AQUATIC THERAPY IN REHABILITATION:

A KINEMATIC APPROACH TO UNDERSTANDING THE EFFICACY OF WATER-BASED EXERCISE

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By:

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**ABSTRACT**

The use of water-based rehabilitation is widespread in both clinical and general health settings, as the properties of water offer several benefits for the human body. However, there is a relative paucity of research regarding the kinematic effects of water immersion, which has resulted in limited guidelines for practitioners wishing to employ water-based exercises in their practice. The primary aim of this thesis was to examine the kinematic effects of water-based squat variations on young, aged, and injured adults to further their application in rehabilitation. This will provide practitioners with novel insights into how water immersion may affect common exercises across different populations. This traditional thesis with publications is composed by five research projects, and one narrative literature review. Chapter 3 presents a validity analysis of the equipment used during the research project and introduces the methodology used throughout the subsequent studies. Three of the following studies (Chapters 4, 6, and 7) assess the kinematic effects of water immersion across three different populations during squat-like exercises. The additional study (Chapter 5) assesses kinematic effects of altered water depth during squats performed in water. These four research projects have been prepared for the purpose of publication in peer-reviewed journals. At the time of submission, two of the manuscripts have been accepted for publication (the literature review and the manuscript in Chapter 4), while the remaining three manuscripts are submitted and under review.

**Chapter 2**

The application of aquatic therapy for health and rehabilitation purposes has been promoted for centuries. Although used predominantly in clinical settings for the treatment, rehabilitation, and management of chronic conditions, the practice has gained popularity
in athletic settings for recovery and the rehabilitation of acute musculoskeletal injuries. To date, most studies on the effects of aquatic-based rehabilitation on the human body have focused on physiological aspects. There is a relative paucity of published research on the biomechanical effects associated with aquatic-based activity, and the existing literature has focused on its effects on running and walking gait. An obvious challenge in this field has been the absence of consistent methodological protocols for assessment of the kinematic effects of aquatic therapy and therefore its role in rehabilitation remain relatively unexplored. For example, previous research has used considerably different methodologies and no standardised protocols have been developed for important variables such as water depth and temperature. Current understanding of the roles of aquatic therapy for rehabilitation is therefore lacking, with medical guidelines highlighting that high-quality research is warranted. This review summarised the current literature on water-based activity, and discussed how it can influence human movement and rehabilitation.

Chapter 3

This chapter provides the reader with in-depth information regarding the methods and methodology employed for this project and describes the data collection and processing protocols used throughout the research. Due to the significant methodological aspect of this thesis, it was necessary to present a detailed description of the equipment and protocols used to collect process and analyse the data. The chapter presents a validation analysis performed to ensure the relative accuracy of the inertial sensors used to collect kinematic data throughout the project.
Chapters 4 - 7 presents publications, and/or submitted manuscripts that compare the kinematic differences of squat exercises performed on land and in water across different populations:

**Chapter 4**

Aquatic exercises can be used in clinical and sporting disciplines for both rehabilitation and sports training. However, there is limited knowledge on the influence of water immersion on the kinematics of exercises commonly used in rehabilitation and fitness programs. This study used inertial sensors to quantify kinematic differences during the ascending and descending phases of bodyweight squats, split squats, and single-leg squats performed on dry land and while immersed to the level of the greater trochanter. During two separate testing sessions, 25 active healthy university students (22.3±2.9 yr.) performed ten repetitions of each exercise, while tri-axial inertial sensors (100 Hz) recorded their trunk and lower body kinematics. Repeated-measures statistics tested for differences in segment orientation and speed, movement variability, and waveform patterns between environments, while coefficient of variance was used to assess differences in movement variability. Between-environment differences in segment orientation and speed were portrayed by plotting the mean difference ±95% confidence intervals (CI) throughout the tasks. The results showed that the depth of the squat and split squat was unaffected by the changed environment while water immersion allowed for a deeper single leg squat. The different environments had significant effects on the sagittal plane orientations and speeds for all segments. Water immersion increased the degree of movement variability of the segments in all exercises, except for the shank in the frontal plane, which showed more variability on land. Without compromising movement depth, the aquatic environment induces more upright trunk and shank postures.
during squats and split squats, which suggests lower loads on the spine and knees compared to land-based movements. The reduced restrictions of strength and balance provided by water allows for increased squat depth during the single-leg squat. Our observations therefore highlight the suitability of aquatic exercises for rehabilitation as it benefits balance and technique without compromising movement depth.

Chapter 5

Small changes in water depth have been shown to alter physiological and neuromuscular responses during water-based exercise, but limited research has assessed kinematic effects of water depth. This study aimed to quantify the kinematic effects of altered water depth during bodyweight squats in a young and healthy population. Six inertial sensors (100 Hz) recorded 15 university students (22.0±2.3 yrs., 1.70±0.09 m, 70.1±13.0 kg) performing ten bodyweight squats in hip-deep and waist-deep water. Repeated-measures statistics determined differences in peak angles, range of motion and peak velocities of the shank, thigh, and trunk between the two depths. Between-depth differences in trunk orientation and speed were portrayed by plotting the mean difference ±95% confidence intervals throughout the squat. Vertical displacement of the sacrum measured squat depth. Primary findings showed increased trunk inclination at the top of the movement and slower sagittal plane movement speeds during squats performed in deeper immersion. Different water depth did not significantly affect the squat depth, or the lower body kinematics. Trivial effects on lower body kinematics are positive findings for practitioners working with individuals of different height. The altered trunk posture during the deeper immersion was most likely a consequence of its partial immersion and exposure to the fluid dynamics. Conversely, immersion to the hip meant the trunk rose above the water, and was no longer exposed to the dynamics of the water. This study
highlighted that practitioners should consider the water depth when employing water-based exercise as it affects kinematics.

Chapter 6

Purpose: The importance of exercise for the health and well-being of older adults is well established; however, the influence of exercising in water is less clear. This study examined the effect of water immersion on exercise technique for the commonly used squat exercise. Methods: Twenty-four active older adults (71.4±5.4 yrs.) performed squats and split squats on land and in water, while inertial sensors (100 Hz) recorded trunk and lower-body kinematics. Range of motion, peak velocities, and joint angles together with the waveforms of the mean differences in joint angles were compared between dry land and aquatic environments. Repeated-measures statistics were used to determine differences in the kinematic variables, and Cohen’s $d$ portrayed effect sizes. Results: Water immersion increased the squat depth during both exercises (squat: +5.66 cm, $P=0.028$, $d=0.63$, split squat: +13.36 cm, $P=0.005$, $d=0.83$). It also increased the range of motion and peak velocities of the hip and knee joints, while the trunk showed reduced range and velocity. The waveforms also revealed differences in trunk, hip, and knee motions, particularly during the deeper parts of the movements, and angle-angle plots showed increased reliance on the hip motions in the water. Conclusion: Performing squats and split squats in water allowed older adults to achieve movement depths that were 28.0% and 86.5% respectively, beyond what was possible on land. Additionally, immersion in water also encouraged hip dominant movement strategies and upright trunks. These results showed that aquatic-based exercise generate a different exercise outcome and therefore provide an alternative option for older adults as it allows them to perform tasks in a manner that is not possible on land.
Chapter 7

Objectives: The purpose of this study was to assess bilateral kinematics during squats and single-leg squats on land and in water in individuals with unilateral anterior knee pain. A secondary aim was to quantify bilateral asymmetry in both environments in affected and unaffected individuals. Study design: Observational study with a cross-sectional design. Methods: Twenty individuals with unilateral knee pain and twenty healthy, matched controls performed body weight squats and single-leg squats in both environments while inertial sensors (100 Hz) recorded trunk and lower body kinematics. Effects on movement depths and peak angles were assessed for the anterior knee pain group and their inter-limb symmetry were compared with the control group. All variables were assessed using repeated-measures statistics. Results: Water immersion allowed for greater movement depths during both exercises (squat: +7 cm, p=0.032, single leg squat: +9 cm, p=0.002) for the knee pain group. The squat exercise was symmetrical on land, but water immersion revealed several asymmetries in the lower body movements. The single leg squat revealed decreased hip flexion and frontal plane shank motions on the affected limb in both environments. Water immersion generally increased the degree of lower limb asymmetry in both groups. Conclusion: Water immersion allowed increased movement depth for individuals with anterior knee pain, but increased bilateral asymmetries. Individuals with unilateral anterior knee pain appear to utilise different kinematics in the affected and unaffected limb in both environments.

Chapter 8

This chapter presents a general discussion and conclusions of the entire thesis content. It summarises the overreaching findings and discusses their effects for the different populations. It highlights practical implications of the research and provides directives
for future research. This chapter draws upon the findings and hypotheses from all previous chapters to offer suggestions and considerations for practitioners in hopes to ensure better application of aquatic therapy. It also discusses limitations with the research presented throughout the thesis and highlights exciting directions for future research.
DElarATION OF ORIGINALLITY

All research presented in this thesis is the original work of the candidate and research team, except where otherwise referenced in the text. This research has not been submitted elsewhere or written by any person other than the candidate with the assistance of the supervising team. The following statements disclose the relative contributions for the authors to publications associated with this thesis:

**Literature review (Chapter 2, Publication 1, Appendix 10.1)**


Severin was responsible for researching the current literature (100%) and the writing of the literature review (80%). Burkett and Sayers each contributed to the writing (5%) and McKeans contributed to the writing and editing of the manuscript (10%).

**Exegesis (Chapter 3)**

Severin was responsible for study design (80%), collecting the data (100%), analysing the data (90%), and writing the manuscript (80%). Sayers contributed to the study design (5%), analysing the data (10%), and writing the manuscript (10%). Burkett contributed to the study design (10%), and the writing on the manuscript (5%). McKeans contributed to the study design (5%), and the writing of the manuscript (5%). Wiegand designed the computer code that processed the data.
Study 1 (Chapter 4, Publication 2, Appendix 10.2)


Severin was responsible for study design (90%), collecting the data (100%), processing, and analysing the data (90%), and writing the manuscript (80%). Sayers contributed to analysing the data (10%) and writing the manuscript (10%). Burkett and McKeen each contributed to the writing of the manuscript (5%). The supervising team combined contributed to study design (10%). Wiegand designed the computer code that processed the data.

Study 2 (Chapter 5, Submission 3)

Severin was responsible for study design (90%), collecting the data (100%), processing, and analysing the data (90%), and writing the manuscript (80%). Sayers contributed to analysing the data (10%) and writing the manuscript (10%). Burkett contributed to writing the manuscript (5%) and McKeen each contributed to the writing of the manuscript (10%). The supervising team combined contributed to study design (10%). Wiegand designed the computer code that processed the data.

Study 3 (Chapter 6, Submission 4)

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contributed to study design (10%). Wiegand designed the computer code that processed the data.

**Study 4 (Chapter 7, Submission 5)**

Severin was responsible for study design (90%), collecting the data (100%), processing, and analysing the data (90%), and writing the manuscript (80%). Sayers contributed to analysing the data (10%) and writing the manuscript (5%). Burkett contributed to writing the manuscript (5%) and McKean each contributed to the writing of the manuscript (10%). The supervising team combined contributed to study design (10%). The supervising team combined contributed to study design (10%). Wiegand designed the computer code that processed the data.
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<td>mmHg</td>
<td>Millimetres of mercury</td>
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<tr>
<td>MVC</td>
<td>Maximal voluntary contraction</td>
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<td>NRMSE</td>
<td>Normalised root-mean square error</td>
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<td>P / p / P / p / P</td>
<td>Alpha level</td>
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<td>r / r</td>
<td>Pearson's correlation coefficient</td>
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<tr>
<td>ROM</td>
<td>Range of motion</td>
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<td>RPE</td>
<td>Rate of perceived exertion</td>
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<td>Seconds</td>
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<td>T3</td>
<td>Third thoracic vertebra</td>
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<td>TEE</td>
<td>Typical error of the estimate</td>
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<td>VO₂</td>
<td>Oxygen uptake</td>
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<td>Yrs.</td>
<td>Years old</td>
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LIST OF ORIGINAL PUBLICATIONS


LIST OF SUBMITTED MANUSCRIPTS


Learn from yesterday, live for today, hope for tomorrow.

The important thing is not to stop questioning.

- Albert Einstein
CHAPTER 1:

INTRODUCTION
INTRODUCTION

An increasing number of clinical and exercise practitioners employ aquatic therapy in their practice as water immersion is known to have several physiological, biomechanical and social benefits (Becker, 2009, Denning et al., 2012, Torres-Ronda and Del Alcazar, 2014, Heywood et al., 2017). Water-based rehabilitation provides an effective, safe, and fun alternative to land-based programmes and is suitable for a wide range of different populations, including older adults (Avelar et al., 2010, Katsura et al., 2010, Tsourlou et al., 2006), athletes (Asimenia et al., 2013, Thein and Brody, 1998, Wicker, 2011), and individuals with chronic medical conditions (Bartels et al., 2007, Bidonde et al., 2014, Hall et al., 2004). This increased popularity necessitates a comprehensive understanding of the efficacy and application of water-based exercise amongst practitioners, as modifications to the parameters of the environment can alter the body’s response to immersion and exercise (Becker, 2009, Denning et al., 2012, Mooventhann and Nivethitha, 2014, Torres-Ronda and Del Alcazar, 2014). The existing literature on the effects of aquatic therapy is extensive. The literature review that was conducted as a component of this project (Chapter 2) highlights several gaps in current understandings that have left practitioners with limited guidelines concerning its optimal application.

This opening chapter introduces the reader to the thesis by stating the problem, defining the aims, and highlighting the significance of the research undertaken for this project. Chapter 2 presents a comprehensive narrative review of the literature on the roles of aquatic therapy in rehabilitation from a biomechanical viewpoint. This chapter presents the known effects of water-based exercise and highlights the gaps in the existing literature. The review establishes the rationale for the research that is presented as individual chapters within the thesis.
It is an overreaching purpose of this project to highlight practical implications for practitioners and provide them with a further understanding of how water-based exercises differ from those performed on land. The findings from this project will assist clinical and exercise professionals to ensure more accurate application of the aquatic environment and provide the best possible care for their clients.

1.1. Statement of the problem

Although aquatic therapy has been used for centuries, surprisingly little research has examined how the aquatic-environment affects human movement (Heywood et al., 2016). Previous research has established the physiological effects of aquatic-based exercise (Wilcock et al., 2006, Alberton et al., 2011, Alberton et al., 2009, Sramek et al., 2000, Nakanishi et al., 1999, Hall et al., 1998), but the biomechanical aspects have received considerably less attention.

Review articles have shown a consensus within the literature that water immersion affects several biomechanical variables of gait, including joint displacements, velocities, muscle activation and coordination (Kaneda et al., 2012b, Masumoto et al., 2009, Heywood et al., 2016, Heywood et al., 2017). These reviews discuss how the physical properties of the aquatic environment alter the demands of movements and therefore require different kinematics compared to land-based equivalents. Their conclusions provide practitioners with practical implications and guidelines how to utilise water-based walking for specific rehabilitation and exercise purposes.

However, the kinematic effects of water immersion on other common exercises, such as squats and split squats, remain unreported and poorly understood. Despite the extensive understanding of the land-based kinematics of these exercises (McKean et al., 2010b,
Schutz et al., 2014, Claiborne et al., 2006, Sato et al., 2013b, Han et al., 2013, Flanagan et al., 2004, Mei et al., 2017, Stastny et al., 2015, McKean et al., 2010a), no research has assessed them during water immersion. It is likely that the altered constraints of the aquatic environment alter the kinematics of squat tasks performed in water. It is important to understand these potential changes as programming for rehabilitation requires comprehensive understanding of the exercise demands and specific adaptations in order to ensure its efficacy (Ekstrom et al., 2007). Without the understanding of the effects of water immersion on squat tasks, practitioners are unable to guarantee the efficacy of the exercise and thereby ensure an optimal outcome of the rehabilitation programme.

1.2. Aims of the research

It was the primary overreaching aim of this thesis to provide novel insights into kinematic differences between squat variations performed in water and on land. The primary aim was to quantify the water-based kinematics of these common exercises across populations that are often prescribed with aquatic therapy. This was achieved through several topically linked studies, each presented in individual chapters that examined specific aims:

**Chapter 2: Biomechanical Aspects of Aquatic Therapy: A Literature Review on Application and Methodological Challenges.**

1. Provide the reader with a narrative review of the current literature on the applications and effects of aquatic therapy.

2. Highlight gaps in current understandings of the biomechanical aspects of aquatic therapy.
3. Outline challenges in current methodological practices for conducting biomechanical research in the aquatic environment and identify alternative methods.

4. Provide suggestions for future research into the applications of aquatic therapy from a biomechanical aspect.

Chapter 3: The implementation and validation of Nanotrak inertial sensors for kinematic analyses.

5. Establish processing protocols for the data recorded by the Nanotrak sensors.

6. Determine the relative accuracy of the Nanotrak sensors compared to a well-established optoelectronic system.

Chapter 4: Quantifying kinematic differences between land and water during squats, split squats, and single-leg squats in a healthy population.

7. Quantify differences in segmental orientation and speed between land- and water-based squats, split squats, and single-leg squats during the ascending and descending phases.

8. Examine whether the aquatic environment elicits more movement variability compared to land during the exercises.

Chapter 5: The impacts of different water depths on the kinematics of aquatic-based squats in a healthy population.

9. Examine differences in trunk and lower body kinematics of bodyweight squats performed in water during immersion to the hip and the waist.
Chapter 6: Effects of water immersion on squat and split squat kinematics in older adults.

10. Assess effects of water immersion on range of motion and peak velocities during squats and split squats.

11. Quantify environmental differences in joint angles during the ascent and descent.

Chapter 7: Limb symmetry during squats and single leg squats on land and in water in adults with long-standing unilateral anterior knee pain.

12. Assess the kinematic effects of water immersion on individuals with anterior knee pain by quantifying differences in frontal and sagittal plane joint and segment angles.

13. Examine the effects on bilateral asymmetry during squats and single-leg squats.

1.3. Significance of the thesis

The research presented in this thesis provides novel insight into the kinematics of water-based exercise, with the aim of providing practitioners with additional understanding to optimise the efficacy of squat tasks performed in water. It will do so by:

1. Establish baseline data by quantifying how young and healthy individuals adapt to water immersion during squats, split-squats, and single-leg squats.

2. Determine how different depth of immersion may influence kinematics during squats.

3. Assess effects of water immersion on an older population, which arguably is the population most often exposed to water-based exercise.
4. Evaluate whether water immersion effect bilateral asymmetry in a young population with long-standing unilateral knee pain.

The findings from this research will make a significant contribution to an industry that helps many individuals attain a healthier lifestyle and return from illness or injury. It is expected that the findings from this research will assist practitioners across several disciplines to develop effective water-based rehabilitation and exercise programmes that cater to the client needs, and provide guidelines for effective application of the aquatic environment. It is also expected that this inaugural research will inspire other researchers to clarify the applications of aquatic therapy in rehabilitation further as it will highlight gaps in the knowledge and provide directions for further research.

1.4. Synopsis of the thesis

This traditional thesis with publications comprises of four original manuscripts that have either been accepted for publication in peer reviewed journals, or submitted and are currently under review. Each article is presented in the thesis as an individual chapter in the format accepted by, or presented to the scientific journal (this includes the occasional use of American English spelling). The general formatting of the individual manuscripts has been modified to comply with the rest of the thesis, including the reference systems and figure and table legends. The main studies are presented in Chapters 4, 5, 6, and 7, with the ones published at the time of submission attached in their actual format in the appendix (Chapter 10). Chapter 3 presents a validation analysis of the equipment and research methodologies that were used during this project, and has not currently been submitted for publication. The references from each chapter have been combined at the
end of the thesis (Chapter 9). All references are presented in a consistent format that is based on the Harvard referencing style, with full in-text references.
CHAPTER 2:

BIOMECHANICAL ASPECTS OF AQUATIC THERAPY: A LITERATURE REVIEW ON APPLICATION AND METHODOLOGICAL CHALLENGES
BIOMECHANICAL ASPECTS OF AQUATIC THERAPY: A LITERATURE REVIEW ON APPLICATION AND METHODOLOGICAL CHALLENGES

Please note: This chapter presents an up-to-date narrative literature review on the biomechanical aspects of aquatic therapy. The review presented here is an updated version of the one that was published in The Journal of Fitness Research in April 2016 (J Fitn Res. 2016;5(1):48-62). The published version is attached in Appendix 10.1.

2.1. Abstract

The application of aquatic therapy for health and rehabilitation purposes has been promoted for centuries. Although predominantly used in clinical settings for the treatment, rehabilitation, and management of chronic conditions, the practice has gained popularity in athletic settings for recovery and the rehabilitation of acute musculoskeletal injuries. To date, most studies on the effects of water-based rehabilitation on the human body have focused on physiological aspects. The considerably smaller amount of research that has assessed biomechanical aspects of water-based activities has been concentrated on running and walking gait. Although the literature agrees that water immersion affects several biomechanical variables, there is a relative paucity of published research assessing effects on other common exercises. The published research on kinematic effects of water-based exercise is contradictory and has resulted in unclear guidelines for practitioners. One apparent reason for this is an absence of consistent methodological protocols for kinematic analyses in the aquatic environment. This has resulted in uncertainty regarding the efficacy of water-based rehabilitation from a biomechanical perspective. Current understanding of the roles of aquatic therapy for rehabilitation is therefore lacking, with medical guidelines highlighting that high-quality research is warranted. This review
aimed to summarise the current literature on water-based exercise to clarify how water immersion can affect human movement and rehabilitation.

**Keywords**: Water; Human movement; Underwater kinematics; Rehabilitation; Fitness; Inertial sensors

### 2.2. Introduction

Aquatic therapy is a component of hydrotherapy and has been utilised for its health benefits for centuries (from Greek: *hydro-* ‘water’, and *therapeia-* ‘therapy’) (Becker, 2009, Edlich et al., 1987). Aquatic therapy employs water-based exercise for health purposes and current clinical protocols consider it a common modality in the management and rehabilitation of chronic conditions such as osteoarthritis and fibromyalgia (Bartels et al., 2007, Hauser et al., 2010, Harmer et al., 2009). It has more recently also gained popularity in weight management, athlete rehabilitation (Haff, 2008), and recovery (Wilcock et al., 2006, Takahashi et al., 2006). This increased application warrants a comprehensive understanding of the many aspects of aquatic therapy.

The benefits of aquatic therapy are linked to the physical properties of water (Becker, 2009, Harrison and Bulstrode, 1987). Therefore, practitioners wishing to employ water-based exercise in their practice must have a thorough understanding of their effects on the human body. A comprehensive understanding of these will allow the practitioner to manipulate the aquatic environment and cater to the needs and requirements of their clients. Decades of research have led to a well-documented understanding of how water immersion affects physiological variables, such as blood flow, heart rate, blood pressure and respiratory function (Alberton et al., 2011, Alkurdi et al., 2010, Alberton et al., 2009). However, an understanding of the biomechanics of aquatic therapy is still limited, as most
studies have only assessed the effects on water-based walking and running gait (Heywood et al., 2016, Kaneda et al., 2012b), jumping performance, and power development (Colado et al., 2010, Triplett et al., 2009). These researchers agree that water immersion alters several biomechanical variables such as stride length, ground reaction forces, and movement speed. However, little attention has been paid to how water immersion may affect the biomechanics of strengthening exercises that practitioners often prescribe during aquatic therapy. Increased understanding of how water immersion affects the kinematics of exercises is important for practitioners in order to ensure increased efficacy of aquatic therapy.

Although the previous research agrees that water immersion effects biomechanical variables, the reports disagree on the specific changes (Heywood et al., 2016, Heywood et al., 2017, Kaneda et al., 2012b, Masumoto and Mercer, 2008). Consequently, medical associations, such as the Cochrane Collaboration, have not been able to determine the efficacy of aquatic-based rehabilitation programmes, and have frequently highlighted that more high-quality research is needed (Bidonde et al., 2014, McNamara et al., 2013, Mehrholz et al., 2011, Fransen et al., 2015). This limited understanding of its efficacy can probably be attributed to considerable methodological differences between published research and a lack of consensus on the most appropriate outcome measures (Heywood et al., 2016, Heywood et al., 2017).

This narrative review briefly introduces the physical properties of water and their effects on the human body. However, its primary focus remains on the biomechanical implications of water immersion and their applications for rehabilitation. The review also discusses current limitations and challenges in research methodologies, highlights gaps in the current knowledge, and provides directions for future research.
2.3. **Human response to water immersion**

The appeal of aquatic therapy as a tool in exercise, recovery, and rehabilitation has increased over recent years (Chu et al., 2004, Foley et al., 2003, Kaneda et al., 2009). Previous research has identified that water immersion affects several systems of the human body, due to the fundamental principles of hydrodynamics and the physical properties of water: density, buoyancy, hydrostatic pressure, viscosity and thermodynamics (Becker, 2009, Alberton et al., 2011, Denning et al., 2012). By manipulating these properties, practitioners can modify their effect on the body and thereby alter the exercise demands to suit the needs and requirements of their clients. It is therefore important that practitioners have a thorough understanding of how the properties of water affect the human body in order to prescribe aquatic therapy effectively.

2.3.1. **Density**

Density quantifies the mass by unit volume of any given substance (Kg·m⁻³) (Torres-Ronda and Del Alcazar, 2014). The density of freshwater at sea level is highest at 4° C (999.97 Kg·m⁻³) (Tanaka et al., 2001), and decreases slightly with increased temperatures (997.05 Kg·m⁻³ at 25° C), but small changes in temperature are unlikely to influence exercise performance (Edlich et al., 1987, Lide, 2009, p. 139, Marsh, 1987, pp. 25-27). The specific density of a human body depends on its composition; fat free mass (bone, muscle, organs and connective tissue) has a density higher than water (close to 1,100 Kg·m⁻³) and fat mass has a density lower than water (close to 900 Kg·m⁻³) (Edlich et al., 1987). Thus, an individual with a higher percentage of fat free mass has a higher density compared to an individual with more fat mass. An average human body, which consist of approximately 60% water, has a density slightly lower than water (approximately 974 Kg·m⁻³) (Becker, 2009).
2.3.2. Buoyancy

A submerged human body with a density lower than water displaces a volume of water that is slightly heavier than the body itself (Becker, 2009). According to Archimedes’ principle; an upwardly directed force will be exerted on the submerged body and that is equal to the volume of the displaced water (Edlich et al., 1987). If the body has a lower density than the water, the volume of the displaced water is greater than that of the body, and the body is pushed towards the surface by the buoyant force (Becker, 2009, Masumoto and Mercer, 2008, Harrison and Bulstrode, 1987). The magnitude of the buoyant force increases proportionally with the mass of the submerged body (Pohl and McNaughton, 2003, Harrison and Bulstrode, 1987). A human body with a specific gravity of 0.974 (a density of 974 Kg·m$^{-3}$) achieves floating equilibrium when 97.4% of the body is submerged (Becker, 2009). Practitioners can therefore modify the degree of offloading by changing water depth, as an individual immersed to chest level experiences a larger buoyancy force compared to someone immersed to the waist.

2.3.3. Hydrostatic pressure

In addition to the upwardly directed buoyant force, the water surrounding the submerged body also exerts a compressive force on it, which is referred to as hydrostatic pressure (Wilcock et al., 2006). The hydrostatic pressure is the product of the depth and density of the surrounding fluid (Edlich et al., 1987). The pressure exerted by the air surrounding a body at sea level is approximately 1013.0 Pa (7.6 mmHg) (Wilcock et al., 2006). The density of water is greater than air, which means that water immersion exerts a considerably higher pressure on the body (Bove, 2002) that increases with the depth of immersion at a rate of approximately 981.0 Pa (73.5 mmHg) each meter (Becker, 2009, Pohl and McNaughton, 2003). Accordingly, standing in neck-deep water will result in a
hydrostatic pressure on the calves that is approximately twice as large as the pressure exerted on the chest. Hydrostatic pressure is commonly utilised for pain management as it improves blood flow and slows nerve conduction and transmission (Torres-Ronda and Del Alcazar, 2014), and also reduces swelling and oedema (Edlich et al., 1987).

2.3.4. Viscosity

Viscosity is the magnitude of internal friction a fluid has during motion and is specific to each fluid (Becker, 2009). Movement through water creates resistive drag forces that act opposite to the direction of travel (Becker, 2009, Masumoto and Mercer, 2008). This viscous resistance is directly proportional to the force exerted against the fluid by the moving body (Becker, 2009), and will increase if the velocity and/or surface area of the moving body is increased (Poyhonen et al., 2000, Edlich et al., 1987). When movement ceases and no longer exerts force on the water, the resistive force ceases immediately (Becker, 2009). Therefore, a practitioner can easily modify the degree and duration of resistance by manipulating movement speed or changing surface area (body position), for example, an open hand produces a greater resistance when moving through water compared to a fist.

2.3.5. Thermodynamics

The ability of water to retain heat and transfer heat energy is superior to that of air with a heat capacity of approximately 1.0 J·K$^{-1}$ (1,000 times greater than air) (Becker, 2009). The heat capacity of water is also higher than that of human body tissues (0.83 J·K$^{-1}$) (Torres-Ronda and Del Alcazar, 2014). This means that a temperature difference between the body and water will result in the body temperature approaching that of the water rather than the opposite (Becker, 2009, Wilcock et al., 2006). Accordingly, a person immersed
in water that is colder than core temperature will lose heat, and warmer water will increase the body temperature.

2.4. Human responses to water-based exercise

Combined or individually, the physical properties of water have several biomechanical, neurological, physiological and hormonal effects on the human body (Alberton et al., 2011, Becker, 2009, Denning et al., 2012, Mooventhlan and Nivethitha, 2014). By manipulating factors such as temperature, water depth, or water flow, these effects can be modified to suit individual clients. Hydrostatic pressure has been reported to shift blood distribution and alter the blood pressure, which can be beneficial for cardiopulmonary and respiratory rehabilitation (Becker, 2009, Edlich et al., 1987). Increased compressive forces and reflex regulations of blood vessel tone in water increases cardiac output, and muscular blood flow (Epstein, 1992). Hydrostatic pressure combined with thermodynamic effects has also been found to improve oedema and reduce pain (Ernst et al., 1991). The gravitational offloading from buoyancy along with reduced pain is also beneficial for patients with fibromyalgia (Bidonde et al., 2014) and arthritis (Bartels et al., 2007) as it increases joint mobility. Research has shown that water immersion has several effects on the human body that, if applied correctly, can have great benefits for exercise and health.

Conversely, it is important for practitioners to recognise that water-based activity may be contraindicated in some populations, where the hydrodynamic effects can be harmful for individuals. The increased pressure can cause breathing difficulties in individuals with extremely weak respiratory muscles (Edlich et al., 1987), and be harmful for individuals with severe heart conditions, (Becker, 2009) and vascular disease (Wilcock et al., 2006).
Water immersion is also contraindicated for individuals with recent wounds and lesions as it may risk infection (Gleim and Nicholas, 1989, Wilcock et al., 2006). As with any exercise modality, it is important that practitioners are aware of specific contraindications for water-based exercise when considering its application.

The many effects of water immersion on physiological, neurological, and hormonal variables are well documented in the literature, but as many of these fall outside the biomechanical scope of this literature review, they will not be discussed further. However, additional information can be found in reviews by Becker (2009), Denning et al. (2012), Torres-Ronda and Del Alcazar (2014) and Moovethan and Nivethitha (2014).

