011) compared matched submaximal workloads with no jets and found similar ratings of perceived exertion between ATM and LTM. Taken together, it appears that the studies that found no difference in rating of perceived exertion during submaximal running used lower jet percentages (0%, 20%, 40%, 44%, and 46%) whereas the study that reported higher ratings of perceived exertion during ATM running used higher jet resistances (60-100%) compared to increasing inclines on the LTM. This suggests that higher amounts of jet resistance may increase the perception of effort during submaximal ATM running. Garner et al. (2014) summarized that in order to exercise at the lactate threshold in ATM running, the rating of perceived exertion may provide useful information. In this study, jet resistance was maintained at 40% and speed was increased in each stage to maximum capacity of the treadmill, thereafter jet resistance was increased by 10% each stage. Nine participants out of 15 required the use of the resistance jets and only three
participants required additional jet stages. Therefore, 12 out of 15 participants were below 70% jet at lactate threshold. It is possible that for individuals running on an ATM at slower speeds and a higher jet resistance, the rating of perceived exertion may not be accurate to predict lactate threshold. Further, during ATM graded exercise testing, protocols incorporating higher resistance jets throughout the entirety of the test could limit the maximally achieved $\dot{V}O_2$ as increased perceived exertion could lead to an early test termination.
Table 3.5 Cardiovascular responses during aquatic treadmill running compared to land treadmill running

<table>
<thead>
<tr>
<th>Publication</th>
<th>Heart Rate (beats·min⁻¹)</th>
<th>( \dot{V}O_2 ) (mL·kg⁻¹·min⁻¹)</th>
<th>Lactate (mM)</th>
<th>Respiratory Exchange Ratio (VCO₂/( \dot{V}O_2 ))</th>
<th>Rating of Perceived Exertion (RPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silvers et al., 2007</td>
<td>No difference at peak.</td>
<td>No difference at peak.</td>
<td>No difference at peak.</td>
<td>No difference at peak.</td>
<td>No difference at peak.</td>
</tr>
<tr>
<td>Rutledge et al., 2007</td>
<td>ATM &lt; LTM, except for speeds at 0% jet for a given ( \dot{V}O_2 )</td>
<td>No difference between ATM and LTM for each stage. ATM speed with jets &lt; LTM speed to match ( \dot{V}O_2 ).</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>ATM &lt; LTM at 2.9 m·s⁻¹ with 75% jet and 3.35 m·s⁻¹ with 50% jet.</td>
</tr>
<tr>
<td>Porter et al., 2014</td>
<td>Slow: ATM &lt; LTM at 0-60% and ATM &gt; LT at 100% jet. Medium: ATM &lt; LTM at 0-40% jet. Fast: ATM &lt; LTM at 0-60% jet.</td>
<td>Slow: ATM &lt; LTM at 0-60% jet and ATM &gt; LTM at 100% jet. Medium: ATM &lt; LTM at 0-40% jet and ATM &gt; LTM at 100% jet. Fast: ATM &lt; LTM at 20% and 40% jet.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>Slow: ATM &gt; LTM at 60, 80 and 100%. Medium: ATM &gt; LTM at 80 and 100%. Fast: ATM &gt; LTM at 80%.</td>
</tr>
<tr>
<td>Pohl &amp; McNaughton, 2003</td>
<td>ATM thigh deep &gt; ATM waist deep &gt; LTM.</td>
<td>ATM thigh deep &gt; ATM waist deep &gt; LTM.</td>
<td>Oxygen cost per stride on LTM &lt; both ATM. No difference between ATM thigh deep and ATM waist deep.</td>
<td>Not Reported.</td>
<td>Not Reported</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Publication</th>
<th>Heart Rate (beats·min⁻¹)</th>
<th>$\dot{\text{VO}}_2$ (mL·kg⁻¹·min⁻¹)</th>
<th>Lactate (mM)</th>
<th>Respiratory Exchange Ratio ($\text{VCO}_2/\dot{\text{VO}}_2$)</th>
<th>Rating of Perceived Exertion (RPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garner et al., 2014</td>
<td>LT point occurred at a lower heart rate on the ATM compared to LTM.</td>
<td>LT point occurred at a lower $\dot{\text{VO}}_2$ on the ATM compared to LTM.</td>
<td>No difference in blood lactate concentration or running speed at LT point.</td>
<td>No difference in respiratory exchange ratio at LT point.</td>
<td>No difference in perceived effort at LT point.</td>
</tr>
<tr>
<td>Brubaker et al., 2011</td>
<td>ATM &lt; LTM at 2.03 m·s⁻¹ with 0% jet and grade.</td>
<td>ATM &lt; LTM at 2.03 m·s⁻¹ and 2.67 m·s⁻¹ with 0% jet and grade.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>No difference between ATM and LTM.</td>
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<tr>
<td>Silvers et al., 2014</td>
<td>Not Reported.</td>
<td>ATM &lt; LTM at all speeds with a moderate effect size.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>Not Reported</td>
</tr>
<tr>
<td>Schaal, Collins &amp; Ashley, 2012</td>
<td>Max: LTM &gt; barefoot on ATM. No difference between LTM and ATM wearing AQx. Submax: No difference in average heart rate.</td>
<td>Max: No difference at peak in any group. Submax: Both ATM conditions &lt; LTM.</td>
<td>Not Reported.</td>
<td>No difference in any group at max or submax.</td>
<td>No difference in any group at max or submax.</td>
</tr>
<tr>
<td>Rife et al., 2010</td>
<td>See $\dot{\text{VO}}_2$ response at a given HR.</td>
<td>For a given heart rate, ATM &gt; LTM and there was no difference between ATM with and without shoes. At a given treadmill speed, ATM with shoes &gt; ATM without shoes.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
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<tr>
<td>Publication</td>
<td>Heart Rate (beats·min⁻¹)</td>
<td>(\dot{V}O_2) (mL·kg⁻¹·min⁻¹)</td>
<td>Lactate (mM)</td>
<td>Respiratory Exchange Ratio ((VCO_2/\dot{V}O_2))</td>
<td>Rating of Perceived Exertion (RPE)</td>
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<tr>
<td><strong>Watson et al., 2012</strong></td>
<td>ATM 1 &lt; LTM for all stages.</td>
<td>ATM 1 &lt; LTM for all stages.</td>
<td>ATM 1 &lt; LTM at 0.67 m·s⁻¹, 2.68 m·s⁻¹ and 3.35 m·s⁻¹.</td>
<td>ATM 1 &lt; LTM at 1.67 m·s⁻¹ and 2.08 m·s⁻¹.</td>
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<td></td>
<td>ATM 2 &lt; LTM in all stages except 1.34 m·s⁻¹.</td>
<td>ATM 2 &lt; LTM in all stages except 1.34 m·s⁻¹.</td>
<td>ATM 2 &lt; LTM at 0.67 m·s⁻¹, 2.68 m·s⁻¹ and 3.35 m·s⁻¹.</td>
<td>ATM 2 &lt; LTM at 1.67 m·s⁻¹ and 2.08 m·s⁻¹.</td>
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<td></td>
<td>ATM 3 &gt; LTM at 1.34 m·s⁻¹.</td>
<td>ATM 3 &gt; LTM at 1.34 m·s⁻¹.</td>
<td>ATM 3 &lt; LTM at 0.67 m·s⁻¹ and 2.68 m·s⁻¹.</td>
<td>ATM 3 &gt; LTM at 0.83 m·s⁻¹.</td>
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<td></td>
<td>ATM 4 &gt; LTM at 3.0 m·s⁻¹ and 4.5 m·s⁻¹.</td>
<td>ATM 4 &gt; LTM at 1.34 m·s⁻¹ and 2.01 m·s⁻¹.</td>
<td>ATM 4 &lt; LTM at 0.67 m·s⁻¹.</td>
<td>ATM 4 &gt; LTM at 1.25 m·s⁻¹.</td>
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<tr>
<td><strong>Greene et al., 2011</strong></td>
<td>Submax: ATM 0 and ATM 25 &lt; LTM for all velocities, except 1.34 m·s⁻¹.</td>
<td>Submax: ATM 0 and ATM 25 &lt; LTM for all velocities, except 1.34 m·s⁻¹.</td>
<td>ATM 0 and ATM 25 &lt; LTM at 1.34 m·s⁻¹ and ATM 50 &gt; LTM at 1.34 m·s⁻¹ and ATM 50 &lt; LTM at speeds &gt;1.79 m·s⁻¹.</td>
<td>Not Reported.</td>
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<td>ATM 75 and ATM 100 &gt; LTM at all velocities.</td>
<td>ATM 75 and ATM 100 &gt; LTM at all velocities.</td>
<td>ATM 75 and ATM 100 &gt; LTM at all velocities.</td>
<td>Not Reported.</td>
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<td>ATM 50 &gt; LTM at 0.89 and 1.34 m·s⁻¹ and ATM 50 &lt; LTM at 2.23 and 2.68 m·s⁻¹.</td>
<td>ATM 50 &gt; LTM at 0.89 and 1.34 m·s⁻¹ and ATM 50 &lt; LTM at 2.23 and 2.68 m·s⁻¹.</td>
<td>ATM 50 &gt; LTM at 0.89 and 1.34 m·s⁻¹ and ATM 50 &lt; LTM at 2.23 and 2.68 m·s⁻¹.</td>
<td>Max: no difference between ATM and LTM.</td>
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<td></td>
<td>Max: ATM &lt; LTM.</td>
<td>Max: ATM &lt; LTM.</td>
<td>Max: ATM &lt; LTM.</td>
<td>Max: no difference between ATM and LTM.</td>
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<tr>
<td>Publication</td>
<td>Heart Rate (beats·min(^{-1}))</td>
<td>$\dot{V}O_2$ (mL·kg(^{-1})·min(^{-1}))</td>
<td>Lactate (mM)</td>
<td>Respiratory Exchange Ratio ($VCO_2/\dot{V}O_2$)</td>
<td>Rating of Perceived Exertion (RPE)</td>
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<td>Gleim &amp; Nicholas, 1989</td>
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<tr>
<td>Depth: ATM &gt; LTM, except for waist depth at 0.67 m·s(^{-1}). Knee and thigh &gt; ankle and waist for all speeds &gt; 1.12 m·s(^{-1}). Waist &gt; all other conditions for a given $\dot{V}O_2$. Temperature: Hot water &gt; warm water at waist depth for a given $\dot{V}O_2$. ATM &gt; LTM. No difference at lower depths.</td>
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<td>Depth: ATM &gt; LTM at speeds &gt; 0.67 m·s(^{-1}) at ankle, knee and thigh. At waist depth, ATM &gt; LTM at speeds between 0.89 and 2.01 m·s(^{-1}). Knee and thigh &gt; ankle and waist for all speeds &gt;1.12 m·s(^{-1}). Temperature: For a given heart rate, hot water &lt; warm water &lt; LTM at waist depth.</td>
<td></td>
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<tr>
<td>Not Reported. Max: ATM &lt; LTM. Not Reported.</td>
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</tbody>
</table>
Respiratory Response

Ventilation

Ventilation was measured in four studies included in this review (Silvers et al., 2007; Greene et al., 2011; Rutledge et al., 2007; Brubaker et al., 2011). During maximal exercise, Silvers et al. (2007) reported that ventilation was significantly higher at peak during an ATM graded exercise test compared to on a LTM, whereas Greene et al. (2011) reported no difference at peak between ATM and LTM. During submaximal running, both Rutledge et al. (2007) and Brubaker et al. (2011) reported no differences in ventilation across all trials.

Tidal Volume

Tidal volume was reported in three studies included in this review (Silvers et al., 2007; Rutledge et al., 2007; Brubaker et al., 2011). Silvers et al. (2007) reported no difference in tidal volume between ATM and LTM at peak exercise, and Rutledge et al. (2007) reported no difference between ATM and LTM for any submaximal running trials. Brubaker et al. (2011) found tidal volume to be significantly lower (1.24 L/breath versus 1.44 L/breath) during ATM running at 2.08 m·s⁻¹, which was the only stage that was not matched for metabolic demand.

Respiratory Rate

Three studies in this review reported respiratory rate (Silvers et al., 2007; Rutledge et al., 2007; Brubaker et al., 2011). Respiratory rate at peak was significantly higher (10.07% mean difference) during ATM compared to LTM running during a graded exercise test (Silvers et al., 2007). Rutledge et al. (2007) reported that respiratory rate during ATM running was lower than LTM at 3.35 m·s⁻¹ with 75% resistance jet and 3.8 m·s⁻¹ with 0%, 50% and 75% jet. All lower speeds and jet resistances produced similar respiratory rate. Brubaker et al. (2011) found that respiratory rate was not different between ATM and LTM running for any of the
three stages. Therefore, current understanding of how ATM running affects respiratory rate compared to LTM running at submaximal and maximal levels remains unclear.
### Table 3.6 Respiratory responses during aquatic treadmill running compared to land treadmill running

<table>
<thead>
<tr>
<th>Publication</th>
<th>Depth</th>
<th>Temperature (°C)</th>
<th>Protocol</th>
<th>Ventilation (L·min⁻¹)</th>
<th>Tidal Volume (mL)</th>
<th>Respiratory Rate (breaths·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silvers et al., 2007</td>
<td>Xiphoid</td>
<td>28</td>
<td>Maximal graded exercise test starting at self-selected pace with 40% jet, increased 0.22 m·s⁻¹ per minute for 4-5 min, then increased jets 10% every minute to fatigue.</td>
<td>Higher at peak during ATM compared to LTM.</td>
<td>No difference at peak.</td>
<td>Higher at peak during ATM compared to LTM.</td>
</tr>
<tr>
<td>Rutledge et al., 2007</td>
<td>Xiphoid</td>
<td>28</td>
<td>Participants completed trials at three speeds: 2.9 m·s⁻¹, 3.35 m·s⁻¹ and 3.8 m·s⁻¹. Each speed was tested with jet resistance set at 0%, 50% and 75%. Land: Treadmill speed (0% incline) were calculated to elicit comparable metabolic costs observed during ATM.</td>
<td>No differences between ATM and LTM.</td>
<td>No difference between ATM and LTM.</td>
<td>ATM &lt; LTM at 3.35 m·s⁻¹ with 75% jet and 3.8 m·s⁻¹ with 0%, 50% and 75% jet.</td>
</tr>
<tr>
<td>Pohl &amp; McNaughton, 2003</td>
<td>1) Thigh deep 2) Waist deep</td>
<td>33</td>
<td>5 minute run at 1.95 m·s⁻¹ for each depth of water and on land.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
</tr>
<tr>
<td>Garner et al., 2014</td>
<td>Xiphoid</td>
<td>30</td>
<td>ATM lactate threshold test: Test began at 40% jet or 1% grade and a speed representing 40% VO₂ peak. The speed increased 0.22 m·s⁻¹ per 3 minute stage. If participants did not exceed suspected lactate threshold by maximum speed of the ATM, jet was increased 10% each stage.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
</tr>
<tr>
<td>Publication</td>
<td>Depth</td>
<td>Temperature (°C)</td>
<td>Protocol</td>
<td>Ventilation (L·min⁻¹)</td>
<td>Tidal Volume (mL)</td>
<td>Respiratory Rate (breaths·min⁻¹)</td>
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<tr>
<td>Brubaker et al., 2011</td>
<td>Xiphoid</td>
<td>28</td>
<td>2 minute stages at 0.64 m·s⁻¹, 1.36 m·s⁻¹, 2.08 m·s⁻¹, and 2.67 m·s⁻¹ with no jet or grade. After jet and grade were added at 30%, 40% and 50% jet and 1%, 2% and 4% grade.</td>
<td>No difference between ATM and LTM.</td>
<td></td>
<td>No difference between ATM and LTM.</td>
</tr>
<tr>
<td>Schaal, Collins &amp; Ashley, 2012</td>
<td>Xiphoid</td>
<td>25.8 [20.6-35.6]</td>
<td>Maximal graded exercise test starting at a self-selected pace with 40% jet. Increased 0.22 m·s⁻¹ per minute for 4 minutes, then increased jets 10% per minute to exhaustion. If 100% jet stage was completed, speed was increased 0.22 m·s⁻¹ per minute until exhaustion or the maximum capabilities of the ATM. Sub max: 30 minute run at approximately 70% ( \dot{V}O_2\text{max} ).</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
</tr>
<tr>
<td>Watson et al., 2012</td>
<td>Xiphoid</td>
<td>33-35</td>
<td>Four maximal graded exercise tests on the ATM. During each test initial speed was 0.67 m·s⁻¹ and increased 0.67 m·s⁻¹ every 3 minutes. Jet resistances during ATM tests 1-4 were off, 1/3 full, 2/3 full and full jet, respectively. The Bruce protocol was used for the land trials.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
</tr>
<tr>
<td>Greene et al., 2011</td>
<td>4th intercostal</td>
<td>32-34</td>
<td>Speed increased 0.44 m·s⁻¹ every 3 minutes from 0.89 m·s⁻¹ to 3.13 m·s⁻¹. Each speed was completed on land with 0% grade and on an ATM with 0%, 25%, 50%, 75% and 100% jet resistance.</td>
<td>No difference at peak between ATM and LTM.</td>
<td>Not Reported.</td>
<td>Not Reported.</td>
</tr>
</tbody>
</table>
3.4 Meta-Analyses

Due to large inconsistencies in the findings and protocols in the included literature, a meta-analysis was completed using trials that included a matched $\dot{V}O_2$ during ATM and LTM running. The aim is to allow the cardiorespiratory response to ATM running to be better understood and greater confidence be taken that the response is environment specific versus inconsistencies in workload.

Submaximal Cardiovascular Responses

Heart Rate

In total, 26 trials (Watson et al., 2012; Rutledge et al., 2007; Porter et al., 2014; Brubaker et al., 2011) were part of the meta-analysis to compare heart rate between running on an ATM and a LTM. Only trials that had no significant difference in $\dot{V}O_2$ between LTM and ATM were analyzed to ensure heart rate was not different between conditions due to differences in workload. It should be noted that a discrepancy between written results and the provided table was found in Brubaker et al. (2011) for stage 4. For the purpose of this review, stage 4 was included as a matched $\dot{V}O_2$ stage. It was found that for a matched $\dot{V}O_2$, there was a trivial difference in heart rate (ES= 0.132, 95% CI = -0.023, 0.286) during ATM versus LTM running.

Respiratory Exchange Ratio

In total, 6 trials (Watson et al., 2012) were part of the meta-analysis to compare the respiratory exchange ratio between running on an ATM and a LTM. It was found that during submaximal running with a matched $\dot{V}O_2$, respiratory exchange ratio was
significantly greater on the ATM compared to the LTM with a small, nearly moderate effect size (ES = 0.490, 95% CI = 0.156, 0.825).
Figure 3.2 Forest plot of the change heart rate (95% CI) for a matched metabolic demand while running on an aquatic treadmill (ATM) in chest deep water compared to land treadmill running (LTM).
Submaximal Respiratory Responses

As with the cardiovascular responses, all respiratory responses were only analyzed in trials that had a matched VO₂ during ATM running compared to LTM running.

Respiratory Rate

In total, only 2 trials (Brubaker et al., 2011) were part of meta-analysis to compare respiratory rate between running on an ATM and a LTM. It was found that during submaximal running with a matched VO₂, respiratory rate was higher during ATM compared to LTM (ES = 0.227, 95% CI = -0.366, 0.821) with a small effect size.

Minute Ventilation

In total, only 2 trials (Brubaker et al., 2011) were part of meta-analysis to compare ventilation between running on an ATM and a LTM. It was found that during submaximal running with a matched VO₂, ventilation has a trivial difference between ATM and LTM (ES = -0.057, 95% CI = -0.648, 0.534).

Tidal Volume

In total, only 2 trials (Brubaker et al., 2011) were part of meta-analysis to compare tidal volume between running on an ATM and a LTM. It was found that during submaximal running with a matched VO₂, tidal volume has a trivial difference between ATM and LTM (ES = -0.180, 95% CI = -0.773, 0.412).
Figure 3.3 Forest plot of the change in respiratory response (95% CI) for a matched metabolic demand while running on an aquatic treadmill (ATM) in chest deep water compared to land treadmill running (LTM).
Maximal Cardiorespiratory Response

Heart Rate

Four studies (Silvers et al., 2007; Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012) were part of the meta-analysis comparing maximal heart rate between ATM and LTM running. The findings suggest that maximal heart rate is lower on an ATM versus a LTM with a small effect size (ES = -0.246, 95% CI = -0.683, 0.190).

Metabolic Demand ($\dot{V}O_2$)

Four studies (Silvers et al., 2007; Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012) were part of the meta-analysis comparing maximal $\dot{V}O_2$ between ATM and LTM. The findings suggest that $\dot{V}O_2$ peak has a trivial difference on an ATM versus LTM (ES = -0.078, 95% CI = -0.353, 0.198).

Respiratory Exchange Ratio

Four studies (Silvers et al., 2007; Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012) were part of the meta-analysis comparing maximal respiratory exchange ratio values between ATM and LTM running. The findings suggest that respiratory exchange ratio is significantly lower on an ATM versus LTM with a moderate effect size (ES = -0.720, 95% CI = -1.216, -0.225).

Ventilation

Two studies (Silvers et al., 2007; Greene et al., 2011) were part of the meta-analysis comparing maximal ventilation between ATM and LTM. The findings suggest that ventilation has a trivial difference on an ATM versus LTM (ES = 0.063, 95% CI = -0.403, 0.529).

Blood Lactate
Two studies (Silvers et al., 2007; Watson et al., 2012) were part of the meta-analysis comparing the lactate response during ATM and LTM maximal running. The findings suggest that lactate has a trivial difference on an ATM versus LTM (ES = -0.166, 95% CI = -0.695, 0.363).
Figure 3.4 Forest plot of the change in cardiorespiratory response to maximal running on an aquatic treadmill (ATM) compared to land treadmill running (LTM).
3.5 Discussion

Considering the inconsistencies in findings and protocols in the ATM literature, a systematic review was warranted. During submaximal running, there is a trivial difference (ES = -0.115, 95% CI = -0.268, 0.038) in heart rate between ATM running and LTM running for a matched $\dot{V}O_2$. It has been commonly found that heart rate during deep water running and head-out water immersion is lower compared to land. The lower heart rate has been attributed to the hydrostatic pressure of the water which causes a central shift in blood volume, a physiological response that increases central venous return, concomitantly increasing preload and stroke volume with a decrease in heart rate (Khosla & DuBois, 1979; Christie et al., 1990; Arborelius Jr, Ballidin, Lilja, & Lundgren, 1972; McCally, 1964; Gabrielsen et al., 2002).

It has also been suggested that a decreased heart rate during water immersion exercise may be a function of decreased sympathetic activity which is normally higher during land exercise to regulate heart rate (Connelly et al., 1990; Mano, Iwase, Yamazaki, & Saito, 1985; Krishna, Danovitch, & Sowers, 1983; O'hare et al., 1986). A reduction in sympathetic neural outflow should have a greater impact on heart rate at workloads above 50% $\dot{V}O_{2\text{max}}$ (Christie et al., 1990), as the rise in heart rate with work above this intensity is primarily dependent on increased sympathetic neural outflow (Robinson, Epstein, Beiser, & Braunwald, 1966).

In other studies, heart rate has been found to be similar in water and on land during mild to moderate exercise, but is significantly lower during heavy exercise (Christie et al., 1990; Sheldahl et al., 1987; Sheldahl et al., 1984). This supports the findings of the present review which suggests there is no difference in heart rate during ATM running compared to LTM running when matched for a submaximal $\dot{V}O_2$, however, there is a small decrease in maximal heart rate on an ATM (ES = -0.246, 95%CI = -0.683, 0.190). It appears that heart rate follows a
similar trend during ATM running compared to other modes of aquatic exercise even with the use of resistance jets and a running gait more similar to land running.

The results of this review suggest \( \dot{V}O_2 \) peak is similar during ATM and LTM running (ES = -0.078, 95% CI= -0.353, 0.198). Several studies examining other modes of aquatic exercise have reported lower a \( \dot{V}O_2 \) max during exercise in water (Dowzer, Reilly, Cable, & Neville, 1999; Nakanishi, Kimura, & Yokoo, 1999). Dowzer et al. (1999) reported \( \dot{V}O_2 \) max averaged 83.7% and 75.3% of \( \dot{V}O_2 \) peak for shallow water running and deep water running, respectively. It has been suggested that lower \( \dot{V}O_2 \) max values for deep water running compared to those of LTM running are attributed to the buoyancy effects caused by water and different muscle recruitment patterns. During ATM running, the resistance jets exerting pressure against runner increases the resistance compared to deep water running. In addition, it would be expected that the increase in water resistance would elicit a greater response from the working muscles (ie. arms and legs) as opposed to shallow water running. Lastly, running on an ATM provides a more similar muscle recruitment pattern to LTM running than deep water running (Kato et al., 2001) and the recruitment of more trained versus untrained muscles would be consistent with LTM running.

As mentioned previously, maximal heart rate is lower during ATM running. A lower maximal heart rate exemplifies the importance of completing both an ATM and a LTM graded exercise test in order to produce accurate percentages of maximal heart rate for both environments. Such normative data would be useful for practitioners when prescribing exercise intensity in each environment using a percentage of maximal heart rate. Rife et al. (2010) attempted to compare the percentage of maximal heart rate and the percentage of \( \dot{V}O_2 \) max based on a LTM graded exercise test. The findings of this review show a small difference (ES = -0.246) in maximum heart rate and a trivial difference in \( \dot{V}O_2 \) peak (ES = -0.078) on an ATM
versus LTM. As a result, comparing the percentage of maximal heart rate or the correlation of percentage of maximal heart rate to the percentage of $\dot{V}O_2_{\text{max}}$ may yield inaccurate results. In the future, when trying to compare equivalent workloads using only a LTM graded exercise test, it is recommended to exercise at the same percentage of $\dot{V}O_2_{\text{max}}$ and examine the cardiorespiratory responses instead of using the same absolute or relative heart rate.

The results of this analysis when examining respiratory exchange ratio during a matched workload are compelling. During submaximal running, respiratory exchange ratio is significantly greater during ATM than LTM running. The difference is small, albeit approaching moderate (ES = 0.490, 95% CI= 0.156, 0.825). In contrast, when comparing maximal exercise, peak respiratory exchange ratio is significantly lower during ATM running with a moderate effect size (ES= -0.720, 95% CI= -1.216, -0.225). These findings suggest that when using respiratory exchange ratio as a criterion for reaching maximum exercise during an ATM graded exercise test, the same values that are used for a LTM graded exercise test may not be appropriate.

Ventilation is unaltered between ATM running and LTM running during maximal exercise (ES = 0.063, 95% CI= -0.403, 0.529) and during submaximal running (ES= -0.057, 95% CI = -0.648 0.534). Interestingly, although ventilation is unchanged, there is a small increase in respiratory rate (ES = 0.227, 95% CI = -0.366, 0.821) during ATM running, as well as a trivial, nearly small, decrease in tidal volume (ES = -0.180, 95% CI = -0.773, 0.412). Each of these submaximal measures were without the use of resistance jets, so understanding of how resistance jets affect ventilation cannot be drawn. Previous findings were in agreement with this result as it has been shown that ventilation did not differ between land and aquatic exercise conditions during water immersed cycling studies that have shown an increase in respiratory rate in water at 40% and 80% $\dot{V}O_2_{\text{max}}$, as well as a significantly lower tidal volume in water at 80% $\dot{V}O_2_{\text{max}}$
(Sheldahl et al., 1987). Sheldahl et al. (1987) suggested that the engorgement of the lung vasculature with blood during water immersion decreases pulmonary compliance, thus making it more efficient to increase ventilation above rest levels by proportionate increases in respiratory rate rather than in tidal volume compared with values on land. In the present review, during ATM running, individuals were immersed to chest level versus neck level which limits the engorgement of the lungs and may influence tidal volume. However, only a couple trials were included for the meta-analyses of ventilation, respiratory rate, and tidal volume. Given the limited number of trials in the meta-analyses, future work measuring these variables at a matched workload and during maximal exercise is warranted in order to better understand the response. It is possible that respiratory rate is higher during ATM running compared to LTM running due to the hydrostatic pressure on the chest causing a higher breathing rate in order to maintain a similar ventilation. This may be compounded with the addition of resistance jets.

The findings of this review suggest that the peak lactate response is similar between running on an ATM versus a LTM (ES = -0.166, 95% CI = -0.695, 0.363). In addition, Garner et al. (2014) found lactate threshold to occur at the same running speed and blood lactate concentration during ATM and LTM running, however, the lactate threshold occurred at a lower $\dot{V}O_2$ and heart rate during ATM running. Previous literature has shown blood lactate to be similar during water immersed cycling and land cycling until about 80% $VO_2\text{max}$, however lactate values were lower during water immersion exercise at higher intensities (Connelly et al., 1990). Given the fact that ventilation appears to be similar during ATM and LTM running during submaximal and maximal exercise, and $\dot{V}O_2$ appears to be similar during maximal exercise, it appears that ventilatory thresholds may also be a viable option to prescribe training intensities. It is possible if blood lactate is measured in units per volume of blood, the hemodilution that occurs
with water immersion through fluid shifts could influence the concentration during ATM exercise. In light of all of these considerations, research specific to ATM running is warranted.

3.6 Future Direction

Future studies should focus on matching metabolic demand in order to study the cardiorespiratory response. Further, more studies reporting on absolute changes in $\dot{V}O_2$ are warranted when comparing metabolic demand of exercise. Given a relative measure of $\dot{V}O_2$ includes a measure of body mass in kilograms, the variety of body compositions and depths of water immersion would have an impact on the results. With reduced gravitational forces and the influence of the buoyancy in water, absolute changes may be more appropriate. More studies comparing the respiratory response during maximal and submaximal ATM running are warranted in order to add to the current literature and better understand the response. In addition, studies should aim to determine the cardiovascular response with manipulations that can be made while using an ATM versus only comparing the responses to land. Manipulations should include using multiple immersion levels above waist level, investigating the response of small changes in temperature, and determining the response of running at various distances from the resistance jets.

Current investigations have implemented a large variety of water temperatures (20.6 – 35.6°C) during ATM running. For only a 6°C difference in temperature, Gleim and Nicholas (1989) reported that exercising at 36.1°C increased heart rate for a given $\dot{V}O_2$ compared to 30.5°C. McArdle, Magel, Lesmes and Pechar (1976) immersed participants to the level of the first thoracic vertebrae at 18°C, 25°C and 33°C water in order to compare cardiac output and associated cardiorespiratory responses during similar levels of work using exercise on an immersed arm-leg cycle ergometer. When increasing exercise intensity to 120 Watts, air and
33°C water were almost identical. However, during submaximal work in 25°C and 18°C water the $\dot{V}O_2$ was significantly higher than that observed in water of 33°C ($\dot{V}O_2$ was 9% greater in 25°C than 33°C). At a given submaximal $\dot{V}O_2$, heart rate in 18°C water averaged 5 beats per minute lower than in 25°C water and 15 beats per minute lower than in 33°C water or air.

Shimizu, Kosaka and Fujishima (1998) found statistically significant changes in heart rate when comparing 60 minutes of ATM walking at 25°C, 30°C and 35°C while immersed to the middle of the chest. Heart rate was highest among participants exercising in water at 35°C, followed by 25°C and 30°C being the lowest. Therefore, given the range of the current temperatures included in this review, it is difficult to accurately compare the cardiovascular response between and within studies. Future research should focus on how smaller changes in water temperature, above or below thermoneutral, may influence the cardiovascular responses seen during ATM running.

It is suggested future studies use the same level of water immersion, belt speed, and water resistance in order to better understand the influence water temperature has on the cardiovascular response.

Lastly, very few papers controlled for the running position of the participants with respect to the jet-to-chest distance from the resistance jets. A better understanding of the effect that the resistance jets have on the cardiorespiratory response, as well as the effect of different running distances from the jet is important. Future work should aim to quantify the cardiorespiratory responses to various distances from the resistance jets.

Readers should take caution when drawing conclusions from the current literature as many studies compare responses at different water temperatures, distances from the resistance jets, depth of water immersion, or at various exercise intensities compared to land. In addition,
this review highlights the importance of completing a graded exercise test on an ATM when reporting relative heart rate values, as the maximum heart rate during ATM running is lower than that of LTM running. In future studies that report relative heart rate during ATM and LTM running, percentages should be derived from a graded exercise test both in water and on land.

Research into appropriate secondary termination criteria during ATM graded exercise testing is also justified. As $\dot{V}O_2_{max}$ is unchanged between ATM and LTM running, $\dot{V}O_2$ plateau as the primary criteria for reaching maximal exercise may be appropriate. However, only one study included a plateau in $\dot{V}O_2$ as a criterion for reaching maximal exercise. This study did not report on how many participants were able to reach a plateau during ATM running. Therefore, further validation is needed to accept this criterion. Secondary criteria commonly used, such as age-predicted maximal heart rate, rating of perceived exertion, lactate values, and the respiratory exchange ratio may not be acceptable. During ATM running, maximal heart rate and respiratory exchange ratio are lower compared to land. It is possible that rating of perceived exertion is higher with increasing resistance jet versus running speed or $\dot{V}O_2$. During graded exercise tests where high resistance jets are used due to the capacity of the treadmill speed, rating of perceived exertion may be higher during ATM running. Given that motivation is a factor at higher levels of exercise, a higher perception of effort may possibly lead to lower maximal responses during graded exercise tests on an ATM. Therefore, it is suggested that the commonly used secondary criteria to establish maximum exercise during LTM graded exercise testing be adjusted for ATM graded exercise testing purposes and research into appropriate values be investigated.

Additionally, the ability to maintain a pedal rate of 60 revolutions per minute is commonly used during cycling as a termination criteria to ensure a progressive increase in intensity with each stage (Poole, Wilkerson, & Jones, 2008; Day, Rossiter, Coats, Skasick, &
Whipp, 2003). With buoyancy forces acting on an individual during ATM running, a similar criterion needs to be developed for ATM graded exercise testing to ensure there in an intensity increase with each stage and a relative termination point for the running distance from the jet.

More research is needed to understand the respiratory responses to ATM running. These include how running at different distances from the resistance jets and how various water immersion depths between the waist and chest during ATM running can impact the respiratory response. In addition, future work determining whether or not ventilatory thresholds are a valid measure during ATM running and the relationship to lactate thresholds would be beneficial. Of the studies that do measure respiratory responses, matched trials are very limited and therefore are warranted for future study.

3.7 Conclusion

To summarize the findings of this review, during submaximal ATM running there are no differences in heart rate, ventilation, or tidal volume at a given \( \dot{V}O_2 \), and a significant increase in respiratory exchange ratio, compared to LTM running. For maximal exercise on an ATM there is no difference in \( \dot{V}O_2 \), ventilation, and lactate, but a small decrease in heart rate and a significant decrease in respiratory exchange ratio during ATM compared to LTM running. The responses of ventilation, tidal volume, and respiratory rate during submaximal running at a matched \( \dot{V}O_2 \) and maximal running on an ATM compared to a LTM are limited in the current research and are recommended for future studies. In addition, it is important to create more consistent protocols in order to accurately compare results and ensure the responses are reflective of the mode of exercise. This includes the temperature of the water, the running position relative to the resistance jet, and the level of water immersion at a matched metabolic demand. Although more
studies comparing ATM to LTM running are needed, it is also important to manipulate these factors to better understand the impact each has on the cardiorespiratory response.

This review discusses the importance of conducting an ATM graded exercise test in order to reflect accurate submaximal intensities, however new or modified maximal exercise criteria may be necessary. The use of an ATM can be effectively incorporated into rehabilitation and training, however a greater understanding of the expected responses is needed to increase the likelihood that desired adaptations are being achieved. It is important to consider and understand the manipulations that can be made to enhance the effectiveness of ATMs as a training or rehabilitation tool. These manipulations include water immersion depth, water temperature, added jet resistance, the running distance from the resistance jets, and belt speed. Future studies should aim to understand how small manipulations in these factors could influence cardiovascular and respiratory responses.
Chapter 4: A Systematic Review of the Efficacy of Lower Body Aquatic Plyometric Training. The Development of Evidence-Based Recommendations for Practitioners.


4.1 Introduction

Plyometric training is a popular form of explosive training commonly used in sport and health-related fitness settings. Previous literature has demonstrated the effectiveness of plyometric training to increase various performance markers, such as vertical jump, muscular strength, and speed (Johnson, Salzberg, and Stevenson, 2011; Markovic, 2007). By design, plyometric training increases the stress placed on muscles and joints. The increased stress experienced in connective tissue may deter practitioners from implementing plyometric exercises with athletes recovering from an injury.

Recently, aquatic plyometric training has become a popular alternative to land-based plyometric training due to the buoyancy of the water reducing a large amount of the gravitational stress typically observed with land-based plyometrics (Donoghue, Shimojo, & Takagi, 2011), along with reduced levels of muscle damage indicators (Wertheimer, Antekolovic, & Matkovic, 2018). For instance, peak impact force and impact force rate is lower in water than on land, whereas peak concentric force has shown to be higher for aquatic plyometric training during both double leg and single leg jumping (Colado, Garcia-Masso, González, Triplett, Mayo, & Merce, 2010;
This observation may be of particular interest to practitioners while their athletes are recovering from injury or in the return-to-play stage. The positive effects of plyometric training are well understood and dependent on program duration, the number of sessions, and the number of jumps per session (de Villarreal, Kellis, Kraemer, & Izquierdo, 2009). Therefore, the primary purpose of this review was to 1) complete a systematic review to critically examine the efficacy of plyometric training performed in water when compared to land for eliciting adaptation in select musculoskeletal fitness markers of performance, and 2) to provide evidence-based recommendations for practitioners on how to best utilize this form of training.

4.2 Methods

Inclusion and exclusion criteria

A systematic approach was used to find relevant articles that compared the effect of plyometric training in water and on land according to the PRISMA guidelines (Liberati et al., 2009). Studies that involved the same plyometric program between land and water groups, and measured changes in performance measures [such as strength, speed, and power (vertical jump)] were eligible for inclusion. Excluded studies included those utilizing equipment to increase resistance, studies without human participants, studies in which participants completed different programs between land and water, studies that included complex training of plyometrics and strength, studies that did not include a strength, speed, or vertical jump performance measure, case studies, and review studies. The criteria for study inclusion was also limited to journal articles published in English with full-text available.

Search Strategy

The following electronic databases were used to complete literature searches:
• MEDLINE (OVID Interface);
• EMBASE (OVID Interface);
• SPORTDiscus (EBSCO Interface).

Broad subject headings and key words were used as search terms to identify appropriate articles. The search strategy and results for each electronic database is included in Table 4.1. All search results were subsequently downloaded onto RefWorks (Bethesda, MD, USA), an online bibliographic management program.

Table 4.1 Details of Search Strategy

<table>
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<tr>
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<th>Search history</th>
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</tr>
<tr>
<td>2</td>
<td>Jump *</td>
<td>22974</td>
</tr>
<tr>
<td>3</td>
<td>Squat jump</td>
<td>640</td>
</tr>
<tr>
<td>4</td>
<td>Depth jump</td>
<td>63</td>
</tr>
<tr>
<td>5</td>
<td>Drop jump</td>
<td>495</td>
</tr>
<tr>
<td>6</td>
<td>Stretch shortening cycle</td>
<td>356</td>
</tr>
<tr>
<td>7</td>
<td>Countermovement jump</td>
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<td>8</td>
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<tr>
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</tr>
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<td>11</td>
<td>Pool</td>
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<td>284989</td>
</tr>
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<td>13</td>
<td>8 and 12</td>
<td>453</td>
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<td>14</td>
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EMBASE (via OVID)

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</tr>
<tr>
<td>2</td>
<td>Jump* (exploded)</td>
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</tr>
<tr>
<td>3</td>
<td>Squat jump</td>
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<tr>
<td>4</td>
<td>Depth jump</td>
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</tr>
<tr>
<td>5</td>
<td>Stretch shortening cycle</td>
<td>376</td>
</tr>
<tr>
<td>6</td>
<td>Drop jump</td>
<td>413</td>
</tr>
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</table>
Study selection

Three reviewers screened all identified articles using a multi-step process. At each level of the process, discrepancies were recorded and reassessed by consensus. The number of articles that were excluded at each step of screening was also recorded (Figure 4.1). The combined articles from the three electronic databases were reviewed and duplicates were excluded. Titles and abstracts were then screened for inclusion. Once all of the articles were identified following the abstract screening, full-text articles were obtained. Full-text articles were thoroughly vetted by two reviewers for inclusion. A reason for an excluded article during full-text review was noted (Figure 4.1). An in-depth review of the references of the included articles was completed by two reviewers to identify additional articles that were eligible for inclusion.
Records identified through database searching (n = 989)

Additional records identified through other sources (n = 1)

Records after duplicates removed (n = 954)

Records screened (n = 954)

Records excluded (n = 935)

Full-text articles assessed for eligibility (n = 19)

Studies included in qualitative synthesis (n = 8)

Full-text articles excluded, with reasons (n = 11)
- No measures of included performance tests (n = 4)
- No comparison to land plyometric group (n = 3)
- Aquatic resistance training versus plyometrics alone (n = 2)
- Not a peer reviewed journal (n = 1)
- Use of medicine ball and weight vest (n = 1)

Figure 4.1 PRISMA flow diagram for search strategy
Data extraction

Articles included in this review are provided in Table 4.2. Data were extracted from the included articles using a standardized extraction form as confirmed by three reviewers. The focus of the extraction was the comparison of plyometric training on land and in water. Data extraction included the population characteristics, the program design, and the pre- and post- adaptation in strength, speed, and vertical jump following land- and water-based plyometric training.
<table>
<thead>
<tr>
<th>Publication</th>
<th>Population</th>
<th>Age, years (mean ± SD)</th>
<th>Program Frequency and Duration</th>
<th>Number of Jumps per Session</th>
<th>Water Depth</th>
<th>Performance Tests Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atanaskovic, Georgiev &amp; Mutavdzic, 2015</td>
<td>30 male children</td>
<td>12.9 ± 1.5</td>
<td>2x/week for 6 weeks</td>
<td>Progressed from 90-160</td>
<td>1.3 m (~77% of the body submerged)</td>
<td>Vertical jump: Squat Jump and CMJ</td>
</tr>
<tr>
<td>Shiran, Kordi, Ziaee, Ravasi &amp; Mansournia, 2008</td>
<td>21 male wrestlers</td>
<td>20.3 ± 3.6</td>
<td>3x/week for 6 weeks</td>
<td>Progressed, but not recorded.</td>
<td>Not reported</td>
<td>Strength: back squat Speed: 5m, 10m, 20m</td>
</tr>
<tr>
<td>Arazi, Coetzee &amp; Asadi, 2012</td>
<td>18 male semi-professional basketball players</td>
<td>Overall: 18.8 ± 1.4</td>
<td>3x/week for 8 weeks</td>
<td>Progressed from 117-183</td>
<td>Chest deep</td>
<td>Vertical Jump: CMJ</td>
</tr>
<tr>
<td>Stemm &amp; Jacobson, 2007</td>
<td>21 physically active, college aged men</td>
<td>24 ± 2.5</td>
<td>2x/week for 6 weeks</td>
<td>135</td>
<td>Knee depth</td>
<td>Vertical Jump: CMJ</td>
</tr>
<tr>
<td>Miller, Berry, Bullard &amp; Gilders, 2002</td>
<td>40 (21 women, 19 men) inactive to recreationally active individuals</td>
<td>Aquatic: 22.0 ± 2.5</td>
<td>2x/week for 8 weeks</td>
<td>2x/week for 8 weeks</td>
<td>Waist depth</td>
<td>Vertical Jump: CMJ Strength: Knee Isokinetic Torque</td>
</tr>
<tr>
<td>Ploeg, Miller, Holcomb, O'Donoghue &amp; Berry, 2010</td>
<td>39 (16 males, 23 females) untrained individuals</td>
<td>Males: 21.8 ± 2.3</td>
<td>2x/week for 6 weeks</td>
<td>Males: 21.8 ± 2.3</td>
<td>1.07 m (~61% of the body submerged)</td>
<td>Vertical Jump: CMJ Strength: Knee Isokinetic Torque</td>
</tr>
<tr>
<td>Publication</td>
<td>Population</td>
<td>Age, years (mean ± SD)</td>
<td>Program Frequency and Duration</td>
<td>Number of Jumps per Session</td>
<td>Water Depth</td>
<td>Performance Tests Included</td>
</tr>
<tr>
<td>--------------------------------------------------------</td>
<td>-------------------------------------------------</td>
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<td>----------------------------</td>
<td>----------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Robinson, Devor, Merrick &amp; Buckworth, 2004</td>
<td>32 physically active women</td>
<td>Overall: 20.2 ± 0.3</td>
<td>3x/week for 8 weeks</td>
<td>Progressed In 3-4 sets of 10-20 reps for 10 exercises</td>
<td>1.2 – 1.4 m (~73% of the body submerged)</td>
<td>Vertical Jump: CMJ Speed: 40 m Strength: Knee Isokinetic Torque</td>
</tr>
<tr>
<td>Arazi &amp; Asadi, 2011</td>
<td>18 male semi-professional basketball players</td>
<td>Overall: 18.8 ± 1.5</td>
<td>3x/week for 8 weeks</td>
<td>Progressed from 117-183</td>
<td>Chest deep</td>
<td>Strength: Leg press Speed: 36.5m and 60m</td>
</tr>
</tbody>
</table>

*CMJ* = Counter Movement Jump
Level of evidence

A modified Downs and Black scoring system (Downs and Black, 1998) was used to score the quality of the included studies. The questions from the original Downs and Black scoring system that were considered relevant to the topic of this systematic review were included to measure the level of evidence. The scoring of the articles was completed independently by two reviewers and consensus was reached through discussion as necessary. The outcomes of the modified Downs and Black scoring system is provided (Table 4.3).

Table 4.3 Modified Downs and Black Scoring System (listed in order to total score)

<table>
<thead>
<tr>
<th>No.</th>
<th>Article</th>
<th>Questions</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 9 10</td>
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<tr>
<td>1</td>
<td>Robinson et al., 2004</td>
<td>1 1 1 1 2 1 1 1 1</td>
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<tr>
<td>2</td>
<td>Miller et al., 2002</td>
<td>1 1 1 1 1 1 1 1 0</td>
</tr>
<tr>
<td>3</td>
<td>Atanaskovic et al., 2015</td>
<td>1 1 1 1 1 0 1 1 1</td>
</tr>
<tr>
<td>4</td>
<td>Ploeg et al., 2010</td>
<td>1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>5</td>
<td>Shiran et al., 2008</td>
<td>1 1 1 0 0 1 1 1 1</td>
</tr>
<tr>
<td>6</td>
<td>Stemm &amp; Jacobson, 2007</td>
<td>1 1 1 1 1 1 0 1 0</td>
</tr>
<tr>
<td>7</td>
<td>Arazi et al., 2012</td>
<td>1 1 1 1 1 0 1 1 0</td>
</tr>
<tr>
<td>8</td>
<td>Arazi &amp; Asadi, 2011</td>
<td>1 1 1 1 1 1 0 1 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Article</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Robinson et al., 2004</td>
<td>17 18 19 20 21 22 23 26 27</td>
</tr>
<tr>
<td>2</td>
<td>Miller et al., 2002</td>
<td>1 1 1 1 1 1 1 1 5</td>
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<td>3</td>
<td>Atanaskovic et al., 2015</td>
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<td>Shiran et al., 2008</td>
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<td>Stemm &amp; Jacobson, 2007</td>
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<td>7</td>
<td>Arazi et al., 2012</td>
<td>1 1 1 1 1 1 1 1 3</td>
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<td>8</td>
<td>Arazi &amp; Asadi, 2011</td>
<td>1 1 1 1 1 1 1 1 3</td>
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</table>
4.3 Results

Strength

Five articles examined muscular strength following aquatic and land plyometric training (Arazi and Asadi, 2011; Miller, Berry, Bullard, and Gilders, 2002; Ploeg et al., 2010; Ravasi, Mansournia, Kordi, Shiran, and Ziaee, 2008; Robinson, Devor, Merrick, Buckworth, 2004). Results are presented in Table 4.4. Strength was examined using the back squat (Ravasi et al., 2008), leg press (Arazi and Asadi, 2011), and by isokinetic knee torque (Miller et al., 2002; Ploeg et al., 2010; Robinson et al., 2004). Of these articles, two reported improved strength outcomes following aquatic and land plyometric training with no differences between the conditions (Ravasi et al., 2008; Robinson et al., 2004). Increases reported in the study by Robinson et al. (2004) were for both concentric and eccentric strength. Arazi and Asadi (2011) reported no significant differences in one-repetition maximum leg press in both groups. Ploeg et al. (2010) found no significant differences in peak torque in the land training group, the matched aquatic training group, and the second aquatic training group that completed twice as many jumps as land. The testing was completed at 60°•s\(^{-1}\), which is the same protocol as in Robinson et al. (2004) that reported significant increases in strength. The training program used in Ploeg et al. (2010) was six weeks in duration with two sessions per week, whereas Robinson et al. (2004) trained for eight weeks with three sessions per week. Miller et al. (2002) performed tests of concentric knee flexion and extension at three speeds, 90°•s\(^{-1}\), 180°•s\(^{-1}\), and 360°•s\(^{-1}\). Significant improvement in strength output was observed in knee flexion at the highest velocity (360°•s\(^{-1}\)) in both the aquatic and land plyometric training groups, with no differences between conditions. Given the relationship between sprint performances in distances greater than 20-m and the importance of the hamstrings during maximal running speed (36-100m) (Delecluse, 1979), it is interesting to note the only
significant increase in muscle torque was with knee flexion at highest velocity. Taken together, these results suggest aquatic plyometric training is as effective as land plyometric training at increasing lower body strength.

Table 4.4 Strength Adaptations between Aquatic and Land Plyometric Training

<table>
<thead>
<tr>
<th>Study</th>
<th>Program Frequency and Duration</th>
<th>Water Depth</th>
<th>Number of Jumps per Session</th>
<th>Strength</th>
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<td>Land Group</td>
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<td></td>
<td>Pre</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pre</td>
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<tr>
<td>Shiran, Kordi, Ziaee, Ravasi and Mansournia, 2008</td>
<td>3x/week for 6 weeks</td>
<td>Not reported</td>
<td>Progressed, but not recorded.</td>
<td>Back Squat: 131 ± 14.2 kg</td>
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<td>Miller, Berry, Bullard and Gilders, 2002</td>
<td>2x/week for 8 weeks</td>
<td>Progressed from 80-120</td>
<td>3x/week for 6 weeks</td>
<td>Flexion 90° • s⁻¹: 71.6 ± 19.5</td>
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<td></td>
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<td>59.6 ± 16.9</td>
</tr>
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<td>360° • s⁻¹: 57.5 ± 16.9</td>
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<td>46.3 ± 15.5</td>
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<td>Extension 90° • s⁻¹: 137.4 ± 35.6</td>
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<td>180° • s⁻¹: 180° • s⁻¹:</td>
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<td>100.3 ± 28.5</td>
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<td>360° • s⁻¹: 360° • s⁻¹:</td>
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<td>73.3 ± 37.7</td>
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<table>
<thead>
<tr>
<th>Study</th>
<th>Program Frequency and Duration</th>
<th>Water Depth</th>
<th>Number of Jumps per Session</th>
<th>Strength</th>
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<tr>
<td>Ploeg, Miller, Holcomb, O'Donoghue and Berry, 2010</td>
<td>2x/week for 6 weeks</td>
<td>1.07 m (~61% of the body submerged)</td>
<td>AG1: Progressed from 90-120</td>
<td>Flexion 1.05 rad s⁻¹: 71.3 ± 21.0</td>
</tr>
<tr>
<td></td>
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<td>AG2: Progressed from: 180-240</td>
<td>Extension 1.05 rad s⁻¹: 123.5 ± 24.2</td>
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<td>AG1: 1.05 rad s⁻¹: 66.9 ± 21.9</td>
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<td>Extension 1.05 rad s⁻¹: 124.0 ± 24.3</td>
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<td>AG2: 60° • s⁻¹: 75.4 ± 31.5</td>
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<td>Extension 1.05 rad s⁻¹: 119.4 ± 37.7</td>
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<td></td>
<td>AG1: 1.05 rad s⁻¹: 73.5 ± 33.0</td>
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<td></td>
<td>AG2: 1.05 rad s⁻¹: 117.1 ± 39.9</td>
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<td>Flexion 1.05 rad s⁻¹: 68.1 ± 26.5</td>
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<td></td>
<td></td>
<td>Extension 1.05 rad s⁻¹: 73.5 ± 33.0</td>
</tr>
<tr>
<td>Robinson, Devor, Merrick and Buckworth, 2004</td>
<td>3x/week for 8 weeks</td>
<td>1.2 – 1.4m (~73% of the body submerged)</td>
<td>Progressed in 3-4 sets of 10-20 reps for 10 exercises</td>
<td>Concentric Flexion 60.16° • s⁻¹: 82.7 ± 2.9</td>
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<td>Concentric Extension 60.16° • s⁻¹: 151.0 ± 7.2</td>
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<td>Eccentric Flexion 60.16° • s⁻¹: 185.0 ± 9.3</td>
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<td>Eccentric Extension 60.16° • s⁻¹: 137.0 ± 4.8</td>
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<td>Concentric Flexion 60.16° • s⁻¹: 120.0 ± 4.2</td>
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<td></td>
<td></td>
<td>Concentric Extension 60.16° • s⁻¹: 189.0 ± 6.8</td>
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<td>Eccentric Flexion 60.16° • s⁻¹: 230.0 ± 10.3</td>
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<td>Eccentric Extension 60.16° • s⁻¹: 188.0 ± 7.2</td>
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<td>Concentric Flexion 60.16° • s⁻¹: 86.3 ± 3.4</td>
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<td>Concentric Extension 60.16° • s⁻¹: 161.0 ± 5.2</td>
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<td>Eccentric Flexion 60.16° • s⁻¹: 201.0 ± 5.4</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eccentric Extension 60.16° • s⁻¹: 235.0 ± 6.2</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>Concentric Flexion 60.16° • s⁻¹: 125.0 ± 3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Concentric Extension 60.16° • s⁻¹: 201.0 ± 5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eccentric Flexion 60.16° • s⁻¹: 147.0 ± 4.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eccentric Extension 60.16° • s⁻¹: 235.0 ± 6.2</td>
</tr>
<tr>
<td>Arazzi and Asadi, 2011</td>
<td>3x/week for 8 weeks</td>
<td>Chest deep</td>
<td>Progressed from 117-183</td>
<td>Leg Press (kg): 185 ± 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Leg Press (kg): 200 ± 15</td>
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<td>Leg Press (kg): 180 ± 20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Leg Press (kg): 200 ± 20</td>
</tr>
</tbody>
</table>

superscript `a` = significant difference between post-training and pre-training

superscript `b` = significant difference between aquatic group and land group
Clinical Recommendations:

i) Aquatic plyometric programs can be used for improving concentric and eccentric muscular strength once the athlete is capable of withstanding the required skeletal loading during the rehabilitation process. Impact forces can be progressed from chest-deep water (lower impact forces) to knee-deep water (impact force is more similar to land-based plyometrics) as tolerable.

ii) Practitioners are encouraged to include aquatic plyometric exercises in rehabilitation and the return-to-play process for developing power output prior to entering competition.

iii) Aquatic plyometric training can be used for maintaining muscular strength during periodized rest weeks within the yearly training plan. Alternatively, this form of training can be used during the off-season to adequately reduce the experienced load and volume of training to allow for rest and recovery without negatively impacting muscular performance.

Sprinting

Three articles examined sprint performance following aquatic and land plyometric training (Arazi and Asadi, 2011; Ravasi et al., 2008; Robinson et al., 2004). Results are presented in Table 4.5. Robinson et al. (2004) observed that peak speed during a 40-m sprint was significantly increased following both aquatic and land plyometric training, with no difference between the groups. Arazi and Asadi (2011) found a significant improvement in sprint performance over 36.5-m and 60-m in both land and aquatic plyometric training with no difference between groups. Ravasi et al. (2008) measured sprint time over 5-m, 10-m, and 20-m where a significant improvement over 20-m following land plyometric training was present. Although a significant improvement was demonstrated in 20-m sprint performance in the land group, a nonsignificant improvement between the aquatic and land group when comparing the difference in post-test and pre-test measurements was observed. These findings suggest a possible improvement in sprint
performance over longer distances following land and aquatic plyometric training. It is possible that plyometric training may help increase maximal speed compared to acceleration. Sprint performance is often viewed multi-dimensionally as an acceleration phase (0-10 m), a phase of maximum running speed (36-100-m), and a transition phase in between (Delecluse, 1979). A previous investigation has suggested that the hamstrings, the adductor magnus, and the gluteus maximus are considered to make the most important contribution in producing the highest level of speed (Delecluse, 1979). It is possible that the increases in maximum speed versus acceleration relate to the increases in lower body power through the Margaria-Kalamen test versus a counter movement jump in regard to the similarity of movement and duration of the test. It appears that both aquatic and land plyometric programs provide a stimulus capable of increasing sprint ability, especially for distances greater than 20-m.

Table 4.5 Speed Adaptations between Aquatic and Land Plyometric Training

<table>
<thead>
<tr>
<th>Study</th>
<th>Program Frequency and Duration</th>
<th>Water Depth</th>
<th>Number of Jumps per Session</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shiran, Kordi, Ziaee, Ravasi and Mansournia, 2008</td>
<td>3x/week for 6 weeks</td>
<td>Not reported</td>
<td>Progressed, but not recorded</td>
<td>Land Group: Pre 5 m: 1.13 ± 0.1 s 10 m: 1.83 ± 0.2 s 20 m: 3.5 ± 0.2 s Aquatic Group: Pre 5 m: 1.14 ± 0.1 s 10 m: 1.78 ± 0.3 s 20 m: 3.37 ± 0.2 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Land Group: Post 5 m: 1.07 ± 0.1 s 10 m: 1.68 ± 0.4 s 20 m: 3.46 ± 0.2 s Aquatic Group: Post 5 m: 1.07 ± 0.1 s 10 m: 1.68 ± 0.4 s 20 m: 3.46 ± 0.2 s</td>
</tr>
<tr>
<td>Robinson, Devor, Merrick and Buckworth, 2004</td>
<td>3x/week for 8 weeks</td>
<td>1.2 – 1.4 m (~73% of the body submerged)</td>
<td>Progressed in 3-4 sets of 10-20 reps for 10 exercises</td>
<td>Land Group: Pre 40 m: 6.70 ± 0.2 s 285.7 s Aquatic Group: Pre 40 m: 6.30 ± 0.2 s 307.7 s</td>
</tr>
<tr>
<td>Study</td>
<td>Program Frequency and Duration</td>
<td>Water Depth</td>
<td>Number of Jumps per Session</td>
<td>Speed</td>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pre</td>
</tr>
<tr>
<td>Arazi and Asadi, 2011</td>
<td>3x/week for 8 weeks</td>
<td>Chest deep</td>
<td>Progressed from 117-183</td>
<td>36.5 m:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.50 ±</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5 s</td>
</tr>
<tr>
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<td></td>
<td>60 m:</td>
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<td></td>
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<td></td>
<td></td>
<td>8.95 ±</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>0.6 s</td>
</tr>
</tbody>
</table>

\(^a\) = significant difference between post-training and pre-training
\(^b\) = significant difference between aquatic group and land group

**Clinical Recommendations:**

i) Aquatic plyometric training can be used to improve sprint ability, particularly maximum running speed, once the athlete is capable of withstanding the required skeletal loading during the rehabilitation process.

ii) Practitioners are encouraged to include aquatic plyometric exercises in rehabilitation and the return-to-play process for improving sprinting ability and tolerance prior to competition, particularly if longer runs (>20m) at maximum speed are common in their respective sport.

**Vertical Jump**

Six articles measured vertical jump performance following plyometric training in water and on land (Arazi, Coetzee, and Asadi, 2012; Atanasković, Georgiev, and Mutavdžić, 2015; Miller et al., 2002; Ploeg et al., 2010; Robinson et al., 2004; Stemm and Jacobson, 2007). Results are presented in Table 4.6. Of these articles, four identified vertical jump performance to be significantly increased in both land and aquatic plyometric training groups with no significant difference between conditions (Arazi et al., 2012; Atanasković et al., 2015; Robinson et al., 2004; Stemm and Jacobson, 2007). Ploeg et al. (2010) and Miller et al. (2002) found no significant
increase in vertical jump performance with either land or aquatic plyometric training. Miller et al. (2002) used the Margaria-Kalamen test as a second measure of lower body power and found that the aquatic group significantly increased power production compared to pre-testing, whereas the land group did not. Additionally, Ploeg et al. (2010) included two aquatic plyometric groups. The first group completed the same plyometric program as the land group, only in water, whereas the second group completed twice as many jumps each session. Neither aquatic group increased vertical jump performance in this study. The findings of Ploeg et al. (2010) were in contrast to previous investigations that demonstrated significant improvement (Arazi et al., 2012; Atanasković et al., 2015; Robinson et al., 2004; Stemm and Jacobson, 2007). One difference was the use of an immersed cone and step. Although participants were asked to provide maximal effort throughout each session, it is possible that when instructed to jump on the step or over the cone, maximal effort was not required to complete the task. Although the authors attempted to match intensity between land and aquatic groups, it is likely that the buoyancy of water opposing gravity required less effort to achieve the task of jumping over a cone or step. It appears that vertical jump performance, and possibly other measures of lower body performance, can be improved following aquatic and land plyometric training, regardless of being on land or in water.
Table 4.6 Vertical Jump Adaptations between Aquatic and Land Plyometric Training

<table>
<thead>
<tr>
<th>Study</th>
<th>Program Frequency and Duration</th>
<th>Water Depth</th>
<th>Number of Jumps per Session</th>
<th>Vertical Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Land Group</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pre</td>
</tr>
<tr>
<td>Atanaskovic, Georgiev and Mutavdzie, 2015</td>
<td>2x/week for 6 weeks</td>
<td>1.3 m (~77% of the body submerged)</td>
<td>Progressed from 90-160</td>
<td>SJ: 22.61 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CMJ: 26.27 cm</td>
</tr>
<tr>
<td>Arazi, Coetzee and Asadi, 2012</td>
<td>3x/week for 8 weeks</td>
<td>Chest deep</td>
<td>Progressed from 117-183</td>
<td>CMJ: 44.33 cm</td>
</tr>
<tr>
<td>Stemm and Jacobson, 2007</td>
<td>2x/week for 6 weeks</td>
<td>Knee depth</td>
<td>135</td>
<td>CMJ: 67 ± 3 cm</td>
</tr>
<tr>
<td>Miller, Berry, Bullard and Gilders, 2002</td>
<td>2x/week for 8 weeks</td>
<td>Waist depth</td>
<td>Progressed from 80-120</td>
<td>CMJ: 1046.5 ± 247.3 cm</td>
</tr>
<tr>
<td>Ploeg, Miller, Holcomb, O'Donoghue and Berry, 2010</td>
<td>2x/week for 6 weeks</td>
<td>1.07 m (~61% of the body submerged)</td>
<td>Progressed from 90-120 (second aquatic group: 180 - 240)</td>
<td>CMJ: 49.4 ± 13.2 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CMJ: AG2: 41.8 ± 9.8 cm</td>
</tr>
<tr>
<td>Robinson, Devor, Merrick and Buckworth, 2004</td>
<td>3x/week for 8 weeks</td>
<td>1.2 – 1.4 m (~73% of the body submerged)</td>
<td>Progressed in 3-4 sets of 10-20 reps for 10 exercises</td>
<td>CMJ: 32.6 ± 1.7 cm</td>
</tr>
</tbody>
</table>

SJ = Squat Jump; CMJ = Counter Movement Jump; AG1 = same number of jumps as land; AG2 = double the number of jumps as land; 

* = significant difference between post-training and pre-training

Clinical Recommendations:

i) Aquatic plyometric training can be used for improving vertical jumping ability once the athlete is capable of withstanding the required skeletal loading during the rehabilitation process. Impact
forces can be progressed from chest-deep water (lower impact forces) to knee-deep water (impact force is more similar to land-based plyometrics) as tolerable.

ii) Practitioners are encouraged to include aquatic plyometric exercises in rehabilitation and the return-to-play process for developing power output prior to entering competition, particularly in sports that require a large number of jumps.

iii) Aquatic plyometric training can be used during periodized rest weeks within the yearly training plan in order to prescribe plyometric exercise without overloading the musculoskeletal system.

4.4 Discussion

Number of Jumps

The articles included consisted of a variety of number of jumps each session throughout the plyometric training program. Interestingly, two articles (Miller et al., 2002; Ploeg et al., 2010) that consisted of the least number of jumps per session (beginning at 90 and 80, respectively compared to 117 or higher) did not experience increases in vertical jump. The only other article that began at 90 jumps per session was in children and progressed to 160 jumps versus 120. These findings suggest that either the higher increase in jumps throughout the program or the participants being children may have provided a greater stimulus to create positive adaptation. In contrast, Ploeg et al. (2010) also included a second aquatic plyometric group that completed twice as many jumps each session compared to the land group and the other aquatic group. Similar to the matched aquatic and land group, the group that completed twice as many jumps each session (180-240 versus 90-120) did not significantly increase any performance measures. Consequentially, it is challenging to conclude how critical the number of jumps in a training session is. One consideration that does appear to be a factor in designing a plyometric training program is that the
number of jumps increases throughout the duration of the program as the athlete adapts to the stimulus.

**Clinical Recommendations:**
i) Aquatic plyometric programs should progress the number of jumps the athlete completes per training session as tolerable. The number of jumps should originally be based on what the athlete can tolerate and how he or she responds to the aquatic plyometric training session.

**Duration and Frequency of Training Program**

A variety of durations and number of training sessions were used in the protocol designs included in this review. Of the eight included articles, three protocols consisted of training twice per week for a period of six weeks (Atanasković et al., 2015; Ploeg et al., 2010; Stemm and Jacobson, 2007), one protocol was three times per week for a period of six weeks (Ravasi et al., 2008), one protocol was two times per week for eight weeks (Miller et al., 2002), and three protocols were three times per week for eight weeks (Arazi and Asadi, 2011; Arazi et al., 2012; Robinson et al., 2004). Three of the four studies that completed six weeks of plyometric training significantly improved vertical jump and strength, regardless of completing two or three sessions per week. Only Ploeg et al. (2010) did not report performance increases in either the land or the aquatic group. Miller et al. (2002) experienced an increase in peak knee torque at the highest velocity during eight weeks of plyometric training twice a week; however, there was no increase in either group for vertical jump. Considering, Miller et al. (2002) is the only article consisting of two sessions per week for eight weeks, it would be inappropriate to suggest the duration and frequency of the protocol was responsible.
During the protocol of eight weeks of plyometric training consisting of three sessions per week, all three investigations demonstrated a significant improvement in both the aquatic and land groups for vertical jump performance (Arazi et al., 2012; Robinson et al., 2004), sprinting performance at 36.5-m, 40-m, and 60-m (Arazi and Asadi, 2011; Robinson et al., 2004), and strength (Arazi and Asadi, 2011; Robinson et al., 2004). Although Robinson et al. (2004) used an 8-week protocol, the authors also included mid-testing during week four. It was found that four weeks of plyometric training significantly increased vertical jump, sprinting, and strength performance compared to pre-testing. In addition, there were further significant increases in the three performance measures during post-testing following eight weeks of plyometric training compared to mid-testing in both land and aquatic training groups.

The results suggest that a variety of durations of plyometric training between four and eight weeks may provide improvements in vertical jump, sprinting, and strength. Secondly, a frequency of either two or three times per week may provide similar increases.

Clinical Recommendations:

i) Aquatic plyometric programs should include two to three aquatic plyometric sessions per week for four to eight weeks, and possibly longer depending on the time to return to competition.

Training Status

The articles in this review included a variety of participant fitness levels, including physically active and inactive adults, children aged 11-14, college-aged volunteers, trained wrestlers, and semi-professional basketball players. Interestingly, the only article that experienced no increase in performance in either group for any measure was the only study that used completely untrained participants (Ploeg et al., 2010). Martel, Harmer, Logan and Parker (2005) suggested that trained individuals might be able to experience larger increases with less within-group
variation. It was further suggested that motivation for improvements might be a factor (Martel et al., 2005). Although muscle soreness was not measured by Ploeg et al. (2010) it may be possible that muscle soreness in an untrained population, especially with consistent increases in intensity, may have impacted motivation and ability to perform a maximal effort, or potentially provided too much of a stimulus. The positive adaptations in trained wrestlers and semi-professional basketball athletes provides a promising rationale for implementing aquatic plyometric training with a variety of rehabilitating athletes, especially in later stages of the rehabilitation and return-to-play process, as well as for healthy athletes either in-season or during the off-season.