2.5. Biomechanical effects of water immersion

Buoyancy, viscosity and hydrostatic pressure are the primary biomechanical considerations for water-based exercise (Kaneda et al., 2012b), as they provide gravitational offloading, resist movements and challenge proprioception (Roth et al., 2006, Harrison and Bulstrode, 1987, Killgore et al., 2006). Even though biomechanical studies form only a small part of the body of literature on the efficacy of water-based exercise (Masumoto and Mercer, 2008), research has reported that water immersion affects several biomechanical variables. Most of these studies assessed differences in gait characteristics between land and water, and reported differences in joint motions, muscle activity, and spatiotemporal parameters (Kaneda et al., 2012b, Heywood et al., 2016). The theoretical effects of water immersion on the biomechanics of gait are generally well understood, however, the results of previous studies are conflicting (Table 2.1). This is most likely due to the important differences in their methodologies relating to water depth, temperature, and exercise type. These factors probably affected the results, as both depth
and temperature are known to influence biomechanical aspects of immersion (Becker, 2009, Wilcock et al., 2006). Table 2.1 presents the current literature on water-based gait and highlights both methodologies and key results. It should be acknowledged that some studies presented in Table 2.1 focused more on physiological effects such as, as heart rate and oxygen uptake, rather than biomechanical variables. However, due to the purpose of this literature review, only the biomechanical aspects are included below.
<table>
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<tr>
<th>Author</th>
<th>Protocol</th>
<th>Population</th>
<th>Depth</th>
<th>Temp</th>
<th>Data collection</th>
<th>Main findings</th>
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<tbody>
<tr>
<td>Barela and Duarte (2008)</td>
<td>Water- and land-based walking. Self-selected speed on a walkway (6m).</td>
<td>10 older adults Xiphoid process</td>
<td>Not reported</td>
<td></td>
<td>Sagittal view video (60 Hz) and force platform (1000 Hz).</td>
<td>No significant difference in stride length, but significantly lower stride frequency in water. Slower walking speed in water. Reduced GRFz. and reduced knee ROM in water.</td>
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<tr>
<td>Barela et al. (2006)</td>
<td>Water- and land-based walking. Self-selected speed on a walkway (6m).</td>
<td>10 young adults Xiphoid process</td>
<td>Not reported</td>
<td></td>
<td>Sagittal view video (60 Hz) and force platform (1000 Hz).</td>
<td>Lower average walking speed in water. No differences in lower body joint ROM but segmental angles ROM were smaller in water for knee and ankle.</td>
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<td>Author</td>
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<td>Fantozzi et al. (2015)</td>
<td>Water- and land-based walking.</td>
<td>11 healthy adults</td>
<td>1.20 metres</td>
<td>28° C</td>
<td>Eight inertial sensors (128 Hz).</td>
<td>Lower average walking speed in water (40%).</td>
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<td></td>
<td>Self-selected speed on a walkway (10m).</td>
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<td>Longer stride duration and shorter strides in water.</td>
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<td>More knee flexion and dorsiflexion at heel strike, and more hip flexion at toe-off in water.</td>
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<td>Smoother joint angle patterns in the frontal plane and more ankle inversion at toe-off.</td>
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<td>Reliance on lower trunk musculature during DWR with no eccentric contraction.</td>
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<td>Hall et al. (2004)</td>
<td>Treadmill in water and on land.</td>
<td>15 females</td>
<td>Xiphoid process</td>
<td>34.5° C</td>
<td>Manually counting stride frequency at three different speeds (2.5, 3.5 and 4.5 km·h⁻¹).</td>
<td>Significantly lower stride frequency at all speeds in water.</td>
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<tr>
<td>Author</td>
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<td>Hall et al.</td>
<td>Treadmill in water and on land</td>
<td>8 females</td>
<td>Xiphoid process</td>
<td>28°C</td>
<td>Manually counting stride frequency at three different speeds (3.5, 4.5 and 5.5 km·h⁻¹).</td>
<td>Significantly lower stride frequency in water.</td>
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<td>(1998)</td>
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<td>and 36°C</td>
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<tr>
<td>Kaneda et al.</td>
<td>Water- and land-based walking.</td>
<td>6 adults</td>
<td>1.35 meters</td>
<td>27°C</td>
<td>Sagittal video (25 Hz) analysis of right limb.</td>
<td>Subject-dependent changes in the ankle joint between elements.</td>
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<td>(2012a)</td>
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<td>Differences in hip joint actions.</td>
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<td>Kato et al.</td>
<td>Treadmill in water and on land.</td>
<td>6 males</td>
<td>Waist level on</td>
<td>29°C</td>
<td>Sagittal view video (shutter speed of 1/250 seconds), digitized for analysis.</td>
<td>Lower stride frequency for all speeds in water.</td>
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<td>(2001)</td>
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<td>each subject.</td>
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<td>Increased non-support phase in water.</td>
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<td>Walking to running transition occurred at lower speeds in water.</td>
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<tr>
<td>Killgore et al.</td>
<td>DWR and treadmill on land.</td>
<td>20 distance</td>
<td>3.96 metres</td>
<td>27.2°C</td>
<td>Sagittal view video (30 fps).</td>
<td>Lower stride frequency in water.</td>
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<td>(2006)</td>
<td></td>
<td>runners</td>
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<td>Author</td>
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<tr>
<td>Macdermid et al. (2017)</td>
<td>Treadmill in water (2.61 m·s⁻¹) for three minutes at three depths.</td>
<td>8 adults</td>
<td>mid-shin, mid-thigh, xiphoid process</td>
<td>23-24°C</td>
<td>One triaxial accelerometer on anterior surface of distal right tibia.</td>
<td>Stride frequency, ground contact time, and impact loading rates decreased with increased depth. Stride length increased with increased depth.</td>
</tr>
<tr>
<td>Marinho-Buzelli et al. (2017a)</td>
<td>Water- and land-based walking. Self-selected speed on a walkway (4 steps).</td>
<td>7 females</td>
<td>1.1 metres</td>
<td>35°C</td>
<td>Sagittal view video (60 fps) and force platform (1024 Hz).</td>
<td>Increased step duration, slower step velocity, and unchanged step length in water. Increased ankle ROM during swing phase and unchanged knee ROM in water.</td>
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<td>Masumoto et al. (2009)</td>
<td>DWR and treadmill on land. Different intensities (RPE 11, 13 and 15).</td>
<td>7 adults</td>
<td>Neck</td>
<td>28°C</td>
<td>EMG (1500 Hz) of biceps femoris, rectus femoris, tibialis anterior and lateral head of gastrocnemius.</td>
<td>Increased stride frequency with increased RPE in water but lower stride frequency compared to land. Lower muscle activity and changed patterns for tibialis anterior and gastrocnemius in water, no change in activity for rectus femoris and biceps femoris.</td>
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<td>Masumoto et al. (2008)</td>
<td>Treadmill in water and on land.</td>
<td>9 older females</td>
<td>Xiphoid process</td>
<td>31° C</td>
<td>EMG (1000 Hz) of vastus medialis, rectus femoris, biceps femoris, tibialis anterior and lateral head of gastrocnemius.</td>
<td>Greater stride length at matched speeds but lower stride frequency in water. Lower muscle activity in water for all muscles at all speeds.</td>
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<td>Different speeds (water: 1.2, 1.8 and 2.4 km·h⁻¹, land: 2.4, 3.6 and 4.8 km·h⁻¹).</td>
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<td>Miyoshi et al. (2005)</td>
<td>Water- and land-based walking.</td>
<td>16 healthy adults</td>
<td>Axillae</td>
<td>34° C</td>
<td>2 cameras, sagittal view (30 Hz), force platform (1000 Hz) and EMG (sampling rate not reported).</td>
<td>Decreased ankle plantar flexion moment in water. Changed knee extensor moment characteristics in water. Constant hip extensor moment in water, which increased with speed. Increased biceps femoris activity in water.</td>
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<td>Self-selected speed on a walkway.</td>
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<td>Miyoshi et al.</td>
<td>Water- and land-based walking.</td>
<td>15 healthy</td>
<td>Axillae</td>
<td>34° C</td>
<td>2 cameras. Sagittal view, (30 Hz), force platform (1000 Hz) and EMG (sampling</td>
<td>Reduced knee ROM in water, but no change at hip or ankle.</td>
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<td>(2004)</td>
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<td>adults</td>
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<td>rate not reported).</td>
<td>Reduced GRFz and constantly anteriorly directed GRFy in water.</td>
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<td>Lower joint moments in water in water.</td>
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<td>Constant hip extensor moment in water.</td>
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<td>Participant-dependent changes in muscle activity.</td>
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<td>Miyoshi et al.</td>
<td>Water- and land-based walking.</td>
<td>8 healthy</td>
<td>Axillae</td>
<td>34° C</td>
<td>2 cameras, sagittal view, (30 Hz) and force platform (1000 Hz).</td>
<td>No change in lower body ROM during stance phase.</td>
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<td>Constant hip extensor moment in water.</td>
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<td>Orselli and Duarte (2011)</td>
<td>Water- and land-based walking.</td>
<td>10 young adults</td>
<td>Xiphoid process</td>
<td>30°C</td>
<td>Sagittal view video (60 Hz) and force plate (100 Hz).</td>
<td>Shorter stride length and 2.7 times longer stride duration in water. Reduced joint loading in water (65% offloading). No changes in joint angle, but slower velocities and lower peak torques in water. Decreased hip joint forces in water.</td>
</tr>
<tr>
<td>Pohl and McNaughton (2003)</td>
<td>Treadmill in water and on land.</td>
<td>6 university students</td>
<td>Waist-deep (umbilicus) and Thigh-deep (mid-thigh)</td>
<td>33°C</td>
<td>Stride frequency manually counted.</td>
<td>Lower stride frequency in water during running and lower frequency in the thigh-deep water than waist-deep.</td>
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<tr>
<td>Shono et al. (2001)</td>
<td>Treadmill in water and on land.</td>
<td>6 older females</td>
<td>Xiphoid process</td>
<td>30.7°C</td>
<td>Stride frequency manually counted.</td>
<td>Stride frequency in water nearly 50% of land-based walking.</td>
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<td>Shono et al. (2007)</td>
<td>Treadmill in water and on land</td>
<td>8 older females</td>
<td>Xiphoid process</td>
<td>30.7° C</td>
<td>Sagittal view video (sample rate not reported), and EMG of tibialis anterior,</td>
<td>Greater stride length and lower stride frequency in water.</td>
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<td>medial head of gastrocnemius, vastus medialis, rectus femoris, and biceps femoris.</td>
<td>Smaller peak knee flexion and extension angles and slower peak velocities in water.</td>
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<td>Sagittal view video (sample rate not reported).</td>
<td>Similar muscle activity in tibialis anterior, vastus medialis and biceps femoris, and decreased activity in medial gastrocnemius and rectus femoris in water.</td>
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<td>Four-minute intervals (water: 1.2, 1.8 and 2.4 km·h⁻¹, land: 2.4, 3.6 and 4.8 km·h⁻¹).</td>
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<td>and EMG of tibialis anterior, medial head of gastrocnemius, vastus medialis,</td>
<td>and EMG of tibialis anterior, medial head of gastrocnemius, vastus medialis,</td>
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<td>rectus femoris, and biceps femoris.</td>
<td>rectus femoris, and biceps femoris.</td>
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<tr>
<td>Town and Bradley</td>
<td>DWR, shallow water running and land-based</td>
<td>9 college students</td>
<td>DWR – 4 metres</td>
<td>Not specified</td>
<td>Manually counted stride frequency.</td>
<td>Greater stride frequency during shallow water running compared to DWR, and lower frequency in water than on land.</td>
</tr>
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<td>(1991)</td>
<td>treadmill.</td>
<td></td>
<td></td>
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<td>Shallow water running – 1.3 metres.</td>
<td>Greater stride frequency during shallow water running compared to DWR, and lower frequency in water than on land.</td>
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The table shows that most studies reported on spatiotemporal characteristics such as stride frequency while a few addressed ground reaction forces or muscle activity. It also highlights the inconsistencies in water depth and temperature between studies, and reveals that several studies assessed activities with considerably different demands on the human body. For example, deep water running has the participant suspended in water without touching the floor and therefore lacks impact and propulsion, and is substantially different to overground or treadmill running (Kaneda et al., 2008b, Cuesta-Vargas and Cano-Herrera, 2014). Some studies used different treadmill speeds on land and in water (Masumoto et al., 2008, Shono et al., 2007), or chose not to control the speed at all (Masumoto et al., 2009, Miyoshi et al., 2003, Orselli and Duarte, 2011). Despite previous researchers having highlighted the lack of methodological consensus (Cuesta-Vargas and Cano-Herrera, 2014), the concern remains and complicates comparisons between studies.

This issue probably contributes to the contradictory results across the literature and explains why the efficacy of water-based exercise has not been clearly established (Bidonde et al., 2014, Fransen et al., 2015). The issue was highlighted in a recent systematic review, which suggested that ambiguous definitions of what ‘aquatic exercise’ entails has contributed to the conflicting results (Heywood et al., 2017). The previous research has shown that water-based exercise is often substantially different from land-based exercise; however, uncertainty remains regarding straightforward comparisons between matched exercises in both environments. Future research should acknowledge the methodological differences in the previous studies, and aim to develop consistent research protocols that provide practitioners with a comprehensive understanding of how the physical properties of water can be manipulated to suit individual needs.
2.5.1. Kinematics in the aquatic environment

While most biomechanical investigations have reported spatiotemporal parameters, only some have assessed the kinematic responses to water immersion. A 2012 review noted that most kinematic reports observed similar lower body angles between the environments during walking gait (Kaneda et al., 2012b). However, some studies reported either larger or smaller angles in water compared to land-based walking. It should be noted that the studies included in the review used underwater video and only reported on sagittal plane kinematics (Miyoshi et al., 2003, Orselli and Duarte, 2011, Barela and Duarte, 2008, Barela et al., 2006, Kaneda et al., 2009, Kato et al., 2001, Miyoshi et al., 2004). Another important consideration is that, like with the reports on spatiotemporal parameters, these studies also differed in their methodology, which likely affected their results. More recently, advances in technology have allowed underwater motion capture to be used, and this has provided insight into the frontal and transverse plane movements (Abdul Jabbar et al., 2017). This study revealed that water immersion often reduced peak angles, particularly in these secondary movement planes. However, further work is required and should assess if corresponding changes in muscle activity take place. Regardless, this information may be very useful for practitioners as it highlights that walking gait differs considerably between the environments.

A consistent observation across previous studies was increased moments and activity of the hip joint (Miyoshi et al., 2003, Kaneda et al., 2008b, Abdul Jabbar et al., 2017). The authors suggested that buoyancy encouraged increased hip flexion during the swing phase and that water viscosity necessitated increased reliance of the hip joint for propulsion. According to the kinetic chain principle suggested by Putnam (1991), changed kinematics at the hip joint probably result in changes at other segments along the kinetic chain.
Researchers have reported altered kinetics and kinematics about the knee and ankle during water-based walking (Orselli and Duarte, 2011, Abdul Jabbar et al., 2017), which supports the kinetic chain principle. Importantly, despite reduced joint torques at the knee and ankle during water-based gait, it has been reported that the torque at the hip joint remained similar to land-based walking (Orselli and Duarte, 2011). It has also been highlighted that increased resistive drag forces acting on the distal segments in water demand more activity from the hip for propulsion (Abdul Jabbar et al., 2017, Orselli and Duarte, 2011, Miyoshi et al., 2003). It was hypothesised this increased activity was probably accompanied by increased muscle activity at the hip joint (Abdul Jabbar et al., 2017), but this is yet to be confirmed. The literature agrees that water immersion affects several biomechanical aspects of gait, but limited research has assessed other activities. The fact that water immersion alters kinematics highlights the need for practitioners to understand the effects of water immersion, as it may affect the rehabilitation programme for their clients.

2.5.2. Electromyography in the aquatic environment

The kinematic alterations associated with water immersion suggest a corresponding change in muscle activity. However, most kinematic studies did not measure muscle activity (Abdul Jabbar et al., 2017, Orselli and Duarte, 2011, Miyoshi et al., 2003), and studies that assessed muscle activity in water did not report kinematics (Bressel et al., 2011, Masumoto et al., 2009, Masumoto et al., 2008). One study combined electromyography (EMG) and kinematics during deep water running (Kaneda et al., 2008b). However, as this activity does not include propulsion or ground contact, it offers limited information about muscle activity during water-based gait.
Like most aquatic-based research, the bulk of studies on muscle activity in water have been conducted on walking or running gait (Kaneda et al., 2009, Masumoto et al., 2009, Masumoto et al., 2008), but once again, there are methodological inconsistencies in these studies (Kaneda et al., 2012b) (Table 2.1). Most research has reported decreased muscle activity in water (Alberton et al., 2011, Kaneda et al., 2008b, Masumoto et al., 2009), however, a systematic review noted that there are few comparative analyses between the environments (Cuesta-Vargas and Cano-Herrera, 2014). The authors also concluded that although much of the previous research supports lower muscle activity in water, the causation has not been established. A reasonable explanation for the reduced muscle activity is that the offloading in water decreases muscle recruitment (Masumoto et al., 2008). However, practitioners should not assume consistently lower muscle activity in water as researchers have reported levels of muscle activity in water that are higher (Cuesta-Vargas et al., 2013) or similar to those on land (Pinto et al., 2010, Silvers and Dolny, 2011). Other researchers showed that walking against a water flow yielded higher muscle activation than overland walking (Shono et al., 2007). This is a terrific example of one way that practitioners can manipulate the aquatic environment to change its effects on exercises.

Some attention has also been paid to the effects of water immersion on the pattern of muscle recruitment during walking (Barela and Duarte, 2008, Barela et al., 2006). The authors suggested that the muscle activation pattern during gait depends on the walking speed (to overcome drag forces) and the depth of immersion (amount of gravitational offloading). Other researchers agreed that the activation pattern depends on the depth of immersion of each individual muscle (Cuesta-Vargas and Cano-Herrera, 2014). For example, because the calf muscles are deeper than hip muscles during walking, their
recruitment patterns would differ. Consequently, the authors cautioned against direct comparisons between land and water, or between different water depths.

Finally, researchers have cautioned that protocols for land-based EMG analyses may not be applicable in water (Masumoto and Mercer, 2008). EMG signals are normalised based on a maximal voluntary contraction (MVC), and for unclear reasons, water immersion appears to reduce the MVC (Poyhonen and Avela, 2002, Poyhonen et al., 1999). Researchers are yet to determine whether a land- or water-based MVC is more appropriate for normalising water-based signals (Masumoto and Mercer, 2008). In addition, using EMG underwater requires caution because not only may water interfere with the signals, but the use of electrical components in water has important safety considerations (Masumoto and Mercer, 2008, Cuesta-Vargas and Cano-Herrera, 2014). Further work is required to clarify the effects of water immersion on muscle activity in order to provide practitioners with a deeper understanding of how to better prescribe aquatic therapy.

2.5.3. Balance in the aquatic environment

Authors have also theorised that the aquatic environment may be beneficial for static and dynamic balance training (Kaneda et al., 2008a, Katsura et al., 2010, Kim and O'Sullivan, 2013, Resende et al., 2008). The viscosity, density and buoyancy challenges the body’s proprioception (Roth et al., 2006), and reduces the activity of postural muscles (Louder et al., 2014), thereby potentially requiring different strategies to maintain balance. Importantly, although studies have reported significant improvements in balance following aquatic-based exercise, the improvements were similar to those achieved with land-based programmes (Avelar et al., 2010, Roth et al., 2006). In addition, the studies assessed the effects on land-based balance, and did not assess balance during water
immersion. It is therefore not possible to determine how water immersion may affect balance and proprioception.

There is obvious logic in quantifying balance in the aquatic environment as water-based exercise is a common modality in falls prevention interventions for older adults (Resende et al., 2008, Arnold et al., 2015, Avelar et al., 2010, Booth, 2004, Geigle et al., 1997). Interestingly, research found that water immersion increased perturbation and reduced postural control, which was associated with increased instability (Bressel et al., 2016, Marinho-Buzelli et al., 2017b). The aquatic environment may therefore be unsuitable for high fall-risk individuals. However, the resistance of water generally slows movements and thereby provides more time for postural corrections, which is believed to retard falls (Geigle et al., 1997, Resende et al., 2008). Reduced risk of falling is a key rationale for prescribing water-based exercise to older adults in particular (Devereux et al., 2005, Skelton and Dinan, 2009, Booth, 2004, Oh et al., 2015). Water immersion also reduces the fear of falling due to increased stability and gravitational offloading (Devereux et al., 2005, Kim and O'Sullivan, 2013), and therefore has psychological benefits. Consequently, performing exercises in the aquatic environment that would otherwise be perceived difficult or challenging on land, offers clear advantages for individuals with restricted mobility and populations with high fall-risk, such as older adults and post-surgical patients.

It is obvious that water immersion affects several parameters of human movement, although the existing biomechanical literature is heavily biased towards gait. Methodological inconsistencies have resulted in significant gaps in the understanding of biomechanical effects of water immersion. Future research is needed in order to establish methodological protocols that elucidate the effects of water immersion on biomechanics,
muscle activity, and balance. Moreover, researchers should examine activities other than gait that may be prescribed in the aquatic environment. An increased understanding of how water immersion affects movements that are common in everyday life, exercise, and rehabilitation is essential in order to further the application of aquatic therapy.

2.6. Biomechanical aspects of water-based rehabilitation

Several of the biomechanical adaptations associated with water immersion can have considerable benefits for rehabilitation (Becker, 2009, Di Monaco and Castiglioni, 2013, Heywood et al., 2017, Villalta and Peiris, 2013). The Cochrane Collaboration recognizes that water-based activity can be beneficial for rehabilitation of several chronic conditions. Although as previous research has been unable to clearly determine the efficacy of water-based rehabilitation, its current position stand is that water-based and land-based rehabilitation protocols are equally effective (Bartels et al., 2007, Bidonde et al., 2014, Grande et al., 2014, McNamara et al., 2013). The authors highlight a need for more high-quality research in order to establish the roles of water-based rehabilitation. It is important that practitioners understand any biomechanical different between land and water in order to prescribe water-based exercises in an efficient manner.

2.6.1. Gravitational offloading

Rehabilitation protocols for many soft tissue injuries recommend early commencement of functional treatments while under reduced loads (Bartels et al., 2007, Kim et al., 2010, Werner, 2014). The hydrostatic pressure and buoyancy caters to these aims (Kim et al., 2010, Nualon et al., 2013), and are primary biomechanical considerations for rehabilitation (Becker, 2009, Denning et al., 2012). Practitioners can easily manipulate the offloading by changing the water depth, and thereby select a degree of offloading that
suit needs of their clients (Becker, 2009, Orselli and Duarte, 2011, Harrison and Bulstrode, 1987). Similarly, a gradual reduction of the depth will progressively reintroduce load (Harrison and Bulstrode, 1987), and allow safe progression of exercises.

The degree of offloading differs slightly between genders due to differences in their fat-mass distribution (immersion to the anterior superior iliac spine generally offloaded males by ~46% and females by ~53%) (Harrison and Bulstrode, 1987). However, these differences are very small, so current practical guidelines have been generalised, and agree that immersion to the pubic symphysis offloads approximately ~40%, to the umbilicus offloads ~50%, and xiphoid process offloads ~60% (Becker, 2009). Reduced joint and muscle loads may allow an injured individual a return to partial weight bearing earlier than what is possible under full gravitational load. This is an obvious benefit for both acute and chronic injuries across different populations, (Kim et al., 2010, Pozzi et al., 2013, Uthman et al., 2013, Wicker, 2011, Asimenia et al., 2013) as it facilitates early return to movement.

Water-based rehabilitation has been reported to have greater short-term outcomes compared to land-based programmes for ligamentous injuries (Kim et al., 2010). Importantly, the authors highlighted that few objective studies have assessed the effects of water-based exercise during early stages of rehabilitation, which is surprising considering its widespread use. The gravitational offloading has obvious benefits for early commencement of activity, but guidelines for reintroducing load gradually by using the aquatic environment are still lacking and deserves attention in future research.
2.6.2. Effects for muscular function and strength

Theoretically, reduced loading and pain may be beneficial for improved ROM during early stages of rehabilitation (Heywood et al., 2016, Barela and Duarte, 2008, Devereux et al., 2005, Skelton and Dinan, 2009), although the literature once again, disagrees regarding this matter. As discussed previously (section 2.5.1), most of the previous research on water-based gait agrees that the ROM is similar between environments (Barela et al., 2006, Heywood et al., 2016, Kaneda et al., 2012b, Miyoshi et al., 2003, Miyoshi et al., 2004, Orselli and Duarte, 2011), although studies have reported considerable different joint kinematics between the environments (Abdul Jabbar et al., 2017, Kato et al., 2001). Water-based exercise programmes have been reported to increase the ROM in older individuals (Lord et al., 2006) and individuals with movement restricting conditions such as arthritis (Suomi and Lindauer, 1997). Although little research has compared the effects of water-based exercise on ROM between populations, it is possible that it benefits certain individuals more than others, for example those with reduced mobility. More research is needed to determine both immediate and long-term effects on water-based rehabilitation on ROM and its transferability to land-based activities.

Another important aim in musculoskeletal rehabilitation is to build muscle strength and endurance (Werner, 2014, Comfort et al., 2015). The viscosity and density in water provides resistance to movements that does not exist in air (Becker, 2009), and suggests that water-based exercise may be beneficial for strength training. Water-based exercise for strength gains is yet another conflicting topic in the literature. Researchers have reported that water-based exercise results in significant strength improvements in older individuals and individuals with osteoarthritis (Kim and O’Sullivan, 2013, Katsura et al.,...
Conversely, studies on athletes have shown that strength improvements during water-based training are inferior to those achieved on land (Tovin et al., 1994, Faccini et al., 2013, pp. 212-220). However, the exercise protocols differed considerably between these studies (frequency, intensity, and exercises for intervention and control groups), which complicates comparisons. Like with ROM, it is possible the efficacy of water-based strength programs differs between populations. However, more comparative studies are needed to evaluate this hypothesis. The populations reported in the literature that showed significant strength gains were either older (Katsura et al., 2010, Kim and O’Sullivan, 2013) or had osteoarthritis (Wang et al., 2007) and therefore likely had reduced muscle strength. One can question if these findings are applicable to healthy adults, athletes or adolescents who may not suffer from muscle weakness. A recent systematic review stressed that it is difficult to overload muscles adequately for developing muscle strength while in water, due to insufficient resistance (Heywood et al., 2017). However, the authors did not consider the populations assessed in the studies, although the efficacy of water-based exercise to develop strength may be dependent on the population, as only individuals with reduced functionality appear to improve.

Although the insufficient resistance in the aquatic environment may slow the development of strength compared to land (Heywood et al., 2017), practitioners should consider the possibility of early commencement of movement. It is possible that early return to partially loaded movements is more important than rapid strength gains for certain clients. As with any exercise modality, practitioners must understand both benefits and limitations of water-based rehabilitation, and consider the needs and restrictions of their clients when deciding whether to employ the aquatic environment.
The current knowledge on the roles of aquatic therapy in rehabilitation is clearly lacking, with contradicting reports on its benefits for ROM, strength, and overall efficacy. It is therefore important that future research establishes protocols to ensure high-quality investigations, and develops guidelines for practitioners so that rehabilitation is optimised.

2.7. Methodological challenges in water-based research

Earlier commencement of rehabilitation coupled with reduced joint and muscle loading should be considered benefits of water-based rehabilitation amongst practitioners (Becker, 2009, Denning et al., 2012, Mooventhan and Nivethitha, 2014). Nevertheless, the paucity of high-quality scientific literature on its efficacy is obvious and lacking protocols are often highlighted (Cuesta-Vargas and Cano-Herrera, 2014, Heywood et al., 2016, Heywood et al., 2017, Kaneda et al., 2012b, Masumoto and Mercer, 2008). Researchers having highlighted that underwater EMG analyses require modified normalisation protocols (Masumoto and Mercer, 2008), or that motion capture systems require different calibrations for the cameras (Silvatti et al., 2013). Despite this, biomechanical researchers continue to conduct water-based research based on protocols developed for land-based analyses.

2.7.1. Underwater motion capture

Most previous research on the kinematic effects of water immersion have relied on sagittal plane video analysis, often using sample rates as low as 30 or 60 Hz (Table 2.1). Several researchers placed video cameras along an underwater walkway and record participants walking past (Barela and Duarte, 2008, Barela et al., 2006, Miyoshi et al., 2003, Miyoshi et al., 2004, Miyoshi et al., 2005, Orselli and Duarte, 2011, Chevutschi et al., 2009). Caution has been advised when analysing kinematics with video footage.
because of the parallax error causing distortion of the image (Figure 2.1) (Gissot et al., 2007, Silvatti et al., 2013).

![Diagram depicting the parallax error](image)

**Figure 2.1.** Diagram depicting the parallax error.
An individual positioned at A would portray different gait parameters than one positioned at B.

In addition, sagittal plane analyses also overlooks the secondary plane motions, and many important movements occur outside of the sagittal plane during functional tasks (Almeida et al., 2015, Stickler et al., 2015, Hollman et al., 2014, Lamoth et al., 2002). The use of underwater video for kinematic analyses has been questioned as water immersion changes spatiotemporal variables (stride frequency, stride length and walking speed), which in turn affects joint kinematics (Masumoto and Mercer, 2008). The authors suggested that EMG analyses would provide more comprehensive information on gait, however as discussed previously (section 2.4.1), there are still concerns with using EMG in water.

Biomechanical research considers optoelectronic systems the benchmark for motion capture analyses (Comfort et al., 2015, Pohl and Buckley, 2008, Sinclair et al., 2014, Kadaba et al., 1990, Mei et al., 2017, El-Gohary et al., 2017). These systems tracks
reflective markers allocated to participants using infra-red cameras, and are capable of capturing at very high frequencies (up to 50 kHz) (Komnik et al., 2015, McClelland et al., 2009). Although these systems are very accurate, they are expensive and confined to laboratory settings (Saber-Sheikh et al., 2010), which restricts their availability and application in clinical and practical settings. Although special optoelectronic systems are able to track motions in water (Silvatti et al., 2013), they are more expensive than land-based equivalents and their application remain challenging.

Inertial sensors are considered a reliable method for analysing human movement that also addresses the portability and cost issues (Khurelbaatar et al., 2015, Muro-de-la-Herran et al., 2014, Ohberg et al., 2013, El-Gohary et al., 2017). Biomechanical researchers and health professionals can use the sensors to record three-dimensional (3D) data in clinics, gyms, and on sporting fields, instead of being confined to a laboratory (Ertzgaard et al., 2016). Recent reports have also used inertial sensors to track movements in water (Fantozzi et al., 2015, Macdermid et al., 2017). As inertial sensors are portable and can operate in different environments, researchers and practitioners can perform testing outside of the laboratory and thus maintain ecological validity.

The accelerometers and gyroscopes within inertial sensors can track motions in 3D (James, 2006), and researchers have quantified their accuracy during walking, timed-up-and-go tests, and sit-to-stand tests, and agrees that the sensors are highly accurate (over 85%) (Henriksen et al., 2004, Mayagoitia et al., 2002, Tong and Granat, 1999, El-Gohary et al., 2017). When compared to optoelectronic systems, research has reported coefficient of multiple correlations (CMC) scores of ≥0.98 (Mayagoitia et al., 2002), and Pearson’ correlation (r) values of ≥0.71 (Khurelbaatar et al., 2015, Liu et al., 2014, Qi et al., 2015). High inter-system agreements has also been reported for linear and angular velocities,
with CMC scores of ≥0.96, \( r \) values of ≥0.91 (Mayagoitia et al., 2002, Kavanagh and Menz, 2008, Jasiewicz et al., 2007), and normalised root-mean square error (NRMSE) scores of ≤0.5 (Tong and Granat, 1999). Finally, it has been reported that sensors have high test-retest reliability (ICC >0.7, ME <0.01) during gait (Henriksen et al., 2004) and sit-to-stand tasks (Regterschot et al., 2014). However, it has been highlighted that the quality of individual gyroscopes can differ, which may affect the accuracy of a sensor (Luinge and Veltink, 2005). It may therefore be recommended that anyone considering using inertial sensors should determine their relative accuracy prior to testing.

The potential of employing inertial sensors in the aquatic environment in order to analyse kinematic effects of water immersion is appealing. However, at the time of submission, only one publication has reported underwater kinematics obtained with inertial sensors (Fantozzi et al., 2015) (Table 2.1). The authors successfully quantified differences in frontal and sagittal plane gait kinematics between land and water and reported several differences between the environments. However, the study excluded the transverse plane data as other researchers have questioned that inertial sensors are able to accurately track movements in the transverse plane due to drift (Ertzgaard et al., 2016, Ohberg et al., 2013). Regardless, inertial sensors provide exciting possibilities for researchers as they may provide new insights into kinematic effects of water immersion.

2.7.2. **Comparative studies between land- and water-based exercise**

Numerous literature reviews have assessed intervention studies that compared the outcomes of water- and land-based exercise programmes in attempts to determine the efficacy of the environments (Bartels et al., 2007, Bidonde et al., 2014, Grande et al., 2014, McNamara et al., 2013). These authors agree that research is yet to determine which environment is more efficient for rehabilitation.
The review articles show a pressing need for high quality comparative studies in this domain. Most of the analysed research used on subjective outcome measures such as pain scales (Fransen et al., 2007, Han et al., 2015, Harmer et al., 2009), tests that were timed with stopwatches (Rahmann et al., 2009, Valtonen et al., 2011), isolated muscle tests measured with hand-held dynamometers (Lau et al., 2014, Zeni et al., 2013), and isolated ROM tests measured with goniometers (Han et al., 2015, Zeni et al., 2013). Although these tests have been scientifically validated in clinical settings (Bellamy et al., 1988, Weiss et al., 2010), their application in empirical research has been questioned (Hatfield et al., 2011). These researchers cautioned that subjective reports often produce skewed results, while others stressed that pain does not necessarily reflect functional outcomes (Christiansen et al., 2011, Christiansen et al., 2013, Farquhar et al., 2008, Mandeville et al., 2008). However, it must be acknowledged that subjective measures, such as perceived pain and functionality, are very important for client well-being and practitioners should always consider them when evaluating the efficacy of a rehabilitation programme.

Even motion capture testing has several known limitations, such as skin movement (della Croce et al., 1999) and confinement to laboratory settings (Saber-Sheikh et al., 2010). However, it provides objective information on human movement that subjective data cannot provide (McClelland et al., 2009). At the time of this review, only one investigation used motion capture to show kinematic differences in gait between the two environments (Abdul Jabbar et al., 2017). This shows that there is a pressing need for further comparisons using empirical methods to clarify the kinematic effects of water immersion.
2.7.3. Research protocols

This review has highlighted that considerable methodological differences exist in aquatic therapy research numerous times. The same issue is underlined in the literature (Heywood et al., 2017, Cuesta-Vargas and Cano-Herrera, 2014, Heywood et al., 2016, Kaneda et al., 2012b, Masumoto and Mercer, 2008), with substantial differences in water depth, temperature, activity, and intensity (Alberton et al., 2011, Barela et al., 2006, Masumoto et al., 2008) (Table 2.1). These factors are all known to affect biomechanical responses to exercise (Becker, 2009, Denning et al., 2012, Mooventh an and Nivethitha, 2014), and practitioners must currently navigate a labyrinth of research and be very careful when interpreting and comparing studies on the efficacy of aquatic-based exercise.

In addition, researchers have stressed that the details on exercise intensity, level of resistance, and progressions of aquatic-based rehabilitation programmes often are inadequately reported and have therefore questioned the validity of previous studies (Bandholm and Kehlet, 2012, Heywood et al., 2017). The lack of clearly established research protocols has resulted in conflicting reports and unanswered questions with regards to the efficacy, application, and effects of water-based exercise (Heywood et al., 2016, Bartels et al., 2007, Bidonde et al., 2014, Heywood et al., 2017). It is likely that this issue has affected the guidelines that are available for practitioners. There is a pressing need for future research to establish clear guidelines for equipment standards (such as motion capture and EMG), environmental variables (water temperature and depth), and research protocols (activity type and intensity) for aquatic-based exercise and research.
2.8. Summary

Aquatic therapy can undoubtedly aid in the rehabilitation of musculoskeletal, cardiovascular, and neurological conditions, as it provides a safe (and fun) alternative to conventional land-based protocols. Previous research has shown positive effects of water immersion on several systems of the human body, and a theoretical understanding exists of how water may affect our response to exercise. The existing biomechanical research in the aquatic environment has been conducted on gait, and the literature agrees that water-based walking is considerably different to walking overland. Indisputable differences in kinematics, kinetics, muscle activity, and balance requirements have shown that movement demands of the aquatic environment are substantially different from on land. From a biomechanical perspective, the aquatic environment offers several beneficial alterations to rehabilitation, including gravitational offloading, reduced pain, external resistance, and reduced joint forces.