**Clinical Recommendations:**

i) Aquatic plyometric programs can effectively be incorporated into the rehabilitation programs for a variety of athletes, from children to adults and untrained to high level athletes, to improve strength, sprinting, and vertical jump.

ii) Aquatic plyometric programs should consider the current training status of the athlete, as well as the physical demand of the sport that the athlete is returning to.

**Water Depth**

Various water depths were used in the selected articles for the aquatic groups. Four articles used individualized water depths of either chest-, waist-, or knee-depth water immersion. Of these, two articles used chest-deep water (Arazi and Asadi, 2011; Arazi et al., 2012), one article used waist-depth (Miller et al., 2002), and one article used knee-depth water (Stemm and Jacobson, 2007). The remaining studies used a fixed depth, which creates variance for individuals of different heights in the aquatic groups. When comparing the depth to the average height of the individuals, Atanaskovic et al. (2015) had 77% of the body immersed, Robinson et al. (2004) had 73% of the body immersed, and Ploeg et al. (2010) immersed 61% of the body. Only one article did not report
the water depth used during aquatic plyometric training (Ravasi et al., 2008). For the purpose of this review, 77% and 73% of the body immersed was considered chest-deep water immersion, whereas 61% of the body immersed was considered waist-depth immersion.

For the four articles using chest-deep water immersion, vertical jump and sprinting performance was increased significantly in both groups with no difference between conditions. Strength was significantly increased during both aquatic and land plyometric training in one article (Robinson et al., 2004), but not in another (Arazi and Asadi, 2011). For waist-depth water immersion, there was no increase in vertical jump performance in two articles. Strength was not significantly increased in one article (Ploeg et al., 2010) at a velocity of 60°•s−1. In contrast, Miller et al. (2002) observed strength was only significantly increased at the highest velocity (360 °•s−1) in knee flexion.

With knee-depth water immersion, vertical jump, sprinting ability, and strength were increased significantly in both aquatic and land plyometric training groups with no difference between groups. Ploeg et al. (2010) followed a similar protocol to Robinson et al. (2004) with different results in similar performance measures. One difference between the two protocols was that Ploeg et al. (2010) used waist-deep water immersion and Robinson et al. (2004) used chest-deep water immersion. Whether the difference in water depth can explain the difference in the results is unknown. Although there are other variations in programming, it appears that performance measures can be increased at multiple depths of water immersion. Chest-deep and knee-deep water immersion may increase vertical jump, strength, and sprinting performance. For waist-deep water immersion, there were mixed results. It should be noted that the land group followed the same results as the aquatic group, so water depth may not be the only factor. The only difference between groups was during the Margaria-Kalamen test where the aquatic training group
had significant improvements. One possible explanation may be that chest-deep water immersion requires greater force and power output during the upward phase of the jump compared to waist-deep water immersion and land-based plyometric exercise due to the resistance of the water (Louder, Searle, and Bressel, 2016). Similarly, knee-deep water immersion is more similar to land and improvements may be made with higher velocity and less water resistance in the upwards phase, combined with greater eccentric forces during the landing due to increased jump height. It is possible that waist-deep immersion is a transition phase that provides too much resistance to increase high velocities, and not enough to experience increases in peak power.

Donoghue et al. (2011) compared impact forces and landing impulse between land and aquatic training at a depth of three centimeters below the xiphoid process. The findings presented in this investigation demonstrated that impact forces were 33-54% lower in aquatic groups compared to land groups for various exercises. Of note, counter movement jumps produced a 40% reduction in impact forces in the aquatic group. In terms of landing impulse, there was a reduction of 19-54% in the aquatic training group. Considering the improvements at multiple depths of water immersion, it may be recommended for sport practitioners to base the water depth off of impact forces to ensure the amount of stress experienced is appropriate to rehabilitation goals.

Clinical Recommendations:

i) Aquatic plyometric programs should base water-depth on desired impact forces that the athlete can tolerate during various stages of the rehabilitation process.

ii) Chest-deep water immersion provides a greater resistance during the concentric or upwards movements of the jump while providing lower impact forces. In contrast, knee-deep water immersion is more similar to land in terms of resistance in the upwards movement, as well as impact forces. Both of these depths improved lower-body strength, speed, and power.
iii) Using a variety of depths that produce impact forces that the athlete can tolerate and provide a concentric and eccentric load similar to the required demands of the sport or activity is recommended as part of the rehabilitation and return-to-sport protocol.

4.5 Conclusions

The results of this systematic review suggest that aquatic plyometric training is as effective as land plyometric training at improving markers of performance, including lower body strength, vertical jump, and sprinting performance. One advantage to aquatic plyometric training is that the amount of eccentric loading and impact forces on the musculoskeletal system may be reduced while concurrently enhancing performance. Although individual differences are frequently observed in all training programs, it appears that aquatic plyometric training elicits positive adaptations in many athletes, and does not appear to have detrimental effects on performance measures in those who did not experience increases. Therefore, the use of aquatic plyometric training to improve muscular power, strength, and speed during the rehabilitation process while reducing the additional musculoskeletal load experienced during traditional plyometric training provides a valuable tool for practitioners with rehabilitating athletes.

4.6 Practical Applications

The utilization of aquatic plyometric training can be an important piece of a rehabilitation program in order to reduce the stress on the joints and muscle soreness, while improving lower body power. Peak impact force and impact force rate has been demonstrated to be lower in water as compared to land, whereas peak concentric force is higher for aquatic plyometric training during both double leg and single leg jumping (Colado et al., 2010; Triplett et al., 2009). Such an outcome may be beneficial during multiples phases of the rehabilitation process and aid in the primary goal
of returning athletes to sport successfully and efficiently. In addition, a reduced perceived muscle
soreness following aquatic versus land plyometric training may be experienced by athletes
(Robinson et al., 2004).

Based on the literature, it is recommended that aquatic plyometric training be incorporated
with rehabilitating athletes as a means of improving lower body strength, speed, and power, while
reducing the risk of re-injury or exceeding load tolerance. Specifically, the program should
progress the number of jumps in a session as tolerable with two to three aquatic plyometric sessions
per week for four to eight weeks. Aquatic plyometric programming should consider the current
training status of the athlete, as well as the physical demand of the sport that the athlete is returning
to. When determining water depth for aquatic plyometric training, it is recommended that
practitioners prescribe based on desired impact forces. Chest-deep water immersion provides a
greater resistance during the concentric or upwards movements of the jump while providing lower
impact forces. In contrast, knee-deep water immersion is more similar to land in terms of resistance
in the upwards movement, as well as impact forces. Both of these depths improved lower-body
strength, speed, and power. Therefore, using a variety of depths that produce impact forces that
the athlete can tolerate and provide concentric and eccentric loads similar to the required demands
of sport or activity is recommended as part of the rehabilitation and return-to-sport protocol.
Chapter 5: Biomechanical Alterations during Aquatic Treadmill Running


5.1 Introduction

Running is a popular form of exercise for recreational and competitive athletes. In the United States alone an estimated 36 million individuals participate in running each year, with 10.5 million running 100 or more days per year (American Sports Data, 2003). Unfortunately, overuse injuries (e.g. stress fractures) are common among runners with rates ranging from 5% to 16% (Matheson et al., 1987) and epidemiological studies have reported that between 19% and 76% of all distance runners experience at least one lower extremity injury per year (Daoud et al., 2012; Van Gent et al., 2007). Systematic reviews on injuries in distance runners have identified high training loads to be a strong risk factor for injury (Van Middlekoop et al., 2008; Yeung and Yeung, 2001). Given the amount of training stress, it is common practice to use alternative forms of running, such as deep water and shallow water running, to aid in recovery of lower body injuries in runners (Town and Bradley, 1991).

The water provides unique characteristics as there are fluid forces acting on the body during immersion. The buoyancy force acts in the opposite direction to the force of gravity, whereas the drag force acts in the opposite direction to the movement of an object (e.g., limb movement) through the water (Masumoto and Mercer, 2008). When walking in the water immersed to the xiphoid process level, the buoyancy force will reduce weight bearing by 71% compared with being on dry land (Harrison et al., 1992). Previous findings have suggested that deep water running, where individuals run in place with a flotation belt or across a pool without
touching the ground, is different from land running in terms of lower-extremity muscle recruitment and kinematics (Moening et al., 1993). Shallow water running, running while touching the pool floor in shallow water, is biomechanically more similar to land running than deep water running (Reilly et al., 2003; Frangolias and Rhodes, 1996), however the increased frontal plane resistance of the water produces a different strategy of locomotion compared to land running (Moening et al., 1993; Kato et al., 2001).

Similar to deep and shallow water running, numerous studies have compared the physiology and biomechanics of ATM and LTM running (Silvers et al., 2007; Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012; Rutledge et al., 2007; Porter et al., 2014; Brubaker et al., 2011; Pohl and McNaughton, 2003; Gleim and Nicholas, 1989; Garner et al., 2014; Rife et al., 2010; Silvers et al., 2014; Bressel et al., 2016). It appears that although there are biomechanical alterations during ATM running, ATM running involves a more similar kinematics to running on land as compared to deep water and shallow water running. ATM running eliminates forward locomotion through the water due to the moving treadmill belt, which mitigates the increased frontal resistance inherent to shallow water running. Thus, ATMs allow for a more natural gait pattern (Silvers et al., 2007). Considering the increasing popularity of ATM running a clearer understanding of the biomechanical alterations is warranted. Therefore, the purpose of this review is to discuss the kinematic, kinetic, spatiotemporal, and muscle activation differences between ATM and LTM running. Secondly, the possible benefits and limitations of applying an ATM running intervention as a means for returning to run or sport will be discussed.
5.2 Properties of Water Immersion During Exercise

Aquatic exercise is well accepted as a form of conditioning for individuals recovering from injury and/or seeking an effective mode of cross-training (Reilly et al., 2003; Silvers et al., 2014). When considering the biomechanical responses to ATM running, there are two primary factors to consider. The first factor is the buoyancy that an aquatic environment provides (Newman, 1997). It has been reported that based on the depth of immersion, the upward-lifting force of buoyancy unloads the lower extremities as demonstrated by the reduced vertical ground-reaction forces during walking in water (Barela et al., 2006; Nakazawa et al., 1994; Roesler et al., 2006).

The second factor to consider is the drag force imposed when limbs move through water (Newman, 1997; di Prampero, 1986) which increase the resistance to movement since water is approximately 800 times denser than air (di Prampero, 1986). The magnitude of the drag encountered is proportional to the relative squared limb velocity and frontal surface area of the moving limbs (di Prampero, 1986). Considering the contribution of the upper body to ATM running, the drag resistance is an important factor to consider when comparing alterations during ATM and land running. It has also been found that the transition from walking to running occurs at a slower speed during ATM compared LTM locomotion (Kato et al., 2001).

5.3 Kinematic Differences Between Land and ATM Running

Many kinematic measures are critical for understanding injury risk potential (Daoud et al., 2012) and have been associated with impact peaks and loading rates in studies assessing injury risk in distance running (Bonacci et al., 2013; Chambon et al., 2015; Lieberman et al., 2010; Squadrone et al., 2015). Many have suggested that alterations in gait kinematics in water reflect a strategy to overcome buoyancy and the dynamic drag forces in water (Kato et al., 2001;
Silvers et al., 2014; Bressel et al., 2016). In addition, it has been suggested that distal segment kinematics could be more affected in water than proximal kinematics (Bressel et al., 2012). Peak ankle plantar flexion, knee flexion, and hip flexion angles have been reported to be greater during ATM compared to LTM running (Kato et al., 2001). During ATM running, individuals demonstrate a greater hip joint flexion to move the knee position higher and enable a greater knee joint flexion (Kato et al., 2001). It is possible that these adjustments occur in order to reduce the hydrodynamic resistance of the water and achieve economical locomotion (Kato et al., 2001). In addition, although the maximum range was greater during ATM running speeds at 2.78 m·s⁻¹ and 3.33 m·s⁻¹ for thigh angle, knee angle, and ankle angle, the entire range of these joints during ATM running was only greater in the knee joint and was similar in the thigh and ankle joints (Kato et al., 2001). It has been reported that during ATM running at the hip level the ankle joint velocity was lower between 10% and 90% of stride duration and the knee joint velocity was lower between 20-70% and at 100% of stride duration (Kato et al., 2001). Interestingly, Kato et al. (2001) also reported that the velocity of the ankle joint in water at 3.33 m·s⁻¹ running was almost always held to 1.7 m·s⁻¹ between 40% to 80% stride duration which occupied part of the non-support phases. This differed from the knee joint velocity and it was suggested that there may be a physiologically maximum speed of movement in water for each body segment (Kato et al., 2001).

Other kinematic measures that have been associated with reduced impact peaks and loading rates include stride index, overstride angle, and knee contact angle (Bressel et al., 2016). Stride index is defined as the centre of pressure location at foot strike and is often reported as percentage of total foot length (Cavanagh and Lafortune, 1980). In general, lower percentages (i.e., 0-33%) indicate a rear-foot strike pattern while higher percentages (i.e., 34-67% and 68-
100%) indicate a mid-foot and forefoot strike pattern, respectively (Bressel et al., 2016). Overstride angle is defined as the absolute angle between the shank and the horizontal plane at foot strike (Bressel et al., 2016). Knee contact angle is defined as the relative knee angle at foot strike where greater values equate to more knee extension (Bressel et al., 2016). It has been reported that strike index during ATM running immersed to the xiphoid process was 61.3% compared to LTM running at 42.7%, representing at 18.6% difference between the two environments (Bressel et al., 2016). These percentages suggest that participants appeared to adopt a mid-foot strike in both environments, however, participants contacted more with their forefoot during ATM running. Interestingly, foot strike index was statistically greater during ATM running compared to LTM running at all speeds between 2.9 – 3.8 m·s$^{-1}$, however, there did not appear to be a difference between speeds within each condition. Knee contact angle tended to decrease (greater knee flexion) and overstride angle tended to either increase (less overstride) or not change during ATM compared to LTM running (Bressel et al., 2016), possibly suggesting a more compliant strike pattern in the ATM environment (Lieberman, 2014).

One concern with ATM running and the influences of buoyancy could be the increase in vertical displacement of the center of mass. It was reported that there was no difference in the vertical displacement of the hip joint during ATM and LTM running at speed of 2.2 – 3.33 m·s$^{-1}$ (Kato et al., 2001). However, it must be noted that participants were running at waist level water immersion as opposed to the level of the xiphoid process which is more common in the literature. Therefore, it is unclear whether a deeper level of immersion and increased amount of buoyancy would influence the vertical displacement of the hip joint differently.
5.4 Kinetic Differences Between Land and ATM Running

Measuring kinetic forces, such as vertical ground reaction forces, while running on land is very common in the literature and has been linked to many lower-extremity injuries including stress fractures and patellofemoral syndrome (Pohl et., 2008; Milner et al., 2006; Milner et al., 2010). Vertical ground reaction force represents the force exerted by the ground on the body in contact with it in the vertical axis. During running, the mass of an individual along with the downwards force of gravity creates a vertical ground reaction force of 2.5-2.8 times the body weight (Miller, 1990). This amount of repetitive force through the joints can either increase the risk of injury or limit the amount of running an individual can complete following injury as repetitive loading is a key part of the pathophysiology of stress fractures and other injuries (Beck, 1998; Bennell et al., 1999; Jones et al., 2002; Pepper et al., 2006). It has been suggested that various running injuries can be related to the kinetic forces during the gait cycle including vertical-force loading rates during the early part of stance phase in running (Davis et al., 2004; Milner et al., 2006).

In environmental space studies, locomotion under a simulated reduced gravity condition has been investigated to determine kinetic alterations. Davis and colleagues (1996) measured ground reaction forces using a land-based hypo-gravity simulator and reported lower peak ground reaction forces during locomotion. With increasing depth of water immersion, the upward-lifting force of buoyancy markedly unloads the lower extremities as demonstrated by the reduced vertical ground-reaction forces during walking in water (Barela et al., 2006; Nakazawa et al., 1994; Roesler et al., 2006). Immersion to the anterior superior iliac spine, xiphoid process, and the seventh cervical vertebra reduces limb loading by 57%, 71%, and 85%, respectively during walking (Harrison et al., 1992). Vertical ground reaction forces during shallow water
running in hip deep water reached a peak of 100% of body weight and were reduced to 80% in chest deep water (Haupenthal et al., 2010). Similarly, Barela et al. (2006) reported that the rate and magnitude of peak vertical ground reaction forces were about 90% and 23% lower, respectively, during shallow water versus overground walking. Although these studies provide insight into the kinetics of ATM running, the outcomes may differ when compared to shallow water running and deep water running to ATM running. Participants completed shallow water running on a stationary floor at a self-selected pace and stepped on an underwater force plate (Haupenthal et al., 2010). Ground reaction forces positively correlate with running speed and as running speed increases ground reaction forces increase as well (Nilsson and Thorstensson, 1989). As suggested above, compared to deep water and shallow water running, ATM running allows for a more comparable gait to LTM running by eliminating forward locomotion through the water due to the moving treadmill belt and mitigating the increased frontal resistance seen in shallow water running (Silvers et al., 2007). Therefore, the kinetic forces reported during shallow water running may be quite different from ATM running. Although the percentages listed above are not specific to running on an ATM, it is likely that ATM running would result in reduced kinetic forces as the effects of buoyancy during water immersion act to counterbalance the force of gravity as seen in various microgravity environments.

5.5 Spatiotemporal Differences between Land and ATM Running

Due to the combined effects of buoyancy and drag forces during ATM running, various alterations in spatiotemporal characteristics of running have been noted. For a matched speed and metabolic demand during ATM and LTM running, it was found that stride cycle and swing duration were greater during ATM running at xiphoid level immersion. It was also reported that stance duration was similar between environments, however, stance duration was lower and the
swing duration was higher during ATM running compared to land running when expressed as a percentage of the stride cycle (Silvers et al., 2014). It should be noted that these characteristics are only qualitative trends based on means and standard deviations as they were secondary measures that did not include statistical analyses. In agreement, Kato and colleagues (2001) reported that the stance duration was similar and the swing phase was significantly longer during ATM running. It is important to note that Silvers and colleagues (2014) were using xiphoid level water immersion, whereas Kato and colleagues (2001) used hip level immersion. Therefore, the agreement between these two investigations suggests similar alterations among various levels of water immersion.

It has also commonly been reported that stride frequency is lower during ATM running by 22% to 30% at speeds between 1.95-3.8 m·s\(^{-1}\) (Rutledge et al., 2007; Pohl and McNaughton, 2003; Rife et al., 2010; Kato et al., 2001; Silvers et al., 2014). Interestingly, it has been suggested that the highest stride frequency occurred at 1.67 m·s\(^{-1}\) for both ATM and LTM running (Kato et al., 2001). In contrast, Silvers and colleagues (2014) reported increasing stride frequency with increasing speeds up to 3.8 m·s\(^{-1}\). It is possible that the transition from walking to running at 1.67 m·s\(^{-1}\) as reported by Kato et al. (2001) may have led to a very short non-support phase duration that is not typical of land running and could have resulted in a higher stride frequency (Newman et al., 1994). In addition, although it can be agreed that stride frequency is lower during ATM running using both hip level and xiphoid level water immersion, the differences in water depth could have influenced the speed at which the highest stride frequency occurs.

5.6 Muscle Activity Differences Between Land and ATM Running

Many studies have investigated electromyographic activity during various modes of aquatic exercise including ATM walking (Chevutschi et al., 2007; Masumoto et al., 2008;
Masumoto et al., 2004), shallow water walking (Barela et al., 2006; Kaneda et al. 2007; Kaneda et al., 2008), deep water running (Kaneda et al., 2008), and stationary running (Alberton et al., 2011). One theme that has often been reported during aquatic exercise is that normalized muscle activity was consistently reduced in select lower-extremity muscles during ATM locomotion (Masumoto and Mercer, 2008). However, averaged muscle activity during ATM walking has been reported to be greater (Chevutschi et al., 2007) and muscle-activation patterns during shallow water walking were flatter compared with land when submersion depths, treadmill speeds, and/or metabolic demands were matched (Barela et al., 2006). In response to external loading during LTM running or walking, it has been reported that metabolic cost and normalized muscle activation increased (Bourdon et al., 1995; Groppo et al., 2005), whereas vertical unloading decreased metabolic cost (Grabowski and Kram, 2008; Colby et al., 1999; Farley and McMahon, 1992; Teunissen et al., 2007) and muscle activation (Colby et al., 1999; Klarner et al., 2010; Liebenberg et al., 2011). Therefore, considering that the upward thrust of buoyancy causes an unloading effect during ATM running it would be expected that changes in muscle activity would occur.

Despite the analyses of muscle activation during other forms of aquatic exercise, only one study has investigated the electromyographic response to ATM running (Silvers et al., 2014). These authors examined normalized muscle activation in the lower extremities during ATM and LTM running at matched running speeds, as well as the absolute duration and total amount of muscle activation during the running stride cycle. It was reported that the percentage of maximal voluntary contraction was 44% and 26.9% lower during ATM running in the vastus medialis and gastrocnemius, respectively (Silvers et al., 2014). In contrast, the percentage of maximal voluntary contraction for the rectus femoris during the swing phase was 48.7% greater during
ATM running (Silvers et al., 2014). It was further reported that during ATM running significant increases in the percentage of maximal voluntary contraction in the rectus femoris and tibialis anterior were seen with increasing running speed. The absolute duration of activation for the vastus medialis, rectus femoris, biceps femoris, and tibialis anterior were 213.1% 128.1%, 41.3%, and 33% greater during ATM compared with LTM running (Silvers et al., 2014). When comparing the total activity of the lower extremity, it was reported that the vastus medialis, tibialis anterior, and biceps femoris were 41.9%, 35.7%, and 29.2% greater during ATM compared to LTM running. In contrast, total activity for the gastrocnemius was 40.1% lower during ATM running (Silvers et al., 2014). It was also reported that total activity of the tibialis anterior increased with increasing speed during ATM running (Silvers et al., 2014).

Therefore, it appears that due to the resistance of the water and the influence of buoyancy there are alterations in muscle activation between environments and based on running speed.

5.7 Benefits of Applying an Aquatic Running Intervention for Returning to Run

Considering the properties of water, the reduced impact force, and the similar metabolic demands (Silvers et al., 2007) between ATM and LTM running, individuals may be able to begin running earlier in the rehabilitation process in an effort to return to running. This not only includes biomechanical aspects of returning to running, but also allows individuals to incorporate energy system development training specific to running earlier in the rehabilitation process. It would be beneficial for practitioners and participants returning to running if the characteristics of ATM running could positively alter the biomechanical measures during LTM running. In this way it would help determine if ATM running is a useful substitute for LTM running.

During a six-week ATM running intervention, acute carry-over changes in strike index and knee contact angles from ATM to LTM running has been shown, however, no retention was
reported in any measures within one week of withdrawing the ATM intervention (Bressel et al., 2016). Specific to strike index, it was suggested that individuals who displayed a rearfoot strike pattern on land in baseline testing shifted towards a more mid-foot strike pattern on land following the ATM intervention. This pattern would be favourable if the alterations were maintained during land running to reduce impact peaks. It is possible that a frequent use of ATM running over a longer period or as a larger percentage of total training could potentially increase the retention of a greater strike index and other positive alterations previously shown to reduce running-related injuries (Napier, MacLean, Maurer, Taunton & Hunt, 2019). Although the lack of long-term alterations in running mechanics by implementing ATM running may be seen as a limitation, it could also be seen as a benefit assuming that an individual possesses an effective and efficient gait pattern. Based on the current literature, an individual’s running gait is not likely to be altered by including ATM training. This could be beneficial for individuals returning to running after injury, or adding additional miles to training with reduced musculoskeletal load who do not wish to adopt mechanics that are associated with ATM running (Bressel et al., 2016).

In order to better understand the influence of ATM running on land running mechanics, more research is recommended that includes longer interventions or pairing multiple interventions together (i.e., ATM running and visual feedback) as previous literature suggests that training interventions that include alterations to footwear (Willson et al., 2014), stretching (Caplan et al., 2015), augmented feedback (Agresta and Brown, 2015), and the use of real-time visual feedback (Crowell et al., 2010) have demonstrated the possibility to alter land running kinematics.

There are other important considerations when examining the current literature on the acute and chronic effects of ATM running from a biomechanical perspective. First of all, the
only study completed (Bressel et al., 2016) used a single-subject design analysis of only three participants which limits the ability to generalize results (Bates, 1996). Secondly, the design of the intervention was to assess the effectiveness of alterations during ATM running to land running mechanics. Therefore, it did not include education on running mechanics that could possibly lead to enhanced retention. It is possible that completing the same intervention with the addition of verbal feedback and education on desired adaptations could potentially lead to greater retention in land-based running mechanics. Similarly, including visual feedback via underwater cameras that are common in some ATM (i.e., HydroWorx series ATMs) could further enhance retention and create awareness of desired adaptations. However, these are currently speculations as further research is needed.

Studies in microgravity environments have indicated that fast-twitch muscle fibers would be more active than slow-twitch muscle fibers. (Kozlovskaya et al., 1984). Additionally, a microgravity environment simulated by water immersion may alter the recruitment order of motor units facilitating recruitment of larger motor units as force gradation within a muscle follows the size principle (Sugajima et al., 1995). It is possible that facilitation of a recruitment order change and selective activation of fast twitch muscle fibers could influence work efficiency (Kato et al., 2001). During ATM running, recruitment inefficiency may have a negative influence on running mechanics throughout the entirety of an exercise session or possibly lead to adaptation of muscle fibers that would not be beneficial during land running. Conversely, it is possible that completing ATM running as a smaller portion of total running could be used to selectively train fast twitch muscle fibers.

Improvements in running performance in long distance runners can be attained by enhancing running economy. Strong correlations have been shown between steady state oxygen
consumption at various speeds and 10-km time (Conley and Krahenbuhl, 1980). One mechanism for improved running economy appears to be alterations in lower leg musculotendinous stiffness (Spurrs et al., 2003) leading to an ability of the muscles to store and release elastic energy (Saunders et al., 2004). During running, kinetic energy is stored during forced stretch of a muscle and is partly reused during the subsequent phase of concentric work (Asmussen and Bonde-Petersen, 1974; Simonsen et al., 1985). However, ATM running with a reduced impact force could potentially limit the reuse of stored energy in the series elastic component (Kato et al., 2001). For this reason, it is possible that frequent ATM use could negatively influence outdoor or LTM running economy. However, it has been suggested that plyometric training can increase running economy (Saunders et al., 2006) and multiple studies suggest that plyometric training while immersed in water may offer similar benefits that are experienced with land based plyometrics (Arazi and Asadi, 2011; Held, Perrotta, Buschmann, Bredin, & Warburton, 2019; Robinson et al., 2004). Therefore, effective programming that includes some aquatic plyometric training could help offset this potential limitation and perhaps further enhance load tolerance and economy when returning to running on land.

5.8 Conclusion

Various biomechanical alterations occur during ATM running compared to LTM running. These modifications occur due to the effects of buoyancy and drag force during water immersion and alter the kinematics, kinetics, spatiotemporal, and muscle activity measures of running. Currently, it is suggested that chronic biomechanical adaptations of ATM running do not occur as any acute adaptations are not maintained (Bressel et al., 2016). In order to better understand the influence of ATM running on land running mechanics, more research is warranted that includes longer interventions or pairing multiple interventions together (e.g. ATM
running and visual feedback). Further information would help practitioners to determine the appropriate implementation of ATM running to enhance the rehabilitation and return-to-run process, as well as the long-term adaptations to regular ATM use.
Chapter 6: Maximal Cardiorespiratory Responses to ATM and LTM

Running

6.1 Introduction

The purpose of this investigation was to compare the maximal cardiorespiratory responses during aquatic treadmill (ATM) and land treadmill (LTM) running. Although maximal exercise has been measured during ATM running in four other studies, the results are conflicting and more research is warranted. Completing maximal exercise testing to determine \( \dot{V}O_{2\text{max}} \), as well as the aerobic and anaerobic threshold, is common practice on a LTM for exercise prescription and measuring cardiorespiratory fitness. However, this study was the first to compare the aerobic threshold, anaerobic threshold, and maximal cardiorespiratory responses in the same study between an ATM and LTM. In addition, this intervention was the first to compare core temperature changes during ATM running to understand how it relates to LTM graded exercise testing.

6.2 Methods

Prior to all testing, all participants read and signed an informed consent form approved by the university institutional review board and completed a PAR-Q+ form for health and safety purposes (Warburton, Jamnik, Bredin, Gledhill, & PAR-Q+ Collaboration, 2011). Each participant completed a familiarization session on the ATM prior to the start of the study to ensure they were familiar with running on the ATM.

Recreationally active, male participants (n=16), defined as running or participating in a sport at least three times per week for a minimum of 30 minutes, were randomly assigned to group one or two in a crossover design. Group one completed a graded exercise test on the ATM first, whereas group two completed a graded exercise test on a LTM first. This consideration was
in place to help prevent an order effect from influencing the results. These protocols were separated by 72 hours and were conducted at the same time of day to control for circadian rhythms. A number of studies have suggested that maximal physiological variables or the metabolic response to incremental exercise can be influenced by pre-test glycogen levels and the diet consumed prior to the test (Sabapathy, Morris & Schneider, 2006; McLellan & Gass, 1989; Hughes, Turner & Brooks, 1982; Yoshida, 1984). Thus, participants were encouraged to consume an optimal, high carbohydrate diet for the purpose of inducing full muscle glycogen levels (Bentley, Newell & Bishop, 2007). Participants were asked to record all dietary consumption in the previous day as well as the morning prior to the first test. Participants were asked to follow the same diet as recorded for both tests. Participants were asked to avoid vigorous exercise, caffeine, and alcohol for 24 hours before each test, as well as asked to avoid vigorous exercise between tests.

Prior to coming to Fortius Sport and Health, participants ingested an e-Celsius Performance core temperature pill (BodyCap, Caen, France) a minimum of two hours prior to beginning data collection (Becker et al., 2007). Participants reported to Fortius Sport and Health on the first day of the intervention for collection of height, weight, and body composition using skinfold and girth measurements. Following collection of anthropometric measurements, participants completed a graded exercise test and verification phase on either the ATM or a LTM. As mentioned above, each participant completed a graded exercise test on both treadmills, however, the order was randomized. After approximately 72 hours of rest, participants returned to Fortius Sport and Health to complete a second graded exercise test and verification stage using the opposite treadmill. Similar to the first day, a core temperature pill was ingested a minimum of two hours prior to data collection. Measures analyzed and compared included \( \dot{V}O_2 \), heart rate,
respiratory exchange ratio, ventilation, tidal volume, respiratory rate, core temperature, and ratings of perceived exertion. Detailed methodologies of the two graded exercise tests are provided below.

6.2.1 Aquatic Treadmill Graded Exercise Test

Participants entered into the Hydrotherapy Lab to complete the graded exercise test on a HydroWorx 2000 ATM (HydroWorx, Middletown, PA). Previous pilot data was used to provide a template for matching metabolic demand for each stage in an attempt to ensure that any differences in the measures collected occurred mainly due to the differing environment. For the purpose of the graded exercise test, the water temperature was maintained at approximately 31-33°C (31.17 ± 0.13°C), as previous literature examining aquatic exercise has suggested that core temperature increases similarly in this water temperature compared to air temperature of approximately 22-25°C during graded exercise (Christie et al., 1990; Shedahl et al., 1987; McArdle et al., 1976; Craig & Dvorak, 1969). Water temperature was constantly monitored and adjusted using a built-in digital pool heater (Coates, Kent, WA), as well as manually tested with a water thermometer prior to each participant.

Participants wore spandex shorts and no shirt during the test, and ran barefoot immersed to the level of the xiphoid process. Prior to entering the water, the participants were given a waterproof Polar T31 telemetric heart rate chest strap (Polar T31, Polar, Lake Success, NY) to wear for the duration of the test. Core temperature readings were collected immediately before and following the exercise protocol. Participants were immersed to the level of the xiphoid process and the water height remained at this height for the duration of the test.

Metabolic gas exchange was collected using an automated metabolic system (True One 2400, Parvo Medics, Sandy, UT) at a sampling rate of 30 seconds that was calibrated
immediately before each test. A 30-second sampling rate appears to provide the best compromise between precision and reliability for $\dot{V}O_2\text{max}$ determination (Midgley, McNaughton & Caroll, 2007). This brand of metabolic cart has been used in previous research measuring submaximal and maximal cardiovascular response to ATM running (Rutledge, Silvers, Browder & Dolny, 2007; Garner et al., 2014; Silvers, Rutledge & Dolny, 2007). The graded exercise test was continuous with incremental stages lasting three minutes in duration. Previous research has found that incremental exercise protocols comprising of stages lasting three minutes can be used to measure maximal physiological values in conjunction with valid submaximal physiological variables (Bentley, Newell & Bishop, 2007).

Based on data from pilot studies, participants were asked to remain 1.37 metres from the resistance jet to ensure a constant jet resistance. A string was placed across the pool at this distance so each participant could have immediate feedback of their running position. Participants were asked to run with their chest against the string as best as possible. Participants were also asked to run with palms facing inwards and hands in a fist position to prevent a swimming motion through the water which may lead to assisted forward propulsion. Prior to the beginning of warm-up, each participant was reminded that there were two emergency stop switches if needed, one outside the pool and one inside the pool. Participants were shown that they could stand on the non-moving ledge beside the treadmill belt, if necessary.

The test began with a five minute warm-up at the self-selected pace. After the warm-up, participants walked at 1.8 miles per hour for two minutes. Following the two minute walk the graded exercise test began. During the test, the treadmill speed increased every three minutes by one miles per hour until the maximal ATM speed of 8.5 miles per hour was reached. After this point, the resistance jet was increased by 10% jet from 30% up to 100%, or volitional
exhaustion. Throughout the entire test, one person was dressed in attire to enter the water if needed. The responsibility of this person was to monitor the participant and sit at the edge of the pool at the later stages of the test for safety purposes. In the final stages of the test, standardized verbal encouragement was provided to the participant. After completion of the test participants walked for five minutes at a comfortable pace on the treadmill with 0% jet resistance in preparation to complete the verification phase.

6.2.2 Land Treadmill Graded Exercise Test

LTM graded exercise tests were held in the Fortius Lab at Fortius Sport and Health. Participants were advised, both verbally and in the informed consent, that they were expected to complete a maximal run on a treadmill and arrived in the proper attire. Participants were asked to avoid vigorous exercise, caffeine, and alcohol for 24 hours before each test, as well as asked to avoid vigorous exercise between tests. The tests were separated by approximately 72 hours. The graded exercise test was continuous with incremental stages lasting three minutes in duration. During the graded exercise test participants wore a Polar T31 telemetric heart rate chest strap (Polar T31, Polar, Lake Success, NY). Expired air was continuously measured at a sampling rate of 30 seconds (Midgley, McNaughton & Carroll, 2007) throughout the test using the same automated metabolic system (True One 2400, Parvo Medics, Sandy, UT) that was calibrated immediately before each testing session.

The test began with a five-minute warm-up at the self-selected pace. After the warm-up, participants walked at 1.8 miles per hour for two minutes. After the two-minute walk the exercise test began. Every three minutes the speed was increased by 0.5 miles per hour until volitional exhaustion. Throughout the entire test, one person monitored the participant to ensure safety remained a priority. In the final stages of the test, verbal encouragement was provided to
the participant. After completion of the test, participants walked at a comfortable pace on the treadmill with 0% incline for five minutes in preparation to complete the verification phase.

6.3 Statistical Analysis

All data was assessed using the SPSS statistical software package (version 25) with the significance level set at $\alpha = 0.05$. Means and standard deviations were calculated, as well as the mean difference with 95% confidence intervals, between ATM and LTM measures. Two-tailed paired sample t-tests were used to determine the differences in all measures between ATM and LTM running for maximal graded exercise testing.

6.4 Results

All participants (n=16) completed the graded exercise tests on both the ATM and LTM. Participant demographics can be found below in Table 6.1. LTM graded exercise testing was completed in the Fortius Lab with an ambient temperature of 22.24 +/- 0.49°C and a humidity of 52.47 +/- 7.78%. The ambient temperature during ATM graded exercise testing was 22.85 +/- 0.76°C with a humidity of 51.84 +/- 3.26% and a water temperature of 31.19 +/- 0.14°C.

Table 6.1 Participant demographics for maximal ATM versus LTM running (n = 16)

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>30.19 (6.42)</td>
<td>18 - 41</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.79 (7.24)</td>
<td>167.3 - 197.1</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>78.18 (8.18)</td>
<td>61.9 - 95.6</td>
</tr>
<tr>
<td>$\dot{V}$O$_{2\text{max}}$ (mL.kg.min$^{-1}$)</td>
<td>47.18 (5.18)</td>
<td>38.47 - 57.02</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.27 (4.98)</td>
<td>4.60 – 21.8</td>
</tr>
</tbody>
</table>

The maximal cardiorespiratory responses during the ATM and LTM graded exercise testing are reported in Table 6.2. Significant differences (p < 0.05) were observed for maximal
heart rate, post-test core temperature, the change in core temperature from pre- to post-test, test time, and the recovery of heart rate during the five minutes post-test walk. No differences (p < 0.05) were observed for maximal $\dot{V}O_2$, the highest recorded values for respiratory exchange ratio, ventilation, respiratory rate, and tidal volume, the values for respiratory exchange ratio, ventilation, respiratory rate, and tidal volume at the maximal achieved $\dot{V}O_2$, rating of perceived exertion, and pre-test core temperature. Additionally, there were no significant differences (p < 0.05) observed for ambient wet bulb globe temperature and humidity in either environment.

Table 6.2 Comparison of maximal cardiorespiratory responses during ATM and LTM running

<table>
<thead>
<tr>
<th></th>
<th>Land Treadmill Mean (SD)</th>
<th>Aquatic Treadmill Mean (SD)</th>
<th>P Value</th>
<th>Mean Difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{V}O_2$ (L·min$^{-1}$)</td>
<td>3.73 (0.30)</td>
<td>3.68 (0.36)</td>
<td>0.33</td>
<td>-0.05 (-0.15 to 0.05)</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (mL·kg·min$^{-1}$)</td>
<td>47.62 (4.35)</td>
<td>47.18 (5.18)</td>
<td>0.48</td>
<td>-0.44 (-1.63 to 0.75)</td>
</tr>
<tr>
<td>Heart Rate (beats·min$^{-1}$)</td>
<td>190.94 (13.48)</td>
<td>186.13 (11.55)</td>
<td>0.001</td>
<td>-4.81 (-7.11 to -2.51)</td>
</tr>
<tr>
<td>Respiratory Exchange Ratio (VCO$_2$/V$\dot{O}_2$)</td>
<td>1.09 (0.04)</td>
<td>1.08 (0.05)</td>
<td>0.40</td>
<td>-0.01 (-0.04 to 0.01)</td>
</tr>
<tr>
<td>Ventilation (L·min$^{-1}$)</td>
<td>136.40 (17.64)</td>
<td>139.41 (19.07)</td>
<td>0.29</td>
<td>3.01 (-2.42 to 8.44)</td>
</tr>
<tr>
<td>Respiratory Rate (breaths·min$^{-1}$)</td>
<td>54.06 (6.92)</td>
<td>55.82 (8.33)</td>
<td>0.25</td>
<td>1.76 (-1.15 to 4.66)</td>
</tr>
<tr>
<td>Tidal Volume (mL)</td>
<td>2.79 (0.49)</td>
<td>2.76 (0.50)</td>
<td>0.65</td>
<td>-0.02 (-0.13 to 0.08)</td>
</tr>
<tr>
<td>Respiratory Exchange Ratio at $\dot{V}O_{2\text{max}}$</td>
<td>1.08 (0.03)</td>
<td>1.07 (0.04)</td>
<td>0.37</td>
<td>-0.01 (-0.02 to 0.01)</td>
</tr>
<tr>
<td>Ventilation at $\dot{V}O_{2\text{max}}$ (L·min$^{-1}$)</td>
<td>132.73 (15.84)</td>
<td>138.76 (19.32)</td>
<td>0.08</td>
<td>6.03 (-0.24 to 12.29)</td>
</tr>
<tr>
<td>Respiratory Rate at $\dot{V}O_{2\text{max}}$ (breaths·min$^{-1}$)</td>
<td>52.39 (7.79)</td>
<td>54.71 (8.23)</td>
<td>0.17</td>
<td>2.32 (-0.86 to 5.50)</td>
</tr>
<tr>
<td>Tidal Volume at $\dot{V}O_{2\text{max}}$ (mL)</td>
<td>2.57 (0.37)</td>
<td>2.57 (0.38)</td>
<td>0.99</td>
<td>-0.001 (-0.10 to 0.10)</td>
</tr>
<tr>
<td>Rating of Perceived Exertion</td>
<td>19.56 (0.63)</td>
<td>19.38 (1.09)</td>
<td>0.33</td>
<td>-0.19 (-0.55 to 0.18)</td>
</tr>
<tr>
<td>Pre-Test Core Temperature (°C)</td>
<td>37.14 (0.18)</td>
<td>37.10 (0.26)</td>
<td>0.54</td>
<td>-0.04 (-0.15 to 0.08)</td>
</tr>
<tr>
<td></td>
<td>Land Treadmill Mean (SD)</td>
<td>Aquatic Treadmill Mean (SD)</td>
<td>P Value</td>
<td>Mean Difference (95% CI)</td>
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<tr>
<td>--------------------------------</td>
<td>--------------------------</td>
<td>----------------------------</td>
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<td>-------------------------</td>
</tr>
<tr>
<td>Post-Test Core Temperature (°C)</td>
<td>38.57 (0.41)</td>
<td>38.26 (0.36)</td>
<td>0.0005</td>
<td>-0.31 (-0.44 to -0.17)</td>
</tr>
<tr>
<td>Core Temperature Change (°C)</td>
<td>1.43 (0.40)</td>
<td>1.16 (0.37)</td>
<td>0.02</td>
<td>0.27 (0.06 to 0.48)</td>
</tr>
<tr>
<td>Test Time (mins)</td>
<td>19.69 (4.47)</td>
<td>17.41 (3.97)</td>
<td>0.03</td>
<td>-2.28 (-4.09 to -0.46)</td>
</tr>
<tr>
<td>5 minutes recovery of heart rate (beats min⁻¹)</td>
<td>125.50 (15.68)</td>
<td>112.50 (11.98)</td>
<td>0.0001</td>
<td>-13.00 (-17.80 to -8.20)</td>
</tr>
<tr>
<td>Wet Bulb Globe Temperature (°C)</td>
<td>17.99 (0.95)</td>
<td>18.45 (0.72)</td>
<td>0.13</td>
<td>0.45 (-0.09 to 1.00)</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>52.62 (7.90)</td>
<td>51.78 (3.47)</td>
<td>0.65</td>
<td>-0.84 (-4.42 to 2.74)</td>
</tr>
</tbody>
</table>

* p < 0.05

6.5 Discussion

Previous investigations into water immersed exercise compared to land-based exercise have frequently reported lower $\dot{V}O_2\text{max}$ and maximal heart rate values during exercise in the water (Butts, Tucker & Greening, 1991; Butts, Tucker & Smith, 1991; Frangolias & Rhodes, 1995; Mercer and Jensen, 1998; Svedenhag & Seger, 1992; Town & Bradley, 1991). However, given the similarities between the type of exercise and gait during ATM and LTM running, similar cardiorespiratory responses are attained. These similarities are partially due to the movement of the treadmill which helps to mitigate the resistance of the water to maintain a more similar stride to running on land (Kato et al., 2001). Understanding the maximal cardiorespiratory values that individuals are able to achieve during ATM running provides insight into the enhanced use of ATMs for physical rehabilitation, exercise performance, and health. Although maximal exercise has been previously measured during ATM running, our investigation provides additional support for previous conflicting findings.

Of the four previous studies, only two studies used three minute stages to compare continuous graded exercise on an ATM and LTM to maximal intensity. Given the drag resistance of the water and the influence on muscle activation and fatigue (Bressel et al., 2012; Silvers et
al., 2014; Held, MacLean & Warburton, 2018), the ability for the participant to match their LTM \( \dot{V}O_{2\text{max}} \) during longer duration tests could be impacted. Specifically, peripheral muscle fatigue, such as fatigue of the tibialis anterior which has been previously reported to have a 35.7% greater total activation compared to land (Silvers et al., 2014), may be a main reason for a participant to end a test early without reaching his or her true \( \dot{V}O_{2\text{max}} \). One advantage to using three minute stages during land-based exercise is that it allows individual submaximal thresholds (i.e. VT1 and VT2) to be determined for more accurate exercise prescription while still providing reliable values for the achievement of \( \dot{V}O_{2\text{max}} \) (Bentley, Newell & Bishop, 2007).

Our investigation was the first to compare submaximal aerobic threshold, anaerobic threshold, and maximal cardiorespiratory responses in the same study using the same participants between an ATM and LTM. In addition, this study was the first time that core temperature has been measured to observe the influence on achieving maximal values, as well as to corroborate thermoneutral water temperatures during maximal graded exercise testing on ATMs. Previous thermoneutral water temperatures have often been based on submaximal and maximal exercise testing during water immersed cycling (Sheldahl et al., 1987; Christie et al., 1990; McArdle et al., 1976). Not only is the mode of exercise different compared to ATM running, but the amount of body surface area immersed in the water is different as well. Additionally, during ATM running the arms are working through more resistance and requiring more work compared to LTM running, land-based cycling, and water immersed cycling. Each of these considerations could influence the relationship between water temperature, exercise intensity, and core temperature. As such, the additional insight this study provides is valuable to past and future comparisons of cardiorespiratory responses to ATM running. In addition, this study provides further support to a limited body of literature on maximal respiratory responses during ATM and
LTM running as only one other study (Silvers et al., 2007) compared ventilation, respiratory rate, and tidal volume. The results of the present study suggest that maximal cardiorespiratory responses during ATM running are similar to those reached during LTM running, with the exception of heart rate.

Previous investigations comparing maximal cardiorespiratory responses (Silvers et al., 2007; Greene et al., 2011; Schaal et al., 2012; Watson et al., 2012; Garner et al., 2014) have reported some inconsistent findings in literature. Our study is in alignment with the previous four investigations which found no difference between peak $\dot{V}O_2$ during an ATM and LTM graded exercise test. Although many investigations suggest that $\dot{V}O_2$ is lower during shallow-water running and deep-water running compared LTM running, it appears running on an ATM mitigates these differences. Previous findings have reported that running on an ATM can decrease the frontal resistance applied by the water during forward locomotion by running in place on the treadmill and could help to elicit a more similar gait and muscle recruitment pattern as seen during running on land (Kato et al., 2001). Additionally, running on an ATM allows for increases in belt speed, as well as incorporated resistance jets, that may have allowed individuals to push themselves to maximal intensity instead of relying on the individual to increase their cadence, stride length, or effort.

Similar peak $\dot{V}O_2$ values during ATM and LTM running have been reported for individuals of various ages (mean age range of 20.92 +/- 1.5 years to 41 +/- 14 years) and fitness levels (mean peak $\dot{V}O_2$ range of 30.81 +/- 8.51 mL kg$^{-1}$ min$^{-1}$ to 55.7 +/- 5.52 mL kg$^{-1}$ min$^{-1}$). It appears that peak $\dot{V}O_2$ is similar whether testing with one minute stages (Silvers et al., 2007) or three minute stages (Watson et al., 2012). Additionally, similar results have been found when the
test time is shorter (Silvers et al., 2007), longer (Watson et al., 2012), and even if there is a significant difference in test time, as is seen in our study.

Of the previous four studies measuring maximal ATM running, two reported the running distance used which were reported to be similar to this study and within the recommended testing zone proposed in Chapter 8 (Silvers et al., 2007; Greene et al., 2011). Of the previous studies, all have used high percentages of resistance jets in order to reach peak \( \dot{V}O_2 \) (Silvers et al., 2007; Greene et al., 2011; Watson et al., 2012). The mean percentage of resistance jet used in our study was 51.3% indicating that similar maximal \( \dot{V}O_2 \) responses can be achieved without high jet resistances which could be beneficial for longer duration tests as the additional water resistance could lead to a greater peripheral muscle fatigue. Previous research has shown that higher resistance jets of 2/3 of full capacity and full capacity were needed to match peak \( \dot{V}O_2 \) in a land-based Bruce protocol (Watson et al., 2012). Therefore, it is recommended that higher jet resistance be used for shorter duration tests and that lower jets may be more appropriate for longer duration tests. Additionally, closely matching the design of the testing between ATM and LTM graded exercise testing may be important.

Previous literature has demonstrated the linear relationship between heart rate and \( \dot{V}O_2 \) during ATM running, similar to LTM running (Watson et al., 2014). However, during maximal ATM running, mixed conclusions have reported a maximal heart rate either equivalent to or lower than LTM running. The lower maximal heart rate is not well understood with two main possible explanations this discrepancy. First, the lower maximal heart rate response is attributed to the central shift in blood volume that results from the hydrostatic pressure of the water exerted on the body during water immersion (Arborelius, Balldrin, Liga & Lundgren, 1972). This shift in
blood facilitates a greater venous return, greater preload, and an increased stroke volume (Arborelius et al., 1972; Christie et al., 1990; Connelly et al., 1990).

Alternatively, another possible explanation for the lower heart rate during higher intensity water immersion exercise is that sympathetic neural outflow is reduced in water (Christie et al., 1990). A reduction in sympathetic neural outflow should have a greater impact on heart rate at workloads above 50% \( \dot{V}O_{2\text{max}} \), as Robinson et al. (1966) showed that the rise in heart rate with work above this intensity is primarily dependent on increased sympathetic neural outflow. However, at lighter work intensities, parasympathetic neural withdrawal primarily contributes to the rise in heart rate (Robinson et al., 1966). In addition, previous studies have shown plasma norepinephrine to be reduced during passive water immersion (Krishna, Danovitch, & Sowers, 1983; O’Hare et al., 1986), and both norepinephrine and epinephrine reduced during high-intensity water immersion cycling suggesting an altered response of the sympathoadrenal response that is intensity dependent (Connelly et al., 1990).

It has also been suggested that during a graded exercise test, plasma catecholamines demonstrated a threshold where both norepinephrine and epinephrine increase nonlinearly (Mazzeo & Marshall, 1989). Furthermore, the inflection in plasma catecholamines shifted in an identical manner and occurred simultaneously with that of the anaerobic threshold regardless of the testing protocol or training status of the individual (Mazzeo & Marshall, 1989). Therefore, the large increase in the rate of epinephrine release beyond the anaerobic threshold may be reduced during ATM running and be responsible for the lower maximal heart rate exhibited in our investigation.

Considering our findings (see Chapter 7) that stroke volume is not increased during ATM running without a resting period prior to exercise, the most likely explanation is the reduced
sympathetic neural outflow and catecholamine response. Interestingly, two previous ATM running studies have reported similar maximal heart rates compared to LTM running (Silvers et al., 2007; Watson et al., 2014). One main difference between these two studies and ours is the high jet resistance. For a similar maximal \( \dot{V}O_2 \) compared to land, Silvers et al. (2007) appeared to have a mean jet resistance of approximately 80% of maximal resistance and Watson et al. (2014) incorporated full jets into their design. Jet resistance has been shown previously to influence the \( \dot{V}O_2 \)-heart rate relationship (Greene et al., 2011). For a given \( \dot{V}O_2 \) at lower intensities, heart rate was similar between ATM and LTM running with a jet resistance of less than 50%. However, for higher intensities at a given \( \dot{V}O_2 \), heart rate was statistically greater during ATM running with jet resistances of at least 75% maximal capacity (Greene et al., 2011). In our investigation, our mean jet resistance was only 51.3%, which is much lower relative to other studies that attained \( \dot{V}O_{2\text{max}} \). Therefore, it is possible that the discrepancy found between our results for maximal heart rate and the other two studies that found similar maximal heart rates was due to the percentage of resistance jet incorporated. That being said, it is not understood whether the influence of the resistance jet on maximal heart rate was related to a physiological alteration or the influence on the accuracy and/or the connection of the heart rate monitor itself. Depending on the distance the individual is running from the resistance jet, the jet stream would contact the individual at the chest level and provide reduced contact to the skin. Although this is not founded in the literature, it could be possible that the higher jet resistances could provide some inconsistent measurements.

Although water temperature has an effect on heart rate with temperatures lower than 30°C reducing heart rate (Craig & Dvorak, 1966), this does not explain current and previous findings. For example, Silvers et al. (2007) and Watson et al. (2014) reported similar heart rate
responses during ATM and LTM maximal running, however, these studies utilized water temperatures of 28°C and 33-35°C, respectively. The water temperature in the present investigation and that by Greene et al. (2011) who also reported a lower maximal heart rate during ATM running was 31°C and 32-34°C. Therefore, it is possible that the use of water resistance jets in ATM studies that were not previously used in water immersion cycling or deep water running influence the maximal cardiovascular response. Surprisingly, Schaal et al. (2012) used high percentages of resistance jets (i.e. 96%) yet still reported lower maximal heart rate during barefoot ATM running. Additionally, Schaal et al. (2012) reported that peak heart rate was lower during barefoot ATM compared to LTM, but not during shod running on the ATM. Given that the protocol used a one minute ramp design this further supports the idea that an increased resistance, either by wearing shoes or using a higher percentage of jet, may lead to more equivalent maximal heart rates during ATM running. At this point in time, it appears the best explanation for the physiologically lower maximal heart rate during maximal ATM running is the reduction in both norepinephrine and epinephrine during high-intensity water exercise (Connelly et al., 1990), specifically related to the response after the anaerobic threshold. Given the inconsistencies, more research into the mechanism controlling maximal heart rate during ATM running is warranted.

Three of the four previous studies comparing respiratory exchange ratio (Silvers et al., 2007; Schaal et al., 2012; Watson et al., 2012) are in agreement with our investigation and report similar respiratory exchange ratios between maximal ATM and LTM running. In contrast, Greene et al. (2011) found respiratory exchange ratio to be lower during maximal ATM running as compared to LTM running. Therefore, the findings in this study are in agreement with a large majority of the previous literature.
Respiratory measures are less frequently compared in the literature during maximal running on an ATM and LTM. Only two previous studies have compared ventilation (Silvers et al., 2007; Greene et al., 2011), and only one has compared respiratory rate and tidal volume (Silvers et al., 2007). The current study adds further support to the limited understanding of the alterations that occur to respiration during maximal ATM running.

Our investigation is in agreement with Greene et al. (2011) which reported no difference in ventilation during maximal exercise, however, Silvers et al. (2007) reported that ventilation was significantly higher at peak during an ATM graded exercise testing compared to on a LTM. In contrast to our findings, Silvers et al. (2007) reported a significantly higher peak respiratory rate during ATM running compared to LTM running. However, our findings support previous findings that there is no difference between peak tidal volume during ATM and LTM running (Silvers et al., 2007). When comparing respiratory measures during ATM and LTM maximal running, it is not always clear whether the reported values are the peak values obtained per measure, or if the respiratory measures compared are the values at peak $\dot{V}O_2$. It is possible that clarity around the reported measures may help reduce the inconsistencies noted in the literature. Our results found no difference between any of the respiratory measures for both the highest recorded measures and the measures at $\dot{V}O_2\text{max}$.

Methodical considerations could help explain the contrast in the findings. Silvers et al. (2007) and Greene et al. (2011) had participants run at distances that provided a similar physiological response from the jet (1.07 metres to 1.37 metres). Additionally, all participants ran at similar depths of water immersion across all three studies. Possible differences that could influence respiratory responses could be the use of high levels of resistance jets and stage length.
Both the present investigation and Greene et al. (2011) used three minute stages whereas Silvers et al. (2007) used one minute stages.

Previous investigations during deep water running have found similar (Fragnolias & Rhodes, 1995) and lower (Nakanishi, Kimura, & Yokoo, 1999) ventilation compared to LTM running. Interestingly, Fragnolias & Rhodes (1995) incorporated one minute stages, whereas Nakanishi et al. (1999) used two minute stages. It is possible that the incorporation of shorter stages may increase ventilation as the respiratory system works against the pressure of water and increasing exercise intensities. One limitation of these findings is that only our investigation and Silvers et al. (2007) investigated the response of tidal volume and respiratory rate. Given the relationship between these two values and ventilation, reporting these two measures would allow for further insight into the mechanism of change for an altered ventilation. In the present investigation, maximal tidal volume and respiratory rate were no different in the two environments. In contrast, Silvers et al. (2007) found a significant increase in respiratory rate which was responsible for the increase in ventilation. Given the high jet resistance and the shorter stage durations, it is possible that these two elements created a compensation in respiratory rate which led to the increased ventilation. In support of this, our results demonstrated that as the person moves away from the resistance jet, ventilation significantly decreases and respiratory rate follows a similar nonsignificant downwards trend (See Chapter 8.1). Therefore, the use of stronger resistance jets in the study by Silvers et al. (2007) could be responsible for the increase in ventilation and respiratory rate which contrast our findings.

It has been previously suggested during deep water running that an increase in ventilation from an increase in respiratory rate is necessary to achieve similar levels of \( \dot{V}O_2 \) compared to land (Hong, Cerretelli, Cruz, & Rahn, 1969). Our findings do not support this given the
equivalent VO$_2$, ventilation, and respiratory rate between both environments. Further research is necessary to understand the alterations in ventilation during ATM compared LTM running. Future research should include respiratory rate and tidal volume to provide a clearer explanation into possible mechanisms of change. In addition, future investigations should aim to determine how various methodological constraints (i.e. water depth, jet resistance) could influence the cardiorespiratory response.

All studies that have investigated the rating of perceived exertion during maximal exercise were in agreement with our investigation. Silvers et al. (2007), Greene et al. (2011), and Schaal et al. (2012) each reported no difference in rating of perceived exertion during maximal exercise on an ATM versus LTM. Therefore, for higher intensity exercise it may be appropriate to use ratings of perceived exertion considering the inconsistencies with maximal heart rate. Given the popularity of using ratings of perceived exertion as a global measurement of exercise intensity for the purposes of training and exercise, it appears that these findings can be extended to ATM running as well. Importantly, practitioners who use ratings of perceived exertion to develop a training load for their athletes may be similarly able to incorporate ATM running into their training load calculations for the day or week. This method may be more available and practitioners may be more confident in their findings compared to only using heart rate for ATM running.

Our investigation was the first to measure the change in core temperature during ATM running. Exercise intensity influences the metabolic and thermal response to exercise. It is challenging to determine an appropriate water temperature when implementing a graded exercise test that incorporates a variety of intensities. It is important to consider how water temperature influences the cardiovascular response when comparing water exercise to land exercise.
Thermoneutral water immersion during dynamic exercise does not mean that the core temperature does not change. Rather, it means that with increasing exercise intensity the core temperature change and metabolic response mimics land in a temperate environment. In other words, a temperature should be selected in an attempt to avoid a superimposed metabolic response.

Previous studies have suggested that the thermoneutral range for dynamic aquatic exercise is between 30°C and 35°C (Sheldahl et al., 1987; Christie et al., 1990; McArdle et al., 1976). Further, throughout exercise up to maximal intensity, a water temperature of 31–33°C may be optimal for maintaining thermoneutrality compared to land-based cycling while immersed to neck level (McArdle et al, 1976; Chirstie et al., 1990). During ATM running, it is common for participants to be immersed to the xiphoid process. At higher intensities of exercise, it is likely that evaporation will be more effective in an attempt to exchange heat with the environment as less of the body is immersed in the water compared to water-immersed cycling. In addition, the active muscle recruitment is different during ATM running versus cycling. Therefore, it is reasonable to believe that the thermoneutral water temperature during ATM running would be different than during water immersed cycling.

In our investigation, the water temperature was within the recommended range of 31-33°C with a mean water temperature of 31.17 +/- 0.13°C and an ambient air temperature of 22.90 +/- 0.80°C. Our findings suggest that when compared to an ambient air temperature during the LTM running of 22.31 +/- 0.44°C this water temperature led to a significantly lower peak core temperature and a significantly lower change in core temperature following ATM running. Therefore, during ATM graded exercise, a higher range of water temperature may be appropriate to elicit similar core temperature change and be considered thermoneutral. Although further
research is warranted to confirm a recommended range, a water temperature of 32-33°C seems appropriate.

6.6 Limitations

A limitation of our study is that we chose to only include male participants. It is possible that our findings may not extend to female participants. The purpose of including only males was to better understand the physiological response to ATM compared to LTM running while trying to ensure that alterations are were due specifically to the differences in environment by controlling as many other variables as possible.

Previous research has suggested that males and females may respond differently to water immersion (Fisher et al., 2019; Rutledge et al., 2007; Rife et al., 2010), although these differences may be minimized when adjusted for body mass (Watenpaugh et al., 2000; Fisher et al., 2019), or as a percentage of maximal values (Rife et al., 2010). In our study, we chose to express our results as absolute \( \dot{V}O_2 \) as compared to relative \( \dot{V}O_2 \) which includes the body mass of the participant. This decision was made as we felt it was difficult to determine the body mass expressed in the water due to the buoyancy forces and the differing body compositions between individuals. Therefore, inclusion of females could have accentuated this. By including both males and females, it is possible that some of the alterations would be due to sex as opposed to physiological alterations of running on a LTM as compared to an ATM.

Future research could aim to follow our recommendations and separate the groups into male and female to see if any results differ. Specific to ATM running, investigations have reported that protocol design and the cardiovascular responses do not differ by sex (Silvers et al., 2007; Greene et al., 2009). Therefore, we believe this limitation is minor and does not detract
from the findings as results obtained in men during water immersion can be extrapolated to women (Watenpaugh et al., 2000).

A second limitation is that the water temperature was slightly lower than we had hoped for (31.17°C vs. 32°C). It is possible that peak core temperature would have been similar between ATM and LTM maximal running if the measured temperature was at 32°C. Although this may have allowed for a corroborated finding of a thermoneutral water temperature during ATM graded exercise testing, none of our cardiorespiratory findings appeared to be influenced by the temperature difference compared to LTM responses.

6.7 Conclusions

In conclusion, our investigation further supports that graded exercise during ATM running provides a similar cardiorespiratory response to LTM exercise testing, even with a water temperature that produced a lower peak core temperature and core temperature change from pre-testing. Only maximal heart rate appears to be significantly lower during ATM running. Practitioners can confidently use ATMs for exercise training and testing without concern of not being able to reach maximal intensity or having a significantly altered cardiorespiratory response.
Chapter 7: Submaximal Cardiorespiratory and Hemodynamic Responses to ATM and LTM Running

7.1 Introduction

The purpose of the study was to compare the submaximal cardiorespiratory responses between aquatic treadmill (ATM) and land treadmill (LTM) running at a matched $\dot{V}O_2$ in thermoneutral water temperature. A second purpose of this study was to compare the hemodynamic responses of ATM and LTM submaximal running. Our study is the first to collect hemodynamic measures during ATM exercise and will provide additional insight into the cardiovascular alterations that occur in this environment. Previous literature has investigated hemodynamic responses during immersed cycling and land cycling (Christie et al., 1990; Shedahl et al., 1987; Shedahl et al., 1984; Park et al., 1999; Garzon et al., 2015), however, responses may be altered during ATM running due to variations in water depth, the surface area exposed to room air, the use of a treadmill and running gait, the use of resistance jets, and the increase in musculature used for running in the water, such as the use of the arms.

7.2 Methods

Prior to all testing, all participants read and signed an informed consent form approved by the university institutional review board and completed a PAR-Q+ form for health and safety purposes (Warburton, Jamnik, Bredin, Gledhill, & PAR-Q+ Collaboration, 2011). Submaximal measurements were derived from graded exercise testing during ATM and LTM running incorporating three minute stages in a randomized crossover design. Recreationally active male participants (n=16), defined as running or participating in a sport at least three times per week for a minimum of 30 minutes, were recruited for this study.
For the purpose of evaluating submaximal hemodynamic responses, cardiac measures were collected by impedance cardiography using the Physio Flow Enduro (Physio Flow; Manatec Biomedical; Macheren, France) during both ATM and LTM running. The impedance cardiography method of cardiac output determination uses changes in transthoracic impedance during cardiac ejection to calculate stroke volume. The Physio Flow Enduro emits a high-frequency (75 kHz) and low-amperage (1.8 mA) alternating current via electrodes. Two sets of electrodes, one “transmitting” electrode and one “sensing” electrode, are applied above the supraclavicular fossa at the left base of the neck and along the xiphoid process, respectively (Charloux, Lonsdorfer-Wolf, Richard, Lampert, Oswald-Mammosser, Mettauer, Geny & Lonsdorfer, 2000). Another set of two electrodes is used to monitor a single ECG lead. No specific skin preparation is needed, except for shaving when necessary. Values for stroke volume obtained over a 12-beat period are averaged with the Physio Flow deleting unacceptable curves (Charloux et al., 2000).

Hemodynamics measures were recorded throughout the entire exercise protocol with the device secured to the participant throughout the test to provide minimal disturbance. During ATM running the Physio Flow was contained in a waterproof container designed for underwater use. The electrodes were waterproofed using surgical waterproof, transparent, adhesive film (Opsite, Smith and Nephew, Largo, FL) (Tocco et al, 2012). At the end of each test, all electrodes were inspected to ensure that the waterproof condition was maintained. For LTM running, the electrodes were similarly taped in place in order to improve the connection against the skin.

Impedance cardiography meets many criteria for use during exercise as it is noninvasive, versatile, cost-effective, and suitable for continuous monitoring of cardiac function (Jensen,
Yakimets, Teo, 1995). A limitation of impedance cardiography is that absolute values of stroke volume cannot be evaluated, however, relative changes can be estimated with sufficient reliability (Ehlert & Schmidt, 1982). Investigations have reported a reasonable agreement between the estimates of cardiac output using impedance cardiography and other measures of cardiac function during moderate to light levels of exercise (Teo, Hetherington, Haennel et al., 1985; Pianosi & Garros, 1996; Denniston et al., 1976; Du Quesnay, Stoute & Hughson, 1987; Hatcher & Srb, 1986; Miles et al., 1981). Additionally, it has been postulated that impedance cardiography may be more suitable than CO₂ rebreathing for exercise conditions as higher ventilation and changes in lung volume have relatively little effect on the use of impedance cardiography (Hatcher & Srb, 1986). This may be important during ATM running due to the hydrostatic pressure of the water and the potential influence of respiratory rate and lung mechanics (Moon, Cherry, Stolp & Camporesi, 2009; Sheldahl et al., 1987; Coast et al., 1993).

The coefficients of variation for impedance cardiography have generally been reported in the literature to be similar to that of other methods (Warburton, Haykowsky, Quinney, Humen & Teo, 1999). Between duplicate measurements, the coefficients of variation ranged from 3% to 6%, whereas between two different days the coefficients of variation ranged from 5% to 12% (Moore, Sansores, Guimond & Abboud, 1992). In addition, high reproducibility has been shown between two maximal exercise tests completed one week apart. A high test-retest correlation (r=0.98) has been reported with no significant difference between tests (Teo et al., 1985).

The PhysioFlow device differs from standard impedance cardiography with the auto-calibration procedure based on participant age, height, weight, body mass, systolic/diastolic blood pressure, and resting impedance (Charloux et al., 2000). In addition, the PhysioFlow does not require the calculation of basal thoracic impedance, which can be difficult as basal thoracic
impedance is affected by perspiration, adipose tissue, and poor electrical contact (Charloux et al., 2000). These adaptations are thought to improve the accuracy of the technology in comparison to previous impedance cardiography systems that had questionable accuracy during exercise conditions (Warburton et al., 1999). Specifically, comparing the PhysioFlow device to the direct Fick method, correlations of \( r = 0.94 \) have been reported during maximal graded exercise tests (Richard et al., 2001). For comparisons between graded exercise tests separated by three days using the PhysioFlow correlations of \( r = 0.95 \) have been reported with a mean difference of 0.009 L·min\(^{-1}\) (Richard et al., 2001).

Comparisons were made at 40\% \( \dot{V}O_{2\text{max}} \), 60\% \( \dot{V}O_{2\text{max}} \), and the anaerobic threshold which occurred at approximately 83\% \( \dot{V}O_{2\text{max}} \). All measurements occurred at a statistically similar metabolic demand. Since submaximal values were calculated and compared based on maximal exercise testing, the methods are the same as those described in Chapter 6. For full explanation of the methods, please refer to the maximal cardiorespiratory responses to maximal graded exercise testing during ATM and LTM running chapter (Chapter 6).