Despite this, several issues exist in the literature and previous biomechanical reports still disagree on the effects of water-immersion. Different research protocols between studies have caused conflicting results, which is concerning as practitioners therefore lack clear guidelines for the application of water-based rehabilitation. The existing guidelines are based on subjective research and testing procedures that has been questioned in regard to their scientific validity. The understanding of kinematic adaptations to water immersion is inadequate and contradicting, likely because biomechanical research in the aquatic environment is challenging and require specialised equipment. However, inertial sensors offer new and exciting possibilities for researchers and practitioners, as they are able to record kinematic data during water immersion. Inertial sensors have been used in biomechanical research for several years, but despite this, researchers are just starting to
use them for water-based kinematic analyses, which will provide valuable information for practitioners.

This literature review has highlighted several biomechanical benefits of water-based rehabilitation, identified numerous gaps in the current knowledge, and provided exciting directions for future research. By bridging the gaps and gaining new insights into the roles of aquatic therapy in rehabilitation, new and improved protocols and procedures can be established to ensure optimal recovery for individuals with injuries and pathologies.
CHAPTER 3:

THE IMPLEMENTATION AND VALIDATION OF NANOTRAK INERTIAL SENSORS FOR KINEMATIC ANALYSES
THE IMPLEMENTATION AND VALIDATION OF NANOTRAK INERTIAL SENSORS FOR KINEMATIC ANALYSES

3.1. Inertial sensors in research

Inertial sensors have been used in biomechanical research for several years, and have more recently been used in the aquatic environment (Fantozzi et al., 2015, Macdermid et al., 2017). Numerous validation studies agree that inertial sensors are highly accurate when tracking human movements (de Magalhaes et al., 2015, Howcroft et al., 2013, Kavanagh and Menz, 2008, Espinosa et al., 2015, El-Gohary et al., 2017). However, researchers have cautioned that the quality of individual gyroscopes can differ, which may affect their relative accuracy (Luinge and Veltink, 2005). It can thus be recommended that researchers determine the relative accuracy of their sensors prior to data collection. Consequently, this Chapter introduces the sensors used throughout this research project and presents a validation analysis performed to establish the relative accuracy of the individual sensors.

3.2. Introducing the Nanotraks

This research project used Nanotrack sensors (Catapult Sports, Docklands, VIC), which are equipped with triaxial accelerometers and gyroscopes. Each Nanotrack unit measures 48x45x10 mm, weighs 26 grams, and samples at 100 Hz (Figure 3.1). Each individual sensor has an internal coordinate system, which determines the orientation of the acceleration (Kun et al., 2011). The sensors record vertical translations with the ‘up’ accelerometer, mediolateral translations with the ‘sideways’ accelerometer and anteroposterior translations with the ‘forward’ accelerometer.
Figure 3.1. A Nanotrak unit.
Image showing the dimensions of the Nanotrak sensor, and its internal coordinate system.

Rotations of the Nanotrak about a specific axis are recorded with the individual gyroscopes; ‘Yaw’ is recorded with Gyro1, ‘Roll’ with Gyro2, and ‘Pitch’ with Gyro3. Due to the individual internal coordinate system (Figure 3.1), the sensors’ placement determined which plane of movement was recorded with each gyroscope during the testing. To match the movement planes with the gyroscopes, all Nanotraks were attached to a book, and rotated about the known rotational axes, and the recorded data were used to cross-reference the rotations with the movements.

The Nanotraks do not contain magnetometers to reduce the internal drift (Chambers et al., 2015), and a 120-second static trial showed that a drift was present despite a lack of movement. This trial was conducted with the Nanotraks lying flat on a table with the ‘on/off’ switch facing upwards. This showed that the drift was different between individual sensors and between gyroscopes, as cautioned by previous researchers (Luinge and Veltink, 2005). However, there were similar trends between sensors as Gyro1 always displayed larger positive drifts, Gyro2 showed a small negative drift, and Gyro3 displayed
larger negative drifts (Figure 3.2). The different drift between the gyroscopes would require individual smoothing algorithms with a different frequency for each data set.

Figure 3.2. Screenshots from the proprietary software (Catapult Sprint, v. 5.1.7). Depicted is the raw trace from the three gyroscopes within one sensor in deg·s⁻¹ (left) and the integrated displacement (deg), without a filter applied to reduce the drift (right).

3.3. Validation of the Nanotrak sensors

3.3.1. Data collection

The validation study followed convention and compared the Nanotraks against a ten-camera optoelectronic system (Qualisys AB, Gothenburg, Sweden) (Khurelbaatar et al., 2015, Muro-de-la-Herran et al., 2014). Both systems simultaneously recorded the kinematics of twenty-five healthy university students who volunteered for participation (11 females: 1.643±0.060 m, 59.2±10.3 kg, 21.6±2.3 yrs., and 14 males: 1.771±0.082 m, 75.3±10.5 kg, 22.6±3.3 yrs.). The inclusion criteria ensured that all volunteers were healthy and physically active without lower-limb injuries during testing. Approval from the University human research ethics committee and written informed consent from all participants was obtained before testing (approval number S/15/742).
Before any data were collected, the Nanotraks were sent to Catapult Sports for recalibration. Based on previous research (Howcroft et al., 2013), the motions of the shanks, thighs, pelvis, and trunk were selected for the analysis. In order to avoid any measurement errors due to inter-sensor variability, the placement of each Nanotrak was consistent for every participant throughout the data collection (Table 3.1). Rigid sports tape was used to attach the sensors to the participants with the ‘on/off” button facing outward. The ten-camera optoelectronic system (500 Hz) tracked low-mass reflective markers attached to anatomical landmarks on the trunk, pelvis and lower limbs in the internationally standardised set up for motion capture analysis (Komnik et al., 2015). Based on previous recommendations for movements suitable for analysis with inertial sensors (Luinge and Veltink, 2005), the project used motions lasting less than 60 seconds, with a cyclic and slow nature.
Table 3.1. Description of the allocation of each Nanotrak unit during the data collection.

<table>
<thead>
<tr>
<th>Nanotrak number</th>
<th>Anatomical allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>9419</td>
<td>Lateral surface of the left thigh, halfway between the greater trochanter and the lateral femoral epicondyle.</td>
</tr>
<tr>
<td>9412</td>
<td>Lateral surface of the left shank, halfway between the lateral femoral epicondyle and the lateral malleolus.</td>
</tr>
<tr>
<td>9389</td>
<td>Over the spinous process of the third thoracic vertebra (T3).</td>
</tr>
<tr>
<td>9441</td>
<td>Lateral surface of the right thigh, halfway between the greater trochanter and the lateral femoral epicondyle.</td>
</tr>
<tr>
<td>9395</td>
<td>Lateral surface of the right shank, halfway between the lateral femoral epicondyle and the lateral malleolus.</td>
</tr>
<tr>
<td>9418</td>
<td>Over the sacrum at equal distance from the left and right posterior superior iliac spines.</td>
</tr>
</tbody>
</table>

Following a self-selected warm up, which consisted of a few minutes aerobic activity and dynamic stretches, the two systems simultaneously recorded the participants performing ten bodyweight squats, to a tempo indicated by a metronome (Lee et al., 2015). The metronome was set at 100 beats per minute, and participants performed one full repetition to eight beats, with four beats during the descent, and four beats during the ascent. In order to capture the natural technique for each participant, no instructions were provided regarding stance width or squat depth (Roos et al., 2014). A ten-second static trial, during which the participants stood in the anatomical position, preceded the squats in order to establish $0^\circ$ orientations for the sensors and identify any offset in sensor orientation (Fantozzi et al., 2015).

The sensors allocated to the shanks and thighs recorded flexion/extension movements with Gyro1, adduction/abduction movements with Gyro3, and internal/external rotation movements with Gyro2. Since the thoracic and sacral sensors were rotated $90^\circ$ about the transverse plane compared with the other sensors, anterior/posterior tilt motions were recorded with Gyro3, and obliquity motions with Gyro1.
The data were imported into a proprietary software, Catapult Sprint (version 5.1.7, Catapult Sports, Docklands, VIC) as a .raw file. This software allows the graphing of different variables from each individual data set, including the raw accelerometer and gyroscopic data, and the integrated gyroscopic data (displacement) (Figure 3.2). However, the software did not allow any additional data analyses, so the raw accelerometer and gyroscopic data from the squats had to be exported to a comma separated-value (.csv) file.

3.3.2. Data processing – introducing Nanochop

Since Catapult Sprint does not allow processing of the raw data, a special computer code was developed at the University of the Sunshine Coast for the data processing. The code (aptly named Nanochop), automatically processed each dataset, and mathematically integrated the velocity data to yield displacement. Nanochop performed a linear regression analysis on the integrated data to identify its slope, which provided an average rate of the drift (offset), which was subtracted from each datum within the raw dataset. This process yielded a ‘corrected’ set of angular velocity data that was then reintegrated to yield a periodic dataset of angular positions with no drift (Figure 3.3). Due to the different drift gradients between gyroscopes, the code processed each dataset individually.
Figure 3.3. Line graph of raw and filtered data before (top) and after integration (bottom). The data on the graph was recorded with Gyro 1 in sensor 9441 (right thigh).

In order to distinguish between the repetition cycles, Nanochop automatically identified the integrated dataset with the greatest amplitude and identified the locations at which each periodic motion started and ended, as defined by the maxima or minima. The identified start and end-points of all the periods were used to extract the individual, corresponding periods of data from each of the three un-smoothed, integrated datasets. Subsequently, each single gyroscope dataset produced ten individual datasets of periodic motions, which corresponded to ten repetitions of the squat. Nanochop then ‘chopped’ the time series into the individual repetitions for analysis (Figure 3.4).
Figure 3.4. Time-normalised squat displacement data for the Gyro1 in sensor 9441. Sagittal plane graphs of the ten repetitions starting at the bottom of the movement (0%), progressing through the concentric phase before reaching the top position around 50% of the movement and then descend back down.

The minima/maxima time points represented the start of each cycle (0%), and by this method, *NanoChop* successfully identified the repetitions of the squat movement from each sensor. During squat exercises, the sagittal plane movements are often used to define the start and finish of each repetition. The sagittal plane motions consistently had the largest amplitude during the squats, and the identification method used for *NanoChop* was able to correctly identify the repetitions. Later stages in the project required analyses of split squats and single-leg squats that have considerably larger balance demands than the squat, and thus sometimes resulted in larger frontal plane motions causing the identification process to fail. Adjustments in the coding for *NanoChop* was required and a function was added that allowed for manual selection of which gyroscope the ‘chopping’
was based on. Following the ‘chopping’, Nanochop time normalised each repetition cycle to 1000 data points to allow for comparisons.

When the data processing was completed, Nanochop automatically produced individual .xml files for each dataset, which were accessible with standard software, such as Excel or SPSS. Nanochop also produced summary .xml files, or ‘collections’, each containing all files from a single sensor, which simplified the comparison further. This automated procedure saved time during the analysis, and minimised the risk of manual errors associated with repetitive data manipulation.

Visual 3D (C-Motion Inc., Germantown, MD) was used to process the data from the optoelectronic system by applying a second order low-pass digital Butterworth filter (2 Hz) to the data. Standard Euler conventions were used to determine the global reference system for the optoelectronic data (Wu and Cavanagh, 1995); the positive X-axis from left to right from the participants’ perspective, the positive Y-axis directed forward, and the positive Z-axis pointing vertically. Researchers usually consider flexion, adduction, and internal rotation as positive rotations about the X, Y and Z-axis respectively (Wu et al., 2002). However, as the inertial sensors measured segmental rotations in space, and not rotations about an axis, their directional motions (clockwise or anticlockwise) defined their rotations. Standard Euler conventions for joint angles portray clockwise rotations as negative and anticlockwise as positive, so all left-hand side data were converted to comply with the standards (Horan et al., 2014, Wu et al., 2002).

It should be noted that important differences in the data processing protocols existed between the two systems; Visual 3D used the same filter for all data, and identified the repetition cycles based on the sagittal plane velocities. Nanochop smoothed the data with
a custom, variable-width, non-weighted box-smoothing algorithm that differed between datasets, and based the repetition cycles on peak displacement angles.

3.3.3. Coordinate system configuration of the Nanotraks

Each inertial sensor tracked the motions of the segment it was attached to, but due to the opposite rotational directions between left and right limbs, and between thighs and shanks, not all data reflected standard Euler conventions (Wu and Cavanagh, 1995). For example, Gyro1 in sensor 9441 (right thigh) recorded an anticlockwise (positive) rotation during the descending phase of the squat, while Gyro1 in sensor 9395 (right shank) simultaneously recorded a clockwise (negative) rotation (Figure 3.5). To allow comparisons between the sensors, all data were adjusted to comply with the Euler conventions. Thus, all kinematic data presented henceforth constantly show flexion, adduction, and internal rotation as positive (anticlockwise rotations).
Figure 3.5. The global (lab) and internal (sensors) coordinate systems. Note the opposite rotations of the thigh (anticlockwise) and shank (clockwise) sensors during the movement. The arrows indicate the global and internal coordinate systems (X – red, Y – green, and Z – blue).

3.3.4. Statistical analysis

The displacement data from both systems was time-normalised to 100 data points and compared by determining the typical error of the estimate (TEE), coefficient of variance (CV), and ICC (3,k) (Hopkins, 2000, Henriksen et al., 2004) for the ROM values. The ICC scores were ranked according to previous research where <0.40 indicated poor, 0.40<ICC<0.59 fair, 0.60<ICC<0.74 good, and >0.75 high repeatability between measures (Cicchetti, 1994, Shrout and Fleiss, 1979). Cohen’s $d$ determined effect sizes, with $<0.3$, $\leq 0.5$, $\leq0.8$ considered small, moderate and large effect respectively (Cohen, 1988, pp. 24-26). Time series plots of the mean displacement data ± the standard deviations portrayed the intersystem agreements throughout the squat task. Finally,
between-system comparisons of three data points (0%, 50%, and 100%) in each time series determined the sizes of the absolute and relative differences between the systems.

3.3.5. Results

The analysis showed high accuracy for sagittal plane ROM for all sensors except the 9418 (sacrum), as shown by high ICC scores coupled with low TEE and CV values (Table 3.2). Lower accuracy was also evident for ROM in the secondary movement planes, although it was not consistently lower about the Z-axis.

Table 3.2 Comparison of the ROM reported with the reference system and with the inertial sensors for the six segments across the planes of motion.

<table>
<thead>
<tr>
<th>Sensor/Segment</th>
<th>Qualisys ROM (°)</th>
<th>Nanotrak ROM (°)</th>
<th>Difference (°)</th>
<th>TEE (°)</th>
<th>CV (%)</th>
<th>ICC (3,k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9419 / Left thigh</td>
<td>X 71.57</td>
<td>71.32</td>
<td>0.25</td>
<td>3.18</td>
<td>5.11</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Y 10.29</td>
<td>14.64</td>
<td>-4.35</td>
<td>6.02</td>
<td>76.49</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Z 13.37</td>
<td>9.19</td>
<td>4.18</td>
<td>4.05</td>
<td>55.60</td>
<td>0.31</td>
</tr>
<tr>
<td>9412 / Left shank</td>
<td>X 22.46</td>
<td>26.32</td>
<td>-3.86</td>
<td>1.78</td>
<td>8.53</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Y 9.75</td>
<td>9.64</td>
<td>0.11</td>
<td>3.47</td>
<td>45.95</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Z 4.26</td>
<td>4.18</td>
<td>0.08</td>
<td>2.27</td>
<td>76.01</td>
<td>0.51</td>
</tr>
<tr>
<td>9489 / Thorax</td>
<td>X 36.41</td>
<td>34.99</td>
<td>1.42</td>
<td>2.22</td>
<td>6.90</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Y 1.78</td>
<td>1.78</td>
<td>0.00</td>
<td>0.71</td>
<td>53.54</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Z 1.66</td>
<td>2.52</td>
<td>-0.86</td>
<td>1.15</td>
<td>51.66</td>
<td>0.11</td>
</tr>
<tr>
<td>9441 / Right thigh</td>
<td>X 70.75</td>
<td>67.08</td>
<td>3.66</td>
<td>3.45</td>
<td>5.60</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Y 9.70</td>
<td>13.21</td>
<td>-3.51</td>
<td>3.97</td>
<td>57.68</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Z 12.44</td>
<td>7.14</td>
<td>5.30</td>
<td>3.08</td>
<td>45.50</td>
<td>0.61</td>
</tr>
<tr>
<td>9395 / Right shank</td>
<td>X 23.66</td>
<td>26.06</td>
<td>-2.40</td>
<td>2.47</td>
<td>10.29</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Y 8.65</td>
<td>10.15</td>
<td>-1.51</td>
<td>3.14</td>
<td>55.56</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Z 9.17</td>
<td>4.99</td>
<td>4.18</td>
<td>3.00</td>
<td>52.16</td>
<td>0.53</td>
</tr>
<tr>
<td>9418 / Sacrum</td>
<td>X 21.12</td>
<td>17.24</td>
<td>3.88</td>
<td>8.09</td>
<td>59.44</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Y 2.43</td>
<td>3.47</td>
<td>-1.03</td>
<td>1.63</td>
<td>86.37</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Z 2.93</td>
<td>4.64</td>
<td>-1.71</td>
<td>3.63</td>
<td>102.57</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

ROM – range of motion, TEE – typical error of the estimate, CV – coefficient of variance, ICC – intraclass correlation

Similarly, the sagittal plane plots showed excellent intersystem agreements for both velocity and displacement for all sensors except the sacrum (Figure 3.6). The secondary
planes showed inconsistencies in the agreement between the systems with slightly lower accuracy than the sagittal plane (Figure 3.7 and 3.8). All gyroscopes showed values similar to the reference system around 50% of the movement, regardless of sensor allocation. The analysis of the discrete values reported with each system at the three time points provided an additional insight into the sensors relative accuracy (Table 3.3).
Figure 3.6. Mean and standard deviation for sagittal plane displacement and velocity reported with both systems.
Figure 3.7. Mean and standard deviation for frontal plane displacement and velocity reported with both systems.
Figure 3.8. Mean and standard deviation for transverse plane displacement and velocity reported with both systems.
<table>
<thead>
<tr>
<th>Time</th>
<th>X (Gyro1)</th>
<th>X (Gyro1)</th>
<th>X (Gyro3)</th>
<th>X (Gyro1)</th>
<th>X (Gyro1)</th>
<th>X (Gyro3)</th>
<th>X (Gyro3)</th>
<th>X (Gyro3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\overline{X}_{\text{diff}})</td>
<td>(d)</td>
<td>% Diff</td>
<td>(\overline{X}_{\text{diff}})</td>
<td>(d)</td>
<td>% Diff</td>
<td>(\overline{X}_{\text{diff}})</td>
<td>(d)</td>
</tr>
<tr>
<td>0%</td>
<td>0.29</td>
<td>0.02</td>
<td>0.6</td>
<td>3.83</td>
<td>0.50</td>
<td>12.1</td>
<td>-0.37</td>
<td>-0.04</td>
</tr>
<tr>
<td>50%</td>
<td>0.03</td>
<td>0.00</td>
<td>0.2</td>
<td>0.27</td>
<td>0.04</td>
<td>2.6</td>
<td>-0.15</td>
<td>-0.02</td>
</tr>
<tr>
<td>100%</td>
<td>-0.17</td>
<td>-0.01</td>
<td>0.3</td>
<td>3.36</td>
<td>0.44</td>
<td>13.0</td>
<td>-0.26</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>Y (Gyro2)</td>
<td>Y (Gyro3)</td>
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Diff – difference, \(\overline{X}\) - mean, \(d\) – Cohen’s \(d\) effect size
3.3.6. Discussion

The analysis showed that 3D kinematic data recorded with Nanotrak inertial sensors is comparable to that recorded with a Qualisys motion capture system, despite considerable differences in data processing. The results showed that the intersystem agreements differed both between individual sensors and between individual gyroscopes. The former has been highlighted in previous research (Luinge and Veltink, 2005), although the latter has not been highlighted. These findings support the recommendation of conducting a validation analysis prior to data collection, while also providing valuable information regarding the relative accuracy of each sensor in the three planes of motion.

When the gyroscopic data is desired for research, a primary benefit of inertial sensors is that they are less sensitive to precise allocation than motion capture systems as the rigid segments rotates at the same velocity (Ertzgaard et al., 2016, Ishigaki et al., 2011, Takeda et al., 2009). This is encouraging as careful allocation can be very time-consuming and perhaps impractical for practitioners. However, due to different relative accuracy between the individual gyroscopes, practitioners and researchers should ensure the sensors consistently record the same segment between testing occasions whenever movements are monitored over time.

The Nanotraks were most accurate for tracking sagittal plane movements, and the analysis showed agreements similar to those reported in previous research (Ohberg et al., 2013, Qi et al., 2015, Ertzgaard et al., 2016). For the transverse plane ROM, the Nanotraks’ ICC scores (<0.70) and TEE (>1.50) indicated poor to moderate accuracy, and contrary to previous research (Ertzgaard et al., 2016, Ohberg et al., 2013), the transverse plane was not consistently the least accurate. Similarly, the sensors did not consistently report larger or smaller ROM than the reference system, which possibly indicated different quality
between individual gyroscopes (Luinge and Veltink, 2005). This further supports the notion of consistent sensor allocation during practical applications, and that comparison of data collected with different sensors warrants caution.

The statistical analysis showed that the intersystem agreements appeared to be poor for motions in the secondary planes. However, closer examination revealed that absolute differences between the systems were very small, particularly in the transverse plane where the movements were small and slow, the small differences in the data became statistically significant. Analysis of the discrete data showed small effect sizes ($d<0.5$) for most gyroscopes and the relative differences were often less than 10% of the total movement. Despite some gyroscopes showing moderate effect sizes ($d\leq0.66$) with relative differences of up to 18%, the largest absolute difference was $5.52^\circ$. This is a common measurement error when using equipment such as goniometers (McGann et al., 2013, Williamson and Andrews, 2001), and is within a generally accepted range for measurement errors in clinical and practical settings. Researchers and practitioners could therefore question the clinical relevance of these small differences.

The excellent agreement of all gyroscopes around the midpoint of the movement (50%) was a consistent observation, regardless of the axis of rotation. This time point represented the top position of the squat where the participants reinitiated the descending phase of the next repetition. As none of the previous validation studies published time series plots, this has not been reported previously, and the cause of this is difficult to determine. Researchers have proposed a link between movement speed and sensor accuracy (Lai et al., 2008, Mayagoitia et al., 2002), and noted that inertial sensors re-establishes their accuracy when temporarily held in a semi-static condition with minimal rotations (O'Donovan et al., 2007). Perhaps the sensors were reset at this time point due
to a temporarily decreased velocity and semi-static condition occurred while the ‘Up’ accelerometers were also aligned with gravity. If the agreement is dependent on movement speed and minimal rotations alone, it would also be excellent at the bottom of the movement (0 and 100%). As this was not the case, it appeared that the sensors also were required to align with gravity. The accuracy was perhaps determined by both movement speed and sensor orientation, as the accuracy was better where the slope of the displacement curve (rate of change) was flatter, and the sensor was aligned with gravity. This hypothesis requires future research, but these findings support previous research (Luinge and Veltink, 2005) that inertial sensors may necessitate relatively strict movement protocols for accurate tracking.

The sacral sensor showed poor agreements with the Qualisys system even in the sagittal plane, despite previous research having reported high accuracy for sensors attached to the sacrum (Kavanagh and Menz, 2008, Saber-Sheikh et al., 2010, Cutti et al., 2010). The allocation of the sacral sensor was based on the Outwalk protocol for kinematic analyses using inertial sensors (Cutti et al., 2010). However, the poor agreement indicated that the systems might have tracked different motions with the sensor tacking the sacrum, and the motion capture system tracking the pelvis. There are slight differences between the motions of these segments (Cibulka et al., 1998), which might have disallowed direct comparisons. In addition, motion capture systems require three markers allocated to each segment in order to track its motions accurately (Young-Hoo, 2008), and it seems unlikely that a single sensor can track the motions of the sacro-pelvic complex accurately. This is a potential issue that has not been highlighted in the literature, and previous reports provide vague descriptions of the allocation of sensors to the sacrum (Boonstra et al., 2006, Ohberg et al., 2013). It was likely that a combination of variables caused poor
intersystem agreements for the sacral sensor, but future research should perhaps assess alternate methods to use inertial sensors to track the motions of the pelvis.

3.4. Calculation of relative angles

Inertial sensors measure movements of the segment to which they are attached. The angles yielded though integration with Nanochop are absolute angles and therefore indicate the movements of the segments in space (Boonstra et al., 2006). If the absolute angles of two adjacent segments are known, simple mathematics can calculate the relative joint angle between the segments. The following equations were used to calculate the angles between the sensors on the shank and thigh, the thigh and sacrum, and the sacrum and thorax. Henceforth, these angles are referred to as knee, hip, and trunk angle respectively¹:

\[
\theta_{knee} = \theta_{shank} + (180 - \theta_{thigh})
\]

\[
\theta_{hip} = \theta_{sacrum} + (180 - \theta_{thigh})
\]

\[
\theta_{trunk} = \theta_{thorax} + (180 - \theta_{sacrum})
\]

Throughout this thesis, when references are made to these angles obtained with the inertial sensors, the angles were calculated using these equations.

3.5. Limitations

Although great care was taken when identifying the anatomical landmarks for sensor allocations, there are slight risks of discrepancies between participants as the sensors were

¹ It is acknowledged that the relative angles calculated using the above equations does not necessarily represent accurate joint angles but are accurately representing the angles between orientations measured by two adjacent inertial sensors.
attached manually. The selected landmarks (Table 3.1) were carefully identified in manners that were similar to previous research using both optoelectronic systems (Komnik et al., 2015), inertial sensors (Nuesch et al., 2017), and in clinical settings. Unfortunately, this method does not guarantee consistency in sensor allocation as a slight rotation of a sensor, even when allocated correctly, may cause an offset, and affect the recording. However, as highlighted previously (section 3.3.6), as this project used gyroscopic data, the sensors were less sensitive to small inconsistencies in allocation than other motion capture systems (Ertzgaard et al., 2016), and the static trial prior to the data collection allowed identification of offsets associated with sensor allocation. Further, as discussed previously (section 3.3.6), the ability of a single sensor to track the motions of the sacro-pelvic complex accurately may be questioned, and deserves attention in future research. Regardless, the decision to allocate a sensor to the sacrum was based on previous research (Kavanagh and Menz, 2008, Saber-Sheikh et al., 2010). Finally, it is important to emphasise that the data from this analysis should not be generalised for other sensor models, and this validation analysis only applies to the six Nanotraks included in this project.

3.6. Conclusions

Despite considerable differences in data processing between NanoChop and Visual 3D, the intersystem agreement was excellent in the sagittal plane, and had acceptable accuracy in the secondary planes of motion. The noticeably lower agreements in the secondary planes were likely because of small ROM, which made small differences statistically significant. Importantly, the quality of the individual sensors was considerably different, so kinematic analyses conducted with inertial sensors warrant caution and allocation consistency between testing occurrences. Similar to other motion capture systems, the
Nanotraks appeared to be sensitive to movements of skin and clothing, which further highlighted the need for appropriate and thorough protocols. Overall, the Nanotrak sensors used in this project were able to track human movement accurately during bodyweight squats and provided data that was comparable to the optoelectronic reference system.
CHAPTER 4:

QUANTIFYING KINEMATIC DIFFERENCES BETWEEN LAND AND WATER DURING SQUATS, SPLIT SQUATS, AND SINGLE-LEG SQUATS IN A HEALTHY POPULATION
QUANTIFYING KINEMATIC DIFFERENCES BETWEEN LAND AND WATER DURING SQUATS, SPLIT SQUATS, AND SINGLE-LEG SQUATS IN A HEALTHY POPULATION

Please note: This chapter presents the first published research article from this project. It was published in *PLoS One* in August 2017 ([PLoS One. 2017;12(8):e0182320. doi: 10.1371/journal.pone.0182320](https://doi.org/10.1371/journal.pone.0182320)). The published version is attached in Appendix 10.2.

4.1. Abstract

Aquatic exercises can be used in clinical and sporting disciplines for both rehabilitation and sports training. However, there is limited knowledge on the influence of water immersion on the kinematics of exercises commonly used in rehabilitation and fitness programs. The aim of this study was to use inertial sensors to quantify differences in kinematics and movement variability of bodyweight squats, split squats, and single-leg squats performed on dry land and while immersed to the level of the greater trochanter. During two separate testing sessions, 25 active healthy university students (22.3±2.9 yr.) performed ten repetitions of each exercise, while tri-axial inertial sensors (100 Hz) recorded their trunk and lower body kinematics. Repeated-measures statistics tested for differences in segment orientation and speed, movement variability, and waveform patterns between environments, while coefficient of variance was used to assess differences in movement variability. Between-environment differences in segment orientation and speed were portrayed by plotting the mean difference ±95% confidence intervals (CI) throughout the tasks. The results showed that the depth of the squat and split squat were unaffected by the changed environment while water immersion allowed for a deeper single leg squat. The different environments had significant effects on the sagittal plane orientations and speeds for all segments. Water immersion increased the
degree of movement variability of the segments in all exercises, except for the shank in
the frontal plane, which showed more variability on land. Without compromising
movement depth, the aquatic environment induces more upright trunk and shank postures
during squats and split squats. The aquatic environment allows for increased squat depth
during the single-leg squat, and increased shank motions in the frontal plane. Our
observations therefore support the use of water-based squat tasks for rehabilitation, as
they appear to improve the technique without compromising movement depth.

4.2. Introduction

The benefits of aquatic-based exercise constitute its common practice in rehabilitation,
recovery, and fitness (Bidonde et al., 2014, Costa et al., 2011, Takahashi et al., 2006). The reduced joint loading and external resistance provided by the buoyancy and viscosity
are easily modifiable by manipulation of immersion depth (Harrison et al., 1992), and
practitioners can adjust the degree of offloading and resistance to progress exercises in a
safe manner. Further, researchers suggest that viscosity slows movements and therefore
prolongs the time an individual has to regain postural control and that buoyancy provide
additional support (Resende et al., 2008, Geigle et al., 1997), which suggest that balance
in the aquatic environment also is likely affected by water depth (Bressel et al., 2016,
Louder et al., 2014). The adaptability of aquatic exercise protocols means that they are
suitable for exercise and rehabilitation of individuals with injury and pathology, as well
as older and obese populations, where full gravitational loading may be inappropriate
(Harrison et al., 1992). Previous research has indicated differences in muscle activity,
joint angles, and movement speeds when walking and running in water (Kaneda et al.,
2012b, Orselli and Duarte, 2011) and during isolated knee flexion-extension tasks
(Poyhonen et al., 2001b). However, the influence of the aquatic environment on closed-
chain exercises often prescribed for rehabilitation and fitness programs has not been well researched. This has left practitioners without a comprehensive understanding of kinematic effects of water immersion on prescribed exercises, which potentially reduces their ability to ensure optimal efficacy of water-based exercise.

The squat exercise (and its variants) is common to numerous aquatic and land-based rehabilitation programs, with these movements described as functional, closed-chain exercises that involve all major muscles and joints of the lower body (Bartels et al., 2007, Schutz et al., 2014). In addition to the traditional squat, research supports the prescription of the split squat (SS) and single-leg squat (SLS), and their land-based kinematics are well documented in the literature (Schutz et al., 2014, Escamilla, 2001). It is likely that squat kinematics differs, as is the case with walking and running (Kaneda et al., 2012b, Orselli and Duarte, 2011), when performed in water rather than on land. However, despite the significant body of literature on the land-based kinematics of these exercises, their water-based kinematics are not well investigated. To provide practitioners with the understanding to ensure optimal application of aquatic exercises, further examination of how the two environments affect squat kinematics is needed.

The aquatic environment is often considered a safer exercise setting than land, based on the fact that the density of the water slows movement speeds (Miller et al., 2007, Resende et al., 2008), and thereby has been suggested to improve control and stability of movements (Kaneda et al., 2012b). Further, researchers have shown that slower squatting speeds reduce shear and compressive joint loads on the spine and knees (Schoenfeld, 2010, Vakos et al., 1994). Additionally, it is important to control and monitor movement speeds during the ascending and descending phases of an exercise as they induce different muscular responses (Isner-Horobeti et al., 2013, LaStayo et al., 2003), and biomechanics
(McKean et al., 2010b, Flanagan et al., 2003). In water, the buoyancy force decreases the loading during the descending phase, and during the ascending phase, it provides lifting assistance (Roth et al., 2006), while the viscosity also provides additional resistance (Martel et al., 2005). Accordingly, water immersion likely affects the kinematics of the phases differently, although at the time of submission, this has not been reported in the scientific literature, and increased understanding of these effects would be useful practitioners when employing the aquatic environment.

Water-based exercise creates numerous eddies, waves, and currents around the body, causing the accompanying forces to change constantly in response to body movements and water depth. According to the concepts described in dynamic systems theory (Davids et al., 2003), exercising immersed in this ever-changing environment will require the body to adapt and thus increase its movement variability. While research in this area is still rather new, exercises that increase movement variability are probably beneficial as reduced variability linked to overuse injuries (Hamill et al., 2012). Further, as injured populations commonly portray reduced adaptability (Davids et al., 2003), increased movement variability is likely advantageous for rehabilitation programs. However, despite research on movement variability have espoused its roles in athletic performance and rehabilitation, its effect in the aquatic environment has received little attention and remains largely unreported.

The growing use of aquatic exercises in training and rehabilitation, coupled with the relative absence of objective research on the influence of the aquatic environment on movement patterns for squats and squat-based exercises were the key motivations for this study. Accordingly, this study aimed to (1) quantify differences in segmental orientation and speed between land- and water-based squats, SS and SLS during the ascending and
descending phases, and (2) examine whether the aquatic environment affects the degree of movement variability of the exercises when performed by individuals without previous exposure to water-based squats. It was hypothesized that water immersion would change the segmental orientations and reduce the speeds compared to land, and that the degree of movement variability would increase due to unfamiliar environmental constraints.