### 7.3 Statistical Analyses

All data was assessed using the SPSS statistical software package (version 25) with the significance level set at \( \alpha = 0.05 \). Means and standard deviations were calculated, as well as the mean difference with 95\% confidence intervals between ATM and LTM measures. Two-tailed paired sample t-tests were used to determine the differences in all cardiorespiratory and hemodynamic measures between ATM and LTM running for submaximal running.
7.4 Results

All participants (n=16) were part of the analysis for the submaximal cardiorespiratory responses of ATM versus LTM running (Table 7.1), however, only 15 participants were part of the hemodynamic responses analysis due to an equipment malfunction (Table 7.2).

Table 7.1 Participant demographics for the submaximal cardiorespiratory responses to ATM vs LTM running (n=16)

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>30.19 (6.42)</td>
<td>18 - 41</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.79 (7.24)</td>
<td>167.3 - 197.1</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>78.18 (8.18)</td>
<td>61.9 - 95.6</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (mL·kg·min$^{-1}$)</td>
<td>47.18 (5.18)</td>
<td>38.47 - 57.02</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.27 (4.98)</td>
<td>4.60 - 21.8</td>
</tr>
</tbody>
</table>

Table 7.2 Participant demographics for the hemodynamic response to submaximal ATM versus LTM running (n=15)

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>29.25 (6.30)</td>
<td>18 - 41</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.82 (7.24)</td>
<td>167.3 - 197.1</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>78.84 (8.04)</td>
<td>61.9 - 95.6</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (mL·kg·min$^{-1}$)</td>
<td>47.05 (5.33)</td>
<td>38.47 - 57.02</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.23 (5.16)</td>
<td>4.60 - 21.8</td>
</tr>
</tbody>
</table>

The comparison of submaximal cardiorespiratory and hemodynamic responses between ATM and LTM running at 40% $\dot{V}O_{2\text{max}}$, 60% $\dot{V}O_{2\text{max}}$, the anaerobic threshold, and maximal exercise is presented in Table 7.3 and Table 7.4, respectively. Anaerobic threshold, determined by the ventilatory equivalents method and by plotting $\dot{V}_E/\dot{V}CO_2$, occurred at 83.45% of $\dot{V}O_{2\text{max}}$ during LTM running and 82.98% of $\dot{V}O_{2\text{max}}$ during ATM running. All comparisons were
compared at a statistically similar $\dot{V}O_2$. For comparison purposes, the submaximal value is a percentage of the graded exercise test in the same environment. For example, 40% $\dot{V}O_{2\text{max}}$ during ATM running is based on 40% of the ATM maximal response, and 40% $\dot{V}O_{2\text{max}}$ during LTM running is based on 40% of the LTM maximal response.

### 7.4.1 Submaximal cardiorespiratory responses to ATM and LTM running

Means and standard deviations, as well as mean differences with 95% confidence intervals, can be found in Table 7.3 comparing the submaximal cardiorespiratory responses between ATM and LTM running. Heart rate was similar ($p > 0.05$) at 40% $\dot{V}O_{2\text{max}}$, 60% $\dot{V}O_{2\text{max}}$, and the anaerobic threshold, however, it was found to be statistically lower ($p < 0.05$) during maximal running on the ATM. No differences ($p < 0.05$) were reported for respiratory exchange ratio, ventilation, and respiratory rate at any intensity. Tidal volume was found to be lower ($p < 0.05$) during ATM running at 40% $\dot{V}O_{2\text{max}}$, but similar ($p > 0.05$) between ATM and LTM running at all other intensities.
Table 7.3 Comparison of cardiorespiratory responses during ATM and LTM graded exercise

<table>
<thead>
<tr>
<th></th>
<th>40% (\dot{V}O_2)max</th>
<th>60% (\dot{V}O_2)max</th>
<th>(\text{AnT} \sim 83% \dot{V}O_2)max</th>
<th>(V\dot{O}_2)max</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land Mean (SD)</td>
<td>Water Mean (SD)</td>
<td>Mean Difference (95% CI)</td>
<td>Land Mean (SD)</td>
</tr>
<tr>
<td><strong>Respiratory Exchange Ratio</strong> (VCO₂/(\dot{V}O_2))</td>
<td>0.87 (0.05)</td>
<td>0.88 (0.04)</td>
<td>0.004 (-0.03 to 0.04)</td>
<td>0.90 (0.04)</td>
</tr>
<tr>
<td><strong>Ventilation</strong> (L·min⁻¹)</td>
<td>42.26 (4.72)</td>
<td>39.64 (7.63)</td>
<td>-2.61 (-7.88 to 2.65)</td>
<td>55.27 (5.69)</td>
</tr>
<tr>
<td><strong>Respiratory Rate</strong> (breaths·min⁻¹)</td>
<td>23.97 (4.85)</td>
<td>25.65 (5.61)</td>
<td>1.68 (-0.08 to 3.44)</td>
<td>27.46 (6.84)</td>
</tr>
<tr>
<td><strong>Tidal Volume</strong> (mL)</td>
<td>1.84 (0.53)</td>
<td>1.59* (0.35)</td>
<td>-0.24 (-0.43 to -0.05)</td>
<td>2.11 (0.48)</td>
</tr>
</tbody>
</table>

* p < 0.05
7.4.2 Submaximal hemodynamic responses to ATM and LTM running

Means and standard deviations, as well as mean differences with 95% confidence intervals, can be found in Table 7.4 comparing the submaximal hemodynamic responses between ATM and LTM running. One participant’s data was excluded from the submaximal analyses at 40% $\dot{V}O_2_{max}$, 60% $\dot{V}O_2_{max}$, and the anaerobic threshold as the PhysioFlow device was unable to connect. Complete data from all other participants is included. Significant differences (p < 0.05) were observed at 40% $\dot{V}O_2_{max}$, 60% $\dot{V}O_2_{max}$, and the anaerobic threshold for cardiac output and stroke volume with lower values reported during ATM running. No difference (p > 0.05) was reported for left ventricle end-diastolic volume at 40% $\dot{V}O_2_{max}$, however, values were significantly lower (p < 0.05) during ATM running at 60% $\dot{V}O_2_{max}$, and the anaerobic threshold. No difference (p > 0.05) was reported for arteriovenous oxygen difference at 40% $\dot{V}O_2_{max}$, however, values were significantly higher (p < 0.05) during ATM running at 60% $\dot{V}O_2_{max}$, and the anaerobic threshold. No differences (p > 0.05) were observed for ejection fraction at any intensity between the two conditions.
<table>
<thead>
<tr>
<th></th>
<th>Land Mean (SD)</th>
<th>Water Mean (SD)</th>
<th>Mean Difference (95% CI)</th>
<th>Land Mean (SD)</th>
<th>Water Mean (SD)</th>
<th>Mean Difference (95% CI)</th>
<th>Land Mean (SD)</th>
<th>Water Mean (SD)</th>
<th>Mean Difference (95% CI)</th>
<th>Land Mean (SD)</th>
<th>Water Mean (SD)</th>
<th>Mean Difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cardiac Output (L·min⁻¹)</strong></td>
<td>14.44 (2.28)</td>
<td>12.79* (2.77)</td>
<td>-1.65 (-2.96 to -0.34)</td>
<td>19.06 (2.97)</td>
<td>17.34* (3.08)</td>
<td>-1.72 (-3.03 to -0.40)</td>
<td>23.53 (2.59)</td>
<td>21.52* (3.19)</td>
<td>-2.01 (-3.57 to -0.45)</td>
<td>25.01 (3.37)</td>
<td>23.57 (3.85)</td>
<td>-1.43 (-4.70 to 1.84)</td>
</tr>
<tr>
<td><strong>Heart Rate (beats·min⁻¹)</strong></td>
<td>115.99 (12.50)</td>
<td>109.66 (10.78)</td>
<td>-6.32 (-13.90 to 1.25)</td>
<td>143.69 (12.13)</td>
<td>140.58 (13.33)</td>
<td>-3.11 (-7.58 to 1.36)</td>
<td>171.47 (13.63)</td>
<td>168.04 (13.11)</td>
<td>-3.42 (-7.37 to 0.53)</td>
<td>190.94 (13.48)</td>
<td>186.13* (11.55)</td>
<td>-4.81 (-7.11 to 2.51)</td>
</tr>
<tr>
<td><strong>Stroke Volume (mL)</strong></td>
<td>123.59 (14.81)</td>
<td>115.37* (17.29)</td>
<td>-8.21 (-14.01 to -2.41)</td>
<td>131.64 (20.13)</td>
<td>121.85* (19.24)</td>
<td>-9.79 (-17.42 to -2.15)</td>
<td>136.63 (16.84)</td>
<td>127.38* (20.04)</td>
<td>-9.25 (-16.42 to -2.07)</td>
<td>132.15 (16.13)</td>
<td>128.12 (22.26)</td>
<td>-4.03 (-20.76 to 12.70)</td>
</tr>
<tr>
<td><strong>Left Ventricle End Diastolic Volume (mL)</strong></td>
<td>160.41 (22.38)</td>
<td>153.38 (22.79)</td>
<td>-7.03 (-13.07 to 0.99)</td>
<td>173.34 (28.86)</td>
<td>158.08* (23.07)</td>
<td>-11.28 (-20.87 to -1.70)</td>
<td>171.17 (24.56)</td>
<td>161.57* (23.37)</td>
<td>-9.61 (-17.07 to -2.14)</td>
<td>179.12 (32.96)</td>
<td>173.54 (30.09)</td>
<td>-5.58 (-25.58 to 14.42)</td>
</tr>
<tr>
<td><strong>Left Ventricle End-Systolic Volume (mL)</strong></td>
<td>36.82 (12.14)</td>
<td>38.01 (12.18)</td>
<td>1.18 (-3.10 to 5.46)</td>
<td>37.18 (16.61)</td>
<td>35.69 (12.31)</td>
<td>-1.49 (-9.24 to 6.25)</td>
<td>34.55 (14.84)</td>
<td>34.19 (13.18)</td>
<td>-0.36 (-6.46 to 5.74)</td>
<td>46.98 (20.28)</td>
<td>45.42 (14.64)</td>
<td>-1.55 (-10.01 to 6.90)</td>
</tr>
<tr>
<td><strong>Arteriovenous Oxygen Difference (mL·100mL⁻¹)</strong></td>
<td>11.94 (2.21)</td>
<td>12.43 (2.78)</td>
<td>0.49 (-0.61 to 1.59)</td>
<td>12.41 (2.91)</td>
<td>13.83* (2.74)</td>
<td>1.42 (0.28 to 2.56)</td>
<td>13.37 (1.77)</td>
<td>14.46* (2.42)</td>
<td>1.10 (0.12 to 2.08)</td>
<td>14.80 (2.62)</td>
<td>15.66 (3.58)</td>
<td>0.86 (-1.55 to 3.27)</td>
</tr>
<tr>
<td><strong>Ejection Fraction (%)</strong></td>
<td>77.52 (5.74)</td>
<td>75.53 (6.13)</td>
<td>-2.00 (-4.39 to 0.40)</td>
<td>78.79 (7.04)</td>
<td>77.65 (6.50)</td>
<td>-1.14 (-4.43 to 2.16)</td>
<td>80.51 (6.59)</td>
<td>78.89 (6.65)</td>
<td>-1.62 (-4.51 to 1.28)</td>
<td>75.29 (8.05)</td>
<td>74.60 (6.23)</td>
<td>-0.68 (-4.33 to 2.96)</td>
</tr>
</tbody>
</table>

* p < 0.05
7.4.3 Maximal hemodynamic responses to ATM and LTM running

Aggressive movement of the participants and shifting of the water during maximal running caused some data to be lost due to compromised connections of the electrodes on the skin. Therefore, the reported values at maximal exercise only includes matched responses for seven participants. Due to the small sample for comparison of maximal values, it has been reported in Table 7.4 as a reference of potential alterations that occur during maximal ATM running. The complete paired data from seven participants demonstrated no differences (p > 0.05) during maximal exercise for cardiac output, stroke volume, left ventricle end-diastolic volume, arteriovenous oxygen difference, and ejection fraction.
7.5 Discussion

7.5.1 Submaximal Cardiorespiratory Responses to ATM and LTM Running

Our results add to the current literature that has examined the cardiorespiratory responses to submaximal exercise. A strength of our work is that we were able to compare responses throughout the ATM graded exercise test to a matched \( \dot{V}O_2 \) on a LTM at three intensities: 40\% \( \dot{V}O_{2\text{max}} \), 60\% \( \dot{V}O_{2\text{max}} \), and the anaerobic threshold point at approximately 83\% \( \dot{V}O_{2\text{max}} \). Findings from previous literature were used to stringently design our protocol. For example, water temperature was maintained in a small thermoneutral range and the running position from the resistance jet was kept consistent by use of a string line. In addition, resistance jets were kept to a minimum and only used when the maximum speed of the ATM was reached in order to reduce any physiological or technical influence they may have on the cardiorespiratory response. Lastly, only males were used as participants in the study as differences in some cardiorespiratory responses to water immersion exercise have been reported between males and females (Fischer et al., 2019). All of these measures were taken in order to ensure that our approach added to the current literature by increasing the likelihood that our results were due to the water’s influence on the cardiorespiratory response as compared to protocol discrepancies.

The results of our investigation suggest that heart rate is similar between ATM and LTM running at 40\% \( \dot{V}O_{2\text{max}} \), 60\% \( \dot{V}O_{2\text{max}} \), and the anaerobic threshold, even though there was a statistically lower maximal heart rate during ATM running. Previous findings have found submaximal heart rate during ATM running in chest deep water to be lower (Rutledge, Silvers, Browder, & Dolny, 2007; Porter et al., 2014), similar (Schaal et al., 2012; Brubaker, Ozemek, Gonzalez, Wiley, & Collins, 2011), or higher (Pohl & McNaughton, 2003; Gleim & Nicholas,
Previous studies that reported heart rate to be higher during ATM running used water depths of waist and thigh level suggesting the importance of water depth and the heart rate response (Pohl & McNaughton, 2003; Gleim & Nicholas, 1989). It has been reported that the linearity of the $\dot{V}O_2$-heart rate response previously described by Astrand & Rodahl (1986) can be extended to ATM running in thermoneutral water temperatures (Rutledge et al., 2007; Brubaker et al., 2011; Watson et al., 2012). The findings from Greene et al. (2011) demonstrate that alterations in heart rate during ATM compared to LTM also depend on the relationship between speed and water jet resistance. For a matched $\dot{V}O_2$ a similar heart rate was found when the jet was at 50% of maximal capacity, however, for increases in jet to 75% the heart rate was higher on the ATM compared to the LTM. Interestingly, Rutledge et al. (2007) reported heart rate to be greater during LTM compared to ATM running for a matched $\dot{V}O_2$ in trials incorporating a 50% and 75% resistance jet. In the matched trials that did not incorporate a resistance jet, no difference was found. Therefore, although heart rate was reported to be lower during ATM compared to LTM running for a given $\dot{V}O_2$, it is curious as to why heart rate would be lower during ATM running with higher jets and equivalent with lower jets. Based on previous literature it is evident that the resistance jets could influences heart rate, however, this relationship needs to be better understood. Given the use of lower resistance jets in our investigation, this could help explain some of the inconsistencies in the literature.

The distance the individual ran from the resistance jet could also influence the response of running against the jet. Two previous studies asked participants to run one meter from the resistance jets (Rutledge et al., 2007; Porter et al., 2014), whereas the other two did not report the running distance from the jet (Schaal et al., 2012; Brubaker et al., 2011). Future research should
aim to control for the running position from the resistance jets by following the recommended running area in our findings (Chapter 8), as well as reporting the distance used.

Another factor to consider is the relationship between water temperature and heart rate. It has been found that water temperatures greater than or equal to 30°C elicit similar heart rate responses to land and that water temperatures less than 30°C may lower heart rate (Craig & Dvorak, 1966). Specific to ATM exercise differences in the \( \dot{V}O_2 \)-heart rate slope occur when running on a LTM at 24-26.5°C compared to an ATM at water temperatures of 30.5°C and 36.1°C. For a given \( \dot{V}O_2 \), heart rate is greater at 36.1°C compared to 30.5°C and land (Gleim & Nicholas, 1989). In the previous studies reporting lower submaximal heart rate during ATM running, the water temperatures used ranged from 28-30°C. Given the water temperature used in our study was 31.17°C, this may explain the equivalent heart rate compared to previous studies using cooler temperatures. This further supports the evidence of incorporating water temperatures between 32-33°C if attempting to exercise at a similar heart rate to land.

Another influence to consider is the mode of exercise. Christie et al. (1990) reported similar heart rates between land and water immersed cycling at 40% \( \dot{V}O_{2\text{max}} \) and 60% \( \dot{V}O_{2\text{max}} \), with significantly lower water heart rates at 83% \( \dot{V}O_{2\text{max}} \) and 100% \( \dot{V}O_{2\text{max}} \). Interestingly, our results suggest that heart rate during ATM running is similar between ATM and LTM running at 40% \( \dot{V}O_{2\text{max}} \), 60% \( \dot{V}O_{2\text{max}} \), and 83% \( \dot{V}O_{2\text{max}} \). With water depth to the xiphoid process during ATM running, the arms are immersed in the water and are under a greater workload compared to running on land. It is possible that the use of the arms, as well as increases in water jet resistance, could offset the expected declines in heart rate above 60% \( \dot{V}O_{2\text{max}} \) that is seen in water immersed
cycling. Based on our findings, comparable heart rate responses can be extended to 83% $\dot{V}O_{2\text{max}}$ or the occurrence of the anaerobic threshold during ATM running.

Our findings suggest that respiratory exchange ratio is similar at all submaximal workloads during ATM and LTM running. These findings are consistent with the findings of a majority of the previous literature (Pohl & McNaughton, 2003; Schaal et al., 2012; Watson et al., 2012). Therefore, it appears that for similar intensities of exercise on an ATM and LTM the same substrates are being metabolized for energy. Similarly, our findings support previous ATM research that ventilation is similar during submaximal running (Rutledge et al., 2007; Brubaker et al., 2011). Our findings suggest that tidal volume is similar throughout all stages of exercise, except for a significantly lower response during ATM running at 40% $\dot{V}O_{2\text{max}}$. Interestingly a lower tidal volume during ATM running was found by Brubaker et al. (2011) for a similar intensity with no difference in tidal volume at a higher intensity. Hydrostatic pressure of the water may influence lung mechanics (Moon, Cherry, Stolp, & Camporesi, 2009). Considering 40% $\dot{V}O_{2\text{max}}$ occurred rather early in the exercise test, it is possible that the lower tidal volume was due to the hydrostatic pressure. As the exercise test increased in duration the respiratory response was able to normalize with similar tidal volumes and respiratory rates. Although respiratory rate was not different for any submaximal intensity in our study, it was higher at 40% $\dot{V}O_{2\text{max}}$ in order to maintain a similar ventilation. Other papers have supported our findings by suggesting that tidal volume is similar between ATM and LTM running for a matched $\dot{V}O_2$ (Rutledge et al., 2007; Brubaker et al., 2011). Previous literature has reported no difference in respiratory rate (Brubaker et al., 2011) or a lower respiratory rate during ATM running on the highest running intensities (Rutledge et al., 2007). Rutledge et al. (2007) reported a significant gender effect during ATM running. It is possible that the inclusion of only males in our study to
remove gender as a covariate could influence our findings. However, our findings on respiratory rate are in agreement with other ATM studies (Brubaker et al., 2011) who also included both males and females.

7.5.2 Submaximal Hemodynamic Responses to ATM and LTM Running

Our findings suggest that cardiac output and stroke volume are lower during ATM running at 40% $\dot{V}O_2_{\text{max}}$, 60% $\dot{V}O_2_{\text{max}}$, and the anaerobic threshold (approximately 83% $\dot{V}O_2_{\text{max}}$).

Few studies have compared cardiac measures during active exercise on a water immersed and land cycle ergometer (Sheldahl et al., 1984; Sheldahl et al., 1987; Christie et al., 1990; Garzon et al., 2015). Cardiac output and stroke volume are found to be significantly elevated during submaximal immersed cycling (Sheldahl et al., 1987; Christie et al., 1990; Garzon et al., 2015; Park et al., 1999). Previous findings have suggested that the increased cardiac output during immersion exercise relies primarily on the increase of stroke volume (Park et al., 1999; Christie et al., 1990; Sheldahl et al., 1984). Given the lower stroke volume in our study, a lower cardiac output would be expected. It has previously been reported that passive resting immersion creates a hemodilution by increasing plasma volume almost immediately after entering the water.

Previous findings suggest this hemodilution occurs within the first 10 minutes of rest (McMurray, 1983). Interestingly, plasma volume decreases as much as 15% after five minutes of exercise whether on land or immersed in water (McMurray, 1983), and 18.7% specifically during ATM running at 7.5mph compared to a 6.4% decrease during LTM running at an equivalent $\dot{V}O_2$ and heart rate (Zobell, 2009). The latter supports the findings in our study of a lower cardiac output and stroke volume during ATM running as a lower plasma volume may suggest a decreased venous return, preload, stroke volume, and cardiac output.
In our study, participants began running as soon as they entered the water with no resting data collection. In all other comparative studies the participant rested in the water to collect a resting measure for 10-30 minutes (Park et al., 1999; Christie et al., 1990; Sheldahl et al., 1987). It is possible that the disparities in our findings could be related to this rest period. An increase in plasma volume would be expected to lead to an increase in stroke volume as seen during passive water immersion due to an increase in venous return and preload. Previous studies have reported that left ventricular end-diastolic volume was greater during mild and moderate cycling exercise in water compared to land, suggesting that cardiac preload remains elevated during exercise in water, at least to a moderate level of exertion (Sheldahl et al., 1984). The elevated stroke volume in water can be attributed to enhanced preload (the Frank-Starling mechanism) rather than to increased left ventricular emptying as left ventricle end-systolic volumes are greater in water (Christie et al., 1990). Additionally, left ventricular end-diastolic volume at rest during water immersion may be near maximal, resulting in limited ability to increase stroke index with exercise through a further increase in left ventricle end-systolic volume (Christie et al., 1990).

Our findings suggest that left ventricle end-diastolic volume is reduced during ATM running at intensities over 40%\(\dot{V}O_{2\text{max}}\), whereas left ventricle end-systolic volume remains similar to LTM running throughout all of the measured submaximal intensities. At 40%\(\dot{V}O_{2\text{max}}\) the left ventricle end-diastolic volume was trending towards being lower during ATM running although it was non-significant. Ejection fraction appears to be similar during ATM and LTM running throughout all intensities. This finding is in agreement with a majority of other findings in the literature (Garzon et al., 2015; Christie et al., 1990; Sheldahl et al., 1984). Interestingly, our participants had similar increases in stroke volume between ATM and LTM as exercise intensity increased. As mentioned previously this discrepancy may be related to beginning
exercise immediately upon immersion as compared to the inclusion of a passive rest period. In our study, heart rate was similar to LTM running, however, the lower stroke volume led to a reduced cardiac output. In summary, it appears that during ATM running, without a passive rest period, there is no increase in venous return, preload, end-diastolic volume, and in turn stroke volume as is commonly experienced in the aquatic exercise literature. Future research is warranted to verify the hemodynamic response to ATM running found in our investigation. Specifically, hemodynamic alterations during ATM running with and without the use of an initial resting data collection should be completed. Further, it may be appropriate to record the time interval between the participant entering the water and the onset of exercise in future research to help compare the results of various studies.

Our findings indicate that arteriovenous oxygen difference is greater during ATM running at all intensities other than 40% \( \dot{V}O_{2\text{max}} \). At 40%\( \dot{V}O_{2\text{max}} \) the arteriovenous oxygen difference was trending towards being higher during ATM running although it was nonsignificant. These findings are in contrast to two previous studies that measured changes in arteriovenous oxygen difference during water immersed cycling (Garzon et al., 2015; Park et al., 1999). Passive immersion into thermoneutral water increases skeletal muscle blood flow in the legs (Balldin, Lundgren, Lundvall & Mellander, 1971). Based on these two previous studies it can be speculated that this decreased muscle oxygen diffusion remains during immersed cycling due to increasing muscle blood flow and reducing red cell transit time (Garzon et al., 2015). Our findings suggest that the peripheral extraction of oxygen is improved during ATM running.

Based on our previous premise, it is possible that by including a 10-minute passive rest prior to exercise, cardiac output may be increased via an increased end-diastolic volume and stroke volume leading to improved transport and central adaptations. Conversely, if you begin exercise
immediately, this could lead to a decrease in stroke volume and cardiac output in order to improve oxygen extraction and peripheral adaptation. Further investigation is required to confirm the influence of the rest period, however, this approach could lead to novel and improved training and rehabilitation for a variety of populations.

7.6 Limitations

Some limitations existed when attempting to measure hemodynamic responses throughout the graded exercise test. First of all, maximal measurements were only confidently collected on seven of the fifteen participants. At higher jet resistances in the water near maximal intensity some electrodes lost the waterproof seal. This was partially due to the heavy flow of water directed at the torso, as well as due to the aggressive upper body movement during maximal running. The inaccuracy of this data was therefore not part of the analysis and limited the statistical approach to maximal ATM running hemodynamic response. Secondly, due to a malfunction with the PhysioFlow software, we were unable to get an accurate connection with one participant during LTM running to assess the hemodynamic response. Therefore, both the LTM and the ATM hemodynamic data from this individual were removed from the analysis. The malfunction was corrected prior to further testing on any other participants.

Another possible limitation is that a resting data collection was not collected which is common in the literature. The purpose of our project was to examine the responses to ATM and LTM running. It is possible that beginning exercise immediately upon entering the water may have provided additional insight into the differentiation between active and passive responses to water immersion which could actually be considered a strength of our investigation.
7.7 Conclusions

Our findings provide additional support that submaximal cardiorespiratory responses are similar during ATM running compared to LTM for a matched $\dot{V}O_2$. Further, our findings extend these similarities to 83% $\dot{V}O_{2\text{max}}$ specific to ATM running compared to 60% $\dot{V}O_{2\text{max}}$ reported in water immersed cycling. One inherent strength of our investigation into submaximal responses is that our findings are from a single continuous graded exercise test for both ATM and LTM running. Previous literature into submaximal ATM running compared a matched $\dot{V}O_2$ but did not relate this to the percentage of $\dot{V}O_{2\text{max}}$ to compare relative changes (Rutledge et al., 2007; Porter et al., 2014; Watson et al., 2012; Greene et al., 2011; Brubaker et al., 2011); reported significant differences in $\dot{V}O_2$ (Schaal et al., 2012); tested only at one submaximal intensity (Schaal et al., 2012); tested different water speeds and jet resistances on different days or randomized the various intensities which could alter the cardiorespiratory response when moving from a high intensity trial to a lower intensity trial (Rutledge et al., 2007; Porter et al., 2014; Watson et al., 2012; Greene et al., 2011); tested for other purposes (i.e. comparing resistance jet to treadmill incline)(Porter et al., 2014; Schaal et al., 2012; Watson et al., 2012; Greene et al., 2011); or used shorter stage duration which could have limited participants ability to reach steady-state exercise (Brubaker et al., 2011). Some studies also included limited cardiorespiratory measures compared to our investigation (Porter et al., 2014; Watson et al., 2012; Schaal et al., 2012; Greene et al., 2011).

Our participants went through all exercise intensities in one graded exercise testing session on either the ATM or LTM at the same time of day between the two conditions. Therefore, this is the first investigation to include an open-ended maximal graded exercise test on an ATM and LTM for the purpose of investigating the incremental cardiorespiratory
responses to a variety of variables. When exercising on an ATM for the purpose of training or rehabilitation, practitioners can be confident that the cardiorespiratory response is similar to that experienced on land.

Overall, it appears that cardiorespiratory responses are similar during ATM running at submaximal intensities, however, hemodynamic alterations occur compared to LTM running. It is possible that shortening the initial time spent after entering the water should be considered in order to align with the purpose of the ATM running program.
Chapter 8: Aquatic Treadmill Testing: Developing a Standardized Approach

8.1 Cardiorespiratory and hemodynamic responses at varying distances from the resistance jets

8.1.1 Introduction

The aim of this study was to examine the influence of the running position in relation to the resistance jets on the cardiorespiratory and hemodynamic responses during aquatic treadmill (ATM) running. This study is the first to make such measurements. In addition, this study was the first to recommend the running distance from the resistance jet to be used for high intensity interval training, for moderate intensity continuous exercise, for graded exercise testing, and to establish a termination cut-off point during ATM graded exercise testing. These findings are a novel approach to implementing ATM training and research in order to provide further insight into inconsistencies in the literature and recommendations for future protocol designs.

8.1.2 Methods

Recreationally active, male participants (n=17) returned to Fortius Sport and Health 72 hours after their second graded exercise test in order to complete a submaximal exercise trial to determine the change in metabolic response when running at different distances from the resistance jet. Participants were asked to avoid vigorous exercise, caffeine, and alcohol during the testing period. Prior to coming to Fortius Sport and Health participants ingested an e-Celsius Performance core temperature pill (BodyCap, Caen, France) a minimum of two hours prior to beginning data collection (Becker et al., 2007).

Prior to all testing, all participants read and signed an informed consent form approved by the university institutional review board and completed a PAR-Q+ form for health and safety purposes (Warburton, Jamnik, Bredin, Gledhill, & PAR-Q+ Collaboration, 2011). Participants
wore spandex shorts without a shirt, ran barefoot, and were immersed to the xiphoid process on a HydroWorx 2000 ATM (HydroWorx, Middletown, PA). Metabolic gas exchange was collected using an automated metabolic system (True One 2400, Parvo Medics, Sandy, UT) at a sampling rate of 30 seconds (Midgley, McNaughton & Carroll, 2007) and heart rate was collected continuously using a waterproof Polar T31 telemetric heart rate monitor (Polar T31, Polar, Lake Success, NY). Core temperature was collected pre- and post-exercise. Water temperature was maintained at 31.11°C which is considered thermoneutral for exercise in water (Christie et al., 1990; Shedahl et al., 1987; McArdle et al., 1976; Craig & Dvorak, 1969).

The collection began with a five-minute progressive warm-up with the participant running 1.37 metres away from the resistance jet, as determined from pilot testing. The warm-up progressed in intensity until the participant reached an intensity corresponding to a constant heart rate between their aerobic and anaerobic thresholds which was determined by a previous ATM graded exercise test. This intensity was selected in order to be confident the participant is able to reach steady state exercise and avoided any drift associated with the slow component. Moderate exercise has been defined as the work rate which does not induce a significant increase in blood lactate with the upper limit being associated with the individual’s anaerobic threshold (Gaesser & Poole, 1996; Whipp, 1987). During moderate exercise, there is an early fast increase in $\dot{V}O_2$ which is usually completed in the first 15 to 25 seconds of exercise, followed by an exponential increase in $\dot{V}O_2$ until steady state is reached after about two to three minutes (Barstow, 1994; Gaesser & Poole, 1996; Whipp, 1987). During steady state running, $\dot{V}O_2$ changes linearly with work rate (Xu & Rhodes, 1999) by moving closer to or further from the resistance jet. For each participant, the jet was set at 50% of its maximum capacity and only speed was adjusted for individual intensities. This jet resistance was selected as previous research suggests that using the
resistance jet helps to counteract the effects of buoyancy (Silvers et al., 2007) and 50% jet is considered a medium strength jet to run against (Rutledge et al., 2007). In addition, at all running speeds during ATM running 50% jet was an intensity that produced an increased cardiovascular response compared to 25% jet and 0% jet (Greene et al., 2011). Therefore, this jet intensity was appropriate to determine metabolic changes that occur based on different running distances from the jet while maintaining an intensity that will allow the participants to remain below anaerobic threshold at all distances.

Once the test commenced, participants ran at nine different distances from the resistance jet for three minutes at each distance to ensure steady state was achieved. The order of the distances was randomly assigned to each participant and included distances from 0.61 metres to 1.83 metres from the resistance jet in 0.15 meter increments. In order to ensure participants ran at the required distances, measurements were made prior to the start of testing and a string spanned the width of the pool at the corresponding distance. Participants were asked to keep their chest against the string and verbal reminders were provided if necessary. Throughout the test the string was moved to each new distance after three minutes. Cardiorespiratory and hemodynamic measures were recorded throughout the duration of exercise and core temperature was recorded pre- and post-test.

8.1.3 Statistical Analysis

All data was assessed using the SPSS statistical software package (version 25) with the significance level set at \( \alpha = 0.05 \). Data is provided in means with 95% confidence intervals. Observed power was reviewed to understand the meaningfulness of any significant effects. For all measures, the Mauchly’s test of sphericity was calculated and a Greenhouse-Geisser or Huynh-Feldt corrected alpha level was used when appropriate. The Huynh-Feldt corrections was
used when estimates of sphericity were greater than .75, and Greenhouse-Geisser corrections were used when estimates were less than .75 (Barcikowski & Robey, 1984; Girden, 1992; Huynh & Feldt, 1976). A repeated measures ANOVA was used to compare cardiorespiratory and hemodynamics responses to running at various distances from the resistance jet. When significant differences were observed pairwise comparisons with a Bonferroni adjustment were calculated to determine where the differences occurred.

### 8.1.4 Results

All participants (n=17) completed the experiment. Participant demographics can be found in Table 8.1.

**Table 8.1 Participant demographics for varying running positions from the resistance jet during ATM running (n=17)**

<table>
<thead>
<tr>
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<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>30.19 (6.42)</td>
<td>18 - 41</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.79 (7.24)</td>
<td>167.3 - 197.1</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>78.18 (8.18)</td>
<td>61.9 - 95.6</td>
</tr>
<tr>
<td>V̇O₂ (mL kg⁻¹ min⁻¹)</td>
<td>47.18 (5.18)</td>
<td>38.47 - 57.02</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.27 (4.98)</td>
<td>4.60 - 21.8</td>
</tr>
</tbody>
</table>

Water temperature was 31.11 +/- 0.31°C with the ambient temperature and humidity at 23.44 +/- 1.04°C and 61.56 +/- 8.41%, respectively. All environmental measurements were taken prior to each participant. Each participant ran at an individualized speed with a consistent resistance jet set to 50% of maximal capacity. No differences (p > 0.05) were found at any distance from the jet for respiratory rate, stroke volume, left ventricle end-diastolic volume, left ventricle end-systolic volume, ejection fraction, and arteriovenous oxygen difference. Significant differences (p < 0.05) based on different running distances were observed for V̇O₂, heart rate,
cardiac output, ventilation, and tidal volume (Figures 8.1 A-E). The highest \( \dot{V}O_2 \) response was reported for the closest position of 0.61 metres from the jet. All distances from 0.91 metres to 1.83 metres were significantly lower (\( p < 0.05 \)) compared to 0.61 metres, however, 0.76 metres was similar to 0.61 metres (\( p > 0.05 \)). Distances of 1.37 metres to 1.83 metres were different from 0.76 metres and 1.22 metres (\( p < 0.05 \)) with 0.91 metres, 1.07 metres, and 1.22 metres being similar to 0.76 metres (\( p > 0.05 \)). Running 1.52 metres from the resistance jet was lower than 1.37 metres and 0.91 metres (\( p < 0.05 \)). The highest heart rate was also observed when running 0.61 metres from the resistance jet. All distances from 1.07 metres to 1.83 metres were significantly different (\( p > 0.05 \)) than 0.61 metres with the exception of 1.22 metres (\( p > 0.05 \)). Similarly, all distances from 1.52 metres to 1.83 metres were different from 1.22 metres (\( p > 0.05 \)) with 1.52 metres also being different from 0.91 metres. Cardiac output followed a similar response to the resistance jets, however, no differences were observed between 0.61 metres and 1.52 metres. Both 1.68 metres and 1.83 metres were different than 0.76 metres (\( p < 0.05 \)) and 1.68 metres was also different from 0.61 metres (\( p < 0.05 \)). Ventilation followed a similar trend to \( \dot{V}O_2 \), heart rate, and cardiac output in terms of the shape of the response to the resistance jets. All distances from 0.91 metres to 1.83 metres with the exception of 1.22 metres were different from 0.61 metres (\( p < 0.05 \)). All distances from 1.52 metres to 1.83 metres were different compared to 0.76 metres (\( p < 0.05 \)) and 1.52 metres was also different than 1.22 metres (\( p < 0.05 \)). Finally, tidal volume followed to similar trend to other measurements with distances from 1.37 metres to 1.83 metres being different than 0.61 metres (\( p < 0.05 \)).
HIIT – recommended zone for high intensity interval training.

Submax & GXT – recommended zone for submaximal running and graded exercise testing.

Figure 8.1 Cardiorespiratory and hemodynamic alterations to various distances from the resistance jets
8.1.5 Discussion

Previous research into ATM running has either not reported the running distance from the resistance jets or somewhat arbitrarily chose a one metre running distance to position the individual within the underwater camera (Silvers et al., 2007; Greene et al., 2011; Silvers & Dolny, 2008; Rutledge et al., 2007). To this point, the position was based more on pool design instead of physiological responses. The rationale for determining and standardizing the appropriate running position is supported by our findings. \( \dot{V}O_2 \), heart rate, and cardiac output decrease as the individual moves further away from the resistance jet for a given speed and jet resistance. Although stroke volume and respiratory rate followed the same trend of decreasing as the person moved away from the resistance jets the results were not significant. Interestingly \( \dot{V}O_2 \), heart rate, and cardiac output increased at 1.22 metres before further decreasing again. It is possible there is a relationship between the strength of the jet as it contacts the individual and the amount of surface area the jet stream comes into contact with. For example, at 0.61 metres from the resistance jet, although the amount of surface area in contact with the jet is small, the force of the jet is strong. Alternatively, at 1.83 metres from the resistance jet the stream has fanned out to contact more of the body including the arms and legs, however, the jet has lost a lot of strength. 1.22 metres may offer the point at which the jet stream widens to add further resistance to the arms and legs, as opposed to only the torso, as well as provides a strong enough resistance of force to increase the cardiovascular response. More research is needed to determine how this position could be altered using a stronger or weaker jet resistance.

In terms of respiratory measures, ventilation follows a similar trend with decreases in ventilation as the individual moves away from the resistance jet, other than at 1.22 metres. Although both tidal volume and respiratory rate followed a similar pattern, it appears that the
decrease in tidal volume is more influential on ventilation than respiratory rate is. Although the change is not statistically significant there is also a decrease in respiratory rate as the individual moves away from the resistance jets. Taken together, it is clear that the use of resistance jets can alter the respiratory response and work of breathing during exercise. In turn, this could also help explain variations between ATM running studies that do and do not include high resistance jets. These alterations occurred with only a moderate jet intensity of 50% resistance jet in our study and higher jet resistances that are commonly implemented could influence this response even further.

Based on the response of $\dot{V}O_2$ to varying distances from the resistance jets recommendations can be made for exercise prescription and testing. For shorter high-intensity interval training it is recommended that individuals run as close to the resistance jet as possible between 0.61 metres and 0.76 metres (red, narrow shaded area in Figure 8.1). This position elicits the highest $\dot{V}O_2$ response, however, it may be challenging to maintain this position for longer durations as individuals tend to shift forward and back while running. For moderate intensity continuous exercise, longer duration high-intensity running, and exercise testing, it is recommended that individuals run between 0.91 metres and 1.22 metres (green, wider shaded area in Figure 8.1). Although these distances result in a $\dot{V}O_2$ that is significantly lower than 0.61 metres, the $\dot{V}O_2$ is not significantly different at those distances. Running in this position would allow the individual some freedom to move 0.15 metres forward or 0.15 metres back and maintain confidence that the $\dot{V}O_2$ response is similar. This distance has also been shown to produce equivalent maximal and submaximal $\dot{V}O_2$ responses to LTM running based on our running position during ATM graded exercise (Chapter 6 and 7). Another benefit of running between 0.91 metres and 1.22 metres during exercise testing is an additional stage of higher
intensity can be added to the protocol by moving the participant forward to 0.61 metres from the resistance jet after the maximal treadmill speed and resistance jet has been reached.

During land-based graded exercise testing on a cycle ergometer it is common to have a cut-off criterion in repetitions per minutes that if the participant cannot maintain, the test is terminated (Poole, Wilkerson, & Jones, 2008; Day, Rossiter, Coats, Skasick, & Whipp, 2003). During ATM graded exercise testing, it is recommended that a string be placed 1.52 metres from the jet as an absolute cut-off. This way, if the participants back touches the string line once, he or she can receive a warning with a second touch resulting in terminating the test. In summary for exercise testing, it is recommended that a string is placed at 0.91 metres from the resistance jet that represents the furthest distance towards the jet. Participants should be encouraged to stay within 0.30 metres of this line. A second line can be placed at 1.52 metres from the resistance jet acting as the termination criterion. Similarly, participants should be encouraged to run between two and 0.76 metres from the resistance jets for short duration high-intensity interval training. A string line can be placed at 0.91 metres to help gauge the participants distance and act as a reference or encouragement if the individual’s back touches the string line.

8.1.6 Limitations

One limitation of this study is that only one jet intensity was used. Rationale for choosing the 50% jet resistance is provided above. It is expected that using a higher jet percentage would lead to similar trends in the cardiorespiratory response, assuming each running position did not surpass the individual’s anaerobic threshold. Therefore, these findings can likely be extrapolated to higher jet percentages, however, future research would have to be conducted to confirm this. A lower jet percentage may have led to a different trend as the flow of water may have been too weak and the cardiorespiratory response may have been more similar to not using the resistance
jet at all. Additionally, it is not as common to incorporate lower jet resistances in the literature. Silvers et al. (2007) recommended using 40% jet while running in order to reduce aerial time and normalize running gait. Therefore, it is possible that incorporating more jet resistances would have provided similar trends, and lower jet resistances (i.e. 10-30%) would be less practical. In support of this, previous literature has suggested the $\dot{V}O_2$ response is the same whether running on an ATM without the use of the resistance jet or using 25% jet (Greene et al., 2011). Even though only one jet intensity was used, it is expected that these results can be extrapolated to common resistance jet intensities that are often used in ATM running.

### 8.1.7 Conclusions

Based on our findings, it is evident the running position from the resistance jets influences the cardiorespiratory and hemodynamic responses and it is imperative that future research clearly reports and maintains a constant running position. Our running zone recommendations should be implemented in future investigations to increase comprehension and comparison of the alterations in cardiorespiratory and hemodynamic responses between ATM and LTM running.

### 8.2 The Use of a Verification Phase to Confirm $\dot{V}O_2_{\text{max}}$ during ATM Graded Exercise Testing

#### 8.2.1 Introduction

The purpose of this study was to determine whether a verification phase was able to confirm the attainment of $\dot{V}O_2_{\text{max}}$ during aquatic treadmill (ATM) graded exercise testing. No other study has used a verification phase during ATM running and limited studies have used traditional secondary criteria to confirm $\dot{V}O_2_{\text{max}}$ (Greene et al., 2011; Garner et al., 2014; Silvers
A second aim of this study was to provide descriptive statistics on the number of individuals who met secondary criteria during ATM and land treadmill (LTM) graded exercise. Although previous studies have used the traditional secondary criteria to determine if $\dot{V}O_2\text{max}$ was attained, only one other study reported these statistics (Silvers & Dolny, 2008). The purpose of the study by Silvers and Dolny (2008) was to determine the reliability of graded exercise testing on an ATM. As such, these authors only reported on the satisfied secondary criteria during ATM running. Therefore, our findings are also the first to compare the $\dot{V}O_2$ plateau and the use of traditional secondary criteria during ATM and LTM graded exercise testing.

### 8.2.2 Methods

A verification phase was completed on recreationally active, male participants ($n=16$) following each graded exercise test to ensure that $\dot{V}O_2\text{max}$ was achieved. All participants read and signed an informed consent form approved by the university institutional review board. After each graded exercise test on both the ATM (HydroWorx 2000; HydroWorx, Middletown, PA) and LTM (Chapter 6), participants walked for five minutes as an active recovery prior to beginning the verification phase. A five minute recovery has been used previously in the literature (Rossiter et al., 2006; Midgley et al., 2007; Thoden, 1991) and has been shown to be enough time to replete a depleted phosphocreatine system (Foss & Keteyian, 1998). It has also been noted that short recovery time between the graded exercise test and verification phase, as short as one minute for non-athletes, does not detract from the utility of the verification phase (Foster et al., 2007). However, participant comfort remained an important consideration, as well as the recovery of the phosphocreatine system for the verification phase. For these reasons, a five minutes recovery was selected. Following the recovery period, a verification phase was
completed which consisted of running to volitional exhaustion at one stage higher than that reached in the last completed stage of the incremental test (Thoden, 1991). If the graded exercise test was less than eight minutes in duration, the verification phase was ran at the same workload as the last completed stage (Thoden, 1991). It has been determined that the mean maximal $\dot{V}O_2$ values attained in the verification phases are similar despite different graded exercise test protocols with mean times to exhaustion ranging from 10 to 30 minutes (Midgley et al., 2007).

8.2.3 Statistical Analysis

All data was assessed using the SPSS statistical software package (version 25) with the significance level set at $\alpha = 0.05$. Data is presented in means, standard deviations, and 95% confidence intervals. Observed power was reviewed to understand the meaningfulness of any significant effects. Two-tailed paired sample t-tests were used to determine the differences between ATM and LTM running for maximal graded exercise testing and to confirm the attainment of $\dot{V}O_2_{max}$ between the graded exercise test and the verification phase. Comparisons were made between the ATM graded exercise test and the ATM verification phase, the LTM graded exercise test and the LTM verification phase, the ATM graded exercise test and the LTM graded exercise test, and the ATM verification phase and the LTM verification phase. Descriptive statistics were used to report the participants who achieved the typical secondary criteria during ATM and LTM graded exercise testing, as well as the typical verification phase criteria of a less than a two percent difference in $\dot{V}O_2$ between the graded exercise test and verification phase and a maximal heart rate of within two beats per minute of the graded exercise test.
8.2.4 Results

All participants (n=16) completed a verification phase following a maximal graded exercise test. Participant demographics can be found in Table 8.2.

Table 8.2 Participant demographics for the implementation of a verification phase during ATM running (n=16)

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
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<tbody>
<tr>
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<tr>
<td>(\dot{\text{VO}}_2) (mL kg\text{-min}^{-1})</td>
<td>47.18 (5.18)</td>
<td>38.47 - 57.02</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.27 (4.98)</td>
<td>4.60 - 21.8</td>
</tr>
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</table>

The LTM graded exercise test and verification phase was completed in the Fortius Lab with an ambient temperature of 22.24 +/- 0.49 °C and a humidity of 52.47 +/- 7.78%. The ambient temperature during the ATM graded exercise test and verification phase was 22.85 +/- 0.76°C with a humidity of 51.84 +/- 3.26% and a water temperature of 31.19 +/- 0.14 °C. Descriptive statistics are reported in Table 8.3 to demonstrate the number of participants that would have successfully met \(\dot{\text{VO}}_2\text{max}\) criteria based on traditional secondary criteria and a verification phase during maximal exercise on a LTM and ATM.

Table 8.3 Participants meeting \(\dot{\text{VO}}_2\text{max}\) criteria

<table>
<thead>
<tr>
<th></th>
<th>LTM</th>
<th>ATM</th>
<th>LTM</th>
<th>ATM</th>
<th>LTM</th>
<th>ATM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\dot{\text{VO}}_2) Plateau (&lt; 0.15 L·min(^{-1}) increase)</td>
<td>43.75</td>
<td>31.25</td>
<td>81.25</td>
<td>56.25</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Heart Rate (within 5 beats·min(^{-1}) of age-predicted max)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory Exchange Ratio (&gt;1.10)</td>
<td></td>
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</table>
The results of the graded exercise testing with verification phases for ATM and LTM running is reported in Figure 8.2 A-F. No significant differences (p > 0.05) were observed for the maximal \( \dot{V}O_2 \) during the LTM graded exercise test and verification phase (Figure 8.2 - A), ATM graded exercise test and verification phase (Figure 8.2 - B), the LTM and ATM graded exercise test (Figure 8.2 - E), and the LTM and ATM verification phase (Figure 8.2 - E). Comparisons of maximal heart rate were not different (p > 0.05) for the LTM graded exercise test and verification phase (Figure 8.2 - C), however, the maximal heart rate was lower (p < 0.05) during the ATM verification phase compared to the ATM graded exercise test (Figure 8.2 - D), lower (p < 0.05) during ATM compared to LTM graded exercise testing (Figure 8.2 - F), and lower (p < 0.05) during the ATM compared to the LTM verification phase (Figure 8.2 - F).
Figure 8.2 $\text{VO}_2\text{max}$ and heart rate response during exercise testing and verification phase on an ATM and LTM.

* (p < 0.05) LTM compared to ATM
8.2.5 Discussion

Previous findings have reported that during ATM graded exercise testing 75% of individuals demonstrated a $\dot{V}O_2$ plateau, and 85% of individuals achieved a maximal respiratory exchange ratio of at least 1.10, but only 47% of individuals were able to achieve a heart rate within five beats of their age-predicted maximal heart rate (Silvers & Dolny, 2008). In our investigation, only 44% and 31% of participants demonstrated a $\dot{V}O_2$ plateau, and 75% and 75% achieved a respiratory exchange ratio of at least 1.10 during LTM and ATM testing, respectively. Interestingly, in our study 81% of participants achieved a heart rate within five beats of their age-prediction maximum heart rate during LTM testing, however, this measure was only 56% for ATM testing. Considering the findings from these two studies, the number of individuals that are able to achieve a maximal heart rate within five beats of their age-predicted maximal heart rate further supports our findings that maximal heart rate is lower during ATM versus LTM running. Therefore, with the requirement to reach at least two of these measures to confirm the attainment of $\dot{V}O_2_{max}$, secondary criteria measures may be less appropriate to use during ATM exercise testing. Since twice as many participants satisfied the recommended verification phase criteria for $\dot{V}O_2$, it appears a verification phase is apposite for ATM testing.

Our findings suggest that there is no difference between the $\dot{V}O_2_{max}$ achieved during the graded exercise test and the verification phase for either ATM or LTM testing. However, during ATM testing the maximal heart achieved during graded exercise testing was significantly greater than during the verification phase. This was not the case during LTM testing and the verification phase. Similarly, there was no difference between the $\dot{V}O_2_{max}$ achieved during graded exercise testing on the ATM and LTM or during the verification phase during ATM and LTM testing. The maximal heart rate achieved was lower during ATM testing compared to the LTM for both
the graded exercise test and the verification phase, further strengthening the support for a lower maximal heart rate during ATM exercise. Another way that has been established in the literature to confirm the attainment of $\dot{V}O_2max$ using a verification phase is the achievement of less than a two percent difference in $\dot{V}O_2$ between the graded exercise test and verification phase, as well as a heart rate of within two beats per minute between the maximal values in the exercise test and the verification phase (Midgley et al., 2006). Our findings suggest that 75% and 63% of individuals achieved a $\dot{V}O_2$ of less than a two percent difference during LTM testing and ATM testing, respectively, whereas the achievement of a heart rate within two beats per minute was 69% and 44% for LTM and ATM testing, respectively. During the ATM verification phase, twice as many participants satisfied the attainment of a similar $\dot{V}O_2$ for the verification phase compared to a $\dot{V}O_2$ plateau during the graded exercise test.

Based on previous findings the verification phase appears to be a robust measure that can confirm the attainment of $\dot{V}O_2max$ for a variety of test protocols and recovering periods (Midgley et al., 2007; Midgley & Carroll, 2009). Foster et al. (2007) examined shorter recovery periods using recovery phases of one minute in non-athletes and three minutes for runners, which is shorter than the recovery period used in our investigation. Although the five minute rest period between the exercise test and the verification phase in our study elicited similar $\dot{V}O_2$ responses during ATM and LTM running, the heart rate recovery during the five minute period was significantly lower during ATM running compared to LTM running (112.50 beats mins$^{-1}$ vs. 125.50 beats mins$^{-1}$; p<0.01). It is possible that a five minute recovery period may be too long during ATM testing to attain a similar maximal heart rate during the ATM verification phase. Future research should investigate the use of different lengths of recovery periods during ATM testing to determine the recovery interval that provides an adequate maximal heart rate during the
verification phase. Considering the recovery interval does not influence the attainment of \( \dot{VO}_{2\text{max}} \) and heart rate during the recovery phase in LTM testing, a shorter recovery interval may improve the usefulness of the verification phase during ATM testing. Maximal heart rate verification is advantageous because it is not affected by the inaccuracy associated with age-predicted maximal heart rate (Londeree & Moeschberger, 1984). However, the verification phase may be too short for some participants to obtain their maximal heart rate, so it has been suggested that further validation is required before maximal heart rate verification can be recommended as a valid \( \dot{VO}_{2\text{max}} \) criterion during LTM running (Midgley & Carroll, 2009), and this can be extended to ATM running as well.

### 8.2.6 Limitations

This study included a five minute recovery period between the graded exercise test and the verification phase on the ATM and the LTM. The rationale for selecting this time interval is explained above and has been often used during LTM verification phases. Since our study is the first to include a verification phase during ATM running the same interval was used. A possible limitation to this study is that the heart rate dropped to a lower rate much quicker during the ATM recovery compared to the LTM recovery. Due to this, it may have been easier to confirm the attainment of \( \dot{VO}_{2\text{max}} \) by achieving a heart rate of within two beats per minute of the graded exercise test on the LTM compared to the ATM. In our findings, 69% of participants were able to achieve a heart rate of within two beats per minute on the LTM compared to only 44% on the ATM. It is possible that incorporating an absolute recovery heart rate (i.e. 120 beats per minute), as opposed to a time interval, may have elicited a more similar comparison between those satisfying the criteria on the LTM and the ATM. In future work that incorporates ATM
verification phases the optimal time interval should be investigated or comparison should be made using absolute recovery heart rates to determine if that is a better design for ATM testing.

8.2.7 Conclusions

Our findings extend the use of a verification phase as an appropriate method to confirm the attainment of $\dot{V}O_{2\text{max}}$ during ATM graded exercise testing. It appears that more participants were able to satisfy the criteria to confirm $\dot{V}O_{2\text{max}}$ during the verification phase as compared to using the $\dot{V}O_2$ plateau and traditional secondary criteria. Comparatively, this method may provide more accurate measurement than using the traditional secondary criteria during ATM running. Given the lower maximal heart rate found during ATM running, practitioners should focus on the attainment of a similar $\dot{V}O_2$ during the verification stage to assess whether or not a participant gave maximal effort and achieved a true $\dot{V}O_{2\text{max}}$.

8.3 Comparing Ventilatory Aerobic Threshold (VT1) and Anaerobic Threshold (VT2) during ATM and LTM Running

8.3.1 Introduction

The purpose of this study was to determine whether the occurrence of the first and secondary ventilatory threshold occurred at the same point during aquatic treadmill (ATM) and land treadmill (LTM) running. Currently, no studies have determined ventilatory thresholds during ATM running or how the points may differ compared to LTM running. Further, our investigation is the first to determine the occurrence of both the aerobic and the anaerobic threshold during ATM running. Therefore, the results from this study provide novel insight into how practitioners can prescribe training on ATMs to elicit aerobic performance adaptations.
8.3.2 Methods

Ventilatory thresholds were determined and compared following graded exercise tests on an ATM (HydroWorx 2000; HydroWorx, Middletown, PA) and a LTM in a randomized crossover design with recreationally active, male participants (n=16). All participants read and signed an informed consent form approved by the university institutional review board. A detailed explanation of the methods for the graded exercise testing can be found in Chapter 6. Ventilatory thresholds (VT1 & VT2) were determined by examining changes in expiratory gases utilizing the ventilatory equivalents method of $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/VCO_2$. The ventilatory equivalents for oxygen ($\dot{V}_E/\dot{V}O_2$) and carbon dioxide ($\dot{V}_E/VCO_2$) method, as well as the v-slope method ($VCO_2$ versus $\dot{V}O_2$) were used to determine VT1 (Beaver, Wasserman, & Whipp, 1985; Foster & Cotter, 2006). The ventilatory equivalents for oxygen ($\dot{V}_E/\dot{V}O_2$) and carbon dioxide ($\dot{V}_E/VCO_2$) method, as well as graphing $\dot{V}_E$ versus $VCO_2$ were used to determine VT2 (Beaver, Wasserman, & Whipp, 1985; Foster & Cotter, 2006). These two methods were independently analyzed and compared following previous suggestions that using multiple methods can increase the likelihood of accurately determining ventilatory thresholds (Foster & Cotter, 2006; Gaskell et al., 2001).

8.3.3 Statistical Analysis

All data was assessed using the SPSS statistical software package (version 25) with the significance level set at $\alpha = 0.05$. Data is presented as means and standard deviations, as well as mean differences with 95% confidence intervals between ATM and LTM measures. Two-tailed paired sample t-tests were used to determine and compare the occurrence of the two ventilatory thresholds (VT1 and VT2) between LTM and ATM running. Comparisons were made between
ATM and LTM running for all cardiorespiratory measures at the aerobic and the anaerobic thresholds.

8.3.4 Results

All participants (n=16) completed the graded exercise test on both the LTM and ATM to compare the occurrence of the aerobic and anaerobic threshold. Participant demographics can be found in Table 8.4.

Table 8.4 Participant demographics for comparison of ventilatory thresholds during ATM and LTM exercise testing (n=16)

<table>
<thead>
<tr>
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</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.27 (4.98)</td>
<td>4.60 - 21.8</td>
</tr>
</tbody>
</table>

A comparison of the ventilatory aerobic (VT1) and anaerobic (VT2) threshold between ATM and LTM running is reported in Table 8.5 and Table 8.6, respectively. LTM graded exercise testing was completed in the Fortius Lab with an ambient temperature of 22.24 +/- 0.49°C and a humidity of 52.47 +/- 7.78%. The ambient temperature during ATM graded exercise testing was 22.85 +/- 0.76°C with a humidity of 51.84 +/- 3.26% and a water temperature of 31.19 +/- 0.14 °C. No significant differences (p > 0.05) were found for any of the measured variables between ATM and LTM running. Both VT1 and VT2 occurred at a statistically similar $\dot{V}O_2$, percentage of maximal $\dot{V}O_2$, heart rate, respiratory exchange ratio, ventilation, respiratory rate, tidal volume, and rating of perceived exertion.
### Table 8.5 Comparison of the ventilatory aerobic threshold (VT1) during land treadmill and aquatic treadmill running

<table>
<thead>
<tr>
<th></th>
<th>Land Treadmill</th>
<th>Aquatic Treadmill</th>
<th>P Value</th>
<th>Mean Difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{V}O_2$ (L·min$^{-1}$)</td>
<td>2.39 (0.16)</td>
<td>2.31 (0.17)</td>
<td>0.12</td>
<td>-0.07 (-0.16 to 0.01)</td>
</tr>
<tr>
<td>% $\dot{V}O_2$max</td>
<td>64.46 (3.61)</td>
<td>63.64 (6.22)</td>
<td>0.62</td>
<td>-0.83 (-4.02 to 2.37)</td>
</tr>
<tr>
<td>Heart Rate (beats·min$^{-1}$)</td>
<td>145.77 (10.83)</td>
<td>140.80 (14.65)</td>
<td>0.07</td>
<td>-4.97 (-9.98 to 0.05)</td>
</tr>
<tr>
<td>Respiratory Exchange Ratio (VCO$_2$/$\dot{V}O_2$)</td>
<td>0.90 (0.04)</td>
<td>0.90 (0.05)</td>
<td>0.75</td>
<td>0.005 (-0.02 to 0.03)</td>
</tr>
<tr>
<td>Ventilation (L·min$^{-1}$)</td>
<td>57.86 (7.48)</td>
<td>58.46 (8.07)</td>
<td>0.78</td>
<td>0.60 (-3.55 to 4.75)</td>
</tr>
<tr>
<td>Respiratory Rate (breaths·min$^{-1}$)</td>
<td>27.57 (7.47)</td>
<td>29.61 (7.22)</td>
<td>0.27</td>
<td>-1.46 (-5.55)</td>
</tr>
<tr>
<td>Tidal Volume (mL)</td>
<td>2.20 (0.50)</td>
<td>2.07 (0.47)</td>
<td>0.21</td>
<td>-0.14 (-0.34 to 0.06)</td>
</tr>
<tr>
<td>Rating of Perceived Exertion</td>
<td>10.80 (1.57)</td>
<td>10.93 (1.75)</td>
<td>0.74</td>
<td>0.13 (-0.65 to 0.92)</td>
</tr>
</tbody>
</table>

* p < 0.05

### Table 8.6 Comparison of the ventilatory anaerobic threshold (VT2) during land treadmill and aquatic treadmill running

<table>
<thead>
<tr>
<th></th>
<th>Land Treadmill</th>
<th>Aquatic Treadmill</th>
<th>P Value</th>
<th>Mean Difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{V}O_2$ (L·min$^{-1}$)</td>
<td>3.12 (0.20)</td>
<td>3.00 (0.36)</td>
<td>0.11</td>
<td>-0.06 (-0.17 to 0.05)</td>
</tr>
<tr>
<td>% $\dot{V}O_2$max</td>
<td>84.15 (4.18)</td>
<td>82.13 (8.05)</td>
<td>0.36</td>
<td>-0.33 (-3.48 to 2.82)</td>
</tr>
<tr>
<td>Heart Rate (beats·min$^{-1}$)</td>
<td>171.6 (13.65)</td>
<td>168.20 (13.32)</td>
<td>0.12</td>
<td>-3.40 (-7.46 to 0.66)</td>
</tr>
<tr>
<td>Respiratory Exchange Ratio (VCO$_2$/$\dot{V}O_2$)</td>
<td>0.99 (0.03)</td>
<td>1.01 (0.04)</td>
<td>0.10</td>
<td>0.03 (-0.003 to 0.06)</td>
</tr>
<tr>
<td>Ventilation (L·min$^{-1}$)</td>
<td>85.85 (10.94)</td>
<td>92.47 (14.09)</td>
<td>0.09</td>
<td>6.62 (-0.51 to 13.75)</td>
</tr>
<tr>
<td></td>
<td>Land Treadmill Mean (SD)</td>
<td>Aquatic Treadmill Mean (SD)</td>
<td>P Value</td>
<td>Mean Difference (95% CI)</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------</td>
<td>----------------------------</td>
<td>---------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Respiratory Rate (breaths min⁻¹)</td>
<td>36.10 (8.59)</td>
<td>36.71 (12.70)</td>
<td>0.78</td>
<td>0.60 (-3.63 to 4.84)</td>
</tr>
<tr>
<td>Tidal Volume (mL)</td>
<td>2.46 (0.46)</td>
<td>2.48 (0.63)</td>
<td>0.87</td>
<td>0.01 (-0.15 to 0.17)</td>
</tr>
<tr>
<td>Rating of Perceived Exertion</td>
<td>15.07 (2.28)</td>
<td>15.20 (1.74)</td>
<td>0.82</td>
<td>0.13 (-0.98 to 1.25)</td>
</tr>
</tbody>
</table>

* p < 0.05

### Discussion

Our findings suggest that during ATM running, the occurrence of the first and second ventilatory thresholds occurs at the same \( \dot{V}O_2 \) (both absolute and percent of \( \dot{V}O_{2\text{max}} \)), heart rate, respiratory exchange ratio, ventilation, respiratory rate, tidal volume, and rating of perceived exertion. Only one other study has been published that compared the occurrence of the lactate threshold during ATM running compared to LTM running. Garner et al. (2014) found that the lactate threshold point occurred at a lower heart rate and \( \dot{V}O_2 \) during ATM running. It appears that these authors only reported on the first lactate threshold as the lactate concentration was 2.7 mmol L⁻¹. Our findings are in agreement with Garner et al. (2014) who found that the rating of perceived exertion and respiratory exchange ratio are equal during ATM and LTM exercise at the aerobic threshold, and further at the anaerobic threshold as well.

The discrepancy in these findings compared to our results may not be due to the occurrence points of the anaerobic threshold and more to the efficacy of using lactate thresholds compared to ventilatory thresholds during ATM running. Extra care must be taken for all measurements in water immersion exercise due to the accuracy of equipment in or near the water and the humidity in the room. Previous literature has suggested that special precautions must be in place to prevent liquid samples, such as blood samples, from being diluted with water (Foster & Cotter, 2006). Even a finger prick blood sample can easily be diluted from water dripping.
from the hair or arm after the hand has been wiped dry (Foster & Cotter, 2006). Garner et al. (2014) took blood samples via an earlobe sample. It is possible that this method was chosen to avoid pricking the wet hand and placing it back into the water, however, any water that may have been in the hair (i.e. showering before, sweating) could dilute the sample leading to inaccurate results. Further, the hydrostatic pressure of the water causes fluid shifts into the intravascular space. Blood lactate measurements may be less accurate during aquatic exercise due to a possible hemodilution. In contrast ventilation is not restricted by increased intrathoracic blood volume (Alberton et al., 2014).

The ventilatory thresholds have been compared during land and water exercise using other forms of exercise other than ATM running (Frangolias & Rhodes, 1995; Alberton et al., 2013; Alberton et al., 2014). Previous studies using water calisthenics have reported no differences in \( \dot{V}O_2 \) at the first and second ventilatory threshold in water when matched for an equivalent percentage of \( \dot{V}O_{2\text{max}} \) on land (Alberton et al., 2013; Frangolias & Rhodes, 1995). In addition, it appears that there is no difference between the percentage of maximal heart rate at the first and second ventilatory threshold on land and in water (Alberton et al., 2014). Additionally, the rating of perceived exertion appears to be the same at the first and second ventilatory threshold (Alberton et al., 2013; Frangolias & Rhodes, 1995). All of these previous findings are in agreement with our investigation.

Research has shown a significantly lower blood lactate in water exercise over 80% \( \dot{V}O_{2\text{max}} \) compared to land during water immersed cycling (Connelly et al., 1990), however ventilation remains similar to land at multiple intensities and water temperatures (McArdle, Magel, Lesmes & Pechar, 1976). Considering the anaerobic threshold in our study occurred at 83% \( \dot{V}O_{2\text{max}} \) it is possible the results would have shown a significant difference in the anaerobic
threshold between ATM and LTM running if lactate analysis was used to determine the two thresholds.

Therefore, determining the aerobic and anaerobic threshold based on ventilatory measures is recommended during ATM running. A further benefit of using ventilatory measures to determine the aerobic and anaerobic threshold during graded exercise testing is that participants do not have to stop exercising after each stage in order to collect a lactate sample.

8.3.6 Conclusions

There has been a growing popularity of incorporating aerobic interval training or high intensity interval training protocols in both apparently healthy (Gibala & McGee, 2008) and clinical patients (Wisløff et al., 2007) in order to improve cardiorespiratory adaptation and reduce cardiometabolic risk in several clinical populations (Kessler, Sisson, & Short, 2012). It appears that similar protocols could lead to similar adaptation during ATM exercise (Bressel, Wing, Miller & Dony, 2014; Nagle, Saunders & Franklin, 2017).

Our findings provide further understanding into the use of ATMs for threshold-intensity training while minimizing the vertical loading forces and joint-stress typically experienced during LTM running. Our results suggest that practitioners can prescribe high intensity exercise for either ATM or LTM exercise based on ATM or LTM submaximal testing results. Further, practitioners can take confidence in prescribing and monitoring exercise training based on $\dot{V}O_2$, heart rate, or the rating of perceived exertion if ventilatory measures are used to determine the aerobic and anaerobic threshold. This may provide means to monitor training for facilities that may not have access to more expensive measurement tools and prefer to use less expensive subjective methods.
Overall the use of any of these measures to prescribe exercise training will enhance the use of ATMs for improving aerobic performance and rehabilitation. It is recommended in future research and practice when completing submaximal testing to use ventilatory measures in order to determine the aerobic and anaerobic thresholds as opposed to using blood samples and lactate thresholds. Future studies could aim to compare the occurrence of the lactate thresholds and ventilatory thresholds during ATM and LTM running in a single study.

8.3.7 Limitations

A possible limitation of our study design is that we completed the graded exercise test along with the threshold determination by starting each participant at the same absolute speed. Alternatively, we could have completed the exercise test prior to the threshold testing to ensure each participant had the same relative starting speed or even allowed the participant to choose his self-selected starting pace. We selected our starting speeds after consulting previous research on ATM and LTM testing, as well as completing extensive pilot testing. Additionally, it is common in an applied environment to complete threshold testing at the same time as the maximal exercise test. Therefore, we expect this limitation to be minor and to be more applicable in an applied setting.
Chapter 9: Comparing Hemodynamic Responses while Running in Three Different Water Temperatures and Air: How Does Temperature Influence Comparisons to Land Treadmill Running?

9.1 Introduction

The purpose of this study was to examine how a narrow range of water temperatures could influence the hemodynamic response to aquatic treadmill (ATM) running in chest deep water. No previous study has investigated the hemodynamic responses to various water temperatures during ATM running. Further, the only other study to examine the influence of water temperature during ATM running on cardiorespiratory responses used waist depth water immersion (Gleim & Nicholas, 1989). This study has particular importance in understanding the cardiovascular response to the ATM and land treadmill (LTM) environment as previous investigations have included a water temperature range of 25.8°C to 35°C. A greater understanding of the influence of water temperature could better explain discrepancies found in the current ATM literature, as well as determine how hemodynamic responses may vary due to daily fluctuations in water temperature that occur from the imprecision of consumer water heaters.