4.3. Materials and methods

4.3.1. Participants

Twenty-five healthy university students (11 females: 1.64±0.06 m, 59.2±10.3 kg, 21.6±2.3 yrs., and 14 males: 1.77±0.08 m, 75.3±10.5 kg, 22.6±3.3 yrs.) volunteered for participation in this study. The participants were healthy at the time of testing and had at least 3 years’ experience in gym-based activity with no prior exposure to aquatic-based exercise. Inclusion criteria ensured that participants were without any past lower limb surgeries and injury free at the time of testing. Self-reported leg dominance was recorded (left=2, right=22) by determining participants preferred kicking leg, and written informed consent was obtained prior to any testing in accordance with the approval from the University of the Sunshine Coast Human Research Ethics Committee.

4.3.2. Instrumentation

The use of inertial sensors for biomechanical analyses provide an accurate and portable method for analyzing segmental kinematics and has the advantage of being readily adaptable for use both on land and in water (Ertzgaard et al., 2016, Ohberg et al., 2013). Few researchers have used inertial sensors to assess underwater kinematics, however a recent study reported sagittal and frontal plane kinematics for the lower limbs and trunk during underwater gait (Fantozzi et al., 2015). The inertial sensors used in this study were
waterproof and contained tri-axial accelerometers and gyroscopes (100 Hz) (Nanotrak, Catapult sports, Docklands, VIC). Each sensor has its own internal coordinate system and with the direction of segmental rotations differing both between left and right sides and between segments during the exercises (that is in the sagittal plane, the left thigh and right shank rotated in an anticlockwise direction during the ascending phase, while the left shank and right thigh rotated in a clockwise direction), the individual sensors differed in recording positive or negative values. Therefore, the data were adjusted so recordings from all sensors complied with a global coordinate system with the positive Y-axis directed anteriorly, the positive X-axis directed from left to right and the positive Z-axis pointing vertically.

Four sensors were attached bilaterally to the participant’s lateral mid-thigh and shank, halfway between the proximal and distal joint centers and one sensor was positioned over the spinous process of the third thoracic vertebra. The allocation of the sensors was measured to be at equal distance from the proximal and distal joint centers for the lower body segments to ensure consistency, although researchers have highlighted that a considerable advantage of portable systems is that they are less sensitive to exact placement on the segments (Ertzgaard et al., 2016). To measure squat depth, one additional sensor was attached to the sacrum, at equal distance from the posterior superior iliac spines. Before each exercise, a static calibration was performed with the participant standing still in an upright posture for ten seconds to establish 0° orientations for the sensors and identify any offset in sensor allocations (Fantozzi et al., 2015). Each sensor was attached to the participant using 38mm rigid sports tape, and to avoid any intra-sensor bias, the same sensor was allocated to the same segment for all participants.
4.3.3. Experimental protocol

Each participant attended two testing sessions; one land-based and one water-based, both with identical testing protocols and occurring within one week of each other. Following a self-selected warm up that included a few minutes of aerobic activity, stretches and between five and ten practice repetitions of each exercise for familiarization of the protocols and environments, the participants performed ten repetitions of the exercises; squat, SS, and SLS. All unilateral exercises were performed on both legs however, to avoid any bilateral asymmetries associated with leg dominance (Newton et al., 2006), the dominant leading leg data is presented.

In order to capture each participants’ natural technique, and to ensure consistency between environments, no instructions were provided concerning foot positions or depth of the exercises (Roos et al., 2014). Participants were instructed to maintain their elbows extended, palms facing down, arms straight and horizontal during all exercises, and during the SLS, the contralateral leg was flexed at the knee to between 70-90°, and kept behind the participant during the task. Participants performed all exercises to a tempo indicated by a metronome (Lee et al., 2015, Lynn and Noffal, 2012) set at 100 beats a minute with four beats during the ascent and four beats during the descent, and were allowed between one and two minutes rest between the exercises.

No randomization of the order of the exercises was used to allow the same task familiarization for each participant, and due to the natural sequencing progression of the movements. Also, as this was an inaugural study on kinematics the traditional approach is to use a homogeneous sample to begin with and future research should assess other populations. We based this on the current needs and demands of the local population to make the study relevant and practical.
The second testing session occurred at an outdoor pool complex and took place within one week of the first session. To ensure a consistent water depth and allow between-subject comparisons, participants performed the exercises on a platform of adjustable height, which was set so the water depth was level with the greater trochanter on each individual participant. The pool was of Olympic standard that was 1.35 meters deep without the platform, and had lane-ropes in place to reduce water turbulence, and the water temperature was maintained at 29.1°C±1.0 during the testing period.

4.3.4. Data processing

The data from the inertial sensors was imported using Catapult Sprint (version 5.1; Catapult sports, Docklands, VIC), and the raw data from the gyroscopes (angular velocity in three spatial dimensions) was extracted into a comma-separated value (.csv) file. Each of the three gyroscope datasets were integrated and any gyroscopic drift was quantified with linear regression; the raw datasets were corrected for the drift and integrated again to yield non-drifting datasets of angular displacement as a function of time.

The start and completion times of each repetition were identified from the minima and maxima of the dataset, which had the largest amplitude of motion. This dataset was smoothed with a custom, variable-width, non-weighted box-smoothing algorithm, so that all true minima and maxima (peak angles) were correctly identified and false peaks due to noise were ignored, with a minimum amount of smoothing (excessive smoothing has potential to slightly “shift” maxima and minima). The individual repetitions in each of the three datasets were extracted, collated into sets, and processed. The data were processed so that the start of each cycle occurred at the bottom of the movement where the peak angle was most obvious, so for the analysis, the start of the movement (0%) represented the bottom of each task (the point of peak knee flexion), and subsequently,
the top of the movement (point of peak knee extension) occurred around 50% (Figure 4.1). Further, the accelerometer data from the sacral sensor was used to determine its vertical displacement, which indicated movement depth (McKean et al., 2010b).
Figure 4.1. Photographs of the exercise protocol employed during the water-based testing sessions.
Participant performing the three exercises during immersion to highlight the top (0 and 100%) and bottom (50%) position of the three exercises and the position of the contralateral leg during the SLS.
4.3.5. Data analysis

The data for each of the ten repetitions was time-normalized to 1000 data points and imported to Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) for comparison and analysis. As previous research has questioned the accuracy of transverse plane data recorded with inertial sensors (Fantozzi et al., 2015, Ohberg et al., 2013), only sagittal and frontal plane kinematics was analyzed in this study. All statistical analyses were performed with IBM SPSS software version 22 (IBM, New York, NY). Absolute values were used for all velocity data to allow comparisons between environments throughout both the ascending and descending phases, so it is portrayed as non-directional speed of movement.

To identify differences between the phases of movement, time series data for displacements and speeds were divided into four phases; the early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%). Kinematic variables of interest included the average angular displacement and speed for each phase, total range of motion, and peak velocities. The movement depths were tested for covariance, and all kinematic variables were tested for compliance with the assumptions of an analysis of covariance. Wherever the assumptions were met, an analysis of covariance determined significant differences between the environments, and elsewhere, a repeated measures one-way analysis of variance was used.

To allow comparison of environmental differences in displacements and movement speed throughout the tasks, the differences between the group mean waveforms ±95% confidence limits (95% CI) were plotted as a time series (Stuelcken et al., 2010, Schache et al., 2003) for the full movements (0-100%). The 95% CI was calculated using the
critical $t$-value and degrees of freedom, and wherever it (shaded areas on figures) did not include zero, the environments were considered to have a significant effect on the variable. The mean differences were calculated as the land-based values less the aquatic-based values, thus a shaded area above zero indicated a trend of higher recorded values on land, and vice versa. Variability of the individual waveforms was analyzed by calculating the coefficient of variance (CV), with additional calculations analyzing variability in pattern (CV$_P$) and offset (CV$_O$) (O'Dwyer et al., 2009) in both environments. The latter two techniques have been applied successfully to cyclic data and have been shown to be more sensitive to changes in movement patterns than the more traditional CV analysis techniques (O'Dwyer et al., 2009, Steele et al., 2014). To portray the influence of the changed environment on variability, the differences between environments are presented as the land-based percentage less the pool-based percentage. Effect sizes were calculated and ranked using the method developed by Cohen (1988, pp. 24-26), with scores $d>0.2$ considered small, $d>0.5$ moderate and $d>0.8$ considered large effect. The alpha level was set at $p<0.05$.

4.4. Results

The analysis showed that immersion in water did not significantly affect the depth of the squat (land: 0.43±0.18 m, pool: 0.45±0.15 m, $p=0.700$, $d=0.12$) and SS (land: 0.34±0.06 m, pool: 0.38±0.09 m, $p=0.091$, $d=0.53$). However, the environment had a significant effect on the depth of the SLS (land: 0.22±0.09 m, water: 0.31±0.11 m, $p=0.006$, $d=0.89$). The analysis of the angular displacement time series showed that water immersion had moderate and large effects on all segments in the sagittal plane during at least one exercise (Figure 4.2). Though, only the movements of the shank segment were affected
in the frontal plane (Figure 4.3). *Moderate* and *large* effects were also observed in the movement speeds in the both planes of motion in all three exercises (Figure 4.4 and Figure 4.5). The waveforms also revealed differences in both orientation and speeds that differed between the phases when performing these exercises immersed in water.
Figure 4.2. Waveforms of the mean difference (±95% CI) of sagittal plane displacements for the three segments between land- and aquatic-based squats during the movements.

Differences between the group means (solid line) ±95% confidence limits (shaded area) for sagittal plane displacements for the thorax, thigh, and shank segments between land- and aquatic-based during the squat, split squat, and single leg squat throughout the movement. 95% confidence interval above zero indicates larger segmental inclination on land and vice versa. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%). α indicates a large environmental effect size at Cohen’s D >0.8, β indicates a moderate environmental effect size at Cohen’s D >0.5.
Figure 4.3. Waveforms of the mean difference (±95% CI) of frontal plane displacements for the three segments between land- and aquatic-based squats during the movements.

Differences between the group means (solid line) ±95% confidence limits (shaded area) for the thorax, thigh, and shank segments between land- and aquatic-based during the squat, split squat, and single leg squat throughout the movement. 95% confidence interval above zero indicates larger segmental inclination on land and vice versa. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%).  indicates a large environmental effect size at Cohen’s D >0.8,  indicates a moderate environmental effect size at Cohen’s D >0.5.
Figure 4.4. Waveforms of the mean difference (±95% CI) of sagittal plane movement speeds for the three segments between land- and aquatic-based squats during the movements.
Differences between the group means (solid line) ±95% confidence limits (shaded area) for the thorax, thigh, and shank segments between land- and aquatic-based during the squat, split squat, and single leg squat throughout the movement. 95% confidence interval above zero indicates faster segmental speed on land and vice versa. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%). α indicates a large environmental effect size at Cohen’s D >0.8, β indicates a moderate environmental effect size at Cohen’s D >0.5.
Figure 4.5. Waveforms of the mean difference (±95% CI) of frontal plane movement speeds for the three segments between land- and aquatic-based squats during the movements.

Differences between the group means (solid line) ±95% confidence limits (shaded area) for thorax, thigh, and shank segments between land- and aquatic-based during the squat, split squat, and single leg squat throughout the movement. 95% confidence interval above zero indicates faster segmental speed on land and vice versa. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%). α indicates a large environmental effect size at Cohen’s D >0.8, β indicates a moderate environmental effect size at Cohen’s D >0.5.
The CV analysis showed several *moderate* and *large* significant effects on the segments movement variability in both planes of motion, with CV values often larger in the aquatic environment (Table 4.1). Only the shank segment portrayed more variability on land in the frontal plane during the SLS. The individual CV values for each segment in the two environments are provided in the supplementary material (S4.1 Table). The overall range of motion and peak velocities were also affected by the changed environment, with the data presented in the supplementary material (S4.1 Table, and S4.2 Table).

Table 4.1. Difference in movement variability (%) between land and water for the segments during the three exercises.

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<td></td>
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<td></td>
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<td>-7.7</td>
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<td>-27.8</td>
<td>-6.6</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td>-6.8</td>
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<tr>
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<td>CVO (%)</td>
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<td>30.4</td>
<td>-4.2</td>
<td>-15.5</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>-7.4</td>
<td>57.1</td>
<td>-0.4</td>
<td>-18.4</td>
<td>-4.8</td>
</tr>
</tbody>
</table>

CV – Coefficient of variance, CV<sub>P</sub> – Coefficient of variance for pattern, CV<sub>O</sub> – Coefficient of variance for offset

Negative percentages indicate larger movement variability in the aquatic environment

* indicates significant difference between environments at P<0.05

<sup>a</sup> indicates *large* effect size at Cohen’s d >0.8

<sup>b</sup> indicates *moderate* effect size at Cohen’s d>0.5

4.5. Discussion

Our study shows that immersion in water alters squat, SS, and SLS trunk and lower body kinematics in young, healthy adults. These results support previous research on the influence of immersion in water on gait kinematics (Kaneda et al., 2012b, Fantozzi et al.,...
To the best of our knowledge, this is the first study to use inertial sensors to compare the kinematics of squat variations on land and in water. A key finding is that water immersion to the greater trochanter does not limit the depths of squats and SS, and allows participants to maintain a range of movement similar to that they typically use on land. However, the aquatic environment does allow performers increased squat depth during the SLS.

During squats and SLS, the sagittal plane orientation of the thorax was particularly affected by the immersion protocols (Figure 4.2). These changes were indicative of a more vertically aligned trunk posture throughout the movements, being particularly apparent closer to the bottom position of both tasks (0-25% and 75-100% in Figure 4.2). This is a positive find as research highlights the important role that maintaining an upright trunk during squats and lifting tasks has in minimizing spinal compressive loads and shear forces (Schoenfeld, 2010, Bazrgari et al., 2007), and decreasing reliance on passive structures for support (Schmitz et al., 2015). The more vertically aligned trunk posture in the aquatic environment is most likely an indication of the added support provided by the water coupled with the influence of the buoyant force acting up through the thorax.

Further, the forward inclination of the trunk during squats performed on land is no doubt a strategy to maintain balance, and the participants may feel unstable if they attempt to employ a more vertical trunk posture, as it shifts their center of mass backwards (Hof et al., 2005). Therefore, it appears the gravitational offloading and viscosity of the water reduces the performers’ reliance on their body position for stability and allows them to use a more upright trunk posture. Theoretically, the trunk posture employed in the aquatic environment during squats and SLS reduces spinal forces beyond what is already achieved with buoyancy, and provides a more stable movement with less reliance on the...
individuals’ balance skills. Our study assesses kinematic variables, so future research is needed to examine kinetic effects of water immersion during these exercises to provide additional understanding of the mechanical aspects of water-based exercise.

However, it remains important for practitioners to understand the kinematic effects of water immersion to assist in the prescription of exercises. For example, researchers have highlighted increased forward trunk inclination during squats in older populations and individuals with lower back pain (Sterud and Tynes, 2013, Fukagawa et al., 2012), so the upright posture in the aquatic environment is likely beneficial for these populations. These results suggest that practitioners can employ the aquatic environment to improve squatting depth while simultaneously minimize spinal loads and improving trunk orientation. Further, although the analysis showed moderate and large effect sizes on the frontal plane speed of the trunk during the squat between the environments, these differences are probably too small to be of clinical importance.

The additional support in the aquatic environment is also evident in more vertically aligned shanks during the squats and SS, especially during the deeper phases of the tasks as the performer can ‘sit back’ in the movement without compromising balance. Again, this is a positive find, as the upright shank positions are associated with reduced strain on the knees (Escamilla et al., 2008a). Contrary to the other exercises, the SLS had a slight, temporary increase in sagittal plane shank inclination in the aquatic environment during the ascending phase, which probably was associated with balance.

On land, participants employ a forward trunk inclination to maintain the center of mass within the base of support, but the supportive and offloading properties of the water allow them to maintain vertical trunk posture and instead shift their entire body forward (that is
increasing their shank inclination), without compromising balance. The buoyant force provided by the water would both reduce joint loading and offer lifting assistance during the ascending phase (Roth et al., 2006). Combined, this means that participants probably were less limited by muscle strength and balance when they performed SLS in water and were thus able to squat deeper. Research have previously reported different muscle activation patterns between land and water and suggested that the offloading and reduced movement speeds dictated the muscular responses (Barela et al., 2006). Future research is needed to assess muscle activity and kinetics during water-based squat tasks to determine neuromuscular responses to water immersion.

Unsurprisingly, our examination revealed faster sagittal plane movement speeds for the segments in the environment with larger movement range (Figure 4.4). However, when the ranges are similar, the speeds appear highly individual and the environmental effects differ throughout the movement phases, particularly for the thigh and shank. Although, there seems to be some tendency to faster speeds in water during the late ascent, which could be explained by the buoyancy force adding to the muscular force providing an upthrust (Heywood et al., 2016). These preliminary findings could indicate that practitioners can employ the aquatic environment to train movements their clients may be unable to perform on land, likely as a part of early rehabilitation. A reduced restriction of strength and balance would allow clients to perform exercises such as SLS will full range earlier in the water than what is possible on land.

Our data also reveal more frontal plane movements of the shank in the aquatic environment during the SLS and the descending phase of the squat (Figure 4.3). While the frontal plane speeds of both lower body segments show similar trends to the sagittal plane, few differences are large enough to be of clinical interest (Figure 4.5). Nevertheless,
lower body mediolateral alignment is an important consideration during squat performance as increased translation is linked to knee instability and injury (Escamilla, 2001).

Despite the aquatic environment often is considered unstable (Colado et al., 2013). It is possible that the properties of water can benefit balance through a few different features: First, the offloading reduce limitations by muscular strength for stability, second, slower movements provide increased time for postural corrections (Geigle et al., 1997, Resende et al., 2008), and third, it is possible that density and viscosity of the fluid can provide some support. The combination of these aspects could explain the increased frontal plane shank movements employed by our participants as they utilized the water to stabilize themselves while performing the exercises. Previous research suggests that the aquatic environment reduces muscle activity of prime movers due to gravitational offloading (Masumoto and Mercer, 2008), and similar trends are likely occurring in the stabilizing muscles, although further research is needed for confirmation. The practical implications of the increased frontal plane movements during water-based SLS require further examinations of whether it affects the leg muscle activity, and whether any changes are beneficial for rehabilitation.

Reduced reliance on muscle force for stability can also explain the increased movement variability in the aquatic environment. Increased movement variability indicates that the performer adapts to the constant movements of the surrounding water. Previous research suggests that injury and pain changes movement patterns by reducing movement variability (Lamoth et al., 2006), leaving the individual with decreased ability to adapt to surroundings and consequently, reduced functionality (Davids et al., 2003). The increased movement variability during these squat exercises in the aquatic
environment can potentially assist in restoring the adaptability in an injured population, further supporting its use in rehabilitation.

Interestingly, during the SLS the shank portrays less variability in the frontal plane while in water but maintains a larger movement range. This could be linked to the strategy of using the vicious fluid for balance that we proposed earlier. Performers would not be able to apply this strategy on land under full gravitational loading as no additional support is provided by the air. It is also possible that the balance strategies employed on land are more variable than those applied in water, however future research should examine this further. Comparative research on movement variability in aquatic settings is lacking, thus preventing further comparisons and conclusions regarding its clinical significance.

One limitation of our study is that although our sensor allocation was thorough, there is a risk of slight discrepancies in sensor positions between testing sessions and participants. However, our method of landmark identification is the same as is used in practical settings and previous research and the risk of errors should be further reduced with the static capture (Fantozzi et al., 2015). Further, the sensors used in this study did not contain magnetometers, which potentially increased their susceptibility to internal drift (Ohberg et al., 2013), but the analysis compared only data recorded with the same sensor in the two environments, and any drift remaining after the filtering should be the same within each sensor. Additionally, we acknowledge that the greater variability in the water may be attributed to the participants performing the exercises in a novel environment. All participants were experienced in performing the exercises on land, but had not performed the exercises in water prior to the day of testing. It is possible that the inexperience of the participants increased their movement variability in the water. Future research should
assess if habituation decreases the movement variability in the aquatic environment to further the research into this area.

Further, researchers have shown kinematic differences between males and females during squatting tasks (Nakagawa et al., 2012), and changing the depth of immersion can potentially also affect the kinematics of the exercises (Colado et al., 2013). However, the small sample size of this study did not allow for analysis of differences between sexes and we limited our analysis to one depth however, we highlight that future research should assess if water immersion affects the kinematics differently between sexes, and quantify effects of different water depths on kinematics.

4.6. Conclusion

This study reveals several kinematic differences between land and water when healthy adults perform bodyweight squats, SS and SLS. Our data shows that immersion in water to the greater trochanter does not limit the overall movement range or depth during the squat and SS, while it allows performers to achieve greater depth during the SLS. The aquatic environment encourages more vertically aligned trunk and shank segments with an overall smaller range of motion, which consequently decreases the speed of the segments. We also observe increased motions in the frontal plane during water-based SLS, and that all three exercises show increased movement variability in water. This study also highlights the need for further research into the applications of water-based squatting tasks in order to provide practitioners with a more comprehensive understanding of movement mechanics in water. Combined, the findings of our study highlight the suitability of aquatic-based squats, SS and SLS for lower body rehabilitation as water
immersion emphasizes improved technique without changing the overall movement pattern.

4.7. Acknowledgements

The authors would like to thank all participants who volunteered for participation in this study.

4.8. Supplementary material
<table>
<thead>
<tr>
<th></th>
<th>Shank</th>
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<th>Thorax</th>
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<tbody>
<tr>
<td></td>
<td>CVP (%)</td>
<td>CVO (%)</td>
<td>CV (%)</td>
</tr>
<tr>
<td>Squat: Land</td>
<td></td>
<td></td>
<td></td>
</tr>
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</tr>
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</tr>
<tr>
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<td>23</td>
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<td>18.3</td>
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CV – Coefficient of variance, CVp – Coefficient of variance for pattern, CVO – Coefficient of variance for offset
Table S4.3. Mean (SD) range of motion and the movement variability (%) between the two environments during the concentric phase of the movement.

<table>
<thead>
<tr>
<th></th>
<th>Shank</th>
<th>Thigh</th>
<th>Thorax</th>
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<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>X</td>
</tr>
<tr>
<td><strong>Squat</strong></td>
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<tr>
<td>Land (°)</td>
<td>25.7 ± 8.3</td>
<td>10.7 ± 6.1</td>
<td>68.7 ± 10.5</td>
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<td>Pool (°)</td>
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<td>70.4 ± 14.2</td>
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</tr>
<tr>
<td>Land (°)</td>
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<td>49.5 ± 8.8</td>
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<td>Pool (°)</td>
<td>25.0 ± 8.8β</td>
<td>10.2 ± 5.3</td>
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<td><strong>Single leg squat</strong></td>
<td></td>
<td></td>
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<tr>
<td>Land (°)</td>
<td>24.7 ± 7.2</td>
<td>7.2 ± 4.8</td>
<td>41.6 ± 9.3</td>
</tr>
<tr>
<td>Pool (°)</td>
<td>25.3 ± 6.2</td>
<td>10.9 ± 6.0β</td>
<td>52.5 ± 12.3*α</td>
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CV, coefficient of variability
Positive percentages indicate larger movement variability in the aquatic environment, and negative percentages indicates larger movement variability on land
* indicates significant difference between environments at P<0.05
α – indicates large effect size at Cohen’s d >0.8
β – indicates moderate effect size at Cohen’s d>0.5
Table S4.4. Mean (SD) peak velocity between the two environments during the concentric phase of the movement.

<table>
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<th>Thigh Y</th>
<th>Thorax X</th>
<th>Thorax Y</th>
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<td>19.5 ± 8.1</td>
<td>8.8 ± 4.3</td>
<td>42.9 ± 8.5</td>
<td>13.7 ± 8.9</td>
<td>23.1 ± 7.2</td>
<td>2.1 ± 0.9</td>
</tr>
<tr>
<td>Pool (°∙s⁻¹)</td>
<td>20.2 ± 8.3</td>
<td>12.3 ± 8.4β</td>
<td>48.7 ± 18.6</td>
<td>14.5 ± 12.8</td>
<td>18.9 ± 10.0</td>
<td>2.7 ± 2.0</td>
</tr>
<tr>
<td>Split squat Land (°∙s⁻¹)</td>
<td>24.1 ± 8.9</td>
<td>10.3 ± 5.5</td>
<td>33.2 ± 9.2</td>
<td>14.6 ± 10.9</td>
<td>6.6 ± 5.2</td>
<td>2.8 ± 2.2</td>
</tr>
<tr>
<td>Pool (°∙s⁻¹)</td>
<td>20.0 ± 7.3β</td>
<td>10.1 ± 4.3</td>
<td>23.9 ± 8.9</td>
<td>10.9 ± 5.2</td>
<td>6.7 ± 4.7</td>
<td>3.1 ± 2.7</td>
</tr>
<tr>
<td>Single-leg squat Land (°∙s⁻¹)</td>
<td>7.9 ± 3.8</td>
<td>10.3 ± 5.5</td>
<td>30.7 ± 9.7</td>
<td>14.6 ± 9.8</td>
<td>21.6 ± 8.1</td>
<td>2.8 ± 2.2</td>
</tr>
<tr>
<td>Pool (°∙s⁻¹)</td>
<td>11.4 ± 6.4β</td>
<td>10.4 ± 4.3</td>
<td>35.2 ± 13.3</td>
<td>10.9 ± 5.2</td>
<td>17.4 ± 7.0β</td>
<td>3.1 ± 2.7</td>
</tr>
</tbody>
</table>

X, Extension Y, Abduction Z, External rotation. Positive percentages indicate larger movement variability in the aquatic environment, and negative percentages indicates larger movement variability on land.
CV, coefficient of variability.
* indicates significant difference between environments at P<0.05
α – indicates large effect size at Cohen’s d >0.8
β – indicates moderate effect size at Cohen’s d>0.5
Figure S4.1. Displacement waveforms of sagittal plane movements for the three segments between land- and aquatic-based squats. Average sagittal plane displacement on land (solid line) ±95% confidence limits (green area), and in water (dashed line) ±95% confidence limits (blue area) for thorax, thigh, and shank segments during the squat, split squat, and single leg squat. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%).
Figure S4.2. Displacement waveforms of frontal plane movements for the three segments between land- and aquatic-based squats. Average frontal plane displacement on land (solid line) ±95% confidence limits (green area), and in water (dashed line) ±95% confidence limits (blue area) for thorax, thigh, and shank segments during the squat, split squat, and single leg squat. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%). Positive values indicate valgus movements at the thigh and shank.
CHAPTER 5:

THE EFFECTS OF DIFFERENT WATER DEPTH ON SQUAT KINEMATICS
THE EFFECTS OF DIFFERENT WATER DEPTH ON SQUAT KINEMATICS

Please note: This chapter presents the second manuscript from this project. It was submitted for publication in *Journal of Sports Sciences* in August 2017, and is currently under review.

5.1. Abstract

Small changes in water depth alter physiological and neuromuscular responses during water-based exercise, but limited research has assessed kinematic effects. This study aimed to quantify kinematic effects of altered water depth during bodyweight squats in a healthy population. Six inertial sensors (100 Hz) recorded 15 university students (22.0±2.3 yrs., 1.70±0.09 m, 70.1±13.0 kg) performing ten bodyweight squats in hip-deep and waist-deep water. Repeated-measures statistics determined differences in peak angles, range of motion and peak velocities of the shank, thigh, and trunk between the depths. Differences in trunk orientation and speed were portrayed by plotting the mean difference ±95% confidence intervals throughout the squat. Results showed increased trunk inclination and slower sagittal plane movement speeds during deeper immersion. Changed water depth did not affect the squat depth, or the lower body kinematics. Trivial effects on the lower body kinematics are positive findings for practitioners working with individuals of different height. The altered trunk posture was likely a consequence of its partial immersion and different exposure to the fluid dynamics. At the full extension position, the trunk was out of the water while immersed to the hip, and was therefore no longer exposed to the effects of water. Practitioners should consider the water depth when employing water-based exercise as it affects kinematics.
5.2. Introduction

Aquatic therapy is often used in the rehabilitation of musculoskeletal injuries and chronic medical conditions as the environment allows practitioners to manipulate loading and resistance easily (Heywood et al., 2017, Colado et al., 2013). The physical properties of water are known to elicit changes in the human response to exercise compared to land-based training (Miyoshi et al., 2004, Pohl and McNaughton, 2003). From a biomechanical perspective, the changes are predominantly caused by buoyancy and viscosity (Kaneda et al., 2012b), while the movements of the water also adds sensory and mechanical perturbation and therefore alters balance demands (Marinho-Buzelli et al., 2017b). Recent literature reviews have highlighted that current understandings of biomechanical effects of water immersion are inconclusive and the literature disagrees on the efficacy of water-based exercise (Heywood et al., 2017, Heywood et al., 2016). A likely reason for this is considerable methodological differences in the previous research, with inconsistencies in water depth and exercise intensity (Barela et al., 2006, Fantozzi et al., 2015, Miyoshi et al., 2004).

Changes to the water depth is particularly important from a biomechanical perspective, as it determines the degree of gravitational offloading (Harrison and Bulstrode, 1987). The offloading is a primary reason why practitioners use the aquatic environment for rehabilitation, as it allows them to employ a degree of loading that is suitable for the needs of their client (Lund et al., 2008). Shallower water reduces the offloading (Harrison and Bulstrode, 1987), so practitioners can gradually increase the loading and progress clients in a safe and effective manner, simply by progressively decreasing the water depth.
Exercising individuals of different height in the same pool means that they experience slightly different depths of immersion, which potentially affects the efficacy of rehabilitation programs. Even small differences in water depths has been shown to affect balance and posture (Louder et al., 2014, Marinho-Buzelli et al., 2017b, Bressel et al., 2016), and should therefore be considered by practitioners. Despite this, several researchers have failed to specify the water depth used in studies assessing the efficacy of aquatic-based rehabilitation programs (Lund et al., 2008, Lau et al., 2014, Simmons and Hansen, 1996). Although the previous research showed biomechanical effects of changed water depths during quiet standing (Bressel et al., 2016, Louder et al., 2014, Marinho-Buzelli et al., 2017b), a considerable gap still exists in the literature concerning the effects of different water depths on dynamic rehabilitation exercises.

Water immersion has been shown to affect the kinematics of tasks such as walking compared to land-based equivalents (Barela et al., 2006, Fantozzi et al., 2015, Miyoshi et al., 2004). Previous research has shown that water immersion to the hip also changed squatting kinematics by encouraging a more upright trunk and slower velocities, while allowing similar squat depths (Severin et al., 2017). These findings support the use of water-based rehabilitation, as immersion appears to encourage improved technique. The earlier study used water immersion to the greater trochanter, which offloaded approximately 40% of the participants’ bodyweight (Harrison and Bulstrode, 1987), and has been used in previous research on postural sway (Bressel et al., 2016, Louder et al., 2014). However, water depths vary considerably between research areas, with gait researchers most often using immersion to the chest (Barela et al., 2006, Miyoshi et al., 2004), therapeutic pools usually have a water depth to the lumbar region (Marinho-Buzelli et al., 2017b), and swimming pools vary in depth along the length of the pool.
(Simmons and Hansen, 1996). The most frequent depths used in research ranges from thigh-depth to chest-depth (Heywood et al., 2016), and previous research has highlighted lacking understandings on kinematic effects of different water depths (Bressel et al., 2016).

It is likely that changes to the water depth changes the kinematics of exercises performed in the aquatic environment, and practitioners would benefit from an increased understanding of these effects. This study therefore aimed to examine differences in trunk and lower body kinematics of bodyweight squats performed in water during immersion to the hip and the waist.

5.3. Methods

5.3.1. Participants

Fifteen healthy university students (5 females, and 10 males, 1.70 ± 0.09 m, 70.1 ± 13.0 kg, 22.0 ± 2.3 yrs.) volunteered for participation. The inclusion criteria ensured that all volunteers were physically active and without trunk or lower limb injuries at the time of testing, and had no previous experience in water-based exercise. Written informed consent was obtained prior to any testing in accordance with the institutional research ethics approval.

5.3.2. Instrumentation

Inertial sensors (100Hz) tracked the movements of the shanks, thighs, sacrum, and thorax providing kinematic data of the motions of these segments. Two sensors were allocated on the lateral surface of the mid-thigh and the shank on the participant’s right leg, halfway between the proximal and distal joint centres. One sensor was attached to the sacrum, centre to the posterior superior iliac spines, and one sensor was positioned over the
spinous process of the third thoracic vertebra. To avoid any intra-sensor bias, the same sensor was allocated to the same segment for all participants, and great care was taken to ensure consistent sensor placement on the segments, although previous research has highlighted that, for gyroscopic measurements, inertial sensors are relatively insensitive to exact positioning (Ertzgaard et al., 2016).

5.3.3. Experimental procedure

The participants performed ten bodyweight squats while immersed to the umbilicus (waist-depth) and to the greater trochanter (hip-depth) (Figure 5.1). The testing took place in an outdoor pool that was of Olympic standard and maintained a water temperature of 29.1° C±1.0. Participants performed the squats standing on a platform of adjustable height in order to ensure appropriate depths between individuals regardless of stature. The depths were selected as they have been used previously in water-based research (Marinho-Buzelli et al., 2017b, Louder et al., 2014), and provides a known degree of offloading (hip: 40% and waist: 50%) (Harrison and Bulstrode, 1987).
To ensure each participant squatted with natural technique, no instructions on stance width or squat depth were provided (Roos et al., 2014). The only instructions were to maintain the arms outstretched in front of the body with elbows extended and palms facing down, and to maintain a tempo that was indicated by a metronome. The platform was adjusted at 2.5 cm increments to the level closest to the desired landmark. The adjustment of the platform ensured participants three to five minutes’ rest between the sets, and the sensors remained attached during the adjustment to ensure consistent allocation. To ensure the same task-familiarization between participants, the hip-deep squats were always performed before the waist-deep squats.
5.3.4. **Data processing**

The data from the gyroscopes was imported using Catapult Sprint (version 5.1; Catapult Sports, Docklands, VIC), and each dataset was processed individually using a variable-width, non-weighted box-smoothing algorithm. The slope for the internal drift was mathematically identified and subtracted from the angular velocity data, which was then integrated to yield displacement. The identification of the repetition cycles for each sensor was based on the data from the gyroscope with the largest amplitude (sagittal plane) and the data from the other gyroscopes were subsequently sliced at the same time point. To optimize the accuracy of the slicing procedure, the data were processed so that the start of each cycle occurred at the bottom of the squat movement where the peak angle was most obvious. Therefore, unlike standard convention, all data were analysed with the ascending phase (0-50%) preceding the descending phase (50-100%). A more in-depth description of the data processing has been described previously (Severin et al., 2017). This study followed the convention used previously where inertial sensors excluded the transverse plane data (Fantozzi et al., 2015), as its accuracy has been reported to be relatively poor (Ertzgaard et al., 2016, Ohberg et al., 2013). Further, vertical displacement of the sacral sensor was used to measure squat depth.