In summary, the purpose of altering the water temperature was two-fold: 1) to reflect on how water temperatures that were used in ATM protocols in previous literature may have influenced the differing cardiovascular responses reported, and 2) to determine the influence of commonly used water temperatures on the cardiovascular response to ATM running in order to aid in future exercise prescription.
9.2 Methods

Recreationally active, male participants (n=15) returned to the Fortius Hydrotherapy Lab 48 hours after completing the submaximal run in thermoneutral water. All participants read and signed an informed consent form approved by the university institutional review board. Participants were asked to avoid vigorous exercise, caffeine, and alcohol during the testing period. Prior to coming to Fortius Sport and Health participants ingested an e-Celsius Performance core temperature pill (BodyCap, Caen, France) a minimum of two hours prior to beginning data collection (Becker et al., 2007). Participants wore spandex shorts without a shirt, ran barefoot, and were immersed to the xiphoid process. Metabolic gas exchange was collected using an automated metabolic system (True One 2400, Parvo Medics, Sandy, UT) at a sampling rate of 30 seconds (Midgley, McNaughton & Carroll, 2007) and heart rate was collected continuously using a waterproof Polar T31 telemetric heart rate monitor (Polar T31, Polar, Lake Success, NY). Core temperature was collected pre- and post-exercise. Participants were randomly assigned into the cooler water temperature first or the warmer water temperature first, however all participants completed both in addition to the thermoneutral water temperature (31.11°C). Participants completed the identical procedure, including warm-up, as in the thermoneutral water test. Water temperature was adjusted to 30°C as a cooler water temperature and to 34°C as a warmer water temperature which are considered to be at the lower and higher end of thermoneutral, respectively. These protocols were separated by at least 48 hours and were conducted at the same time of day to control for circadian rhythm.
9.3 Statistical Analyses

All data was assessed using the SPSS statistical software package (version 25) with the significance level set at $\alpha = 0.05$. Data is presented in means, standard deviations, and 95% confidence intervals. Observed power was reviewed to understand the meaningfulness of any significant effects. For all measures, the Mauchly’s test of sphericity was calculated and a Greenhouse-Geisser or Huynh-Feldt corrected alpha level was used when appropriate. Repeated measures ANOVAs were used to compare the hemodynamics responses and changes in core temperature during submaximal running in various water temperatures to LTM running. When significant differences were observed pairwise comparisons with a Bonferroni adjustment were calculated to determine where the differences occurred.

9.4 Results

15 participants were part of the analyses for comparing the hemodynamic responses to various water temperatures and running on a LTM. Participant demographics can be found in Table 9.1.

Table 9.1 Participant demographics for the alterations in cardiovascular and hemodynamics response to different water temperatures during ATM running (n=15)

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>29.25 (6.30)</td>
<td>18 - 41</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.82 (7.24)</td>
<td>167.3 - 197.1</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>77.84 (8.04)</td>
<td>61.9 - 95.6</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (mL kg min$^{-1}$)</td>
<td>47.05 (5.33)</td>
<td>38.47 - 57.02</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.23 (5.16)</td>
<td>4.60 - 21.8</td>
</tr>
</tbody>
</table>
Water temperatures were set at 30°C, 32°C, and 34°C, however, when measured prior to each participant the average temperature was 29.15 +/- 0.25°C, 31.10 +/- 0.37°C, and 32.70 +/- 0.10°C, respectively. These water temperatures corresponded to cool, neutral, and warm water temperatures. All water temperatures were significantly different (p < 0.05) from each other (Figure 9.1). Each ATM run was completed at the same speed and jet resistance and matched for \( \dot{V}O_2 \) and percentage of maximal \( \dot{V}O_2 \) between each water temperature and the LTM run.

Ambient temperature was 23.68 +/- 1.03°C during the neutral water temperature, 22.52 +/- 0.33°C during the warm water temperature, 22.56 +/- 0.42°C during the cool water temperature, and 22.33 +/- 0.47°C during the land trial.

![Figure 9.1](image)

**Figure 9.1** Neutral, warm, and cool water temperatures for submaximal comparisons to land.

Submaximal hemodynamic responses are reported in Table 9.2. No differences (p > 0.05) were observed for cardiac output between neutral, warm, and land temperature, and between
neutral and cool water running. However, cardiac output was significantly lower (p <0.05) during cool water running compared to land and warm water temperatures. Stroke volume was similar (p > 0.05) during all water conditions and land. Heart rate was lower (p <0.05) during warm and cool water temperature compared to land, however, no difference (p >0.05) was observed between neutral water and land running. No differences (p >0.05) were observed between any water conditions and land for left ventricle end-diastolic volume, left ventricle end-systolic volume, and ejection fraction. Arteriovenous oxygen difference was similar (p >0.05) between neutral and warm water temperature, neutral and cool water temperature, and warm water temperature and land, however, cool water temperature was higher (p >0.05) than warm water temperature, and neutral and cool water temperatures were higher (p >0.05) than land. Core temperature was similar (p >0.05) between all water temperatures prior to the start of exercise. After exercise, core temperature during neutral and warm water running, and neutral and cool water running were similar (p >0.05), however, the cool water core temperature was lower (p <0.05) than the warm water core temperature.

**Table 9.2 Influence of water temperature on cardiovascular function during ATM and LTM running**

<table>
<thead>
<tr>
<th></th>
<th>Cool (30 °C)</th>
<th>Neutral (32 °C)</th>
<th>Warm (34 °C)</th>
<th>Land (22 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac Output (L·min⁻¹)</td>
<td>17.78 (2.50)⁺⁺</td>
<td>18.53 (1.84)</td>
<td>19.19 (2.60)</td>
<td>20.09 (2.63)</td>
</tr>
<tr>
<td>Stroke Volume (mL)</td>
<td>129.78 (16.14)</td>
<td>129.85 (14.42)</td>
<td>136.01 (18.36)</td>
<td>132.74 (16.06)</td>
</tr>
<tr>
<td>Heart Rate (beats·min⁻¹)</td>
<td>137.02 (10.09)⁺</td>
<td>143.28 (11.19)</td>
<td>141.47 (11.80)⁺</td>
<td>152.01 (17.01)</td>
</tr>
<tr>
<td>Left Ventricle End-Diastolic Volume (mL)</td>
<td>162.08 (18.51)</td>
<td>165.97 (21.59)</td>
<td>170.34 (22.91)</td>
<td>170.35 (21.56)</td>
</tr>
<tr>
<td>Left Ventricle End-Systolic Volume (mL)</td>
<td>32.29 (11.96)</td>
<td>36.12 (15.45)</td>
<td>34.33 (10.94)</td>
<td>37.62 (14.20)</td>
</tr>
<tr>
<td>Ejection Fraction (%)</td>
<td>80.31 (6.51)</td>
<td>78.88 (7.26)</td>
<td>80.91 (5.16)</td>
<td>78.55 (7.04)</td>
</tr>
<tr>
<td>Arteriovenous Oxygen Difference (mL·100mL)</td>
<td>Cool (30 °C)</td>
<td>Neutral (32 °C)</td>
<td>Warm (34 °C)</td>
<td>Land (22 °C)</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-------------</td>
<td>----------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Cool (30 °C)</td>
<td>14.17 (2.52)††</td>
<td>13.60 (2.09)†</td>
<td>13.08 (1.90)</td>
<td>12.64 (1.96)</td>
</tr>
<tr>
<td>Core Temperature (pre)</td>
<td>37.05 (0.27)</td>
<td>37.09 (0.17)</td>
<td>37.00 (0.18)</td>
<td></td>
</tr>
<tr>
<td>Core Temperature (post)</td>
<td>37.63 (0.21)§</td>
<td>37.79 (0.19)</td>
<td>37.81 (0.21)</td>
<td></td>
</tr>
</tbody>
</table>

* Different than warm (p < 0.05); † Different than land (p < 0.05)

### 9.5 Discussion

Our findings suggest that for a matched VO₂ and a temperature range as small as 4°C (29.15°C – 32.70°C) significant alterations in hemodynamic responses occur. In addition, the core temperature change is significantly lower in 29.15°C as compared to 32.70°C water. Heat within the body is transported by two means, by conduction through the tissues and by convection of flowing blood carrying heat from warmer tissues to cooler tissues (Wenger, 1997). Convective heat exchange between the skin and the environment is proportional to the difference between skin and ambient air temperature or water temperature during immersion (Wenger, 1997). Water immersion increases the convective heat transfer coefficient about 200 times compared to still air (Pugh et al., 1960). Both of these pathways are of importance during ATM running depending on water temperature as a majority of the body (i.e. up to the xiphoid process) is immersed and in direct contact with the skin. Depending on the water temperature, convective and conductive means of heat transfer could either be an advantage or disadvantage. Further, evaporative heat loss from the skin is proportional to the difference between the water vapour pressure at the skin surface and the water vapour pressure in the ambient air (Wenger, 1997). Therefore, ATM running compared to LTM could inhibit the metabolic heat transfer through an increase in the contracting musculature with a reduced evaporative heat loss.
It appears that water temperature has a profound influence on cardiac output for a given \( \dot{V}O_2 \). Our findings suggest that cardiac output is significantly lower during immersion at 29.15°C as compared to 32.7°C. Further, cardiac output in warm water of 32.7°C was most similar to land with water temperatures of 29.15°C eliciting a significantly lower cardiac output comparatively. During dynamic exercise the increase in cardiac output must be partitioned between the contracting muscles to meet the oxygen delivery requirements and the skin to meet the heat transfer requirements of the temperature regulatory system (Nadel et al., 1979). Given a similar stroke volume between all water temperatures and LTM running, our results suggest that the increase in cardiac output is caused by changes in heart rate. Indeed, heart rate was found to be lower during ATM running in 29.15°C water compared to land and was trending lower than immersion in warmer water of 32.70°C (mean difference of 4.5 beats mins\(^{-1}\)).

During ATM running in waist deep water it has been suggested that running in 36.1°C water increases heart rate for a given \( \dot{V}O_2 \) compared to 30.5°C water and land temperature of 24-26.5°C (Gleim & Nicholas, 1989). Additionally, it has been reported that at a given submaximal metabolic demand, heart rate in 18°C water was five beats per minute lower than 25°C water and 15 beats per minute lower than in 33°C water or air (McArdle et al., 1976). In these larger ranges in water temperature it was reported that stroke volume increased for the lower temperatures with the opposite alterations to heart rate. Our findings suggest this mechanism of change may occur to a lesser degree in the smaller ranges of water temperature. In agreement, Avellini, Shapiro, Fortney and Pandolf (1982) noted the heart rate to \( \dot{V}O_2 \) curve shifted to the right with higher heart rates (~10 beats mins\(^{-1}\)) at 75% \( \dot{V}O_{2\text{max}} \) in 32°C compared to 20°C. Therefore, it appears that with alterations in cardiac output throughout a range of water temperatures, heart
rate tends to increase to offset reductions in stroke volume as blood is directed to the skin for heat exchange.

Special considerations for water temperature must be taken when monitoring exercise using heart rate during ATM running, specifically when comparing these measures to LTM running as has been common in the literature. In any study that had a range of water temperatures or selected a water temperature greater than 34°C or less than 30°C, it is likely that the results could have been affected. For higher water temperatures (i.e. >34°C) with increasing intensity and duration of exercise, maximal heart rate may be obtained and limit the ability to maintain cardiac output to meet the muscular and thermoregulatory demand.

Arteriovenous oxygen difference was significantly greater during ATM running in 29.15°C water compared to 32.70°C water. Further, water temperatures of 31.10°C and 29.15°C elicited higher arteriovenous oxygen difference compared to LTM running. As the Fick principle suggests, for a given VO₂, the higher arteriovenous oxygen difference in cooler water temperatures is a product of the lower cardiac output. Our findings suggest that the temperature of the water does not significantly influence left ventricle end-diastolic volume, left ventricle end-systolic volume, or ejection fraction.

Future research is warranted to verify the hemodynamic responses to different temperatures in both land and water. It becomes challenging to compare our findings to that of other modes of exercise (i.e. water immersed cycling) as the active musculature and immersion level are different. Toner et al. (1984) suggested that different exercise modes that alter the contracting skeletal muscle mass of the performing limbs could influence thermoregulatory responses during water immersion exercise. It is very important to consider the metabolic heat during ATM running due to the resistance of the water as more muscles are working through a
resistance that is 800 times denser than air (di Prampero, 1986). The muscles that may be more active during ATM running as compared to land running and cycling include the legs, arms, and respiratory muscles due to the fluid resistance and hydrostatic pressure. Heat as a by-product of muscular contraction can be almost immediate. As suggested by Wenger (1997) even during mild exercise the muscles are the main source of metabolic heat and during heavy exercise they may account for up to 90% of metabolic heat. As such, ATM running would be expected to provide varying thermoregulatory responses as compared to cycling.

9.6 Limitations

This study was the first to investigate core temperature during ATM running. One limitation of our study was that we were only able to capture pre- and post-test core temperature responses. Although these measures are able to capture the thermoregulatory response to the varying water temperatures, it would have been preferred to be able to monitor core temperature throughout the entirety of the test. The main problem was the water caused interference for the transmission of the data from the core temperature pills to the monitoring device. Since the main purpose was to measure the cardiorespiratory and hemodynamic responses to varying water temperatures, it was decided that running should remain continuous throughout the exercise trials and only pre- and post-test core temperature measurements would be analyzed, as opposed to having the participant take a break from running to exit the water to obtain a core temperature reading throughout exercise.

The second limitation of the study was that the water temperatures were set at 30°C, 32°C, and 34°C, however, when measured prior to each participant the average temperature was 29.15 +/- 0.25°C, 31.10 +/- 0.37°C, and 32.70 +/- 0.10°C, respectively. Although the warm water temperature was not outside the thermoneutral range at 34°C as we intended, we were still able
to demonstrate hemodynamic alterations that occur within a small water temperature range, which was an aim of the study. In fact, this smaller range of water temperatures than intended may further support our hypothesis that hemodynamic alterations may occur in a range that is possible for daily fluctuations in water temperature.

9.7 Conclusions

In summary, our findings suggest that for submaximal exercise during ATM running and a LTM environment of approximately 22.33°C, a water temperature between 32-33°C may provide the most comparable responses. Future research, as well as training and rehabilitation, should aim to maintain this temperature range to elicit the most similar responses to land training. These findings provide support for maintaining a small range of water temperature during ATM research and emphasizes the caution that must be taken when comparing cardiovascular responses to ATM running in various water temperatures. It appears that some inconsistencies in the ATM running literature may be due to the water temperatures being used and the alterations in these studies comparing ATM to LTM running may be temperature specific as compared to environment specific.
Chapter 10: The Influence of Anthropometrics on Physiological Measures during ATM and LTM Running

10.1 Introduction

The purpose of this study was to examine how anthropometrics may be related to physiological alterations during aquatic treadmill (ATM) and land treadmill (LTM) running. Specifically, this study observed the relationship between body fat percentage, the sum of seven skinfolds, the surface area exposed, the body surface area, body weight, and the body surface area to mass ratio and how each of these related to the $\dot{V}O_2$ and core temperature response during submaximal running and maximal running during ATM and LTM running, as well as at varying distances from the resistance jets and in three different water temperatures during ATM running. Previous literature investigating cardiovascular responses to ATM running has collected anthropometrics for the purpose of describing the participants, however, this study is the first to correlate these variables to physiological alterations between ATM and LTM running. The findings are of value to practitioners to further understand how the cardiovascular responses between ATM and LTM exercise, or between various individuals during ATM running, could differ based on anthropometric measures.

10.2 Methods

All participants read and signed an informed consent form approved by the university institutional review board. Prior to any exercise testing, recreationally active, male participants (n=16) entered the Fortius Lab to obtain measures of height, weight, and body composition. Body density was determined based on the seven-skinfold equation of Jackson and Pollock (1978), whereas body fat was calculated based on body density using the Siri (1961) equation.
Skinfold measurements were taken according to a standardized approach (Norton, 2018). Each skinfold site was carefully located using the correct anatomical landmarks. The site was grasped so that a double fold of skin plus the underlying subcutaneous adipose tissue was held between the thumb and index finger. The nearest edge of the contact face of the caliper was applied 1 cm lateral to the thumb and finger. The caliper was held at 90° to the surface of the skinfold site at all times. Measurement was recorded two seconds after the full pressure of the caliper was applied (Kramer & Ulmer, 1981). A constant recording time enables test-retest comparisons to be made while controlling for the compression of the skinfold. Each site was measured twice in a rotational pattern to avoid experimenter bias and reduce the effects of skinfold compressibility. If the difference between two measurements of the same site differed by more than one millimeter, a third measurement was taken. All sites were measured in the same order each time. All skinfold measurements were taken in the Fortius Lab to avoid any effects of increased humidity and all measurements were taken prior to any exercise or immersion in the pool as exercise, warm water, and heat produce increased blood flow in the skin with an associated increase in skinfold thickness (Norton, 2018).

Height and weight were used to estimate individual body surface area (Du Bois & Du Bois, 1989). Body surface area and weight were used to calculate the body surface to mass ratio (Havenith, 2001). An additional equation, named the surface area exposed, was used to estimate the surface area of each individual that was exposed to air during ATM running. To estimate this value, measurements were taken from the xiphoid process to the suprasternal notch, as well as a shoulder-to-shoulder measurement. The equation for the surface of a cylinder, $2\pi r * h$, where $r$ is the radius from the shoulder-to-shoulder measurement and $h$ is the height from xiphoid process to the suprasternal notch, was used to estimate the surface area exposed to ambient air.
The anthropometric measures of body fat percentage, the sum of seven skinfolds, surface area exposed, body surface area, and body weight were then correlated to metabolic measures and core temperatures during maximal ATM and LTM running, ATM and LTM running at various temperatures, and ATM running at various distances from the resistance jets to understand the influence of body composition on the physiological response to ATM running.

10.3 Statistical Analyses

All data was assessed using the SPSS statistical software package (version 25) with the significance level set at $\alpha = 0.05$ and $\alpha = 0.01$ for all correlations. Observed power was reviewed to understand the meaningfulness of any significant effects. A Pearson’s product moment correlation was used to determine the relationship between anthropometric measures of body fat percentage, the sum of seven skinfolds, the surface area exposed, the body surface area, the body surface area to mass ratio, and body weight to, 1) $\dot{V}O_2\text{max}$ and core temperature responses to maximal exercise on the ATM and LTM, 2) core temperature response during submaximal ATM running in various water temperatures, and 3) changes in $\dot{V}O_2$ response at varying distances from the jet. Effect sizes were calculated and interpreted using Cohen’s thresholds of small (0.1), moderate (0.3), and large (0.5) effects (Cohen, 1988).

10.4 Results

All participants (n=16) completed anthropometric assessment including height, weight, and body composition determined by skinfold assessment. Participant demographics can be found in Table 10.1.
Table 10.1 Participant demographics for the influence of anthropometrics on responses to ATM running

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>30.19 (6.42)</td>
<td>18 - 41</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.79 (7.24)</td>
<td>167.3 - 197.1</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>78.18 (8.18)</td>
<td>61.9 - 95.6</td>
</tr>
<tr>
<td>(\dot{V}O_2) (mL kg min(^{-1}))</td>
<td>47.18 (5.18)</td>
<td>38.47 - 57.02</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>11.27 (4.98)</td>
<td>4.60 - 21.8</td>
</tr>
</tbody>
</table>

10.4.1 Pearson Product Moment Correlation Analysis During LTM and ATM Maximal Running

During maximal running anthropometric measures were correlated to the difference between \(\dot{V}O_{2\text{max}}\) on the LTM and the ATM (\(\Delta \dot{V}O_2\) (LTM-ATM)), the LTM \(\dot{V}O_{2\text{max}}\) (\(\dot{V}O_{2\text{max}}\) (LTM)), the ATM \(\dot{V}O_{2\text{max}}\) (\(\dot{V}O_{2\text{max}}\) (ATM)), the difference between the peak core temperature after LTM and ATM running (\(\Delta T_c\) peak (LTM-ATM)), the change in core temperature from pre-test to post-test during LTM running (\(\Delta T_c\) (LTM)), the change in core temperature from pre-test to post-test during ATM running (\(\Delta T_c\) (ATM)), the peak core temperature during LTM running (peak Tc (LTM)), and the peak core temperature during ATM running (peak Tc (ATM)). The correlations are presented in Table 10.2. Body mass in kilograms was significantly related to \(\dot{V}O_{2\text{max}}\) during LTM running (\(r = .56, p = .03, r^2 = 0.315\)), however, there was no significant relationship between body mass and \(\dot{V}O_{2\text{max}}\) during ATM graded exercise testing (\(r = .38, p = .16\)). Body surface to mass ratio was significantly related to \(\dot{V}O_{2\text{max}}\) on a LTM (\(r = -.55, p = .03, r^2 = 0.305\)), but not an ATM. Body fat percentage (\(r = -.55, p = .03, r^2 = 0.303\)), the sum of seven skinfolds (\(r = -.54, p = .04, r^2 = 0.295\)), body surface area (\(r = -.68, p = .006, r^2 = 0.456\)), and body mass (\(r = -.64, p = .01, r^2 = 0.406\)) were all significantly related to the change in core temperature.
from pre- to post-test during maximal LTM running, however, only body fat percentage \(r = -.61, p = .02, r^2 = 0.371\) and the sum of seven skinfolds \(r = -.60, p = .02\) were significantly related to the change in core temperature from pre- to post-test during maximal ATM running. The body surface to mass ratio was significantly related to the change in core temperature from pre- to post-test during maximal ATM running \(r = 0.53, p = 0.04, r^2 = 0.278\), but not significantly related to the change in core temperature from pre- to post-test during maximal LTM running.

Similar to the change in core temperature, body fat percentage \(r = -0.59, p = .02, r^2 = 0.353\), the sum of seven skinfolds \(r = -0.59, p = .02, r^2 = 0.346\), body surface area \(r = -0.67, p = .006, r^2 = 0.449\), and body mass \(r = -0.60, p = .02, r^2 = 0.358\) were all significantly related to peak core temperature during maximal LTM running, however, no anthropometric measures were significantly related to peak core temperature during maximal ATM running.

**Table 10.2 Anthropometric correlations during LTM and ATM maximal exercise**

<table>
<thead>
<tr>
<th></th>
<th>(\Delta \dot{V}O_2) (LTM)</th>
<th>(\dot{V}O_{2\text{max}}) (LTM)</th>
<th>(\Delta \dot{V}O_{2\text{max}}) (ATM)</th>
<th>(\Delta T_c) peak (LTM)</th>
<th>(\Delta T_c) (ATM)</th>
<th>Peak Tc (LTM)</th>
<th>Peak Tc (ATM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Fat (%)</td>
<td>0.32</td>
<td>-0.16</td>
<td>-0.31</td>
<td>-0.01</td>
<td>-0.55*</td>
<td>-0.61*</td>
<td>-0.59*</td>
</tr>
<tr>
<td>Sum of 7 Skinfolds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm)</td>
<td>0.37</td>
<td>-0.11</td>
<td>-0.29</td>
<td>-0.02</td>
<td>-0.54*</td>
<td>-0.60*</td>
<td>-0.59*</td>
</tr>
<tr>
<td>Surface Area Exposed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm)</td>
<td>0.08</td>
<td>0.13</td>
<td>0.07</td>
<td>-0.17</td>
<td>-0.21</td>
<td>-0.03</td>
<td>-0.22</td>
</tr>
<tr>
<td>Body Surface Area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm)</td>
<td>-0.04</td>
<td>0.50</td>
<td>0.45</td>
<td>-0.47</td>
<td>-0.68**</td>
<td>-0.23</td>
<td>-0.67**</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>0.20</td>
<td>0.56*</td>
<td>0.38</td>
<td>-0.28</td>
<td>-0.64*</td>
<td>-0.38</td>
<td>-0.60*</td>
</tr>
<tr>
<td>Body Surface to Mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio (cm(^2)/kg(^{-1}))</td>
<td>-0.41</td>
<td>-0.55*</td>
<td>-0.27</td>
<td>0.04</td>
<td>0.49</td>
<td>0.53*</td>
<td>0.42</td>
</tr>
</tbody>
</table>

* correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed); \(r=0.10\) - small effect, \(r=0.30\) - moderate effect, \(r=0.50\) - large effect
10.4.2 Pearson Product Moment Correlation Analysis During ATM Submaximal Running in Three Different Water Temperatures

During submaximal running, anthropometric measures were correlated to the change in core temperature from pre- to post-test in a neutral water temperature ($\Delta T_c$ (neutral)), the change in core temperature from pre- to post-test in a warm water temperature ($\Delta T_c$ (warm)), the change in core temperature from pre- to post-test in a cool water temperature ($\Delta T_c$ (cool)), the peak core temperature reached in a neutral water temperature (Peak $T_c$ (neutral)), the peak core temperature reached in a warm water temperature (Peak $T_c$ (warm)), and the peak core temperature reached in a cool water temperature (Peak $T_c$ (cool)). Water temperatures for neutral, warm, and cool water were 31.10 +/- 0.37°C, 32.70 +/- 0.10°C, and 29.15 +/- 0.25°C, respectively. Results for the correlation analyses can be found in Table 10.3. No anthropometric measures were significantly ($p > 0.05$) related to any core temperature measures in any water temperature.

**Table 10.3 Anthropometric correlations during ATM submaximal exercise in three water temperatures**

<table>
<thead>
<tr>
<th></th>
<th>$\Delta T_c$ (neutral)</th>
<th>$\Delta T_c$ (warm)</th>
<th>$\Delta T_c$ (cool)</th>
<th>Peak $T_c$ (neutral)</th>
<th>Peak $T_c$ (warm)</th>
<th>Peak $T_c$ (cool)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Fat (%)</td>
<td>0.03</td>
<td>0.07</td>
<td>0.10</td>
<td>0.25</td>
<td>-0.11</td>
<td>0.04</td>
</tr>
<tr>
<td>Sum of 7 Skinfolds (mm)</td>
<td>-0.06</td>
<td>0.02</td>
<td>0.03</td>
<td>0.15</td>
<td>-0.15</td>
<td>-0.04</td>
</tr>
<tr>
<td>Surface Area Exposed (mm)</td>
<td>0.19</td>
<td>0.35</td>
<td>0.28</td>
<td>0.28</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td>Body Surface Area (mm)</td>
<td>0.26</td>
<td>0.47</td>
<td>0.18</td>
<td>0.23</td>
<td>0.43</td>
<td>0.22</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>0.10</td>
<td>0.31</td>
<td>-0.01</td>
<td>0.23</td>
<td>0.35</td>
<td>0.09</td>
</tr>
<tr>
<td>Body Surface to Mass Ratio</td>
<td>0.22</td>
<td>-0.12</td>
<td>-0.01</td>
<td>0.05</td>
<td>-0.24</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

$r = .10$ - small effect, $r = .30$ - moderate effect, $r = .50$ - large effect.
10.4.3 Pearson Product Moment Correlation Analysis During ATM Submaximal Running at Various Distances from the Resistance Jets

During submaximal ATM running, anthropometric measures were correlated to the change in \( \dot{V}O_2 \) response from the distance that resulted in the highest \( \dot{V}O_2 \) to the distance that resulted in the lowest \( \dot{V}O_2 \) response (\( \Delta \dot{V}O_2 \) (max-min)), and the change in \( \dot{V}O_2 \) response from 0.61 metres from the jet to 1.22 metres from the jet (\( \Delta \dot{V}O_2 \) (0.61m-1.22m)). The purpose of comparing the 0.61 metre distance to the 1.22 metre distance is that 0.61 metres away from the resistance jet provides the maximal \( \dot{V}O_2 \) response, whereas at 1.22 metres there tended to be an increase in the cardiovascular response relative to the downward trend as the individual moves away from the resistance jet. One reasonable explanation for the increase at 1.22 metres is that this distance offers a point of being somewhat close to the resistance jet to receive a strong flow of water, but far enough away that the flow of water fans out to interact with a greater surface area of the individual. Results of the correlation analysis are reported in Table 10.4. No anthropometric measures were significantly related (p > 0.05) to either \( \dot{V}O_2 \) measure.

**Table 10.4 Anthropometric correlations during ATM submaximal exercise at various distances from the resistance jets**

<table>
<thead>
<tr>
<th>Measure</th>
<th>( \Delta \dot{V}O_2 ) (max-min)</th>
<th>( \Delta \dot{V}O_2 ) (0.61m - 1.22m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Fat (%)</td>
<td>-0.11</td>
<td>-0.15</td>
</tr>
<tr>
<td>Sum of 7 Skinfolds (mm)</td>
<td>-0.12</td>
<td>-0.07</td>
</tr>
<tr>
<td>Surface Area Exposed (mm)</td>
<td>-0.34</td>
<td>-0.27</td>
</tr>
<tr>
<td>Body Surface Area (mm)</td>
<td>0.15</td>
<td>-0.08</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>0.28</td>
<td>0.19</td>
</tr>
<tr>
<td>Body Surface to Mass Ratio</td>
<td>-0.40</td>
<td>-0.44</td>
</tr>
</tbody>
</table>

\( r=0.10 \) - small effect, \( r=0.30 \) - moderate effect, \( r=0.50 \) - large effect.
10.5 Discussion

10.5.1 The Influence of Anthropometrics on the $\dot{V}O_2$ Response during Maximal ATM and LTM Running

During maximal ATM and LTM running, body fat percentage, the sum of seven skinfolds, the surface area exposed to air, body surface area, body mass, and body surface area to mass ratio were correlated to $\dot{V}O_{2\text{max}}$ on both the ATM and LTM, the difference in $\dot{V}O_{2\text{max}}$ between the ATM and LTM, the peak core temperature on the ATM and LTM, and the change in core temperature from pre- to post-testing during ATM and LTM running.

The most significant finding from the Pearson product-moment correlation analyses is that body mass showed a significantly large positive correlation to $\dot{V}O_{2\text{max}}$ during LTM running ($r=0.6$, $p=0.03$), however, this relationship was not significant during ATM running. During LTM running, as body mass increased absolute $\dot{V}O_{2\text{max}}$ increased as well, a relationship that has been evidenced in previous literature (Jensen, Johansen, & Secher, 2001). During ATM running when immersed to the xiphoid process approximately 71% of body weight is reduced due to the forces of buoyancy acting on the body (Harrison et al., 1992). Therefore, the body mass measured on land is not necessarily the same relative percentage of body mass for each individual immersed to chest depth during ATM running. Depending on the body composition of the individual the buoyancy of the water may act differently on individuals of similar body masses and would influence the relationship between $\dot{V}O_2$ and body mass. Consequently, our results support our hypothesis and suggest that only absolute $\dot{V}O_2$ may be suitable for ATM running unless an immersed weight measurement can be taken.

Previous literature has shown a negative relationship between body fat percentage and $\dot{V}O_{2\text{max}}$ (Mondal & Mishra, 2017). Our findings showed a nonsignificant, small negative
relationship between body fat percentage and $\dot{V}O_2\text{max}$ on the LTM, and a nonsignificant, moderate negative relationship on the ATM. Body fat does not have any effect on $\dot{V}O_2\text{max}$ and does not necessarily imply a reduced ability to maximally consume oxygen (Goran, Fields, Hunter, Herd & Weinsier, 2000). The major influence of body mass on $\dot{V}O_2\text{max}$ is explained by fat-free mass (Goran et al, 2000). It is more common in the literature to compare body fat percentage to cardiorespiratory fitness as a means to classify the risk of future disease or health outcomes. Therefore, these studies tend to use participants with large ranges of body fat and activity levels. It is possible that the nonsignificant findings in our study is due to the fact that our participants had relatively similar exercise habits with similar fat-free mass and cardiorespiratory fitness.

When comparing ATM to LTM running, it appears that body fat percentage has a similar influence on the metabolic response between the two environments. Considering that during ATM running there was a moderate relationship compared to a small relationship on the LTM, it would be interesting for future research to use a larger range of cardiorespiratory fitness levels and body compositions to see if these relationships become significant. Some ATM running literature has justified various findings by alluding that individual body composition during ATM running could lower $\dot{V}O_2$ due to the effects of buoyancy acting on each individual (Rutledge et al., 2007; Porter et al., 2014). Our results suggest that adiposity may influence metabolic cost during ATM running, however, it is not likely the case if the participants in these studies were of similar body weight and fat free mass.

Taken together, it appears that $\dot{V}O_2\text{max}$ testing can be implemented with similar maximal responses between ATM and LTM running, however, absolute values should be reported because body mass does not have the same relationship to $\dot{V}O_2\text{max}$ on the ATM as compared to
the LTM. Additionally, at this point, body fat percentage does not influence $\dot{V}O_2_{\text{max}}$ during ATM running, however more research is needed in this area.

10.5.2 The Influence of Anthropometrics on the Core Temperature Response during Maximal ATM and LTM Running

Similar to the anthropometric measures in relation to metabolic responses, it appears that the relationship to core temperature during maximal exercise follows similar trends between ATM and LTM running with a few notable differences. Our findings suggest that body fat percentage, the sum of seven skinfolds, body surface area, and body mass were all significantly related to the peak core temperature during LTM running. These findings are supported in previous literature examining the influences on anthropometrics and core temperature (Havenith, 2001; Kenney, 1985; Anderson, 1999). For example, individuals with a large body surface to mass ratios exercising in environments where the skin temperature exceeded the ambient air temperature would be at an advantage with enhanced dissipation of heat, whereas the same individuals would be at a disadvantage when exercising in environments where ambient air temperature surpassed skin temperature, having greater heat gain from the environment and a greater degree of heat strain (Robinson, 1942).

Body fat percentage had a large, negative relationship to the increase in core temperature on the LTM and ATM, as well as the peak core temperature on the LTM and ATM. Body surface to mass ratio had a large positive relationship to the increase in core temperature on the LTM and the ATM, as well as a moderate positive relationship to LTM and ATM peak core temperature. In support of our findings, Havenith (2001) found a positive relationship between body surface to mass ratio and rectal temperature, and a negative relationship between both surface area and mass to rectal temperature. Our findings demonstrate a significantly large
negative relationship between body weight and the increase and peak core temperature on the LTM. Interestingly, body weight has only a moderate nonsignificant negative relationship to the increase in core temperature and the peak core temperature on the ATM. As previously discussed, any relationship between body weight and another measure during ATM running could be erroneous due to the buoyancy acting in the upwards direction to support approximately 71% of body weight.