5.3.5. ** Statistical analysis**

All time series data were time-normalized to 1000 data points and imported to Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA). Peak velocity, peak angle, and total range of motion from all sensors were tested for environmental differences. The squat depth was considered a covariate and was tested for between-environment effects, and all kinematic variables were tested for compliance with the assumptions of an analysis of covariance. Wherever the data met the assumptions, an analysis of covariance determined
significant differences between the environments; otherwise, a repeated measures analysis of variance was used. Data that violated a Shapiro-Wilk test was analysed with a nonparametric Wilcoxon signed-ranks tests. To show differences in displacement throughout the task, the difference between group mean time series ±95% confidence limits (CI) were calculated and plotted as waveforms (Stuelcken et al., 2010, Severin et al., 2017). The 95% CI was calculated using the critical $t$-value and degrees of freedom. Wherever the 95% CI did not include zero, the environments were considered to have a significant effect on the kinematics. The mean difference was calculated as the waist-depth data less the hip-depth data, so a CI above zero indicated larger recorded data during the deeper depth and a CI less than zero indicated larger values during the shallower depth. Effect sizes were calculated and ranked using the method developed by Cohen (1988, pp. 24-26), with $d$ scores >0.2 considered small, >0.5 medium and >0.8 considered large effect. The alpha level was set at $P<0.05$.

5.4. Results

The changed water depth did not have significant effect on the squat depth (waist: 0.46±0.13 m, hip: 0.49±0.14 m, $P=0.552$, $d=0.22$), and no significant differences existed in the thigh and shank kinematics. The waveform analysis revealed different trunk posture in the sagittal plane, especially around the top position of the movement (50%), with greater inclination during immersion to the waist (Figure 5.2). The analysis also showed faster sagittal plane trunk motions during immersion to the hip, while the frontal plane movements were slower.
Figure 5.2. Waveforms of the mean difference (±95% CI) of sagittal and frontal plane displacements and speeds for the thorax between waist-depth and hip-depth.

Differences between the group means (solid line) ±95% confidence limits (shaded area) for sagittal plane displacements for the thorax, thigh, and shank segments between land- and aquatic-based during the squat, split squat, and single leg squat throughout the movement. 95% confidence interval above zero indicates larger segmental inclination on land and vice versa. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%).
Differences in sagittal plane trunk motions were also revealed by the analysis of the discrete data points (Table 5.1). This analysis supported that no significant differences existed in the thigh (peak angle: $P=0.053$, $d=0.41$, peak velocity: $P=0.070$, $d=0.31$) and shank (peak angle: $P=0.772$, $d=0.06$, peak velocity: $P=0.070$, $d=0.26$).

**Table 5.1.** Mean ± SD for peak displacement, velocity, and ROM for the thoracic segment during the two depths.

<table>
<thead>
<tr>
<th></th>
<th>Waist-deep</th>
<th>Hip-deep</th>
<th>P</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak angle (°)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td>3.7 ± 7.7</td>
<td>-1.5 ± 6.0</td>
<td>0.022*</td>
<td>-0.74</td>
</tr>
<tr>
<td>Flexion</td>
<td>23.4 ± 7.3</td>
<td>22.8 ± 6.6</td>
<td>0.754</td>
<td>-0.09</td>
</tr>
<tr>
<td>Lateral flexion (concentric)</td>
<td>0.9 ± 2.6</td>
<td>0.3 ± 2.4</td>
<td>0.394</td>
<td>-0.25</td>
</tr>
<tr>
<td>Lateral flexion (eccentric)</td>
<td>0.8 ± 2.7</td>
<td>0.0 ± 2.5</td>
<td>0.307</td>
<td>-0.29</td>
</tr>
<tr>
<td><strong>ROM (°)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anteroposterior</td>
<td>20.1 ± 6.9</td>
<td>24.2 ± 8.3</td>
<td>0.031*</td>
<td>0.54</td>
</tr>
<tr>
<td>Mediolateral</td>
<td>1.8 ± 0.8</td>
<td>2.2 ± 1.4</td>
<td>0.513</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Peak velocity (°·s⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension</td>
<td>16.5 ± 7.6</td>
<td>19.5 ± 9.6</td>
<td>0.110</td>
<td>0.34</td>
</tr>
<tr>
<td>Flexion</td>
<td>17.7 ± 6.5</td>
<td>19.5 ± 8.4</td>
<td>0.307</td>
<td>0.24</td>
</tr>
<tr>
<td>Lateral flexion (concentric)</td>
<td>2.6 ± 1.0</td>
<td>2.8 ± 1.7</td>
<td>0.245</td>
<td>0.29</td>
</tr>
<tr>
<td>Lateral flexion (eccentric)</td>
<td>2.6 ± 0.9</td>
<td>2.9 ± 1.6</td>
<td>0.895</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

ROM – range of motion, $d$ – Cohen’s $d$
* indicates significant differences between depth at $P<0.05$
5.5. Discussion

Key findings of this study were that changing the water depth from hip-deep to waist-deep significantly influenced the trunk kinematics around the upright position of the squat. However, the changed water depth did not appear to effect the lower body kinematics at any point during the exercise, and did not affect the squat depth. The latter is a positive finding as it suggests that using a pool of a set depth can be appropriate even for participants of different height, as the lower body kinematics appeared to be minimally affected by small differences in water depth.

Importantly, practitioners should consider the lingering anterior trunk lean of approximately 5° at the upright position of the squat during immersion to the waist. This observation was unexpected as previous research showed that water immersion had trivial effects on the trunk motions at this point of squat movements when compared to land (Severin et al., 2017). However, an important difference between the current study and the earlier work is the degree of trunk immersion at the top of the movement. During immersion to the hip (as in the earlier work), the entire trunk rose above the surface and was no longer affected by the fluid dynamics. It was therefore exposed to similar dynamics as squats performed on land.

Conversely, during immersion to the waist, the lower trunk remained under the surface of the water throughout the entire task, and remained affected by the properties of the water. Previous research has highlighted it is important to consider that body parts above the surface of the water experience different dynamics than those that remain submerged (Marinho-Buzelli et al., 2017b). It appears this small difference was sufficient to affect the trunk posture during the squat. Importantly, water immersion has been suggested to affect the coordination of postural movements (Louder et al., 2014), proprioception
(Fantozzi et al., 2015, Lau et al., 2014, Roth et al., 2006), and sensorimotor integration (Sato et al., 2013a). Although previous research has not assessed the effects of different water depths on these variables, it seems plausible that the different degree of immersion might have changed the proprioceptive stimulus and therefore influenced the kinematics. It is possible the dynamics that acted on the partially immersed trunk during immersion to the waist was enough to reduce the proprioceptive stimulus of the back-extensor muscles, and contributed to the altered posture.

The changed trunk posture suggests that deeper immersion reduced the error detection as the participants failed to correct for the trunk lean. Previous research has suggested that the increased support of water may improve postural error detection (Simmons and Hansen, 1996), although other researchers have reported that deeper immersion increased postural instability (Bressel et al., 2016, Louder et al., 2014). The latter was suggested to occur due to increased offloading, which elevates the body’s centre of gravity (COG) (Harrison et al., 1992), and reduces the dependence on corrective muscle actions (Louder et al., 2014). It is possible that increased offloading during the deeper immersion actually reduced the error detection and therefore contributed to the altered trunk posture.

It is difficult to determine postural coordination form kinematic data alone and the practical implications of the lingering trunk inclination at the top of the squat task remain unknown. Future research should assess possible effects on land-based proprioception following water-based exercises. Regardless, whenever trunk posture during squat movements is a focal aspect of rehabilitation or exercise, the results from this project suggests that practitioners should use water immersion to the hip rather than the waist.
The different water depths did not have a significant effect on the peak velocities of the squat. However, the waveform analysis showed that shallower immersion induced faster motions in the sagittal plane, and slower motions in the frontal plane. The sagittal plane data supports previous research that report slower walking speeds in the aquatic environment compared to land (Kaneda et al., 2012b, Heywood et al., 2016). It is generally accepted that the viscosity and density of water provide increased resistance to movements and thereby slows them down (Kaneda et al., 2012b). This is consistent with observations reported previously, as the shallower immersion provided less resistance to the movements of the trunk, and therefore may explain the faster speeds.

Additionally, the larger ROM of the trunk during the shallower immersion probably required faster speed as the tempo of the squats was maintained between the depths. The previous research assessed spatiotemporal parameters of gait and did not examine effects on angular velocity or frontal plane movements (Kaneda et al., 2012b, Heywood et al., 2016). It has been shown that water immersion increases the frontal plane ROM, and it was suggested this indicated a balance strategy as a response to the dynamic environment (Severin et al., 2017). Perhaps the deeper immersion placed higher balance demands on the participants than the shallower depth, as has been suggested in previous research (Bressel et al., 2016, Louder et al., 2014). Perhaps this explains the faster frontal plane movement speeds during immersion to the waist. Although these speeds were significantly different between environments, it should be acknowledged that they were very small (<1°·s⁻¹), so their practical implications could be questioned.

This study indicates that practitioners may be able to manipulate the amount of movement control available for their clients further, by modifying the water depth. Slower velocities in water has been suggested to increase movement control compared to land-based
movements (Kaneda et al., 2012b), and is no doubt positive from a rehabilitation perspective. Practitioners should consider possible effects of water depth on movement speed when programming for water-based exercise, and probably use deeper water for clients in need of increased movement control.

The small sample size in this study did not allow analysis of differences between males and females, despite previous reports of kinematic differences during squatting tasks (McKean et al., 2010b). Research has highlighted the differences in body compositions between sexes affect their response to water immersion (Harrison and Bulstrode, 1987). Despite this, previous studies on biomechanical effects of water immersion has not compared males and females (Barela et al., 2006, Fantozzi et al., 2015, Bressel et al., 2016, Louder et al., 2014, Marinho-Buzelli et al., 2017b). Future research should quantify kinematic effects of various water depths on both sexes to further the understandings of biomechanical aspects of water immersion and provide guidelines to practitioners in order to ensure the best possible prescription of water-based exercise.

This study showed that by increasing the water depth from hip-deep to waist-deep during body weight squats, it was predominantly the trunk posture that changed. An anteriorly inclined trunk posture remained at the top of the movement during waist-deep immersion, which reduced the overall ROM. The small change in water depth was enough to induce a change in movement speed of the trunk, as it moved faster in the sagittal plane during the shallower depth. In addition, the small difference in water depth had little effect on the lower body kinematics and velocities of squats, which no doubt is positive for managing clients of different heights within the same pool. The results from this study provide practitioners with an improved understanding of how different water depths can influence the kinematics of squats performed in the aquatic environment.
CHAPTER 6:

EFFECTS OF WATER IMMERSION ON SQUAT AND SPLIT SQUAT KINEMATICS IN OLDER ADULTS
Effects of Water Immersion on Squat and Split Squat Kinematics in Older Adults

Please note: This chapter presents the third manuscript from this project. It was submitted for publication in Medicine and Science in Sport and Exercise in August 2017, and is currently under review.

6.1. Abstract

Purpose: The importance of exercise for the health and wellbeing of older adults is well established; however, the influence of exercising in water is less clear. This study examined the effect of water immersion on exercise technique for the commonly used squat exercise. Methods: Twenty-four active older adults (71.4±5.4 yrs.) performed squats and split squats on land and in water, while inertial sensors (100 Hz) recorded trunk and lower-body kinematics. Range of motion, peak velocities, and joint angles together with the waveforms of the mean differences in joint angles were compared between dry land and aquatic environments. Repeated-measures statistics were used to determine differences in the kinematic variables, and Cohen’s d portrayed effect sizes. Results: Water immersion increased the squat depth during both exercises (squat: +5.66 cm, \( P=0.028, d=0.63 \), split squat: +13.36 cm, \( P=0.005, d=0.83 \)). It also increased the range of motion and peak velocities of the hip and knee joints, while the trunk showed reduced range and velocity. The waveforms also revealed differences in trunk, hip, and knee motions, particularly during the deeper parts of the movements, and angle-angle plots showed increased reliance on the hip motions in the water. Conclusion: Performing squats and split squats in water allowed older adults to achieve movement depths that
were 28.0% and 86.5% respectively, beyond what was possible on land. Additionally, immersion in water also encouraged hip dominant movement strategies and upright trunks. These results showed that aquatic-based exercise generate a different exercise outcome and therefore provide an alternative option for older adults as it allows them to perform tasks in a manner that is not possible on land.

**KEY WORDS:** Gyroscope; Biomechanics; Aged population; Exercise; Aquatic therapy

### 6.2. Introduction

An individual’s quality of life is dependent on their ability to maintain functional independence and perform everyday tasks without pain (Katsura et al., 2010). Typically aging decreases muscle strength and balance and begins to threaten those abilities, a phenomena often linked to problems such as an increased fear of falling (Moreira et al., 2016), sedentary lifestyle and task avoidance (Alcock et al., 2015, Katsura et al., 2010). These problems are associated with reduced functional independence and quality of life (Katsura et al., 2010), so physical exercise programs for older adults often target strength, balance and transference to daily living (Flanagan et al., 2003). Researchers have emphasized the importance of prescribing exercises that mimic activities of daily living for older adults to maintain their functional independence (Skelton and Dinan, 2009, Moreira et al., 2016, Resende et al., 2008). Many practitioners therefore prescribe this population with squats and split squats, as these exercises are functional, strengthen muscles and improve balance (Alcock et al., 2015, Flanagan et al., 2003, Escamilla, 2001). Although the literature on these fundamental exercises is extensive (Escamilla, 2001, McKean et al., 2010b, Schoenfeld, 2010, Swinton et al., 2012), the physical effects of
Ageing can make it difficult and potentially unsafe for older adults to exercise under full gravitational loads. Both squats and split squats can be challenging for older individuals, who often require safety measures such as a chair or railings for confidence (Flanagan et al., 2003). Although the benefits of physical exercise for quality of life in older adults are undisputable, researchers have highlighted poor adherence to exercise programs due to pain and fear of falling (Forkan et al., 2006). In order to increase the adherence amongst older adults, practitioners must ensure exercises are able to be performed safely and comfortably.

The aquatic environment offers a suitable exercise setting for older adults (Devereux et al., 2005, Bressel et al., 2011) and provides a safe, fun, convenient, and effective alternative to land-based exercise (Flanagan et al., 2003). Immersion in water also reduces joint loads, improves balance (Resende et al., 2008), and has a positive effect on reducing the fear of falling (Devereux et al., 2005). It has also been reported to increase exercise confidence (Skelton and Dinan, 2009) and reduce pain (Bender et al., 2005) when compared with land-based equivalents. Aquatic-based exercise programs have been found to result in similar gains in strength, coordination and balance in older adults that were achieved with land-based training (Katsura et al., 2010, Devereux et al., 2005). Combined, the research appear to support the use of aquatic-based exercise for older adults as it provides a safe and effective exercise environment that can be modified to cater to the requirements and limitations of the individual (Kaneda et al., 2012b). Aquatic-based exercise has also been shown to bridge common exercise barriers for this population (Forkan et al., 2006), which further emphasizes its suitability for older adults. Although, many health practitioners recognize the suitability of aquatic-based exercise
for older adults, the literature on its optimal application specifically for this population is limited.

Previous research has shown that the properties of water affect biomechanical aspects of exercises performed in the aquatic environment (Bressel et al., 2011, Fantozzi et al., 2015, Barela and Duarte, 2008). Importantly, earlier work has shown that young individuals changed their squatting technique while immersed in water (Severin et al., 2017). However, researches have highlighted that the adaptations to water immersion differs between older and younger individuals (Barela and Duarte, 2008, Bressel et al., 2016), and as the previous work only included young participants, the effects of water immersion on older adults remain unknown. Researchers have suggested a reduced dependence on strength and balance in water due to the offloading (Resende et al., 2008, Moreira et al., 2016, Severin et al., 2017). It was also highlighted that water immersion slows movements and thus provides increased time for postural corrections (Resende et al., 2008). This is a primary reason water immersion is considered to reduce the fear of falling in older adults (Devereux et al., 2005), and why professionals often consider aquatic-based exercise safer than conventional training. Slower movements during exercise would probably be beneficial for older adults as it has been suggested it increases movement control (Devereux et al., 2005, Kaneda et al., 2012b). Exercising in water appear to encourage strength gains while reducing the dependence on strength and balance, and would therefore be ideal for older adults. It has also been reported to increase the involvement of the hip joint (Kaneda et al., 2012b), and allow greater range of motion (Devereux et al., 2005), which are often reduced in older individuals (Kerrigan et al., 2001, Skelton and Dinan, 2009). However, research has not clearly settled the effects of the aquatic environment on the kinematics of older adults so further examinations are
warranted to ensure improved application. Accordingly, this study aimed to (1) assess effects of water immersion on range of motion (ROM) and peak velocities during squats and split squats, and (2) quantify environmental differences in joint angles during the ascent and descent in older adults.

6.3. Methodology

Twenty-four active older adults (71.4 ± 5.4 yrs., 1.65 ± 0.08 m, 74.0 ± 12.7 kg, 17 females and 7 males) without previous experience in aquatic-based exercise volunteered for participation. The inclusion criteria ensured that all participants were physically active at the time of testing and experienced no pain while walking down a flight of stairs. Self-reported leg dominance was obtained (right n=21, left n= 3) along with written informed consent prior to any testing, in agreement with the institutional research ethics approval.

6.3.1. Instrumentation

Significant research have verified internal sensors for kinematic analyses (Ohberg et al., 2013, Ertzgaard et al., 2016), and the wireless and waterproof design allows for underwater application (Fantozzi et al., 2015, Severin et al., 2017). Six 100 Hz sensors (Nanotrac, Catapult sports, Docklands, VIC) were used to track trunk, pelvis, and lower limb kinematics. Four were attached bilaterally to the lateral mid-thighs and shanks at a distance that was halfway between the proximal and distal joint center. Another sensor was attached to the sacrum, at equal distance from each posterior superior iliac spines, and another over the spinous process of the third thoracic vertebra. Great care was taken to ensure accurate and consistent sensor allocation throughout the testing despite previous researchers having highlighted that a considerable advantage of portable systems is that they are less sensitive to exact placement on the segments when using data from the
gyroscopes (Ertzgaard et al., 2016). The consistent sensor allocation throughout the data collection reduced the risk of inter-sensor differences.

6.3.2. Testing protocol

The study design required each participant to attend two testing sessions, with one week between sessions. The land-based testing took place in a biomechanics laboratory, while the aquatic-based testing took place at an outdoor pool complex within one week of the first session. During both sessions, participants performed a few minutes of aerobic activity and up to six practice repetitions of each exercise for familiarization purposes, followed by ten squats and ten split squats. No randomization of the exercises occurred due to their natural sequencing nature, and to allow each participant the same task familiarization. The split squats were performed with each leg in front, but to avoid any bilateral asymmetries associated with leg dominance, only the dominant leading-leg data were analyzed.

To ensure natural technique and comfort of the participants, and to warrant the same technique was used in both environments, performers were allowed to self-select their foot positions, movement depth, and speed (Flanagan et al., 2003, Roos et al., 2014). Participants were instructed to maintain their arms horizontal with extended elbows and palms facing down during all exercises. During the land-based session, plastic railings were placed on either side of the participants for additional balance support and a member of the research team stood close by to assist if needed. During the second testing session, participants performed the same exercises while on an underwater platform with railings again for additional support. The platform was of adjustable height and set so the water depth was to the level of the greater trochanter for each participant (Severin et al., 2017).
The pool was of an Olympic standard (27.3° ±0.8), was 1.35 m deep, and had lane-ropes in place to reduce water turbulence.

6.3.3. Data processing

The data were processed and adjusted to comply with a standard global coordinate system with data from a static capture providing 0° segmental reference angles (Wu et al., 2002). The global coordinate system was set up so from the participants’ perspective the positive X-axis pointed from left to right, the positive Y-axis pointed anteriorly, and the positive Z-axis pointed vertically. The data were smoothed using a custom, variable-width, non-weighted box-smoothing algorithm. A more in-depth description of the processing procedures can be found in our previous work (Severin et al., 2017). To obtain angular displacements, the angular velocity data for each segment was integrated, with sagittal plane peak angles used to identify the ten repetitions. The analysis saw each cycle starting at the bottom of the movement, where peak flexion angles occurred, and all data is hence presented with the ascending phase first. The absolute segmental angles were used to calculate relative angles between sensors by the following calculations:

$$\theta_{\text{knee}} = \theta_{\text{shank sensor}} + (180 - \theta_{\text{thigh sensor}})$$

$$\theta_{\text{hip}} = \theta_{\text{sacral sensor}} + (180 - \theta_{\text{thigh sensor}})$$

$$\theta_{\text{trunk}} = \theta_{\text{thoracic sensor}} + (180 - \theta_{\text{sacral sensor}})$$

It is important to acknowledge that these calculations provide the relative angle between two adjacent sensors and do not necessarily represent the true joint angle. However, the specified angles will henceforth be referred to as the knee joint, hip joint, and trunk angle.
Furthermore, the accelerometer data from the sacral sensor determined the vertical displacement of the pelvis and thus provided a measure of movement depth. The squat depth for each repetition was quantified by the difference between the highest and lowest vertical positions of the sacrum.

6.3.4. Data analysis

All data were time-normalized to 1,000 data points and imported to Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) for comparison and analysis. To compare joint angles between environments, the differences between the group mean waveforms ±95% confidence limits (95% CI) were plotted as a time series (Stuelcken et al., 2010), which were calculated using the critical t-value and degrees of freedom. The mean differences were calculated as the land-based data less the aquatic-based data, so positive values indicate larger angles on land, and vice versa. When zero was outside the 95% CI, the movements were considered significantly different between the environments.

The movements were analyzed so the ascending phase represented 0-50% of the motions and the descending phase represented 50-100%. These phases were subsequently divided into the early ascent (0-25%), the late ascent (25-50%), the early descent (50-75%) and the late descent (75-100%). Other kinematic variables of interest were overall peak segmental velocity, and segmental ROM, with angle-angle plots used to assess portray hip-knee coordination. Statistical analyses were performed on the kinematic variables using IBM SPSS software version 22 (IBM, New York, NY). The vertical displacement of the sacral sensor was tested for environmental effects to determine differences between environments and a Shapiro-Wilk test analyzed all variables for normality. Where appropriate, a Wilcoxon signed ranks test determined differences between environments; while elsewhere, a repeated-measures one-way analysis of variance was used. Cohen’s $d$
was used to indicate the relative magnitude of any differences (Cohen, 1988, pp. 24-26), with scores >0.2 considered small, >0.5 moderate and >0.8 considered large effect, and the alpha level was set at $P < 0.05$.

6.4. Results

Participants achieved greater depth in the aquatic environment during both the squat (land: $0.20 \pm 0.08$ m, water: $0.26 \pm 0.10$ m, $P = 0.028$, $d = 0.63$) and the split squats (land: $0.15 \pm 0.18$ m, water: $0.29 \pm 0.14$ m, $P = 0.005$, $d = 0.83$). There were no statistically significant differences between males and females.

The plots for the joint displacements showed significant differences in sagittal plane trunk angle during both the squats and split squats, and the latter also showed differences in hip angle (Figure 6.1). The knee and hip joints showed changes in the frontal plane during the split squats (Figure 6.2).
Figure 6.1. Difference (±95% CI) between environments in sagittal plane joint angles during the squat and split squats. Differences between the group means (solid line) ±95% confidence limits (shaded area) for sagittal plane displacements for the thorax, thigh, and shank segments between land- and aquatic-based during the squat, split squat, and single leg squat throughout the movement. 95% confidence interval above zero indicates larger segmental inclination on land and vice versa. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%).
Figure 6.2. Difference (±95% CI) between environments in frontal plane joint angles during the squat and split squats.
Differences between the group means (solid line) ±95% confidence limits (shaded area) for sagittal plane displacements for the thorax, thigh, and shank segments between land- and aquatic-based during the squat, split squat, and single leg squat throughout the movement. 95% confidence interval above zero indicates larger segmental inclination on land and vice versa. Vertical lines indicate the start and end of each phase; early ascent (0-25%), late ascent (25-50%), early descent (50-75%) and late descent (75-100%).
The angle-angle plots showed noticeable differences in the hip-knee coordination between environments in both exercises (Figure 6.3). The analysis of segmental ROM and peak velocities showed consistently lower sagittal plane values for the thorax and larger ROM for the thigh during water immersion, with the thigh also showing moderate effects on frontal plane velocity (Table 6.1). The shank showed no effects between environment in either ROM or peak velocity.

![Figure 6.3. Angle-angle graphs for the squat and split squat in the sagittal and frontal plane.](image)
The graphs show hip-knee coordination for one representative participant during land- (dashed lines) and water-based exercises (solid lines).

The peak angles showed several significant environmental effects in both movement planes, and water immersion caused mostly larger angles compared to land, except for the trunk in the sagittal plane (Table 6.2).
Table 6.1. Overall range of motion (SD) and peak velocity (SD) during each phase for the segments during the exercises.

<table>
<thead>
<tr>
<th></th>
<th>Trunk</th>
<th>Hip</th>
<th>Knee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal plane</td>
<td>Frontal plane</td>
<td>Sagittal plane</td>
</tr>
<tr>
<td>Squat</td>
<td>ROM Land (°)</td>
<td>34.0 (17.2)</td>
<td>2.0 (1.4)</td>
</tr>
<tr>
<td></td>
<td>ROM Pool (°)</td>
<td>16.5 (8.9)*a</td>
<td>1.9 (1.0)</td>
</tr>
<tr>
<td></td>
<td>Peak angle Land (°)</td>
<td>22.4 (16.9)</td>
<td>1.9 (3.6)</td>
</tr>
<tr>
<td></td>
<td>Peak angle Pool (°)</td>
<td>12.8 (12.7)*β</td>
<td>0.9 (1.8)</td>
</tr>
<tr>
<td></td>
<td>Concentric Land (°·s⁻¹)</td>
<td>43.0 (24.7)</td>
<td>3.7 (1.9)</td>
</tr>
<tr>
<td></td>
<td>Concentric Pool (°·s⁻¹)</td>
<td>24.1 (21.0)*a</td>
<td>4.5 (4.1)</td>
</tr>
<tr>
<td></td>
<td>Eccentric Land (°·s⁻¹)</td>
<td>36.3 (19.0)</td>
<td>3.8 (2.0)</td>
</tr>
<tr>
<td></td>
<td>Eccentric Pool (°·s⁻¹)</td>
<td>16.9 (11.7)*a</td>
<td>3.9 (3.2)</td>
</tr>
<tr>
<td>SS</td>
<td>ROM Land (°)</td>
<td>24.6 (9.0)</td>
<td>3.0 (1.5)</td>
</tr>
<tr>
<td></td>
<td>ROM Pool (°)</td>
<td>9.7 (5.9)*a</td>
<td>2.6 (1.9)</td>
</tr>
<tr>
<td></td>
<td>Peak angle Land (°)</td>
<td>22.5 (12.3)</td>
<td>4.4 (9.0)</td>
</tr>
<tr>
<td></td>
<td>Peak angle Pool (°)</td>
<td>4.9 (5.8)*a</td>
<td>2.4 (3.8)*a</td>
</tr>
<tr>
<td></td>
<td>Concentric Land (°·s⁻¹)</td>
<td>27.0 (15.5)</td>
<td>6.0 (2.8)</td>
</tr>
<tr>
<td></td>
<td>Concentric Pool (°·s⁻¹)</td>
<td>14.3 (9.7)*a</td>
<td>4.6 (3.3)</td>
</tr>
<tr>
<td></td>
<td>Eccentric Land (°·s⁻¹)</td>
<td>23.4 (15.0)</td>
<td>5.0 (2.6)</td>
</tr>
<tr>
<td></td>
<td>Eccentric Pool (°·s⁻¹)</td>
<td>11.7 (7.6)*a</td>
<td>4.3 (2.3)</td>
</tr>
</tbody>
</table>

ROM – range of motion, concentric velocities represent extension and abduction, eccentric velocities represent flexion and adduction.
* indicates significant difference between environments (P<0.05)
α indicates a large effect size (d> 0.8)
β indicates a moderate effect size (d> 0.5)
Table 6.2. Peak sagittal and frontal plane joint angles in both environments.

<table>
<thead>
<tr>
<th></th>
<th>Trunk</th>
<th></th>
<th>Hip</th>
<th></th>
<th>Knee</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Flexion</td>
<td>Lateral flexion</td>
<td>Flexion</td>
<td>Abduction</td>
<td>Flexion</td>
<td>Adduction</td>
</tr>
<tr>
<td>Squat Peak angle Land (°)</td>
<td>22.4 (16.9)</td>
<td>1.9 (3.6)</td>
<td>37.6 (19.0)</td>
<td>10.0 (7.1)</td>
<td>73.2 (18.3)</td>
<td>14.7 (7.8)</td>
</tr>
<tr>
<td>Squat Peak angle Pool (°)</td>
<td>12.8 (12.7)*β</td>
<td>0.9 (1.8)</td>
<td>46.0 (16.8)</td>
<td>14.5 (8.7)*β</td>
<td>78.8 (17.6)</td>
<td>19.4 (10.4)β</td>
</tr>
<tr>
<td>Squat Difference (%)</td>
<td>-42.9%</td>
<td>+53.5%</td>
<td>+22.3%</td>
<td>+44.8%</td>
<td>+7.6%</td>
<td>+31.9%</td>
</tr>
<tr>
<td>SS Peak angle Land (°)</td>
<td>22.5 (12.3)</td>
<td>4.4 (9.0)</td>
<td>30.3 (12.4)</td>
<td>3.5 (4.7)</td>
<td>61.1 (14.9)</td>
<td>9.9 (9.0)</td>
</tr>
<tr>
<td>SS Peak angle Pool (°)</td>
<td>4.9 (5.8)*α</td>
<td>2.4 (3.8)*α</td>
<td>43.7 (12.7)*α</td>
<td>12.1 (9.7)*α</td>
<td>65.5 (16.1)</td>
<td>19.8 (10.4)*α</td>
</tr>
<tr>
<td>SS Difference (%)</td>
<td>-122.0%</td>
<td>-155.4%</td>
<td>+44.2%</td>
<td>+240.3%</td>
<td>+7.3%</td>
<td>+99.7%</td>
</tr>
</tbody>
</table>

* indicates significant difference between environments (P<0.05)
α indicates a large effect size (d> 0.8)
β indicates a moderate effect size (d> 0.5)
6.5. Discussion

Water immersion allowed participants greater movement depth and was accompanied by a more vertically aligned trunk during both squats and split squats. Interestingly, water immersion encouraged a more hip dominant movement strategy than land, where hip flexion (rather than knee flexion) appeared to be the predominant contributor to the greater squat depth. Several researchers have reported increased hip motions in the aquatic environment during gait (Kaneda et al., 2012b, Miyoshi et al., 2005), but to the authors’ knowledge, this is the first time it has been reported during squat tasks.

In particular, the vertically aligned trunk posture in water was a positive adaptation for older adults as previous research has reported increased forward trunk lean during squats, probably due to reduced muscle strength (Fukagawa et al., 2012). Further, upright trunk postures during squats are often encouraged as it reduces compressive and shear forces acting on the spine (Schoenfeld, 2010, Escamilla, 2001). Conversely, the upright posture shifts the center of mass posteriorly, which can compromise balance (Horak, 2006). Perhaps the larger anterior trunk lean on land was necessary to maintain balance while under full gravitational loading.

Reduced muscle strength and balance in this population probably affects their ability to maintain balance with an upright posture on land. However, the offloading and balance support in water (Bressel et al., 2011, Resende et al., 2008) probably reduced the postural dependence for stability and allowed for a more upright trunk without sacrificing balance, as was suggested in a previous study (Severin et al., 2017). The increased movement depth was no doubt a beneficial adaptation to water immersion for this population. In
addition, a reduced postural dependence probably also had a positive effect on the fear of falling, and offers an important benefit that deserves recognition by practitioners.

Furthermore, both the hip dominant movement pattern and the reduced trunk lean are adjustments that have previously been reported during sit-to-stand tasks (Flanagan et al., 2003, Swinton et al., 2012). It appeared that performing squat variations in water may make them biomechanically more similar to sit-to-stand tasks than conventional squats.

It has been suggested that sit-to-stand tasks are more applicable for older adults (Flanagan et al., 2003), and they are often considered more functional than squats as they mimic activities performed in daily living (Dall and Kerr, 2010). The upthrust and support in water (Heywood et al., 2016) probably allowed the participants to sit back into the movements, similar to they would a chair or box, which could explain the resemblance.

Sit-to-stand tasks are biomechanically different from traditional squats, with kinematic, kinetic and neuromuscular differences (Flanagan et al., 2003, Swinton et al., 2012). Specifically, researchers have reported increased hip extensor contribution and less emphasis on the knee extensors during sit-to-stand tasks (Flanagan et al., 2003). The kinematic resemblance between water-based squat tasks and sit-to-stand movements are no doubt positive findings for older adults. In particular as reduced hip extension has been in older populations compared to younger individuals (Kerrigan et al., 2001). The authors also highlighted that older individuals who had previously fallen portrayed even less hip extension compared to those without previous falls.

In addition, decreased knee extensor activity reduces compressive forces acting on the knees (Escamilla et al., 2008b). These adaptations are positive for older adults and support the utilization of aquatic-based squat tasks for older adults.
However, researchers have cautioned about increased extension moments at the hip and knee during the ascending phase of *sit-to-stand* tasks and recommended that older adults be instructed to use assistance when rising (Flanagan et al., 2003). However, gravitational offloading in water has been shown to reduce joint moments (Miyoshi et al., 2005), so the need for external assistance was probably minimized when the movement was performed in the aquatic environment.

The resemblance of aquatic-based squat tasks and *sit-to-stand* movements urges future research to assess whether the kinetic and neuromuscular profiles of these exercises are similar. Regardless, the movement strategies adopted in water were probably beneficial for reducing loads on the spine and knees (Escamilla et al., 2008b, Schoenfeld, 2010), while *sit-to-stand* tasks also better mimic movements in everyday life (Flanagan et al., 2003, Dall and Kerr, 2010). Practitioners should therefore look to employ aquatic-based squat variations for older adults as they may contribute to their functional independence.

The increased frontal plane movements in water were encouraging as they indicated increased varus alignment of the limbs. Previous researchers have reported greater knee valgus in older adults and proposed a link with decreased strength (Fukagawa et al., 2012). The authors noted that although the link between excessive valgus alignment during squat tasks and increased injury risk is well documented in the literature, the age-related effects of these changes are often overlooked (Fukagawa et al., 2012). Although excessive varus alignment has been associated with reduced functionality (Sharma et al., 2013), again, the gravitational offloading may lessen negative consequences of the abnormal alignment.

It is possible the increased hip abduction in water indicated a wider stance, which could have reflected a balance strategy employed in response to the dynamic nature of the
aquatic environment (Colado et al., 2013, Bressel et al., 2016). Researchers have previously shown that water immersion increased postural instability, particularly in the frontal plane (Marinho-Buzelli et al., 2017b, Bressel et al., 2016), which probably explains the adoption of this balance strategy. It is also possible the hip dominant movement pattern was associated with the wider stance as it has been shown to increase hip flexion (Swinton et al., 2012) and subsequent activation of Gluteus Maximus (Swinton et al., 2012, Paoli et al., 2009, McCaw and Melrose, 1999). This further highlighted the need for kinetic and neuromuscular analyses of aquatic-based squat tasks. Future research should also assess the effects of increased frontal plane motions during aquatic-based squatting tasks in older adults to further the understanding of the roles of aquatic exercise for this population.

This study did not assess transverse plane data, although previous research has highlighted its clinical importance during squatting tasks (Fukagawa et al., 2012, Swinton et al., 2012). This decision was based on previous reports that questioned the ability of inertial sensors to track transverse plane motions accurately (Fantozzi et al., 2015, Ohberg et al., 2013). Additionally, it is possible the kinematics were affected by the water being a novel exercise environment for the participants, and the reported adaptations may be subject to habituation after prolonged exposure.

This study showed that water immersion allowed older adults to achieve greater movement depths and encouraged a squatting technique with a more vertical trunk posture than was possible on land. Water immersion also increased the involvement of the hip joint and reduced the reliance on the knee joint. Furthermore, increased frontal plane motions suggested increased varus alignments in water, potentially due to a wider stance, although the effects of which remain unclear. The results from this study
suggested that practitioners should consider aquatic therapy for older adults as it provides an exercise environment that allows tasks be performed with good technique and a movement range beyond what is possible on land.

6.6. Acknowledgements

This study was funded by the Kirk Foundation.

6.7. Conflict of interest

The authors declare no conflict of interest and have no professional relationships with companies or manufacturers that may benefit from this study. The results of this study do not constitute endorsement by the ASCM, and are presented clearly, honestly and without fabrication, falsification, or inappropriate data manipulation.
CHAPTER 7:

LIMB SYMMETRY DURING SQUATS AND SINGLE LEG SQUATS ON LAND AND IN WATER IN ADULTS WITH LONG-STANDING UNILATERAL ANTERIOR KNEE PAIN
LIMB SYMMETRY DURING SQUATS AND SINGLE LEG SQUATS ON LAND AND IN WATER IN ADULTS WITH LONG-STANDING UNILATERAL ANTERIOR KNEE PAIN

Please note: This chapter presents a published research article from this project. It was published in BMC Sports Science, Medicine and Rehabilitation in December 2018 (BMC Sports Sci Med Rehabil. 2017;9(20). doi: 10.1186/s13102-017-0085-x). The published version is attached in Appendix 10.3.

7.1. Abstract

Background: The presence of pain during movement results typically in changes in technique. However, the physical properties of water, such as flotation, means that water-based exercise may not only reduce compensatory movement patterns but also allow pain sufferers to complete exercises that they are unable to perform on land. The purpose of this study was to assess bilateral kinematics during squats and single-leg squats on land and in water in individuals with unilateral anterior knee pain. A secondary aim was to quantify bilateral asymmetry in both environments in affected and unaffected individuals.

Methods: Twenty individuals with unilateral knee pain and twenty healthy, matched controls performed body weight squats and single-leg squats in both environments while inertial sensors (100 Hz) recorded trunk and lower body kinematics. Effects on movement depths and peak angles were assessed for the anterior knee pain group and their inter-limb symmetry were compared with the control group. All variables were assessed using repeated-measures statistics.

Results: Water immersion allowed for greater movement depths during both exercises (squat: +7cm, p=0.032, single leg squat: +9cm, p=0.002) for the knee pain group. The
squat exercise was symmetrical on land, but water immersion revealed several asymmetries in the lower body movements. The single leg squat revealed decreased hip flexion and frontal plane shank motions on the affected limb in both environments. Water immersion generally increased the degree of lower limb asymmetry in both groups.

Conclusions: Individuals with anterior knee pain were allowed increased movement depth during both squats and single-leg squats while in water. Kinematic asymmetries between the affected and unaffected limbs were increased in water. Individuals with unilateral anterior knee pain appear to utilise different kinematics in the affected and unaffected limb in both environments.

Key Words: Inertial sensors; Asymmetry; Kinematics; Aquatic exercise

7.2. Background

Anterior knee pain (AKP) is an umbrella term for pain around the anterior aspects of the knee that is aggravated by physical activity (Werner, 2014) and common tasks in daily life such as descending stairs and squatting (Crossley et al., 2011). It is one of the most common conditions presenting in physiotherapy clinics (Graci and Salsich, 2015, Werner, 2014), and may present as a unilateral or bilateral condition (Livingston and Mandigo, 2003). AKP has been linked to lower body malalignments and deficits in strength, flexibility, and neuromuscular function (Witvrouw et al., 2005). Prolonged pain has been suggested to change muscular function and disrupt inter-muscular coordination (Lund et al., 1991), so it is not surprising that previous research has reported compromised muscle functions in individuals with AKP (Crossley et al., 2011). Similarly, research indicates that these individuals employ compensatory movement strategies during exercises such as single-leg squats (SLS) and running (Souza and Powers, 2009, Nakagawa et al., 2012).
Common strategies include increased pelvic obliquity, lateral trunk lean, and valgus alignment (Powers, 2010), which probably contributes to the continued aggravation of AKP (Crossley et al., 2011, Nakagawa et al., 2012, Graci and Salsich, 2015).

Rehabilitation programs often target hip and gluteal function and include squats and SLS to improve strength, balance, and coordination (Witvrouw et al., 2005, Werner, 2014). Despite AKP frequently presenting unilaterally (Livingston and Mandigo, 2003), most biomechanical studies compared affected individuals with healthy controls and failed to discuss bilateral differences (Nakagawa et al., 2012, Souza and Powers, 2009). This is troubling, as research has reported bilaterally different kinematics following unilateral knee injuries (Roos et al., 2014, Livingston and Mandigo, 2003, Larsen et al., 2015). It is likely that long-standing unilateral AKP also result in bilaterally asymmetrical kinematics, and further examinations are needed to map compensatory movements.

Water-based rehabilitation is anecdotally effective for AKP, and although previous research supports its application for rehabilitating degenerative knee conditions (Bennell and Hinman, 2011), research on its efficacy on AKP is limited. The aquatic environment reduces loading (Harrison et al., 1992, Haupenthal et al., 2013), improves strength (Becker, 2009, Rahmann et al., 2009), and supports balance (Devereux et al., 2005, Roth et al., 2006), thus providing a suitable alternative to land-based rehabilitation for AKP. Aquatic therapy is also known to reduce pain and increase range of motion (Becker, 2009, Severin et al., 2017), which are important benefits for rehabilitation (Werner, 2014).

Importantly, previous research has highlighted that water immersion encourages different kinematics compared to land due to buoyancy, viscosity, and density (Fantozzi et al., 2015, Severin et al., 2017, Haupenthal et al., 2013). Particularly, water-based squat tasks portrayed increased movement depths and different trunk and lower body kinematics.
compared to squats performed on land (Severin et al., 2017). Previous research has not quantified kinematic effects of water immersion on individuals with AKP. Such information would be useful for practitioners when programming for water-based rehabilitation.

Bilateral asymmetries are often quantified in injured populations as their kinematics can reflect compensatory movements, and affect the efficacy of rehabilitation programs (Roos et al., 2014). Few published reports have assessed asymmetry in water, but a recent analysis highlighted increased asymmetries in water for healthy individuals during gait (Cadenas-Sanchez et al., 2015). Despite only assessing spatiotemporal implications, the authors highlighted that symmetry can provide important insights into movement control. No published research has quantified kinematic asymmetries during squats and SLS between land and water at the time of submission.

Traditionally, symmetry index (SI) calculations rely upon discrete data and are not applicable to time series data (Sadeghi et al., 2000, Nigg et al., 2013), but this issue was addressed by Nigg et al. (2013) who developed an SI calculation for continuous data sets. This method has not been used to quantify bilateral asymmetry in individuals with AKP compared to healthy controls. An increased understanding of the effects of water immersion on symmetry in individuals with AKP would clarify the roles of aquatic therapy for rehabilitation further.

Accordingly, this study aimed to assess kinematic effects of water immersion on individuals with AKP during squats and SLS by (1) quantifying differences in frontal and sagittal plane peak joint and segment angles and, (2) compare the environmental effects on bilateral asymmetry with healthy controls.
7.3. Methodology

7.3.1. Participants

Twenty young adults with chronic AKP (10 males and 10 females) and 20 healthy age- and gender-matched adults volunteered for participation (AKP group 22.8±4.0 y, 71.2±13.0 kg, 1.72±0.09 m, control group 22.2±2.9 y, 67.6±13.4 kg, and 1.72±0.10 m). The AKP group reported unilateral pain for at least three months (3-48 months) but were otherwise healthy. All participants were physically active and had at least three years’ experience with body weight exercises, and no prior exposure to water-based exercise. Self-reported leg dominance was determined by establishing the participants’ preferred kicking leg (right: 18, left: 2 in each group). In accordance with the Human Research Ethics Committee approval, any participant with knee pain during stair descent was excluded from participation. The participants provided informed written informed consent before testing.

7.3.2. Experimental design

This study used inertial sensors, which have successfully been used to record underwater sagittal and frontal plane kinematics (Fantozzi et al., 2015, Severin et al., 2017). Four sensors (100 Hz) (Nanotrak, Catapult sports, Docklands, VIC) were allocated bilaterally to the lateral thighs and shanks, halfway between the proximal and distal joint centres. One sensor was positioned over the third thoracic vertebra and another was attached to the sacrum. A ten-second static calibration was performed before each exercise in the anatomical position to establish 0° orientations for the sensors (Fantozzi et al., 2015). To avoid intra-sensor bias, the sensor allocations were consistent throughout testing.
Each participant attended two testing occasions; the first in a motion laboratory and the second at a pool complex within one week of the first session. A platform of adjustable height ensured a water depth to the greater trochanter on each participant (87±5 cm). The Olympic standard pool had a water temperature of 29.1° C±1.0 during the testing.

Both sessions started with a self-selected warm up of two to three minutes of aerobic activity and five to ten practice repetitions of the exercises for familiarization (Devereux et al., 2005), followed by ten squats and ten SLS on each leg. During the SLS, the contralateral limb was flexed at the knee to 70-90° and positioned behind the body. The arms were maintained outstretched in front during both exercises. No instructions were provided concerning stance width and squat depth (Roos et al., 2014), and the tempo was dictated by a metronome (100 bpm). The participants completed one repetition over eight beats, four to descend, and four to ascend. Two minutes’ rest was allowed between the exercises, and no randomization was used to allow the same task familiarization for each participant.

7.3.3. Data processing

The raw data were smoothed with a custom, variable-width, non-weighted box-smoothing algorithm and the slope for any internal drift was quantified using linear regression and subtracted. A more in-depth description of the data processing can be found in Severin et al. (2017). The smoothed data were integrated to yield segmental displacements and the ten repetitions were identified based on peak sagittal plane angles. The segmental angles were used to calculate the relative angles and indicate joint motions.
\[ \theta_{\text{knee}} = \theta_{\text{shank sensor}} + (180 - \theta_{\text{thigh sensor}}) \]

\[ \theta_{\text{hip}} = \theta_{\text{pelvis sensor}} + (180 - \theta_{\text{thigh sensor}}) \]

\[ \theta_{\text{trunk}} = \theta_{\text{thoracic sensor}} + (180 - \theta_{\text{sacral sensor}}) \]

The data were time normalized to 1000 data points in order to simplify comparisons. The squat depth was determined by the vertical displacement of the pelvis (McKean et al., 2010b) and was defined as the difference between the highest and lowest position of the sacral sensor.

7.3.4. Data analysis

This study followed the convention of limiting analyses to the sagittal and frontal planes (Fantozzi et al., 2015, Severin et al., 2017) due to questioned accuracy of internal sensors in the transverse plane (Ohberg et al., 2013). All statistical analyses were performed with IBM SPSS version 22 (IBM, New York, NY). Bilateral kinematic differences in the AKP group were assessed by comparing peak angles for segments and joints between environments. Bilateral asymmetries in displacements were quantified between the affected and unaffected limb in the AKP group, and between the dominant and non-dominant limb in the control group. One SI score was obtained for each data set, where a zero-score indicated perfect symmetry (Nigg et al., 2013).

The movement depths were tested between environments for covariance and all kinematic variables were tested for compliance with the assumptions of an analysis of covariance. Wherever the assumptions were met, an analysis of covariance determined significant differences between the environments, and elsewhere, a repeated measures one-way analysis of variance was used. For the AKP group, the depth of the SLS was also compared between limbs (affected/unaffected). Effect sizes were calculated and ranked.
using the method developed by Cohen (1988, pp. 24-26), with scores $d>0.2$ considered small, $>0.5$ moderate and $>0.8$ considered large effect. The alpha level was set at $p<0.05$.

7.4. Results

The analysis showed that water immersion affected the maximal depth for the AKP group both during the squat (land: 33±8 cm, pool: 40±11 cm, $p=0.032$, $d=0.70$) and the SLS (affected limb: land: 20±7 cm, pool: 29±10 cm, $p=0.002$, $d=1.06$, unaffected limb: land: 19±6 cm, pool: 27±9 cm, $p=0.003$, $d=1.00$). Participants in the AKP group verbally reported that water immersion reduced any sensation of pain or discomfort during both exercises.

Bilateral differences existed in peak angles in both environments, where the affected limb generally achieved lower peak angles in the sagittal plane and larger angles in the frontal plane (Table 7.1 and 7.2).

Water immersion generally increased the degree of asymmetry in the lower body movements during the exercises for both groups. However, there was no apparent trend as to whether injury status increased or decreased the symmetry (Table 7.3).
Table 7.1. Peak sagittal plane angles for the squat between the affected and unaffected limbs in both environments.

<table>
<thead>
<tr>
<th></th>
<th>Land Unaffected</th>
<th>Land Affected</th>
<th>Pool Unaffected</th>
<th>Pool Affected</th>
<th>Cohen’s $d$</th>
<th>Pool Unaffected</th>
<th>Pool Affected</th>
<th>Cohen’s $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squat Shank angle ($^{\circ}$)</td>
<td>21.3 ± 8.0</td>
<td>21.8 ± 8.0</td>
<td>0.05</td>
<td>18.3 ± 8.4</td>
<td>22.0 ± 6.3</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squat Thigh angle ($^{\circ}$)</td>
<td>59.6 ± 27.9</td>
<td>62.6 ± 22.6</td>
<td>0.12</td>
<td>65.4 ± 22.5</td>
<td>58.9 ± 21.9</td>
<td>-0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squat Knee flexion ($^{\circ}$)</td>
<td>94.4 ± 16.7</td>
<td>90.2 ± 19.5</td>
<td>-0.23</td>
<td>95.2 ± 10.4</td>
<td>89.7 ± 14.6</td>
<td>-0.43*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squat Hip flexion ($^{\circ}$)</td>
<td>73.8 ± 17.0</td>
<td>71.7 ± 31.1</td>
<td>-0.08</td>
<td>77.8 ± 19.7</td>
<td>66.7 ± 19.9</td>
<td>-0.56</td>
<td></td>
<td></td>
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<tr>
<td>Squat Shank medial deviation ($^{\circ}$)</td>
<td>9.2 ± 5.3</td>
<td>8.2 ± 5.7</td>
<td>-0.20</td>
<td>10.0 ± 5.0</td>
<td>11.9 ± 4.2‡</td>
<td>0.42</td>
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<tr>
<td>Squat Thigh lateral deviation ($^{\circ}$)</td>
<td>10.3 ± 8.5</td>
<td>13.6 ± 9.4</td>
<td>0.37</td>
<td>12.4 ± 10.4</td>
<td>20.6 ± 9.0‡</td>
<td>0.84*</td>
<td></td>
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</tr>
<tr>
<td>Squat Hip adduction ($^{\circ}$)</td>
<td>6.0 ± 8.5</td>
<td>3.6 ± 5.6</td>
<td>-0.33</td>
<td>4.1 ± 3.8</td>
<td>3.0 ± 3.1</td>
<td>-0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squat Knee adduction ($^{\circ}$)</td>
<td>17.2 ± 12.8</td>
<td>20.0 ± 13.7</td>
<td>0.21</td>
<td>19.8 ± 13.0</td>
<td>30.3 ± 11.6‡</td>
<td>0.85*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squat Hip abduction ($^{\circ}$)</td>
<td>12.0 ± 9.0</td>
<td>12.7 ± 9.9</td>
<td>0.07</td>
<td>10.8 ± 8.0</td>
<td>18.8 ± 10.7‡</td>
<td>0.85*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squat Knee abduction ($^{\circ}$)</td>
<td>3.8 ± 3.1</td>
<td>2.1 ± 2.5</td>
<td>-0.58</td>
<td>3.4 ± 2.8</td>
<td>3.7 ± 3.7</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* indicates significant difference between limbs at $P<0.05$
‡ indicates large within-limb effect size between environments at Cohen’s $d >0.8$
‡ indicates moderate within-limb effect size between environments at Cohen’s $d >0.5$
<table>
<thead>
<tr>
<th></th>
<th>Land Unaffected</th>
<th>Land Affected</th>
<th>Pool Unaffected</th>
<th>Pool Affected</th>
<th>Cohen’s $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank angle (°)</td>
<td>26.0 ± 10.0</td>
<td>24.0 ± 5.8</td>
<td>25.8 ± 8.4</td>
<td>27.8 ± 7.7†</td>
<td>0.25</td>
</tr>
<tr>
<td>Thigh angle (°)</td>
<td>36.1 ± 14.7</td>
<td>36.2 ± 11.8</td>
<td>51.3 ± 9.0†</td>
<td>49.1 ± 8.6†</td>
<td>-0.25</td>
</tr>
<tr>
<td>Thorax angle (°)</td>
<td>23.8 ± 11.5</td>
<td>23.2 ± 9.8</td>
<td>17.9 ± 11.2‡</td>
<td>16.2 ± 8.6‡</td>
<td>-0.16</td>
</tr>
<tr>
<td>Knee flexion (°)</td>
<td>65.0 ± 13.5</td>
<td>61.6 ± 10.4</td>
<td>78.1 ± 13.4†</td>
<td>76.0 ± 12.1†</td>
<td>-0.17</td>
</tr>
<tr>
<td>Hip flexion (°)</td>
<td>42.8 ± 12.9</td>
<td>33.7 ± 11.4</td>
<td>59.8 ± 11.3†</td>
<td>42.5 ± 9.6†</td>
<td>-1.37*</td>
</tr>
<tr>
<td>Trunk flexion (°)</td>
<td>20.6 ± 13.4</td>
<td>19.6 ± 11.2</td>
<td>21.1 ± 9.4</td>
<td>12.4 ± 7.4‡</td>
<td>-1.03*</td>
</tr>
<tr>
<td>Shank medial deviation (°)</td>
<td>2.4 ± 2.3</td>
<td>7.5 ± 4.8</td>
<td>10.4 ± 6.7†</td>
<td>11.3 ± 7.4‡</td>
<td>0.13</td>
</tr>
<tr>
<td>Thigh lateral deviation (°)</td>
<td>5.2 ± 4.1</td>
<td>6.3 ± 5.7</td>
<td>8.7 ± 8.5‡</td>
<td>9.7 ± 7.3‡</td>
<td>0.13</td>
</tr>
<tr>
<td>Thorax lateral deviation (°)</td>
<td>5.0 ± 6.0</td>
<td>3.5 ± 2.9</td>
<td>3.5 ± 2.8</td>
<td>2.6 ± 2.6</td>
<td>-0.34</td>
</tr>
<tr>
<td>Hip adduction (°)</td>
<td>9.4 ± 8.7</td>
<td>6.1 ± 4.2</td>
<td>6.4 ± 5.3</td>
<td>4.9 ± 2.9</td>
<td>-0.51</td>
</tr>
<tr>
<td>Knee adduction (°)</td>
<td>9.5 ± 7.7</td>
<td>12.3 ± 7.9</td>
<td>19.0 ± 13.2†</td>
<td>19.7 ± 12.3‡</td>
<td>0.05</td>
</tr>
<tr>
<td>Hip abduction (°)</td>
<td>7.4 ± 6.3</td>
<td>5.7 ± 5.8</td>
<td>7.8 ± 7.5</td>
<td>11.1 ± 8.1‡</td>
<td>0.42</td>
</tr>
<tr>
<td>Knee abduction (°)</td>
<td>4.2 ± 2.6</td>
<td>2.2 ± 1.6</td>
<td>7.8 ± 6.3‡</td>
<td>2.3 ± 2.2</td>
<td>-1.18*</td>
</tr>
<tr>
<td>Trunk lateral tilt (°)</td>
<td>5.3 ± 4.8</td>
<td>8.2 ± 4.4</td>
<td>4.3 ± 2.4</td>
<td>3.6 ± 3.0†</td>
<td>0.23</td>
</tr>
</tbody>
</table>

* indicates significant difference between limbs at $P < 0.05$
† indicates large within-limb effect size between environments at Cohen’s $d > 0.8$
‡ indicates moderate within-limb effect size between environments at Cohen’s $d > 0.5$
Table 7.3. Asymmetry index score between the unaffected and affected limb.

<table>
<thead>
<tr>
<th></th>
<th>Land</th>
<th>Pool</th>
<th>Cohen’s $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Squat</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank AP (°)</td>
<td>0.4 ± 0.3</td>
<td>0.6 ± 0.3</td>
<td>-0.44*</td>
</tr>
<tr>
<td>Thigh AP (°)</td>
<td>0.6 ± 0.4</td>
<td>0.4 ± 0.3</td>
<td>0.38</td>
</tr>
<tr>
<td>Knee flexion (°)</td>
<td>0.8 ± 1.6</td>
<td>0.9 ± 0.9</td>
<td>0.02</td>
</tr>
<tr>
<td>Hip flexion (°)</td>
<td>0.3 ± 0.2</td>
<td>1.1 ± 0.6</td>
<td>-2.10*</td>
</tr>
<tr>
<td>Shank ML (°)</td>
<td>2.5 ± 1.4</td>
<td>1.9 ± 1.3</td>
<td>0.45</td>
</tr>
<tr>
<td>Thigh ML (°)</td>
<td>2.4 ± 1.6</td>
<td>2.8 ± 1.8</td>
<td>-0.23</td>
</tr>
<tr>
<td>Knee abduction (°)</td>
<td>4.5 ± 1.3</td>
<td>5.4 ± 1.2</td>
<td>-0.66*</td>
</tr>
<tr>
<td>Hip abduction (°)</td>
<td>5.7 ± 4.4</td>
<td>5.5 ± 1.8</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Single Leg Squat</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank AP (°)</td>
<td>0.9 ± 1.1</td>
<td>2.0 ± 1.3</td>
<td>-0.86*</td>
</tr>
<tr>
<td>Thigh AP (°)</td>
<td>0.8 ± 0.5</td>
<td>0.9 ± 0.6</td>
<td>-0.25</td>
</tr>
<tr>
<td>Thorax AP (°)</td>
<td>4.9 ± 1.4</td>
<td>5.7 ± 1.5</td>
<td>-0.51</td>
</tr>
<tr>
<td>Knee flexion (°)</td>
<td>0.7 ± 0.5</td>
<td>1.3 ± 1.8</td>
<td>-0.49</td>
</tr>
<tr>
<td>Hip flexion (°)</td>
<td>1.5 ± 0.8</td>
<td>1.8 ± 1.0</td>
<td>-0.31</td>
</tr>
<tr>
<td>Trunk flexion (°)</td>
<td>2.7 ± 2.4</td>
<td>2.8 ± 1.6</td>
<td>-0.05</td>
</tr>
<tr>
<td>Shank ML (°)</td>
<td>2.3 ± 1.1</td>
<td>4.9 ± 3.2</td>
<td>-1.04*</td>
</tr>
<tr>
<td>Thigh ML (°)</td>
<td>2.8 ± 1.5</td>
<td>3.1 ± 1.8</td>
<td>-0.19</td>
</tr>
<tr>
<td>Thorax ML (°)</td>
<td>6.2 ± 4.5</td>
<td>7.3 ± 5.0</td>
<td>-0.24</td>
</tr>
<tr>
<td>Knee abduction (°)</td>
<td>4.3 ± 1.0</td>
<td>4.7 ± 2.8</td>
<td>-0.18</td>
</tr>
<tr>
<td>Hip abduction (°)</td>
<td>5.2 ± 4.8</td>
<td>5.0 ± 1.6</td>
<td>0.06</td>
</tr>
<tr>
<td>Trunk lateral tilt (°)</td>
<td>4.4 ± 1.7</td>
<td>5.2 ± 2.7</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

* indicates significant difference between environments at $P<0.05$

\( \alpha \) indicates large effect size between environments at Cohen’s $d >0.8$

\( \beta \) indicates moderate effect size between environments at Cohen’s $d >0.5$
7.5. Discussion

Primary findings were that individuals with AKP employed different kinematics in the affected and unaffected limbs during squats and SLS on land and in water. Immersion appeared to increase bilateral differences between limbs, perhaps because of the more dynamic environment (Colado et al., 2013). Further, it appears individuals with AKP employ different movement strategies in both environments compared to healthy controls.

The results suggest that water immersion allows individuals with AKP to achieve greater squat and SLS depth compared to performing the exercises on land. This was also reflected in increased peak hip and knee flexion angles, particularly during the SLS. The reduced loading in water no doubt allowed greater movement depth without producing discomfort or pain at the knee. Water immersion can therefore improve knee joint range of motion in this population, possibly due to the reduced joint loading. Re-establishing knee joint range of motion is a primary goal in early rehabilitation for AKP (Werner, 2014), and practitioners are encouraged to recognize the benefits of increased squat depth during rehabilitation for this population.

Interestingly, the AKP group showed similar peak angles during land-based squats between limbs in both planes of motion. These observations support previous researchers that reported comparable flexion angles during squats in individuals with previous ACL injury (Roos et al., 2014, Salem et al., 2003). However, the authors stressed that kinetic differences existed between the limbs, and cautioned that compensatory movements may not be reflected in the kinematics. The authors also highlighted a difficulty for practitioners to identify joint substitutions without access to kinetic measurements. It is possible the AKP group employed compensatory movement strategies that would have been evident on land during kinetic assessments, despite appearing symmetrical.
Water immersion revealed bilateral differences in the squat that were not evident on land. This finding also agrees with previous research reporting increased asymmetry in water (Cadenas-Sanchez et al., 2015). Interestingly, while the unaffected limb appeared to maintain its kinematics between environments, increased hip abduction in the affected limb indicated a wider stance in water, with a shift in loading towards the unaffected limb. Wider stance was probably a balance strategy as it widened the base of support. Researchers have previously highlighted that water immersion changes balance demands (Devereux et al., 2005, Roth et al., 2006), although the full implications of this remain unknown. Previous research on kinematic asymmetry in water is limited, but it has been suggested that added resistance and greater instability contributes to increased asymmetry in water (Cadenas-Sanchez et al., 2015). These authors suggested the asymmetries in water probably reflected pre-existing functional differences. It is possible the asymmetries that appeared in water were reflections of compensatory movement strategies revealed by the aquatic environment.

Perhaps the gravitational offloading (Harrison et al., 1992), decreased pain (Evcik et al., 2008), and altered proprioception (Roth et al., 2006) changed the demands of the exercises to the extent where established movement strategies were disrupted and asymmetries were revealed. Currently, not enough literature exists to determine whether the bilateral differences in water were associated with compensatory strategies, and future research should assess kinetic profiles and quantify environmental effects on compensatory movements. The possibility that water immersion may reveal bilateral asymmetries is exciting as it provides practitioners with a useful movement assessment tool that is not currently available.
Bilateral differences in both the sagittal and frontal planes were evident also during the SLS in both environments. This was particularly evident in the hip and trunk flexion coupling, and in the knee adduction angle. Land-based SLS on the affected limb showed decreased hip flexion and increased varus alignment and lateral trunk lean. The reduced hip flexion probably indicated a strategy with less hinging from the hip, which shifts the centre of gravity posteriorly, and reduces the demand of the gluteal muscles (Powers, 2010). This increases the demand of the quadriceps, and consequently the compressive loads of the patello-femoral joint (Escamilla et al., 2008b), and potentially contributes to the continued aggravation of AKP. Research has also suggested this may contribute the weak gluteal muscles that are often reported in this population (Powers, 2010). The compensatory movements employed by the AKP group on land may therefore aggravate their condition further. Importantly, this adaptation was not reduced in water, despite the considerable offloading.

The increased lateral trunk lean on land supported previous research that reported increased frontal plane movements in individuals with AKP (Crossley et al., 2011, Nakagawa et al., 2012). Water immersion appeared to provide lateral support to the trunk, as the trunk lean was reduced when immersed. Our The results showed marginally reduced valgus alignment on the affected limb, although previous research has reported increased valgus in this population (Crossley et al., 2011, Nakagawa et al., 2012). The previous authors suggested that increased valgus was associated with hip-muscle weaknesses. The reason for this discrepancy with previous research remains unknown, but the knee abduction angles in the unaffected limb were similar to previous reports for healthy controls (Nakagawa et al., 2012). It is possible that the participants in this study did not have reduced muscle strength. Interestingly, water immersion increased the knee
abduction angles of the affected limb, while it increased the varus alignment in the affected limb. This was probably a positive observation, as increased valgus alignment is associated with decreased functionality and injury (Fukagawa et al., 2012, Graci and Salsich, 2015). However, excessive varus has been associated with the development of osteoarthritis (Sharma et al., 2013). The different adaptation to immersion potentially indicated an aberrant movement strategy in response to the AKP that was enhanced in water. Regardless, further research is needed to determine the functional effects of these adaptations.

The increased frontal plane motions during water-based SLS cannot be attributed to a wider stance, as it is unilateral exercise. Previous research suggested an increased reliance on frontal plane motions in water for balance (Severin et al., 2017). Increased lower body motions may be a normal response to the unstable nature of the aquatic environment, as a balance strategy. This study did not quantify balance so the effects of water immersion on postural control remain unknown. However, previous researchers have reported improved land-based balance following water-based training (Roth et al., 2006, Resende et al., 2008), although these studies did not measure balance during immersion. Other researchers reported increased postural sway in water during quiet standing (Marinho-Buzelli et al., 2017b), but did not assess dynamic movements. Future research should analyse ground reaction forces and perturbations in centre of pressure during water-based exercises to further the understanding water immersion on balance strategies.

The SI analysis showed that water immersion often emphasized bilateral asymmetries in both groups. Research has highlighted that some asymmetry is normal even within a healthy population (Cadenas-Sanchez et al., 2015, Nigg et al., 2013, Sadeghi et al., 2000). However, all statistically significant differences in the current study showed more
asymmetry in water. Although these observations agree with previous research (Cadenas-Sanchez et al., 2015), the effects of increased asymmetry are still unknown. Prolonged asymmetrical motions at the knee joints can potentially lead to osteoarthritis (Roos et al., 2014). However, it is possible that gravitational offloading in water reduces long-term effects of asymmetrical loading. The offloading constitutes a primary rationale for employing aquatic therapy for rehabilitation (Becker, 2009) as it allows for earlier return to partially loaded activities.

Conversely, the emphasized asymmetries in water can potentially be detrimental for rehabilitation. Asymmetrical motor patterns can reduce the efficacy of rehabilitation exercises (Roos et al., 2014), which highlights the need for close monitoring during rehabilitation. Continuous movement assessments throughout a rehabilitation program can highlight asymmetries and potentially indicate the efficacy of the program. Practitioners should acknowledge the presence of asymmetry in all motion tasks (Sadeghi et al., 2000), although research is yet to determine the threshold for when asymmetrical movements should be considered undesirable. The SI scores in this research ranged from 0.3 to 8.2, and researchers using the same SI method reported scores between 8 and 16, but did not refer to whether this should be considered normal (Nigg et al., 2013). Therefore, the practical implications of these values remain unclear.

Our participants had no prior experience with water-based exercise, so it is possible that habituation could change these results. Researchers have highlighted lacking understandings on effects of water immersion on movement symmetry (Cadenas-Sanchez et al., 2015), which deserves attention in future research. Further, the transferability of movements between the environments has not been established and it is possible that any beneficial movement adaptations observed in water is confined to pool-settings. This
necessitates that future research determines the degree of transferability between water and land to optimize current guidelines for practitioners.