Perhaps most notably, body surface area had a significantly large negative relationship to the increase in core temperature and the peak core temperature on the LTM. In comparison, there was only a nonsignificant small negative relationship to the increase in core temperature, and a nonsignificant moderate negative relationship to peak core temperature on the ATM. These contrasting findings are likely due to the influence of the water temperature. During land-based exercise, body surface area is important for heat exchange as heat loss is proportional to the gradient between skin and environment, and to the surface area available for heat exchange (Havenith, 2001). During ATM running, where water immersion is typically to the xiphoid process, the body surface area is both immersed in water and in ambient air. Considering our results suggest that there are only small nonsignificant relationships between the surface area exposed to ambient air and core temperature, it is likely that any relationship is due to the immersed surface area, as long as the ambient air is temperate. When the environment is hotter than the skin, evaporation is the body’s only way to lose heat and must dissipate not only metabolic heat, but also any heat gained from the environment through radiation, conduction, and convection. (Wegner, 1997). Evaporative heat loss from the skin is proportional to the difference between the water vapour pressure at the skin surface and the water vapour pressure in the ambient air (Wenger, 1997). Previous reports have suggested that evaporation is suppressed
during water immersion and thus may limit heat exchange at higher exercise intensities, especially in warmer water temperatures (Pendergast & Lundgren, 2009). During LTM running, it appears that body surface area influences the transfer of heat with the environment, whereas during ATM running the water temperature dictates the heat transfer to a larger degree than body surface area. Any water temperature that is too warm would greatly impair cooling regardless of body surface area. This finding further emphasizes the importance of incorporating a thermoneutral water temperature as warmer and cooler temperatures will have a significant impact on core temperature at higher intensity exercise with an altered heat exchange.

Based on our findings, it does not appear that the amount of surface area exposed to ambient air has any relationship to maximal increases in $\dot{V}O_2$ or peak core temperature when all participants are immersed to the level of the xiphoid process in a temperate environment. However, this relationship may exist when comparing various depths of water immersion or ambient air temperatures during ATM running. Future research would be necessary in order to verify whether the surface area exposed to ambient air has an influence on peak core temperature and $\dot{V}O_2$ in deeper and shallower water during ATM running. In addition, future research could examine the influence of the ambient air on the surface area exposed. Further insight could be gained by running in a thermoneutral water temperature in a hot ambient environment or running in warmer water with cooler ambient air. This research would be valuable to better understand the relationship between the immersed and exposed body surface area. Future research should also examine the core temperature relationship to body surface area for a variety of water temperatures, as well as with individuals with a wider range of body compositions to further understand this relationship.
The discrepancies between environments further supports the significantly lower peak core temperatures during ATM running and helps explain why peak core temperature was lower during maximal ATM running compared to LTM running (Chapter 6). Taken together it appears that anthropometrics influence both the $\dot{V}O_{2\text{max}}$ and peak core temperature reached during LTM running. Although the trend is similar during ATM running, it does not appear that the influence is as strong. It is important for future research to list the significant anthropometric measures when comparing ATM and LTM cardiovascular responses. It is possible that some variation in the cardiorespiratory responses of previous research could be due to the influence of anthropometrics during ATM compared to LTM running. Furthermore, when water temperatures are outside the recommended range, it is possible the responses may be skewed even further. These findings provide a rationale for further research to help strengthen the recommended temperature range for ATM graded exercise.

10.5.3 The Influence of Anthropometrics during Submaximal ATM and LTM Running

Although the relationships between the anthropometric measures and $\dot{V}O_{2\text{max}}$ and peak core temperature are significant during maximal running, our findings suggest that these relationships are not statistically significant during submaximal ATM and LTM running. Therefore, the influence of anthropometrics does not appear to explain the cardiovascular alterations that occurred between the three different temperature ranges. As described previously, there was a significant difference in core temperature between the warm and cool water group (Chapter 9) which may have caused cardiovascular alterations itself irrespective of anthropometric measures. Future research should use larger ranges of anthropometric measures and examine relationships between anthropometrics and water temperature during ATM running.
Previous reports have suggested that evaporation is suppressed during water immersion and thus may limit heat exchange at higher exercise intensities, especially in warmer water temperatures (Pendergast & Lundgren, 2009). Therefore, the relationship is intensity dependent and future research should aim to alter water temperature while maintaining intensity, and alter intensity while maintaining water temperature in order to determine the threshold of each that could lead to significant relationships and to help better understand the relationship between anthropometric measures and ATM running. By conducting further research, practitioners could aim to set water temperatures based on their participants individual anthropometric measures and planned intensity to help ensure the alterations in the cardiovascular response are specific to the exercise environment.

Interestingly, although not significant, the relationship was strongest (moderate relationship) between body surface area and the body surface area exposed to ambient air. However, during maximal exercise, this measure had a very small relationship. Therefore, it is possible that the importance of the body surface area exposed to ambient air is more related to the duration of time running as opposed to the shorter, high intensity graded exercise test. These results exemplify the challenges of finding a single water temperature to use for both submaximal and maximal exercise, as is the case during graded exercise testing. Our study is the first to describe the body surface area exposed measurement and it is recommended that future investigations include this measure and further report on the association with various outcomes. Secondly, our findings suggest the importance of reporting and standardizing the water temperature and ambient air of the environment that the person is running in during exercise.
10.5.4 The Relationship between Anthropometrics and the Running Position from the Resistance Jet during ATM Running

There was no significant relationship between any anthropometric measure and the influence of the resistance jet based on the difference between the highest and lowest $\dot{V}O_2$ response or the difference between the $\dot{V}O_2$ response at 0.61 metres and 1.22 metres. These variables were correlated in order to explain the increase in metabolic demand at 1.22 metres. It was hypothesized that while running 0.61 metres from the resistance jet the size of an individual would not influence the cardiorespiratory response since the jet was direct and streamlined. As the participant moves away from the resistance jet, we speculated that the jet would spread out and come into contact with a greater surface area of the participant. In this scenario, those with a higher surface area would have a $\dot{V}O_2$ response that was more similar to running at 0.61 metres than a smaller individual.

Our findings suggest that none of the anthropometric variables had a significant relationship with the change in $\dot{V}O_2$, although the body surface area to mass ratio did have a moderate, negative nonsignificant relationship. Although these findings are nonsignificant, our participants were of relatively similar body composition which is not often the case in a clinical population. In a more clinical population it is possible that these findings could be significant based on the relationships that do exist. Therefore, future research should continue to examine the relationship between anthropometrics and the cardiorespiratory responses with a wider range of individuals. Eventually, given a large enough study, the body composition of each individual could be interpreted individually into the cardiorespiratory responses to further understand the alterations that occur solely based on the differing environments and to standardize future research methods.
10.6 Limitations

Limitations exist within this study. For correlations of this nature the small sample included in the analyses is a limitation. Further, our participants were relatively homogenous in size, body composition, and activity level. Therefore, our findings are limited when applying the findings to other populations and future studies that include participants with a larger range of body sizes, compositions, and include both males and females are recommended. However, our findings do provide rationale for future studies to include anthropometrics in their design to accurately interpret findings as there appears to be a relationship between a participant’s anthropometric measures and the physiological response to ATM running.

10.7 Conclusions

As a whole, our findings demonstrate that the relationship between cardiorespiratory responses and anthropometric measures differs depending on whether the individual is running on an ATM or LTM. Therefore, future research must ensure that these measures are collected, reported, and interpreted to help explain cardiorespiratory alterations to further understand how each particular environment itself alters the cardiorespiratory response.
Chapter 11: General Findings and Conclusions

11.1 Integration and Interpretation of Major Findings

The popularity and use of ATMs for the purpose of physical rehabilitation, improvements to health outcomes, and sport performance is growing. To date the literature has not provided consistent or convincing evidence of the cardiovascular responses and alterations during ATM compared to LTM running. One concern is whether the resulting evidence within the current literature, as well as the comparisons between these studies, is due to the environment itself (i.e. water versus land) or due to the protocol and methods used. Specifically, many studies tend to incorporate standards that were developed for water immersed cycling rather than specific to ATM running. Given the differences in the posture of exercise, the level of immersion, the involved musculature, and the resistance properties of water, these standards do not provide a strong framework during ATM running. Therefore, the findings of this dissertation provide further support to the cardiovascular alterations that occur during ATM and LTM running, as well as provide standards and criteria specific to ATM running that can be implemented in future research to increase the confidence in the results being mostly due to the environment.

During maximal ATM compared to LTM running, the cardiorespiratory response is similar between environments with the exception of maximal heart rate which tends to be lower during ATM running. Although not tested directly, these findings suggest that high intensity training during ATM exercise may elicit a similar response and adaptation compared to a similar workload on land. However, for the highest levels of exercise, such as those over 85% of the maximal heart rate, prescribing and monitoring training based on land-based values may not provide effective training. Instead, it may be more beneficial to use individual’s ratings of perceived exertion to prescribe high intensity interval training.
A second important finding is that although pre-test core temperatures were similar during ATM and LTM running, post-test core temperature was significantly lower following the ATM graded exercise test. The water temperature selected for the test was based on previous literature incorporating water immersed cycling. Therefore, although core temperature significantly increased from pre-to-post testing in both the ATM and LTM group, a higher water temperature could be incorporated to match the core temperature rise between the groups. Although this difference in peak core temperature was not large enough to hinder the attainment of $\dot{V}O_{2\text{max}}$, it does justify standardizing water temperature specific to ATM running. Further, our findings suggest that the use of a verification stage may be appropriate during ATM running to confirm the attainment of $\dot{V}O_{2\text{max}}$. At this point, it is recommended that the $\dot{V}O_2$ response is used as a criterion instead of heart rate, however, further investigation into various verification phase protocols is warranted.

As with maximal running, the findings suggest that submaximal cardiorespiratory responses are similar between ATM and LTM running. The maximal cardiorespiratory response can be attained during ATM running even with low levels of resistance jets and the use of three minute stages. Practitioners who are looking to incorporate ATM running into their regular training, exercise, or rehabilitation routine can incorporate ATM graded exercise tests that allow for the attainment of $\dot{V}O_{2\text{max}}$ while also being able to identify important submaximal thresholds, such as the aerobic and anaerobic threshold. The major finding of this section is that although maximal heart rate is lower during ATM running, heart rate appears to be similar up to approximately 83% $\dot{V}O_{2\text{max}}$, or in this case the anaerobic threshold. Previous literature has suggested that during water immersed cycling, a lower heart rate can be seen with exercise over 60% $\dot{V}O_{2\text{max}}$ (Christie et al., 1990; Connelly et al., 1990). Therefore, it is likely that the similar
heart rates at higher intensities is ATM specific and it is quite possible that the progressive
increase in heart rate during ATM and LTM running may be due to physiological changes
associated with the anaerobic threshold as opposed solely to the percentage of $\dot{V}O_2_{\text{max}}$. Previous
literature suggests that during a graded exercise test, plasma catecholamines demonstrated a
threshold where both norepinephrine and epinephrine increase nonlinearly (Mazzeo & Marshall,
1989). Furthermore, the inflection in plasma catecholamines shifted in an identical manner and
occurred simultaneously with that of anaerobic threshold regardless of the testing protocol or
training status of the individual (Mazzeo & Marshall, 1989). Therefore, the large increase in the
rate of epinephrine release after the anaerobic threshold may be reduced during ATM running
and be responsible for the lower maximal heart rate often exhibited, as well as explain the lower
comparative heart rate after the anaerobic threshold.

This investigation was the first to compare hemodynamic responses during ATM
running. During submaximal running on an ATM, cardiac output and stroke volume are lower
compared to LTM running at all intensities. Previous literature has often reported a higher stroke
volume during water immersed exercise (Christie et al., 1990; Park et al., 1999; Garzon et al.,
2015). The importance of this contrasting finding is the awareness of a possible relationship
between the amount of time passively immersed in the water prior to exercise and the potential
influence on stroke volume and cardiac output. An initial passive rest period during water
immersion may increase stroke volume through an increase in preload and end-diastolic volume
which in turn could result in a lower heart rate to maintain the necessary cardiac output. In
contrast, beginning exercise immediately upon entering the water, as with our protocol, could
result in a lower plasma volume which may lower stroke volume and provide a more similar
heart rate to land in an attempt to maintain cardiac output.
Based on our findings, the running position from the resistance jets has a profound influence on the cardiorespiratory and hemodynamic response. As the first study to examine the response to various running positions from the resistance jets, the results can be implemented by practitioners depending on the goal of the training session. Running 0.61 metres from the resistance jet elicits the highest cardiorespiratory response and it is recommended that for high intensity training the individual runs within 0.76 metres of the resistance jet. For submaximal running, it is recommended that individuals run between three and 1.22 metres from the resistance jet. Although this position elicits a lower response, it provides the individual with 0.30 metres of variance that is not statistically different. Additionally, even for maximal exercise, the 0.91 metre to 1.22 metre running position has shown to elicit a similar response to LTM exercise. Further, it is recommended that for graded exercise testing, a string be placed at 0.91 metres and 1.52 metres from the resistance jet. That way the back line at 1.52 metres can act as a termination criteria in order to determine the inability of the individual to maintain the running position at a high intensity, similar to the cut-off criteria implemented during graded exercise testing on a cycle ergometer to maintain a predetermined cadence. When comparing future results following this protocol, confidence can be taken that the participant did not increase or decrease the metabolic response by running closer or further away from the resistance jets compared to other participants.

Previous literature has suggested that the lactate threshold occurs at differing points during ATM and LTM exercise (Garner et al., 2014). Our study was the first to report on ventilatory thresholds during ATM running and found that the first and second ventilatory thresholds occurs at the same ŸO₂ and heart rate compared to LTM running. Therefore, when prescribing exercise training sessions based on either ATM and LTM graded exercise tests,
practitioners can monitor training using heart rate and be confident that the response will be similar to land. Based on the various challenges with blood draws for lactate threshold testing in water, as well as the similarities with the ventilatory response between ATM and LTM running, it is recommended that practitioners prescribe training and monitor adaptations by determining ventilatory thresholds rather than lactate thresholds.

Previous literature that examines the cardiovascular responses to ATM and LTM running used a relatively large range of water temperatures (mean range 25.8°C – 35°C) and rationales for whether these temperatures would influence the response are often based on water immersed cycling or deep water running values. This investigation is the first to examine the influence of relatively small changes in water temperature during chest deep ATM running. Our findings suggest that small variations in water temperature of approximately 4°C can influence cardiovascular and hemodynamic responses during ATM running. Specifically, cardiac output and the rise in core temperature are lower in the cool water temperature compared to the warm water temperature. Additionally, cardiac output and heart rate are lower during cool water running compared to LTM running. Based on our findings, it is important that water temperature be maintained between 32°C and 34°C for submaximal ATM running. It is likely that the session to session variation in cardiovascular response, as well as the comparison to land, would be least influenced by water temperature within this range. Additionally, water temperature may be a significant factor in the inconsistencies in results from previous literature that falls outside of this range of water temperature.

No other study has observed the relationship between anthropometric measures and the cardiovascular response, thermoregulatory response, or the running distance from the resistance jet for ATM running. Our findings demonstrate that the relationship between cardiorespiratory
responses and anthropometrics differs depending on whether the individual is running on an ATM or LTM. Specifically, $\dot{V}O_2$ and core temperature may respond differently during maximal running on an ATM and LTM depending on an individual’s anthropometric measures. It is important for future research to include these measures in order to ensure these differences are accounted for.

The findings in this dissertation are beneficial to ATM manufactures as well. The cardiovascular alterations that occur based on different running positions from the resistance jet (Chapter 8.1) can help manufacturers select where to place the underwater cameras. Specifically, it would optimal to place one underwater camera viewing the sagittal plane at 0.61 metres from the resistance jets for high intensity running and a second camera between 0.91 metres and 1.22 metres for moderate intensity running and graded exercise testing. Considering the influence of the resistance jets, it would be valuable if the jets provided an accurate rate of water flow as opposed to a percentage of the resistance jets capacity.

Another important finding is the accuracy of the water heaters that are part of the aquatic treadmills. Given small variances in water temperature can significantly alter cardiovascular responses during ATM running (Chapter 9), it is important that manufacturers ensure the pool heaters they are providing are able to maintain a water temperature with a variance of +/- 1°C.

Providing an estimated of impact force against the treadmill would also be valuable to practitioners. This information would help guide the injury management and return-to-play process for aquatic plyometric training and ATM running. Further, understanding the impact forces during ATM running would provide insight into the influence of anthropometrics on cardiovascular and biomechanical responses.
In summary, when comparing and contrasting previous literature for the purpose of future research or practical use, it appears that many of these cardiovascular alterations can be explained by differences in protocols and methodologies used rather than the differing environment of air versus water. This dissertation has identified new standards and criteria specific to ATM running that can be implemented in future research as a framework for standardizing protocols and methodologies. Further, it has provided additional support for the previous literature examining the cardiovascular response to ATM running. Ultimately, the studies in this dissertation can be used to increase the understanding of the physiological responses to ATM compared to LTM running, as well as increase confidence in the results being due specifically to the aquatic versus terrestrial environments.

11.2 Future Studies

Future studies are recommended below. In addition, this information has been summarized in Table 11.1. The recommended areas of study were suggested based on the findings of our investigations.

Maximal ATM Running

Current literature examining the maximal cardiorespiratory responses during ATM running is limited and future research which includes the recommendations in this dissertation is warranted. Future research should aim to understand how different verification phase protocols (i.e. recovery time length) can be implemented in order to determine the best protocol to use for ATM running. This could alleviate the inconsistencies in maximal heart rate achieved during ATM running and offer a second verification measure for the attainment of \( \dot{V}O_{2\text{max}} \). Further, more research is necessary to understand the response of maximal heart rate during ATM running and the mechanism that causes a lower maximal heart rate. In addition, future research
should aim to understand the hemodynamic response to maximal ATM running as the only research in this area has been completed during water immersed cycling. Future research into the use of submaximal thresholds to guide training prescription should use ventilatory thresholds instead of lactate thresholds. Specifically, future research should investigate the training adaptation to running at or above the anaerobic threshold during ATM compared to LTM training.

**Submaximal ATM Running**

The current literature is scarce for similar protocols and standardized research to understand that cardiorespiratory alterations that are related to exercise on an ATM or a LTM. The purpose of our investigation was to create standardized recommendations and guidelines to follow for future research and practice. Future research should include measurements of respiratory rate and tidal volume to provide a clearer explanation into possible mechanisms of change on the respiratory system. In addition, future investigations should aim to determine how various methodological constraints (i.e. water depth, jet resistance, water temperature, distance from the jet) could influence the cardiorespiratory response. By standardizing the protocols, future studies can accurately determine if the cardiorespiratory alterations are environment specific. Similar to maximal ATM running, future research should aim to mimic our study and examine the hemodynamic response as we were the first to investigate this. Further, investigating the influence of the inclusion of a rest period upon immersion versus immediate exercise on the hemodynamic response will help to better understand variations in the results and guide future research and practice.

**Water Temperature during ATM Running**
Future research should aim to confirm the appropriate temperature range for thermoneutral maximal and submaximal ATM running. Prior literature implements water temperatures that were derived from other forms of water-based exercise, such as water-immersed cycling. Our findings suggest that these ranges could be near those required for equivalent core temperature changes and hemodynamic responses during ATM running. However, these ranges are likely different based on the amount of surface area immersed or exposed to air, as well as the mode of exercise. Our results shed light onto updated recommended ranges that may be appropriate, however, more evidence is necessary in order to verify these ranges. Future research could also aim to investigate larger water temperature ranges in order to understand the influence on maximal and submaximal cardiorespiratory responses. It is possible that the use of various water temperatures could influence the training response and adaptation.

**Anthropometrics and ATM Running**

It is important for future research to report significant anthropometric measures when comparing ATM and LTM cardiovascular responses. Our findings demonstrate that the relationship between cardiorespiratory responses and anthropometrics differs depending on whether the individual is running on an ATM or LTM. Specifically, $\dot{V}O_2$ and core temperature may respond differently during maximal running on an ATM and LTM depending on an individual’s anthropometric measures. It is possible that some variation in the cardiorespiratory responses of previous research could be due to the influence of anthropometrics during ATM compared to LTM maximal exercise. Future research should include more diverse and heterogeneous participants with wider ranges of anthropometric measures compared to our investigation to examine relationships between anthropometrics and water temperature during ATM running. Evaporation is suppressed during water immersion and thus may limit heat
exchange at higher exercise intensities, especially in warmer water temperatures (Pendergast & Lundgren, 2009). Therefore, the relationship is intensity dependent and future research should aim to understand the relationship between ATM running intensity and water temperature to understand this interaction. By conducting further research, practitioners could aim to set water temperatures based on their participants individual anthropometric measures and planned intensity to help ensure the alterations in the cardiovascular response are comparative to LTM values. Eventually, given a large enough study, the body composition of each individual could be interpreted individually into the cardiorespiratory responses to further understand the alterations that occur solely based on the differing environments and to standardize future research methods.

Therefore, future research must ensure that these measures are collected, reported, and interpreted to help explain cardiorespiratory alterations to further understand how each particular environment itself alters the cardiorespiratory response. By reporting these values, future systematic reviews can be undertaken to aid in the understanding and interpretation of results.

In summary, the findings of this dissertation provide further evidence of the cardiovascular alterations that occur during ATM and LTM running, and aim to guide future research to increase confidence in the results occurring due to the water environment compared to the land-based environment. This dissertation has identified new standards and criteria specific to ATM running that can be implemented as a framework for standardizing future ATM running protocols and methodologies in research and practice. While following these recommendations, future research should build on the limited, yet progressive research (Greene et al., 2009; Bressel et al., 2014; Lambert et al., 2014; Lambert et al., 2015; Bressel et al., 2016; Conners, Morgan, Fuller & Caputo, 2014) that examines the health, fitness, and rehabilitation
improvements with consistent ATM exercise as opposed to only the alterations that occur during single bouts of ATM exercise.

Table 11.1 Recommended areas of future study

<table>
<thead>
<tr>
<th>Topic</th>
<th>Recommendations for Future Studies</th>
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<tbody>
<tr>
<td>Maximal ATM Running</td>
<td>- Understand how different verification phase protocols (i.e. recovery time length) can be implemented in order to determine the best protocol to use for ATM running.</td>
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<td></td>
<td>- Understand the response of maximal heart rate during ATM running and the mechanism that causes a lower maximal heart rate.</td>
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<td></td>
<td>- Understand the hemodynamic response to maximal ATM running.</td>
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<tr>
<td>Submaximal ATM Running</td>
<td>- Investigate the training adaptation to running at or above the anaerobic threshold during ATM compared to LTM training.</td>
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<tr>
<td></td>
<td>- Include respiratory rate and tidal volume to provide a clearer explanation into possible mechanisms of change on the respiratory system.</td>
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<tr>
<td></td>
<td>- Further develop how various methodological constraints (i.e. water depth, jet resistance, water temperature, distance from the jet) could influence the cardiorespiratory response.</td>
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<tr>
<td></td>
<td>- Aim to mimic our study and examine the hemodynamic response as we were the first and only study to investigate this.</td>
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<tr>
<td></td>
<td>- The influence of whether or not a rest period is included during initial immersion in the water on the hemodynamic response.</td>
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<tr>
<td>Influence of Water Temperature on</td>
<td>- Confirm the comparable temperature range for thermoneutral maximal and submaximal ATM running compared to LTM running.</td>
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<tr>
<td>ATM Running</td>
<td>- Investigate larger water temperature ranges in order to understand the influence on maximal and submaximal cardiorespiratory responses.</td>
</tr>
<tr>
<td>Anthropometric Considerations</td>
<td>- Include a variety of individuals with larger ranges of anthropometric measures compared to our investigation to examine relationships between anthropometrics and water temperature or ambient air during ATM running.</td>
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<td>during ATM Running</td>
<td>- Through larger studies be able to set water temperatures based on participants individual anthropometric measures and planned intensity to help ensure the alterations in the cardiovascular response are comparative to LTM values.</td>
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References


Appendices

PAR-Q+

2014 PAR-Q+
The Physical Activity Readiness Questionnaire for Everyone

The health benefits of regular physical activity are clear; more people should engage in physical activity every day of the week. Participating in physical activity is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

GENERAL HEALTH QUESTIONS

Please read the 7 questions below carefully and answer each one honestly: check YES or NO.

<table>
<thead>
<tr>
<th>Question</th>
<th>YES</th>
<th>NO</th>
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<tbody>
<tr>
<td>1) Has your doctor ever said that you have a heart condition OR high blood pressure?</td>
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<tr>
<td>2) Do you feel pain in your chest at rest, during your daily activities of living, OR when you do physical activity?</td>
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<tr>
<td>3) Do you lose balance because of dizziness OR have you lost consciousness in the last 12 months? Please answer NO if your dizziness was associated with over-breathing (including during vigorous exercise).</td>
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<tr>
<td>4) Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? Please list condition(s) here:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) Are you currently taking prescribed medications for a chronic medical condition? Please list condition(s) and medications here:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6) Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer NO if you had a problem in the past, but it does not limit your current ability to be physically active. Please list condition(s) here:</td>
<td></td>
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<tr>
<td>7) Has your doctor ever said that you should only do medically supervised physical activity?</td>
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</table>

If you answered NO to all of the questions above, you are cleared for physical activity. Go to Page 4 to sign the PARTICIPANT DECLARATION. You do not need to complete Pages 2 and 3.

- Start becoming much more physically active - start slowly and build up gradually.
- Follow International Physical Activity Guidelines for your age (www.who.int/dietphysicalactivity/en/).
- You may take part in a health and fitness appraisal.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.
- If you have any further questions, contact a qualified exercise professional.

If you answered YES to one or more of the questions above, COMPLETE PAGES 2 AND 3.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at www.eparmedx.com before becoming more physically active.
- Your health changes - answer the questions on Pages 2 and 3 of this document and/or talk to your doctor or a qualified exercise professional before continuing with any physical activity program.
2014 PAR-Q+
FOLLOW-UP QUESTIONS ABOUT YOUR MEDICAL CONDITION(S)

1. Do you have Arthritis, Osteoporosis, or Back Problems?
If the above condition(s) is/are present, answer questions 1a-1c
If NO go to question 2

1a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? YES NO

1b. Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebra (e.g., spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)? YES NO

1c. Have you had steroid injections or taken steroid tablets regularly for more than 3 months? YES NO

2. Do you have Cancer of any kind?
If the above condition(s) is/are present, answer questions 2a-2b
If NO go to question 3

2a. Are you currently receiving cancer therapy (such as chemotherapy or radiotherapy)? YES NO

2b. Are you currently receiving cancer therapy (such as chemotherapy or radiotherapy)? YES NO

3. Do you have a Heart or Cardiovascular Condition? This includes Coronary Artery Disease, Heart Failure, Diagnosed Abnormality of Heart Rhythm
If the above condition(s) is/are present, answer questions 3a-3d
If NO go to question 4

3a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments) YES NO

3b. Do you have an irregular heart beat that requires medical management? (e.g., atrial fibrillation, premature ventricular contraction) YES NO

3c. Do you have chronic heart failure? YES NO

3d. Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months? YES NO

4. Do you have High Blood Pressure?
If the above condition(s) is/are present, answer questions 4a-4b
If NO go to question 5

4a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments) YES NO

4b. Do you have a resting blood pressure equal to or greater than 160/90 mmHg with or without medication? (Answer YES if you do not know your resting blood pressure) YES NO

5. Do you have any Metabolic Conditions? This includes Type 1 Diabetes, Type 2 Diabetes, Pre-Diabetes
If the above condition(s) is/are present, answer questions 5a-5e
If NO go to question 6

5a. Do you often have difficulty controlling your blood sugar levels with foods, medications, or other physician-prescribed therapies? YES NO

5b. Do you often suffer from signs and symptoms of low blood sugar (hypoglycemia) following exercise and/or during activities of daily living? Signs of hypoglycemia may include shakiness, nervousness, unusual irritability, abnormal sweating, dizziness or light-headedness, mental confusion, difficulty speaking, weakness, or sleepiness. YES NO

5c. Do you have any symptoms or complications of diabetes, such as heart or vascular disease and/or complications affecting your eyes, kidneys, OR the sensation in your toes and feet? YES NO

5d. Do you have other metabolic conditions (such as current pregnancy-related diabetes, chronic kidney disease, or liver problems)? YES NO

5e. Are you planning to engage in what for you is unusually high (or vigorous) intensity exercise in the near future? YES NO
2014 PAR-Q+

6. Do you have any Mental Health Problems or Learning Difficulties? This includes Alzheimer’s, Dementia, Depression, Anxiety Disorder, Eating Disorder, Psychotic Disorder, Intellectual Disability, Down Syndrome
   If the above condition(s) is/are present, answer questions 6a-6b
   If NO go to question 7

6a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies?
   (Answer NO if you are not currently taking medications or other treatments)

6b. Do you ALSO have back problems affecting nerves or muscles?

7. Do you have a Respiratory Disease? This includes Chronic Obstructive Pulmonary Disease, Asthma, Pulmonary High Blood Pressure
   If the above condition(s) is/are present, answer questions 7a-7d
   If NO go to question 8

7a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies?
   (Answer NO if you are not currently taking medications or other treatments)

7b. Has your doctor ever said your blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?

7c. If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?

7d. Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?

8. Do you have a Spinal Cord Injury? This includes Tetraplegia and Paraplegia
   If the above condition(s) is/are present, answer questions 8a-8c
   If NO go to question 9

8a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies?
   (Answer NO if you are not currently taking medications or other treatments)

8b. Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?

8c. Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as Autonomic Dysreflexia)?

9. Have you had a Stroke? This includes Transient Ischemic Attack (TIA) or Cerebrovascular Event
   If the above condition(s) is/are present, answer questions 9a-9c
   If NO go to question 10

9a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies?
   (Answer NO if you are not currently taking medications or other treatments)

9b. Do you have any impairment in walking or mobility?

9c. Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?

10. Do you have any other medical condition not listed above or do you have two or more medical conditions?
    If you have other medical conditions, answer questions 10a-10c
    If NO read the Page 4 recommendations

10a. Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months OR have you had a diagnosed concussion within the last 12 months?

10b. Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, kidney problems)?

10c. Do you currently live with two or more medical conditions?

PLEASE LIST YOUR MEDICAL CONDITION(S) AND ANY RELATED MEDICATIONS HERE:

GO to Page 4 for recommendations about your current medical condition(s) and sign the PARTICIPANT DECLARATION.
2014 PAR-Q+

If you answered NO to all of the follow-up questions about your medical condition, you are ready to become more physically active - sign the PARTICIPANT DECLARATION below:
- It is advised that you consult a qualified exercise professional to help you develop a safe and effective physical activity plan to meet your health needs.
- You are encouraged to start slowly and build up gradually - 20 to 60 minutes of low to moderate intensity exercise, 3-5 days per week including aerobic and muscle strengthening exercises.
- As you progress, you should aim to accumulate 150 minutes or more of moderate intensity physical activity per week.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.

If you answered YES to one or more of the follow-up questions about your medical condition:
You should seek further information before becoming more physically active or engaging in a fitness appraisal. You should complete the specially designed online screening and exercise recommendations program - the ePARmed-X+ at www.eparmedx.com and/or visit a qualified exercise professional to work through the ePARmed-X+ and for further information.

Delay becoming more active if:
- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at www.eparmedx.com before becoming more physically active.
- Your health changes - talk to your doctor or qualified exercise professional before continuing with any physical activity program.

- You are encouraged to photocopy the PAR-Q+. You must use the entire questionnaire and NO changes are permitted.
- The authors, the PAR-Q+ Collaboration, partner organizations, and their agents assume no liability for persons who undertake physical activity and/or make use of the PAR-Q+ or ePARmed-X+. If in doubt after completing the questionnaire, consult your doctor prior to physical activity.

PARTICIPANT DECLARATION

All persons who have completed the PAR-Q+ please read and sign the declaration below.

If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that a Trustee (such as my employer, community/fitness centre, health care provider, or other designate) may retain a copy of this form for their records. In these instances, the Trustee will be required to adhere to local, national, and international guidelines regarding the storage of personal health information ensuring that the Trustee maintains the privacy of the information and does not misuse or wrongfully disclose such information.

NAME __________________________ DATE ___________

SIGNATURE __________________________ WITNESS __________________________

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER __________________________

For more information, please contact
www.eparmedx.com
Email: eparmedx@gmail.com

The PAR-Q+ was created using the evidence-based AGREE process (1) by the PAR-Q+ Collaboration chaired by Dr. Darren E. R. Warburton with Dr. Norman Gluehill, Dr. Veronica Jamnik, and Dr. Donald C. McKenzie (2). Production of this document has been made possible through financial contributions from the Public Health Agency of Canada and the BC Ministry of Health Services. The views expressed herein do not necessarily represent the views of the Public Health Agency of Canada or the BC Ministry of Health Services.

Citation for PAR-Q+
Key References:

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08-01-2014
Intervention Timeline

ATM GXT = Aquatic treadmill graded exercise test
LTM GXT = Land treadmill graded exercise test
DFJ = Distance from jet running position investigation
Warm = Run in temperature at 34 °C
Cool = Run in temperature at 30 °C

= Skinfold Assessment
= Core Temperature Pill
# LTM Graded Exercise Test Recording Sheet

## Treadmill Step Test

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<th>Time (min)</th>
<th>Grade (%)</th>
<th>Speed (mph)</th>
<th>HR (bpm)</th>
<th>RER</th>
<th>RPE (6-20)</th>
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<th>Total Time:</th>
<th>Time (min)</th>
<th>HR (bpm)</th>
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**Active Recovery:**

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<th>Speed (mph):</th>
<th>Grade (%):</th>
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# ATM Graded Exercise Test Recording Sheet

## ATM Treadmill Step Test

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<th>Time (min)</th>
<th>Resistance (%)</th>
<th>Speed (mph)</th>
<th>HR (bpm)</th>
<th>RER</th>
<th>RPE (6-20)</th>
<th>Warm-up</th>
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**Total Time:**

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**Active Recovery:**

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<th>Resistance (%)</th>
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## Distance from the Jet Recording Sheet

### ATM TREADMILL DFJ

**Name:**

**Age:**

**Height (cm):**

**DOB:**

**Weight (kg):**

**Tech:**

**Room Temp:**

**Water Temp:**

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### Warm-Up

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<th>Resistance (%)</th>
<th>HR (bpm)</th>
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