7.6. Conclusions

Water immersion allowed individuals with unilateral AKP increased depth during squats and SLS, along with greater flexion angles. The increased movement range catered to early rehabilitation goals for individuals with AKP. The exercise environment also affected the movement patterns differently between limbs. The degree of asymmetry was also affected in both groups during the exercises, although the long-term effects of this remain unknown. Practitioners should consider aquatic therapy as one component of a comprehensive treatment plan for participants with long-standing AKP, and use it in conjunction with established protocols.
CHAPTER 8:

GENERAL DISCUSSION AND CONCLUSIONS
GENERAL DISCUSSION AND CONCLUSIONS

8.1. Overview

This thesis presented four studies that examined the effects of water immersion on trunk and lower body kinematics. Three studies examined different populations: young healthy adults, older adults, and young adults with chronic anterior knee pain, and quantified their kinematic adaptations to water immersion. Quantifying kinematic differences between exercises performed on land and during water immersion across different populations, provided a further understanding of the efficacy of water-based rehabilitation and exercise. The literature review (Chapter 2) suggested the efficacy of water-based exercise potentially differed between populations. The first study (Chapter 4) assessed healthy and active young adults and provided an insight into the kinematic effects on a ‘control’ population. This was necessary due to a lack of previous research on water-based kinematics during squat exercises. An additional fourth study assessed kinematic effects of altered water depth on the young and healthy population (Chapter 5). This analysis provided an insight into kinematic effects of small changes in water depth during squats. This study offered useful information for practitioners working in group-based settings as individuals of different height experiences different degrees of immersion at the same water depth. The following two studies (Chapter 6 and 7) assessed older adults and young adults with unilateral AKP, thereby providing insight into specific populations that often are prescribed water-based exercise.

This project used inertial sensors to collect kinematic data both on land and in water. Although the sensors’ accuracy has been validated in previous research, it was determined that a validation analysis was needed to establish the relative accuracy of the Nanotrak units used (Chapter 3). The analysis supported previous research (Luinge and Veltink,
2005) in that the relative accuracy of individual sensors differed slightly. This meant that for the rest of the project, great care was taken to ensure that the sensors were consistently allocated to the same segment.

The findings of this thesis highlight the suitability of water-based exercise as it shows several positive kinematic adaptations to water immersion. The project also reveals aspects of rehabilitation that the aquatic environment may not be able to correct or benefit directly. By taking an objective approach, and presenting both benefits and limitations of water-based exercise, the findings from this project expands the understanding of applications for aquatic therapy and provides practitioners with new guidelines for programming in the aquatic environment. The overall aim of this thesis was to provide practitioners with increased understanding of how water immersion affects kinematics and this final chapter aims to summarise the key findings and present practical implications and recommendations for professionals.

A secondary outcome from this project was the insight into practical applications for inertial sensors as a tool for practitioners. Therefore, this chapter also briefly discusses practical implications and challenges for using inertial sensors in aquatic settings.

### 8.2. Effects of water immersion on squatting kinematics

The studies presented in this thesis were the first to quantify effects of water immersion on the kinematics of squats, split squats, and single-leg squats. The main findings showed that the kinematics of these exercises, that are well understood when performed on land, changes when they are performed in water. Water immersion to the greater trochanter affected several kinematic variables, including speed of the movements, displacements, peak angles, and ROM (Chapters 4, 6 and 7). Water immersion has previously been
shown to affect several biomechanical aspects of walking and running gait (Kaneda et al., 2012b, Masumoto et al., 2009), and isolated motions of the trunk, knee, and upper limb (Bressel et al., 2011, Poyhonen et al., 2001a, Cutti et al., 2008). However, prior to this project, limited research had assessed its effects on squat exercises, although practitioners often prescribe them for rehabilitation.

8.2.1. The squat depth and range of motion

A common outcome for the three populations was that water immersion increased the maximal depths of the exercises, and thereby increased the ROM of the segments in the lower body. Interestingly, the young and healthy population only increased their depth during the SLS (Chapter 4), while both other populations increased the depth of all exercises (Chapter 6 and 7). The increased movement depths were accompanied by increased peak joint angles and ROM in the lower body. This is a positive observation as they are important aims in early rehabilitation (Werner, 2014, Han et al., 2015, Kim et al., 2010), and is often used as an indicator of functionality (Zhuang et al., 2014, Yamazaki et al., 2010), and recovery (Wilcock et al., 2006).

Although it has been suggested that water immersion may allow increased ROM due to its offloading (Devereux et al., 2005, Becker, 2009), much of the previous research has reported similar ROM during water-based and land-based walking (Kaneda et al., 2012b, Miyoshi et al., 2003, Miyoshi et al., 2004). Interestingly, water immersion has been reported to have a positive effect on ROM in individuals with restricted mobility due to medical conditions (Suomi and Lindauer, 1997), and may therefore be a useful tool in their rehabilitation. The water depth used in this project (to the greater trochanter), offloads approximately 40% of the participant’s bodyweight (Becker, 2009), and the hydrostatic pressure provides additional support to movements (Resende et al., 2008).
This likely made it easier for the participants to reach full movement depth without restrictions from strength, balance, pain, or discomfort.

Interestingly, increased joint ROM in water suggests the older and AKP groups were unable to achieve full movement depths on land, perhaps due to insufficient strength or pain. Reduced muscle strength and function are common consequences of both ageing and pain (Nakagawa et al., 2012, Brooks and Faulkner, 1994), and deeper squat movements are known to increase joint stresses and require larger muscle forces (Escamilla et al., 2008b, Powers et al., 2014). This is an important consideration for practitioners, as clients matching these populations may be unable to achieve full range during land-based, bodyweight squatting exercises. The healthy adults were probably not restricted by strength during land-based squats and SS and were thus able to reach full depth in both environments.

On the other hand, the SLS no doubt challenged the strength even for the young and healthy population, thus preventing them from achieving full depth on land. It is likely that strength contributes to maximal squat depths, and as the offloading in water no doubt reduced strength demands of the exercises, water immersion improved range. This research suggests that the older and AKP populations had restricted ROM on land, which affected both the squats and SS. Whether this restriction was due to pain or muscle weakness remains unknown. Regardless, the findings from this project support the hypothesis proposed in the literature review (section 2.6.2), that the efficacy of water immersion of increasing ROM may be dependent on the population.

Another consideration is that the supporting properties of water also likely changed the balance restrictions. Research has suggested that the movements of the surrounding water
increase sensory and mechanical perturbations that result in changed balance demands (Marinho-Buzelli et al., 2017b). The SLS no doubt challenged the balance of the participants as well as the strength, and increased balance support might have allowed the increased squat depths. Although increased instability has been reported in water (Bressel et al., 2016, Louder et al., 2014), some evidence suggests that the properties of water may facilitate balance (Devereux et al., 2005, Resende et al., 2008). Slower movements in water may indeed increase the time available for postural corrections when balance is lost (Resende et al., 2008), and the gravitational offloading reduces muscular demands (Devereux et al., 2005) for maintaining balance.

The increased squat depths during the unstable exercises that were seen in this project, suggest water immersion may facilitate balance. Conversely, it has been proposed that the offloading in water elevates the centre of gravity and reduces stability (Louder et al., 2014). Research has shown that postural sway is increased during water immersion and highlighted that it probably indicates less perceived stability (Bressel et al., 2016). However, water immersion has been found to reduce the fear of falling, and is a primary reason for using water-based exercise for older populations (Devereux et al., 2005, Kaneda et al., 2008a, Resende et al., 2008, Kim and O’Sullivan, 2013). Water-based exercise has been shown to be better at reducing the fear of falling than land-based programmes (Oh et al., 2015, Simmons and Hansen, 1996). Although water immersion may decrease the perceived stability, it is possible that the participants’ fear of hurting themselves in case of a fall was reduced. Perhaps water immersion increases individuals’ confidence of being able to perform a task without painful consequences of falling over, which might have contributed to the increased movement range in water during unstable exercises.
It is also possible that pain (or the anticipation of pain) contributed to the limited squat depth on land for the older and AKP populations. Pain is known to encourage avoidance behaviours and can cause persistent changes in movement patterns and movement control (Lund et al., 1991, Moseley, 2003, Silder et al., 2010). Importantly, it has been shown that subconscious movement modifications can occur only with anticipation of pain, and does not require the onset of physical pain (Sawamoto et al., 2000). It is possible the participants reduced their range as they felt, or anticipated, pain when the exercises were performed on land. Water immersion is known reduce pain due to the offloading and hydrostatic pressure (Ernst et al., 1991, Martel et al., 2005, Torres-Ronda and Del Alcazar, 2014), and may therefore have promoted increased joint ROM. It was seen that both groups significantly increased their squat depth and lower body peak flexion angles in water. However, since movement modifications can be a subconscious response (Graven-Nielsen et al., 2000), it is not possible to determine whether the increased depth was because participants anticipated less pain (or discomfort) in water or due to other factors (such as strength or balance). However, although pain might have contributed to the restricted range on land, it was unlikely the only reason for the increased squat depth in water in the older and AKP populations, since strength and balance likely played some role.

The results from this project show that practitioners may employ water-based exercises to increase the ROM and depth of squat exercises that may be restricted on land. It is possible the increased ROM is related to different demands of strength and balance, and reduced pain in the aquatic environment. However, it is not possible to determine the specific influence of these variables on altering movements based solely on the kinematic data. To determine the effect of strength, balance, and pain on movement depth would
require kinetic or muscle activity data, which was not available in this study. Future research that assesses muscle activity and joint movement during these squatting variations in water may provide clarification on the causation of increased movement depths.

This project also suggests that practitioners should recognise that full gravitational load may restrict even bodyweight squats for populations such as older adults and individuals with unilateral AKP. Water-based squats may be beneficial in stages of rehabilitation where increased range of motion at the hip and knee joints is important. It may also help to develop desired motor programs for exercises where full range is not possible to achieve on land.

8.2.2. The sagittal plane

The different populations involved in this project showed similar kinematic effects of water immersion on all three squat tasks; however, the magnitude of these changes was different between the groups.

The upper body

One consistent observation was the more vertically aligned trunk posture in water. Trunk alignment during squats is a popular topic in the literature with considerable research having assessed its effects on muscle activity (Vakos et al., 1994), joint forces (Schoenfeld, 2010) and its association with injury (Escamilla, 2001). Biomechanical research often emphasises the importance of maintaining a vertically aligned trunk during squatting and lifting as it reduces shear and compressive forces acting on the spine (Schoenfeld, 2010, Bazrgari et al., 2007, Escamilla, 2001). A forward trunk lean during land-based squats is undoubtedly a balance strategy used to maintain the centre of gravity
within the base of support (Hof et al., 2005), while an upright trunk would shift the centre of gravity posteriorly and compromise balance.

However, it is important to recognise that overemphasising an upright trunk alignment during squatting may result in excessive lumbar extension. Similar to excessive trunk flexion, lumbar extension has also been shown to increase spinal loading. Research on cadavers has shown that as little as 2° lumbar extension is enough to increase compressive spinal forces considerably (Adms et al., 1988). It has been highlighted that despite a heavy emphasis on appropriate lumbar curvature in both research and practical settings, few reports on squatting biomechanics actually quantified the angle of the lumbar spine (McKean et al., 2010a). The authors found that practitioners aiming to change the curvature of the lumbar spine for technique purposes often interfere with the normal lumbar movement during the squat task. Practitioners may therefore prioritise that individuals maintain their own natural spinal curvature throughout the squat motion, and recognise that it may differ between clients.

An upright trunk posture during squatting was promoted due to the buoyancy of the surrounding water, which provided an upward force to the torso (Chapter 4). In addition, the combined buoyancy, density, and viscosity might have allowed shifting the centre of gravity posteriorly without compromising balance. It is difficult to determine whether the spinal curvature was maintained between the environments, as sensors were only allocated to the thorax and sacrum. However, the data showed that the upright trunk angle was achieved with a minimal increase in lumbar extension (angle between the thorax and sacrum) in all populations (Appendix 10.3, Tables 10.1-10.3). The reduced anterior trunk lean was therefore considered to reflect a posterior shift in centre of gravity. This may be a positive adaptation to water immersion as vertically aligned trunk often is considered a
favourable squatting technique (Escamilla, 2001). Although the offloading in water probably reduced spinal loads in a manner that cannot easily be achieved on land, it is probably beneficial to encourage this technique during rehabilitation and exercise programmes performed in both environments. This may be particularly beneficial older adults, as research has shown increased forward lean during squats in this population (Fukagawa et al., 2012). The findings from this study show that practitioners can employ water-based squats for clients to encourage the development of a squatting technique with a more upright trunk posture.

The degree of transferability of this upright trunk posture to land-based movements remains unknown. It is unlikely that full gravitational loading will allow the same amount of vertical trunk alignment due to balance restrictions. In addition, practitioners should recognise that the ability of the aquatic environment to build muscle strength has been questioned (Heywood et al., 2017). Performing squats in water may therefore not amend excessive anterior trunk lean associated with muscle weakness, although it may be beneficial for developing improved movement patterns. Future research should assess the transferability of trunk position from water-based squats to land-based squats.

Another important finding from this project was the change in trunk alignment with deeper water immersion (Chapter 5). Waist-deep (umbilicus) immersion caused a slightly more anteriorly inclined trunk at the top of the squat (~ 5.0°), compared to the hip-deep (greater trochanter) immersion. Previous research has showed that different water depths affect postural sway during quiet standing (Bressel et al., 2016, Louder et al., 2014). These authors suggested that as the water got deeper, the progressively increased offloading decreased the demands of the postural muscles, and therefore increased the postural instability. It is possible that the difference in offloading between the hip and waist (40%
and 50% respectively (Harrison and Bulstrode, 1987)), caused the altered trunk posture during the squats.

It may be important to consider the degree of trunk immersion during the different depths. During immersion to the hip, the top of the squat task saw the trunk completely above the water and thus no longer exposed to the fluid dynamics. However, the trunk remained partially immersed during the waist-deep water, which means that the water dynamics acting on the trunk were different between the depths (Marinho-Buzelli et al., 2017b). Water immersion has been reported to affect the coordination of postural movements (Louder et al., 2014) and proprioception (Fantozzi et al., 2015, Lau et al., 2014, Roth et al., 2006). It is possible that such changes to the postural muscle might have caused the altered trunk muscle during the waist-deep immersion.

This research shows that even a small difference in the degree of trunk immersion was sufficient to alter the trunk posture during squats performed in water. This conclusion is however based solely on the kinematic data, and analyses of muscle activity and joint moments would add to the understanding of the effects of altered water depth on trunk posture. A clearer understanding would assist with understanding the practical implications of this, and provide further recommendations for practitioners. In the meantime, practitioners should recognise that using water-based exercise in a pool with set water depth means that participants of different heights experience different depths of immersion. This project shows that even if these changes are relatively small, they may induce changes in trunk posture. Therefore, this finding is important for anyone who practices water-based exercise in group-settings or a pool of a set depth.
The lower body

This project also showed consistent differences in hip and thigh orientation between land and water during the exercises across the populations (Chapter 4, 6, and 7). The increased movement depth was the result of increased flexion at both the hip and the knee. It was interesting that hip flexion increased more than knee flexion in water immersion across all populations (Appendix 10.3, Tables 10.1-10.3). This unexpected finding suggested a more ‘hip dominant’ movement pattern in water. A hip dominant movement pattern has been reported during ‘sit-to-stand’ tasks (Flanagan et al., 2003, Swinton et al., 2012), which are often considered more functional than squats, as they occur in everyday life (like rising from a chair) (Dall and Kerr, 2010). This project therefore suggests that squat-tasks become more ‘sit-to-stand’-like when they are performed in water. This is particularly beneficial for older adults as they have been found to squat with reduced hip flexion due to reduced muscle strength (Fukagawa et al., 2012). Water-based squat exercises may be beneficial for any individual undertaking rehabilitation, as they mimic everyday activities and tasks of daily living.

It was noted in Chapter 7 that the participants in the AKP group showed less hip flexion on the affected limb during the SLS, while they maintained normal knee motion. This movement substitution has been reported to reduce the demand on the hip extensor muscles, while increasing the joint forces at the knee through increased activity of the knee extensors (Powers, 2010). The author linked this aberrant movement strategy to both the continued aggravation of AKP, and the weaknesses in hip musculature that is often reported in this population (Bolglia et al., 2008, Ireland et al., 2003, Souza and Powers, 2009). Although it is unclear whether these movement patterns are caused by strength deficits or motor control impairments, both aspects are important and should be
considered during rehabilitation (Powers, 2010). Little research has examined the effects of water-based exercise on motor control, so it remains unknown whether the hip dominant movement patterns in water would benefit individuals with AKP. The possibility that water-based squats may assist with the motor control component of rehabilitation is appealing. However, future research is needed in order clarify the understanding of any effects of water-based exercise on motor control and its transferability to exercises performed on land.

It is not possible to establish the reason for the increased involvement of the hip musculature based solely on the kinematic data collected for this project. However, more hip dominant movement strategies have also been reported during water-based gait (Kaneda et al., 2012b, Masumoto and Mercer, 2008, Miyoshi et al., 2004). These authors suggested that the resistance of the water increases the demand of the hip joint in order to move the leg through the fluid. Even though the findings from this project are supported by the previous research, the squat exercise does not require propulsion of the full body. Therefore, the hip-dominant movement pattern should perhaps not be attributed to translation of the limb. It is important that future research assess the effects of water-based squat-tasks on kinetic and muscular profiles in order to determine whether they match the hip dominant kinematics.

It is also possible that the increased hip motion during the water-based squat was used as a balance strategy. Standing in water elevates the centre of gravity, and thereby decreases stability (Louder et al., 2014). It was suggested that this requires increased involvement of the hip in order to maintain balance. Through each repetition, the degree of immersion changes as the submerged body-mass increases and decreases. Therefore, the height of the centre of gravity also changes throughout the repetitions, which potentially increases
the instability even further. Future research should examine whether hip dominant movement strategies are associated with balance during water have, and whether it has functional benefits that are transferrable to land.

This project showed an increased kinematic engagement of the hip joint during the exercises across all populations. Whether this strategy is transferrable to land or not remains to be seen. Regardless, increased involvement of the hip joint during squatting tasks may be beneficial for the rehabilitation of several lower body injuries and increase movement functionality of activities of daily living.

Movement speeds
Another consistent finding was that water immersion altered the speeds of the movements, although some of these changes were no doubt linked to the different movement ranges in water. To allow comparisons between the environments, all participants performed the exercises to a tempo indicated by a metronome that was constant in both environments. It is therefore unsurprising that the movement speeds were faster in the environment with the larger movement range. For example, the trunk moved less in water and had therefore slower movements, while the increased movement depth in water meant that the thigh moved further and thereby faster (Chapter 4 and 6). Previous research agrees that water immersion reduces walking speeds (Kaneda et al., 2012b, Heywood et al., 2016), which may explain why water is generally considered to slow movements (Resende et al., 2008). However, the previous research did not report axial movement speeds and this project was amongst the first to report faster movements in water.

In agreement with the previous literature, the project found that water immersion marginally slowed movements that had similar movement range in both environments. The slower movements in water are a primary reason why water-based activities are
considered safer than those performed on land are (Resende et al., 2008, Geigle et al., 1997), as it prolongs the time available for individuals to regain postural control. Slower movements are also reported to improve movement control (Kaneda et al., 2012b), prevent falls (Abbasi et al., 2012), and improve confidence to encourage participation and adherence to exercise (Devereux et al., 2005). These effects are often associated with exercising for older adults, although they have obvious benefits for individuals with injuries and the general population.

Furthermore, this project showed that water immersion affects the speed of the ascending and descending phases of the squatting tasks differently, with larger effects often observed during the ascending phase (Chapter 4 and 6). It was hypothesised in Chapter 4, that buoyancy provides lifting assistance during the ascending phase, and therefore increases the speed. For the same reason, it is likely that buoyancy slows the descending phase as it acts opposite to the direction of the movement. Few comparisons can be made on this matter, as the previous literature has not reported differences between the ascent and descent in water. Most previous research assessed walking and running gait (Barela et al., 2006, Chevutschi et al., 2009, Fantozzi et al., 2015), which lacks ascending and descending phases, while research on jumping tasks only reported impact forces (Colado et al., 2010, Triplet et al., 2009). Literature reviews on water-based gait have highlighted the consensus of slower walking speed in water (Heywood et al., 2016, Kaneda et al., 2012b). However, despite the considerable amount of research included in the reviews, only walking-speed was assessed with no references to effects on angular segment or joint speeds.

Angular joint velocity is another variable that has not been well documented in the literature. Even studies that reported multiplanar kinematics during water-based walking
did not refer to axial velocities (Abdul Jabbar et al., 2017, Fantozzi et al., 2015). This is surprising as speed of movement is an important variable in rehabilitation (Cronin et al., 2002), especially when focusing on improving coordination and technique (Rutherford, 1988).

This project supports previous research in that the resistance of water generally slows human movement (Kaneda et al., 2012b), but it also highlights that faster segment velocities may occur if ROM increases, even without a changed movement tempo. This has not been highlighted in the previous literature and should be emphasised for practitioners, as it may be an important consideration during exercise prescription. Practitioners and researchers should be aware that larger movements in water may be accompanied by higher speeds, and must consider the use of verbal cues to ensure that exercises are performed at a desirable tempo.

8.2.3. The frontal plane

This project revealed that frontal plane kinematics is affected by water immersion, particularly those of the lower body. However, unlike the sagittal plane adaptations, the frontal plane differences appeared to be more individual and population-specific.

The upper body
Water immersion only affected the frontal plane motions of the trunk in the AKP group during the SLS (Chapter 7). The young healthy and older populations showed no effects of water immersion on the degree of lateral trunk flexion. The AKP group demonstrated more lateral trunk lean on land compared to the control group during the SLS, which often is reported in this population (Nakagawa et al., 2012, Powers, 2010, Souza and Powers, 2009). Weakness of the hip abductor muscles has been reported to cause increased pelvic obliquity during unilateral exercises, and increased ipsilateral trunk lean in order to
maintain balance (Nakagawa et al., 2012). The additional support provided by the water may have reduced the need for increased lateral trunk lean. The potential effects of water immersion on balance and reduced strength demands has been discussed numerous times throughout this thesis (section 2.5.3, section 2.6.2, and Chapters 4-7), and it is possible that these factors allowed the AKP group to maintain a more vertical trunk during the SLS.

Several studies have reported increased lateral trunk lean in individuals with various types of chronic knee pain (Almeida et al., 2015, Dierks et al., 2008, Nakagawa et al., 2012, Powers, 2010, Souza and Powers, 2009, Graci and Salsich, 2015, Herrington, 2014). However, the effects of reduced trunk lean on lower body kinematics in these populations have received less attention in research. The kinetic chain principle (Putnam, 1991) suggests that altered trunk mechanics would be reflected in the lower body kinematics. Although this has been suggested in the literature (Nakagawa et al., 2012, Powers, 2010); the specific effects of the lateral trunk lean on the lower body kinematics are not well documented in the previous research.

The findings from this project show that water immersion affects the frontal plane motions of the trunk, and one must therefore consider how that may affect the rest of the kinetic chain. Practitioners must always be aware of any changes in movement patterns when employing water-based exercise, and cannot assume that the changes are confined to one part of the body, or one movement plane.

The lower body
Water immersion increased the hip abduction and/or knee adduction angles across all populations, resulting in an increased varus alignment of the limbs. Interestingly, the valgus angles were similar between the environments across all populations. The
increased hip abduction during squats and SS suggests an increased stance width in water, perhaps as a strategy to maintain balance by widening the base of support. Squatting with a wider stance has been reported to increase the vertical trunk alignment (McKean et al., 2010a), increase peak hip flexion (Swinton et al., 2012, Escamilla et al., 2001), and emphasise gluteal muscle activation (McCaw and Melrose, 1999, Paoli et al., 2009). The wider stance in water may therefore explain both the upright trunk posture and increased involvement of the hip joint during the exercises (section 8.1.2). Although the same amount of research has not assessed biomechanical effects of stance width during SS, it is likely that similar changes occur. Practitioners should probably consider the stance width when programming squats in water as participants seem to prefer a wider stance if not directed otherwise.

However, the observed increased hip abduction cannot be attributed to a wider stance during the SLS. It is more likely that the participants used the properties of water for balance and relied on frontal plane movements to maintain balance during an exercise with a narrow base of support. A single-leg stance means very little lateral support, and perhaps the movement of the surrounding water was enough to cause disruptions in the balance of the participants and thus, requiring them to increase their frontal plane motions. However, the additional time for postural corrections (Resende et al., 2008) and offloading (Harrison et al., 1992) meant that the participants were able to shift their body sideways through the water without falling over and regain balance.

This concept has not been proposed in the previous research on balance in water. This is perhaps because only two previous studies have reported on frontal plane kinematics during water-based activity (Fantozzi et al., 2015, Abdul Jabbar et al., 2017). These studies assessed gait, and only mentioned that altered frontal plane movements likely
were associated with slower walking speeds and reduced loading. Yet again, the limited research in this field only allows the results from this project to be compared to gait analyses. The kinematics of gait and squat-tasks are considerably different, and the relevance of the information from the previous studies can be questioned.

It remains unclear whether the changes in the frontal plane motions of the lower body during water-based squats and SS are beneficial in increasing the hip muscle activation. Similarly, it is not known whether the suggested balance strategy during the SLS has positive effects on muscle strength or land-based balance. Regardless, this project showed considerable differences in frontal plane movements between land and water, and it seems plausible these changes were because of changed balance demands in water. One must also consider the relationship between the lower body movements, and the changes in trunk posture. It has been shown that trunk posture affects that of the lower body (Powers, 2010), so it is possible that the often reduced lateral trunk movements, played a role in the altered frontal plane motions of the limbs. Further assessments of the kinetic and neuromuscular aspects of water-based squats may assist in providing a clearer understanding of the effects the increased frontal plane movements may have on rehabilitation.

All three populations adopted similar kinematic changes to water immersion, and these were most likely strategies to maintain balance. It remains to be seen whether a wider stance in water can increase the activation of the gluteal muscles. In that case, water-based squat may be useful for clients that require gravitational offloading but has decreased hip involvement, or hip extensor strength. Similarly, it is exciting that water may allow individuals to re-establish balance by using frontal plane movements during SLS, as the reduced balance restrictions might have contributed to increased squat depth in water.
Practitioners can perhaps implement water-based SLS for clients who would benefit from the increased depth and joint ROM, but are unable to maintain balance on land.

Movement speeds
Similar to the sagittal plane speeds, large environmental differences in frontal plane movement ranges were reflected in their speed. However, unlike the sagittal plane, no general trends of slower velocities appeared for the frontal plane in water where the movement range was similar, which suggested individually developed frontal plane movement strategies. Previous research has reported that while the sagittal plane kinematics may be highly consistent and similar between individuals, this is not always the case with the frontal plane (De Wit et al., 2000, Kadaba et al., 1989). It has been proposed that small individual variances in anatomy may result in different kinematics (De Wit et al., 2000). It is likely that differences in anatomy, or technique, or muscle strength, might have caused these individual frontal plane strategies. One can theorise that the participants in this project had developed frontal plane movement strategies based on their individual movement constraints in order to achieve the task.

The frontal plane speeds were considerably smaller than those in the sagittal plane were (often less than 5.0°·s⁻¹), but their importance for movement efficiency has been highlighted in research (McClay and Manal, 1999, Stickler et al., 2015). Despite this, the effects of water immersion on frontal plane speeds are not well documented in the literature (Fantozzi et al., 2015, Abdul Jabbar et al., 2017), which complicates conclusions regarding their practical applications.

Regardless, like in the sagittal plane, this project highlights that larger frontal plane movements in water also are accompanied by faster speeds if the tempo is externally controlled. Practitioners should acknowledge this when prescribing exercises in water for
clients where the speed of movement is an important consideration for the rehabilitation. Second, it is accepted that as human movements predominantly occur in the sagittal plane, the movements in the secondary planes are much more individual (Kadaba et al., 1989). This project shows that this also applies to the frontal plane movement speeds, and it is likely that each participant had developed their own strategy that suits their individual movement constraints.

8.2.4. Effects on bilateral asymmetry

Chapter 7 highlighted that although a significant amount of research has shown kinematic differences between individuals with AKP and healthy controls (Nakagawa et al., 2013, Powers, 2010, Souza and Powers, 2009), kinematic differences between the affected and unaffected limb in this population has not been well documented in the literature. This was surprising as previous research has highlighted that populations with previous knee surgery or injury demonstrate lingering biomechanical asymmetries between the limbs (Roos et al., 2014, Christiansen et al., 2011, Komnik et al., 2015, Salem et al., 2003). Research has highlighted that asymmetries are important for normal functionality (Sadeghi et al., 2000, Fantozzi et al., 2015), and it was noted in Chapter 7 that bilateral asymmetries existed even in the control population, and that the groups displayed very different symmetry patterns.

Chapter 7 further showed that water immersion often increased the degree of bilateral asymmetry. However, the SI calculations have not been used previously to quantify bilateral asymmetries during squats. In addition, the literature on symmetry has predominantly assessed land-based gait, and different quantification methods have been used across the previous research (Nigg et al., 2013, Christiansen et al., 2011). It is difficult to compare the SI scores reported in this research to those reported previously.
The method of quantifying asymmetry used in this project was a rather novel method that analysed continuous data than individual data points (Nigg et al., 2013). The SI scores observed in this project for the young and healthy population and the AKP population ranged from 0.3 and 8.2 during the squat and SLS. This method has previously yielded SI scores between 1.7 and 27.2 for able-bodied gait (Nigg et al., 2013). The authors provided no reference regarding how to categorise the scores, other than that a score of zero indicate perfect symmetry. It is therefore difficult to interpret the results and suggest practical implications based on the findings. One primary conclusion is that both healthy adults and adults with AKP, performed the squat tasks with no more asymmetry than able-bodied walking gait (Nigg et al., 2013), regardless of the environment.

The kinematic analysis showed considerable differences between the limbs. The effects of water immersion on movement symmetry is another topic that has not been well documented in the literature, however, one previous study reported increased asymmetry during walking gait in water (Cadenas-Sanchez et al., 2015). The authors suggest that the increased asymmetry may reflect an exaggeration of pre-existing functional differences between the limbs. Interestingly, the data from this project showed that the AKP group moved symmetrically during land-based squats, but that several asymmetries appeared during water immersion. However, asymmetric movement patterns may not always be reflected in the kinematics, but in the kinetic profile (Roos et al., 2014, Salem et al., 2003). These authors reported different distributions of moments between the hip, knee, and ankle when comparing the affected and unaffected limbs in individuals with previous ACL injury, despite similar joint kinematics. It is possible that the participants with AKP had developed similar movement strategies, where asymmetric kinetic profiles were hidden behind symmetrical squatting kinematics. The altered constraints during water
immersion might have disrupted these movement strategies and by doing so, revealed asymmetries.

However, the equipment available for this study did not allow kinetic analyses, so the underlying factor behind these asymmetries in water remains unclear. Perhaps the asymmetries that appear in water match kinetic profiles for the movements performed on land. This suggests that practitioners may be able use water immersion to detect asymmetries that are invisible on land, without access to kinetic data. This concept urges future research to assess the kinetic profiles of individuals such as the AKP group, during squat tasks on land and in water. The possibility that water immersion may reveal asymmetries that are not visible on land is interesting, as it would provide practitioners with a cheap and easy alternative for detecting asymmetrical movement patterns.

Interestingly, asymmetric motions that appeared in the land-based data were often enhanced during water immersion, which showed that bilateral asymmetries remained despite the considerable offloading. This supported the hypothesis that the AKP group had developed aberrant motor programmes due to the prolonged pain and potential muscle weakness. It has been suggested that asymmetries are often caused by insufficient strength (Roos et al., 2014), which explains the strength focus in many rehabilitation programmes. Conversely, the results presented in Chapter 7 suggest that strength may not be a primary limitation in regaining movement symmetry, as even the considerable offloading did not correct it. It seemed more likely the asymmetric movements were an established part of the motor programming, to such an extent that the aberrant movement patterns were maintained regardless of the strength demands.
Although future investigations are needed to determine the validity of this hypothesis, it may provide important guidelines for practitioners. Current guidelines for rehabilitation often emphasise a focus on rebuilding strength of the injured limb in order to restore function (Werner, 2014). Despite reports of reduced muscle strength in individuals with pain (Nakagawa et al., 2012, Souza and Powers, 2009), the literature is conflicting on whether there is a direct causative relationship between pain and reduced strength, with researchers arguing both sides (Bak and Magnusson, 1997, Struyf et al., 2017). Researchers have even cautioned that the rehabilitation process itself may cause aberrant or asymmetric movement patterns, due to conscious or unconscious avoidance behaviours (Vlaeyen and Linton, 2012). The observations in Chapter 7 suggest that an established movement pattern may not be dependent solely on muscle strength. Therefore, one can question the continued emphasis on strength training, and propose that restoring motor patterns should take priority.

The persistent asymmetries even during offloading suggest an importance to incorporate early rehabilitation protocols that facilitate healthy movements and prevent the development of abnormal strategies. The effects of early incorporation of water-based exercises on movement compensations are not well documented in the literature. Although a systematic review by Villalta and Peiris (2013) concluded that early water-based rehabilitation can yield better functional outcomes in post-surgical patients, but none of the included studies assessed kinematic asymmetries. However, the observations of this project suggest the aquatic environment may provide practitioners an ideal alternative that facilitates range of motion and good technique during squatting tasks. All populations in this project demonstrated adaptations to water immersion that may benefit rehabilitation. However, Chapter 7 highlighted that once movement patterns are
established, even the considerable gravitational offloading during hip-deep water immersion may not be able to correct them. Future researchers should assess the effects of early water-based rehabilitation on the development of aberrant movement patterns and bilateral asymmetry in order to establish improved protocols for minimising the risks of long-standing movement compensations.

It is important for practitioners to be aware that water immersion may not correct or reduce existing lower body bilateral asymmetries in individuals with AKP, and that water immersion, in some cases, even emphasises asymmetric movements in this population. It may be tempting to assume that the reduced muscular demands with gravitational offloading, also allows individuals with muscular dysfunction to return to typical movement patterns. However, the results from this project suggest that the initial response to water immersion did not affect asymmetric movements. It is possible that prolonged exposure to water-based exercises alters the effects of immersion, but this information is valuable for practitioners as it suggests that water-based rehabilitation probably is most beneficial if implemented early, before abnormal movement patterns are developed. This project also showed that practitioners should emphasise re-educating movement patterns to regain asymmetry for clients presenting with long-standing pain. If reduced strength is not a primary determinant of asymmetric biomechanics, the offloading in water may not provide an optimal exercise setting.

8.3. **Practical applications of inertial sensors and NanoChop**

For inertial sensors to be better suited to practitioners, who may have limited time for data processing, software should be developed that yields the desired variables without requiring further processing. If such software existed, inertial sensors would be a very
valuable tool for a range of practitioners as they can perform movement analyses in different settings and thereby obtain comparative data to track progressions in clients. The studies in this project (Chapter 4, 5, 6, and 7) showed that the sensors are able to distinguish between movements accurately and can identify kinematic differences between individuals in at least two planes of motion.

The data collection for this project stretched over a several months and the inertial sensors provided accurate measurements throughout this period. This suggests that practitioners may be able to use sensors to monitor and track clients’ progressions overtime, without the need for frequent recalibrations performed by the manufacturer. At present, using individual inertial sensors to collect data is easier, cheaper, and more flexible than using an optoelectronic system. Similar to software used by many researchers, Nanochop provides smoothed and integrated displacement data quickly. This data could then be used to calculate joint angles, range of motion, and other potential variables of interest to practitioners.

The development and programming of Nanochop was an integral part of this project, as it saved significant time during the data processing and analysis, while reducing the risk of manual errors. It was encouraging that the data recorded with the sensors was comparable to the optoelectronic system, with very small differences between them (Chapter 3), despite substantial differences in data processing between the conventional software (Visual 3D), and Nanochop. The findings presented in this thesis showed that relatively inexpensive inertial sensors could be used to track human movements in non-laboratory settings.
*Nanochop* was designed to identify and distinguish individual cycles, which it did flawlessly. The program may be applicable to many tests that are performed in physiotherapy clinics, such as gait analysis, functional assessment of exercises (such as those employed in this project), and active and passive ROM tests. Further modifications to the code may also allow for its use in sporting situations where tracking field based sessions or several different drills often are required. It is exciting to consider the possibilities of inertial sensors and *Nanochop* in motion tracking across several disciplines.

This project showed that the Nanotrak sensors provided an accurate, portable, and simple alternative for collecting kinematic data both on land and in water. Inertial sensors offer a valuable opportunity to perform motion capture outside the laboratory, which is one of the major limitations with the gold-standard optoelectronic systems (Saber-Sheikh et al., 2010). Therefore, the findings of this project support previous research that inertial sensors probably have a role in practice and research.

**8.4. Limitations and directions for future research**

This project was the first to quantify the effects of water immersion on the kinematics of squat exercises, and amongst the first to use inertial sensors to track underwater kinematics. Due to the considerable methodological component, and the inaugural nature of this project, it has highlighted several exciting possibilities for future research. Expanding the understanding of effects of water-based exercise is necessary in order to optimise the application and delivery of aquatic therapy.
8.4.1. Effects of water immersion on the biomechanics of squatting tasks

Comprehensive biomechanical analyses of exercises performed in the aquatic environment would no doubt benefit many practitioners. This project presented several effects of water immersion that practitioners can apply to improve their understanding of water-based exercise. However, an increased understanding of muscle actions and kinetics is still necessary to fully comprehend the effects of water immersion on squatting biomechanics. So many questions remain before recommendations can be made to practitioners regarding optimal use of the aquatic environment. Increased elaboration of the concepts presented here will provide medical and fitness practitioners with better tools to ensure best possible outcomes for their clients.

This project only presents kinematic data, which may be its most obvious limitation but also the most important directive for future research. Inertial sensors are only able to record rotations and movements in space, and do not provide any information regarding kinetics. In order to gain insight on the kinetics an underwater force platform would have been required in addition to the sensors. Underwater force platforms exist and have been used successfully to present kinetic profiles of water-based gait (Miyoshi et al., 2003, Miyoshi et al., 2005, Orselli and Duarte, 2011). However, these are expensive and unavailable for use in this project. Regardless, an expanded understanding about how water immersion may affect the kinetic aspects of squat tasks would provide practitioners with valuable tools that would benefit the application of aquatic therapy.

This project showed that water immersion changed the kinematics of the exercises, with indications towards more hip dominant movement patterns and upright trunk posture, while also perhaps revealing compensatory movement patterns. The kinematic adaptations to water immersion supported these hypotheses; however, the full picture
remains concealed until research has assessed the kinetic profiles of these exercises. Practitioners must have a comprehensive understanding of the effects of all exercises they prescribe in order to ensure the desired outcomes for their clients are achieved. The research presented in this project highlights several exciting adaptations to water immersion that may have major effects on rehabilitation protocols. Yet, future research should examine the effects of water immersion on joint moments, weight distribution, and joint forces to further this understanding.

Similarly, increased understanding into the effects of water immersion on muscle activity would provide useful information to practitioners. It has been highlighted that previous reports disagree on the effects of water immersion on the levels of muscle activity (Kaneda et al., 2012b). It is possible that the effects on muscle activation are significantly affected by modifiable factors such as water depth, temperature (Cuesta-Vargas and Cano-Herrera, 2014) and water flow (Shono et al., 2007). Although researchers have suggested muscle activity based solely on kinematic data (Abdul Jabbar et al., 2017), water immersion has been reported to affect the muscle activation pattern differently than on land (Barela and Duarte, 2008, Barela et al., 2006). Researchers should therefore be careful when interpreting biomechanical data and not assume the same relationship between muscle activity, kinematics, and kinetics that may be expected on land. This highlights the need for future research to examine neuromuscular aspects of exercises performed in water and establish how different aquatic settings may affect muscle activity.

8.4.2. Protocols

This project showed that small changes in water depth have trivial effects on the lower body kinematics of squats, which is positive information for practitioners with limited
access to pools of adjustable depths. However, the altered trunk posture (Chapter 5) highlighted that more research is needed to clarify effects of different depths on biomechanics. An expanded understanding of the effects of altered water depth would be useful for practitioners as it can help establish protocols for rehabilitation programmes. These protocols should guide practitioners in the timing of commencement and progressions with water-based rehabilitation.

In addition, as this project found that the gravitational offloading was not enough to reduce bilateral asymmetries; it suggested that perhaps early commencement of partially loaded exercises is an important aspect of preventing the development of compensatory movement strategies. Future research should clarify the effects of early aquatic therapy in individuals with musculoskeletal injury and pain, and establish its effects on the development of movement substitution strategies.

8.4.3. Habituation and longitudinal research

The inclusion criteria for the project ensured that all participants were physically active at the time of testing and had substantial experience in performing bodyweight squats. However, the participants lacked prior experience in water-based squatting tasks, and were only allowed a few repetitions to familiarise themselves with the pool environment. It is possible that kinematic differences between land and water occurred due to the novelty of performing squats in the aquatic environment. It should be noted that all participants were accustomed to the aquatic environment as the research was conducted at a coastal region with a strong beach-culture. Regardless, there is a possibility that habituation would alter the effects of water immersion, and future research should examine if the biomechanical adaptations to water immersion changes with familiarisation to the environment.
Another possibility is that the kinematic adaptations seen in water may not transfer to land. The kinematics was affected by the physical properties of water (Kaneda et al., 2012b), and it remains unclear whether alterations can transfer to land where the environmental dynamics are different. There are currently no protocols for gradual re-introduction of gravitational load to progress an individual from water-based to land-based rehabilitation. Similarly, no guidelines exist regarding how much time should be spent in water for the adaptations to be transferrable to land. The studies presented in this thesis suggested that water-based exercises are beneficial for certain populations. However, future research still needs to establish whether water-based training may be transferred to land and establish protocols for optimal transference. The goal of water-based rehabilitation should be to train the client towards full function on land, so it is therefore imperative to establish guidelines and protocols to ensure outcomes.

8.4.4. Using inertial sensors for tracking underwater kinematics

Despite the sensors’ ability to collect 3D data, based on recommendations from previous researchers (Ertzgaard et al., 2016, Ohberg et al., 2013, Fantozzi et al., 2015), and the analysis in Chapter 3, all studies presented in this thesis excluded the transverse plane data. Researchers have highlighted that important motions occur in the transverse plane (Stickler et al., 2015, McClay and Manal, 1999), and it is possible that including it would have provided additional insights into the effects of water immersion. It is therefore strongly encouraged that future researchers aim to include the transverse plane when assessing water-based kinematics.

Another noteworthy consideration that was highlighted in this research was whether a single inertial sensor allocated to the sacrum could track three-dimensional motions of
the sacro-pelvic region. Chapter 3 showed poor agreement between a single sensor allocated to the sacrum, and an optoelectronic system tracking the pelvis, which was attributed to skin movements and the small motions between the sacrum and the pelvis (della Croce et al., 1999). The Outwalk protocol for gait analyses suggests a single sensor allocated in line with the spine at the height of the posterior superior iliac spines (Cutti et al., 2010). This is the same position that was used during this project, and despite this, the agreement between the sensor and the optoelectronic system was relatively poor. Other studies have also used inertial sensors to track the pelvis, but the information regarding the exact sensor allocation was vague (Boonstra et al., 2006, Ohberg et al., 2013). It is very likely that a single reference point is inadequate to model the complex motions of the whole pelvic girdle. Most protocols for optoelectronic systems require at least three anatomical landmarks on the pelvis to track its motion (Winter, 2009, pp. 176-199, Young-Hoo, 2008). This potential limitation with inertial sensors has not been highlighted in previous research, probably as most previous studies did not report pelvic kinematics. Future work should aim to establish a method for tracking pelvic kinematics accurately using inertial sensors.

8.5. Summary

The results from this project revealed several kinematic differences between land- and water-based squats, SS and SLS. Important findings from this project have highlighted several effects of water immersion on squatting kinematics that may be beneficial for rehabilitation and should be considered by practitioners.

The gravitational offloading allows practitioners to use the aquatic environment to increase active ROM of the lower limbs during squat tasks. Performing squat tasks in
water also reduced participants’ forward trunk lean, which often is considered favourable technique for land-based squatting. In addition, the increased reliance of the hip joint may also be beneficial from a rehabilitation perspective for individuals with reduced involvement of the hip joint or hip dysfunction.

Another important finding is that when the exercise tempo is pre-determined, some movement speeds in water may be faster than when the exercise is performed on land. This is valuable information for practitioners as movement speed often is an important consideration during rehabilitation. In addition, individuals employ larger frontal plane motions in water, likely due to different balance strategies in the dynamic environment. Practitioners should recognise that water may have considerable effects on both balance restrictions and balance demands of exercises, and that the effects of these on rehabilitation still are poorly understood.

Another key finding from this project is that water immersion increases asymmetric movements in the lower body. Even tasks that appear symmetrical on land may become asymmetrical when performed in water. Practitioners should also recognise that the offloading in water might not correct pre-existing bilateral kinematic asymmetries that are parts of an established motor programme. This project therefore highlighted that strength deficits may not be the primary cause for prolonged asymmetrical movements.

Overall, this project showed several effects of water immersion on the kinematics of squat exercises that may be beneficial for rehabilitation, and presented evidence in favour of exercises performed in water across three populations. It showed that water immersion can be a valuable tool for practitioners, and provided new insights that practitioners should consider when programming for water-based exercise, as it was shown that
squatting kinematics differs between the environments. Practitioners must consider the demands and benefits of exercises during prescription and cogitate how well water-based kinematics of squat tasks suits the individual needs of the client. By quantifying differences in squatting kinematics between water and land across different populations, this research project took a novel approach to underwater biomechanical analyses. In addition, several directions for future research were highlighted throughout the thesis, which may inspire other researchers to examine further aspects of water-based biomechanics to help guide practitioners to ensure improved prescription of aquatic exercise. Though much research is still needed to obtain a comprehensive understanding of the efficacy of water-based rehabilitation, this project has provided new evidence on the matter, and thereby furthered the understanding of the roles of aquatic therapy in rehabilitation.
CHAPTER 9:

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REFERENCES


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CHAPTER 10:

APPENDICES
10.1. Publication 1 - Biomechanical aspects of aquatic therapy: a literature review on application and methodological challenges.


LITERATURE REVIEW

BIOMECHANICAL ASPECTS OF AQUATIC THERAPY: A LITERATURE REVIEW ON APPLICATION AND METHODOLOGICAL CHALLENGES

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ABSTRACT

The application of aquatic therapy for health and rehabilitation purposes has been promoted for centuries. Although used predominantly in clinical settings for the treatment, rehabilitation and management of chronic conditions, the practice is also gaining popularity in athletic settings in such areas as recovery training and for the rehabilitation of acute musculoskeletal injuries.

To date, most studies on the impact of aquatic-based rehabilitation on the human body have focused on physiological aspects. There is a relative paucity of published research on the biomechanical implications associated with aquatic-based activity. The published findings have been limited to the influence of the aquatic environment on running and walking gait.

A clear challenge in this field is absence of standardised protocols for assessing the impact of aquatic therapy and its possible role in rehabilitation. For example, methodologies often differ considerably between studies, and there are no standardised reporting procedures for important variables such as water depth and temperature. The research knowledge in this area has been questioned, with current medical guidelines highlighting that high quality research into the roles of aquatic therapy in rehabilitation is warranted.

This review will summarise the current literature on water-based activity and how this can impact human movement and subsequent rehabilitation.

Keywords: water; human movement; underwater kinematics; rehabilitation; fitness; isoinertial sensors
INTRODUCTION

The health related benefits of aquatic therapy have been promoted for centuries.\(^1\) Common uses for aquatic therapy in clinical settings is managing\(^2\),\(^3\),\(^4\),\(^5\) and rehabilitating\(^6\),\(^7\),\(^8\) chronic conditions such as osteoarthritis (OA) and fibromyalgia.\(^3\),\(^9\),\(^10\) Aquatic therapy is also used for weight management, athlete rehabilitation,\(^11\),\(^12\),\(^13\),\(^14\) and recovery.\(^15\),\(^16\),\(^17\),\(^18\)

Despite decades of research examining the roles of aquatic therapy in rehabilitation, many of the results from scientific investigations are conflicting, likely due to differences in applied methodologies (Table 1). Because of the limited quality of current research, reviews published by the Cochrane Collaboration concludes that aquatic-based rehabilitation programmes are assumed equally effective to programmes performed on land, but highlights that further high-quality research is warranted.\(^2\),\(^19\),\(^20\),\(^21\),\(^22\) The lack of consensus among previous research regarding the efficacy of aquatic-based rehabilitation is resultant from several methodological challenges and a lack of consensus on the most appropriate outcome measures.

This review will briefly evaluate published literature on water-based activity; its impact on biomechanics and current role in rehabilitation protocols. Existing limitations and challenges in research methodology will also be reviewed along with gaps and limitations in the current knowledge and directions for future research will be recommended.

AQUATIC THERAPY EXPLAINED

The appeal of aquatic therapy as a tool in exercise, recovery and rehabilitation has increased over recent years.\(^23\),\(^24\),\(^25\) Previous research has identified several biomechanical and physiological effects associated with exercising in water that must be thoroughly understood by practitioners to prescribe accurate and effective programmes.\(^1\),\(^26\),\(^27\),\(^28\) These effects occur because of fundamental principles of hydrodynamics and physical properties of water, such as density, buoyancy, hydrostatic pressure, viscosity and thermodynamics.\(^1\),\(^26\),\(^29\)

THE PHYSICAL PROPERTIES OF WATER

Density

Density quantifies a substance’s mass by volume unit (Kg·m\(^{-3}\)).\(^30\) The density of 4°C freshwater is approximately 1,000 Kg·m\(^{-3}\) at sea level (999.97 Kg·m\(^{-3}\)). Although the temperature of the water affects its density, the change is considered small enough to dismiss (997.05 Kg·m\(^{-3}\) at 25°C).\(^31\) An average human body consists of approximately 60% water,\(^32\) and its density is thus slightly lower than that of water (approximately 974 Kg·m\(^{-3}\)).\(^1\) The specific density of a human body depends on body composition.\(^33\) Fat free mass, including bone, muscle, organs and connective tissue, has a density higher than water (close to 1,100 Kg·m\(^{-3}\)) whilst fat mass has a density lower than water (close to 900 Kg·m\(^{-3}\)).\(^33\) Thus, an individual with a higher percentage of fat free mass has a higher density compared to an individual with a higher fat mass percentage.

Buoyancy

A human body with a density lower than water displaces a volume of water that weighs slightly more than the body itself.\(^1\) By Archimedes principle, an upwardly directed force is exerted on the body equal to the volume of the water it displaced. This buoyant force, opposes gravity and pushes the submerged body towards the surface of the water.\(^1\),\(^34\) Accordingly, a human body with a specific gravity of 0.974 (a density of 974 Kg·m\(^{-3}\)) will achieve floating equilibrium when 97.4% of the body is submerged due to buoyancy.\(^1\) As the mass of the submerged body increases, the buoyancy force increases proportionally.\(^35\) Therefore, an individual immersed to chest level experiences a larger buoyancy force compared to someone immersed to the waist.

Hydrostatic pressure

In addition to buoyancy, the volume of water surrounding the submerged body also exerts a compressive force on the body - hydrostatic pressure.\(^36\) At sea level the pressure exerted on the
body by the air surrounding it is approximately 1013.0 Pa (7.6 mmHg), a value that is so small that it is basically imperceptible. However, the proportionally greater mass of water means that immersion in water exposes the body to considerably higher pressure, that like buoyancy, increases with the depth of immersion at a rate of approximately 981.0 Pa (73.5 mmHg) per meter. Accordingly, standing in water at neck depth will result in approximately twice the hydrostatic pressure on the calf muscles than on the chest.

Viscosity
Viscosity is the magnitude of internal friction a fluid has during motion and is specific to each fluid. An immersed body moving through water, experiences resistive drag forces opposite to the direction of travel because of viscosity. The viscous resistance is directly proportional to the force exerted against the fluid. Therefore, the resistance will increase with increased velocity and surface area of the moving body. For example, a fully outstretched arm produces a greater resistance when moving through water than a hand only. As soon as movement ceases and the exerted force on the water disappears, the viscous resistance drops immediately to zero, resulting in no further resistance on the body.

Thermodynamics
Water has a superior ability to retain heat and transfer heat energy than air and has a heat capacity of approximately 1.0 J·K⁻¹ (1,000 times greater than air). Water also has a higher heat capacity compared to human body tissues (0.83 J·K⁻¹), resulting in body equilibrating faster than the surrounding water. Thus, a body immersed in water colder than core temperature will adapt to the temperature of the water and lose heat. Water warmer than core temperature therefore warms the body and raises its core temperature.

EFFECTS OF WATER-BASED EXERCISE ON THE HUMAN BODY

The physical properties of water have large biomechanical, neurological, physiological and hormonal effects on the human body. Previous research has identified many of these effects; however, to explore them individually is outside the scope of this literature review, thus only those variables implicating on human movement will be addressed. For additional insight on the effects not included here, see reviews by Becker (2009), Denning et al. (2012) and Mooventhan and Nivethitha (2014).

Biomechanical effects of immersion
Studies into biomechanical aspects forms a minority of previous research into the effects of immersion on the human body. Of these, most reported on differences in gait parameters between the water- and land-based settings, thus, insights into biomechanical implications of aquatic therapy remains unreported. The published research on water-based gait reports several significant adjustments enforced by the aquatic environment, believed to be mainly associated with buoyancy and drag forces. However, some reports on these adjustments are contradictive, most likely due to the considerable differences in utilised methodologies between studies (Table 1).

The inconsistencies in water depth and temperature alone are likely resulting in differences in reported findings as both properties are known to impact on biomechanical variables. However, as the current understanding of biomechanical adaptations to the aquatic environment is limited to these reports, their findings should still be taken into consideration. Most studies reported similar joint angles during both aquatic and land-based walking. A 2012 review on differences in gait mechanics in water and on land concluded similar joint motions at the knee and ankle during water-walking, but highlighted that the activity at the hip joint and pelvis increased. Several studies have reported on increased reliance on the hip joint.
Table 1: Articles investigating the effects of aquatic therapy on gait kinematics.

<table>
<thead>
<tr>
<th>Study</th>
<th>Activity</th>
<th>Population</th>
<th>Depth</th>
<th>Temp</th>
<th>Protocol</th>
<th>Main Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barela and Duarte (2008)</td>
<td>SR</td>
<td>10 elderly adults</td>
<td>Xiphoid process</td>
<td>Not reported</td>
<td>Sagittal view video recording at 60 Hz. and force platform recording at 1000 Hz.</td>
<td>Self-selected speed on land and in water on a walkway</td>
</tr>
<tr>
<td>Frangolias and Rhodes (1995)</td>
<td>DWR vs L</td>
<td>13 endurance runners</td>
<td>Neck (with buoyancy belt)</td>
<td>28 °C</td>
<td>Sagittal view video (recording rate not reported)</td>
<td>DWR had an initial water resistance of 0.5kg (female) or 0.75kg (male) with increases eachminute</td>
</tr>
<tr>
<td>Hall et al. (2004)</td>
<td>UT vs L</td>
<td>15 females</td>
<td>Xiphoid process</td>
<td>34.5 °C</td>
<td>Manually counting SF</td>
<td>Three bouts of five minutes at 2.5, 3.5 and 4.5 km·h⁻¹</td>
</tr>
<tr>
<td>Hall et al. (1998)</td>
<td>UT vs L</td>
<td>8 females</td>
<td>Xiphoid process</td>
<td>28 °C and 36 °C</td>
<td>Manually counting SF</td>
<td>Three bouts of five minutes at increasing speeds (3.5, 4.5 and 5.5 km·h⁻¹)</td>
</tr>
<tr>
<td>Kato et al. (2001)</td>
<td>UT vs L</td>
<td>6 males</td>
<td>Waist</td>
<td>29 °C</td>
<td>Sagittal view video recording with a shutter speed of 1/250 seconds</td>
<td>Initially 2.0 km·h⁻¹, gradually increased up to 12.0 km·h⁻¹</td>
</tr>
<tr>
<td>Killgore et al. (2006)</td>
<td>DWR vs L</td>
<td>20 distance runners</td>
<td>3.96 m</td>
<td>27.2 °C</td>
<td>Sagittal view video recording at 30 frames per second</td>
<td>60% of maximal VO₂ at 0% incline for 5-6 minutes</td>
</tr>
<tr>
<td>Masumoto et al. (2009)</td>
<td>DWR vs L</td>
<td>7 adults</td>
<td>Neck</td>
<td>28 °C</td>
<td>EMG recording at 1500 Hz. SF recording methodology not reported</td>
<td>Three exercise intensities (RPE 11, 13 and 15) per element, with 4 min per intensity and 1 min rest</td>
</tr>
<tr>
<td>Masumoto et al. (2008)</td>
<td>UT vs L</td>
<td>9 older females</td>
<td>Xiphoid process</td>
<td>31 °C</td>
<td>EMG recording at 1000 Hz. of thigh and shank muscles SF recording methodology not reported</td>
<td>Three bouts of four minutes at: UT – 1.2, 1.8 and 2.4 km·h⁻¹ L – 2.4, 3.6 and 4.8 km·h⁻¹</td>
</tr>
<tr>
<td>Pohl and McNaughton (2003)</td>
<td>UT vs L</td>
<td>6 university students</td>
<td>Umbilicus, Thigh-deep (midway between ASIS and center of patella)</td>
<td>33 °C</td>
<td>SF manually counted</td>
<td>Running and walking in waist-deep and thigh-deep water and on land Walking five minutes at 4.0 km·h⁻¹</td>
</tr>
<tr>
<td>Shono et al. (2001)</td>
<td>UT vs L</td>
<td>6 older females</td>
<td>Xiphoid process</td>
<td>30.7 °C</td>
<td>SF manually counted</td>
<td>Three bouts of four minutes at: UT – 1.2, 1.8 and 2.4 km·h⁻¹ L – 2.4, 3.6 and 4.8 km·h⁻¹</td>
</tr>
</tbody>
</table>

No significant difference in SL, but significantly lower SF in water. Slower walking speed in water. Reduced GRF_z and reduced knee ROM in water.
<table>
<thead>
<tr>
<th>Study</th>
<th>Grouping</th>
<th>Age, Gender</th>
<th>Measure</th>
<th>Setting/METHODS/Conditions</th>
<th>Key findings/Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shono et al. (2007)†</td>
<td>UT vs L</td>
<td>8 older females</td>
<td>Xiphoid process</td>
<td>Three bouts of four minutes at: UT – 1.2, 1.8 and 2.4 km·h⁻¹ L – 2.4, 3.6 and 4.8 km·h⁻¹</td>
<td>Greater SL and lower SF in water</td>
</tr>
<tr>
<td>Town and Bradley (1991)†</td>
<td>DWR vs SR vs L</td>
<td>9 college students</td>
<td>DWR – 2.5-4 m SR – 1.3 m</td>
<td>SF recording methodology not reported</td>
<td>DWR and SR – four minute of running. L – three minute incline increments starting at 5% incline at a predetermined running speed (males 14.48-16.90 km·h⁻¹, females 12.87-14.16 km·h⁻¹). Greater step turnover in SR compared to DWR</td>
</tr>
<tr>
<td>Orselli and Duarte (2011)†</td>
<td>WW vs L</td>
<td>10 young adults</td>
<td>Xiphoid process</td>
<td>Walking at a self-selected speed</td>
<td>Shorter SL in water Reduced joint loading No changes in joint angle Decreased hip joint forces</td>
</tr>
<tr>
<td>Miyoshi et al. (2005)§</td>
<td>WW vs L</td>
<td>16 healthy adults</td>
<td>Axillae</td>
<td>Walking at a self-selected speed</td>
<td>Reduced joint loading Increased hip joint involvement at higher speeds</td>
</tr>
<tr>
<td>Miyoshi et al. (2004)§</td>
<td>WW vs L</td>
<td>15 healthy adults</td>
<td>Axillae</td>
<td>Walking at a self-selected speed, with increases and decreases in speed</td>
<td>Reduced knee ROM in water Reduced GRFz in water</td>
</tr>
<tr>
<td>Miyoshi et al. (2003)§</td>
<td>WW vs L</td>
<td>8 healthy adults</td>
<td>Axillae</td>
<td>Walking at a self-selected speed</td>
<td>No change in lower body ROM during stance phase Decreased lower body joint moments in water Hip extension moment constant during WW</td>
</tr>
<tr>
<td>Kaneda et al. (2012)§</td>
<td>WW vs L</td>
<td>6 adults</td>
<td>1.35 meters</td>
<td>Walking at a self-selected speed for 10 meters</td>
<td>Subject-dependent changes in the ankle joint between elements Differences in hip joint actions</td>
</tr>
<tr>
<td>Farber et al. (2008)§</td>
<td>WW vs L</td>
<td>8 young adults</td>
<td>Xiphoid process</td>
<td>Forward and backwards walking at a self-selected speed for 10 meters with high and low step frequency</td>
<td>Increased asymmetries in SL at higher SF Increased SL at low SF</td>
</tr>
<tr>
<td>Barela et al. (2006)§</td>
<td>WW vs L</td>
<td>10 adults</td>
<td>Xiphoid process</td>
<td>Sagittal view video recording at 60 Hz. and force platform recording at 1000 Hz.</td>
<td>Lower average walking speed in water No differences in lower body joint ROM however, segmental angles ROM were smaller in water for knee and ankle</td>
</tr>
</tbody>
</table>

during water-based walking. Kaneda et al. (2008) reported an increased hip joint range of motion (ROM) during water walking and suggested that it was a consequence of buoyancy allowing an increased hip flexion motion during swing phase. It is possible that these adaptations in hip joint kinematics may influence other movements performed in water, such as squats and lunges. Miyoshi et al. (2003) further noted a hip extension moment throughout the entire stance phase during walking in water that was not present during land-based walking. A similar study reported decreased joint torques about the knee and ankle during water-walking compared to overland, but highlighted that no decreases were noted at the hip joint. Perhaps this is because of the increased resistance supplied by the water as the hip joint attempts to translate the leg forward through the viscous fluid. These studies on gait have concluded that kinematical adaptations occur in aquatic settings, and highlights the need for future kinematic research conducted on exercises used for aquatic-based rehabilitation. One study highlighted that although drag forces of water might be advantageous for rehabilitation, they may be a contra indicator against water-based exercise if not properly understood. The added, and abnormal resistance supplied by the water element may result in compensations or prove too much for an injured tissue and should be considered when programming for rehabilitation.

Biomechanical research has also been conducted into vertical ground reaction forces (GRF) during aquatic activities compared to land-based equivalents, and shown significant differences between the two environments. These differences have been attributed to the decreased loading associated with buoyancy and drag forces. Further, research comparing jumping actions in water and on land, reported increased force production, rate of force development, and power output during water based jumping actions. It was also noted the aquatic environment produced lower impact forces. These studies inferred that the aquatic environment is ideal for plyometric training as it reduces potentially harmful impact forces.

Similarly, Martel et al. (2005) suggested that aquatic-based plyometric training improves land-based plyometric performance and potentially reduces muscle soreness. Although these studies were not performed in a rehabilitation context, they have provided further evidence of biomechanical implications in the aquatic environment, which should be considered in the application of aquatic therapy.

Further, authors have suggested that the aquatic environment might be beneficial for static and dynamic balance training. However, although studies have reported significant improvements in balance following aquatic-based exercise, the improvements were not significantly different from those achieved with land-based programmes. The aquatic environment is often considered a safer environment than land, as it provides increased stability and reduces the risk of injury in case of a fall. Consequently, performing some exercises in the aquatic environment offers clear advantages over the land-based equivalent for populations with a high risk of falls such as older adults and post-surgery patients.

Although previous kinematic research is limited to gait, it seems the aquatic environment has the potential to affect several parameters of human movement. Future research should include other activities common in everyday life, exercise and rehabilitation.

**AQUATIC THERAPY IN REHABILITATION OF HUMAN MOVEMENT**

Buoyancy and viscosity are the two physical properties of water believed to have considerable effect on the biomechanical aspects of rehabilitation. Buoyancy opposes gravity and thus decreases the loading on joints and muscles. Becker (2009), reported that immersion to the pubic symphysis offloads approximately 40% of the body weight, immersion to the umbilicus offloads 50%, and immersion to the xiphoid process...
offloads 60%. Reduced joint and muscle loading during immersion to these depths may allow a patient to perform exercises and activities earlier than may be possible during full gravitational loading. Decreased loading of joints and early rehabilitation could be beneficial across several acute and chronic injuries, and for several different populations including athletes, elderly and patients with various chronic conditions as it facilitates movement.

The viscosity of water provides resistance to movements and may therefore be helpful for building muscle strength and endurance following musculoskeletal injuries or surgery. However, research has shown the improvements in strength achieved with water-based training are significantly less than improvements achieved with similar exercises performed on land. The ability of the aquatic environment to build strength with decreased joint loading constitutes the rationale for the use of aquatic therapy in improving the quality of life for an elderly or obese population, or as a part of a general weight-management programme.

Current rehabilitation protocols for ligamentous injuries recommend early functional treatment. These protocols aim to control inflammation during the acute phase and limit subsequent loading stress. The hydrostatic pressure and decreased joint loading supplied by the water caters to both these aims and constitutes the use of aquatic therapy in rehabilitation of musculoskeletal injuries. Kim et al. (2010) reported that aquatic-based rehabilitation produce superior rehabilitation outcomes at two and four weeks post-injury compared to a land-based programme for ligamentous injuries in the knee. Previously, Bartels et al. (2007) highlighted the low quality of past studies in their meta-analysis on the use of aquatic-therapy as a rehabilitation regime for OA. It was suggested that aquatic-based rehabilitation exercise protocols offer some short-term benefits in rehabilitation of knee OA, but that further research is needed before any definitive conclusions can be drawn. Clearly, current knowledge on the roles of aquatic therapy in rehabilitation is lacking, and future research should aim to settle protocols and guidelines to ensure best outcomes.

**CURRENT METHODOLOGICAL CHALLENGES IN AQUATIC THERAPY RESEARCH**

The growing attractiveness of aquatic-based rehabilitation among medical professionals is likely based on suggestions that the aquatic environment allows for an earlier commencement of rehabilitation and reduces joint and muscle loading. However, despite being a common part of many rehabilitation programmes, there is a paucity of high-quality scientific literature on the efficacy of aquatic-based rehabilitation training regimens. The different context offered by the aquatic environment provides several challenges to researchers rendering it difficult to conduct high-quality research projects.

**MOTION TRACKING IN THE AQUATIC ENVIRONMENT**

Most previous research into kinematical effects of water-based motion have relied on video analysis capturing the sagittal view only and operating at 30 or 60 Hz. Researchers used video cameras placed along an underwater walkway and recorded participants as they walked past. Caution is advised when performing kinematic analysis using video footage because of the risk of parallax error. Further, by limiting the analysis to sagittal view due to camera positions, data on frontal and transverse plane movements are not recorded. Collecting video footage from a sagittal and frontal view allows for a more comprehensive analysis, however, the capacity of video analysis to accurately assess data on frontal and transverse plane movements have been questioned.
Further, the reliance on video analysis for kinematic parameters in gait research has been questioned as the surrounding water induces differences in basic kinematic descriptors such as stride frequency and length. The author thus recommended that electromyography (EMG) would provide valuable additional information during kinematic gait studies. A literature review on surface EMG during aquatic-based exercise concluded that muscle activity generally is lower in aquatic activity performed in water compared to land. However, the review highlighted that the included studies were low in number and that more high-quality research is needed to fully understand the implications of this.

Current practice considers motion capture technologies the gold standard for analysing human movement. Motion capture using infrared cameras to track reflective markers on participants are capable of capturing at frequencies of up to 50 KHz. However, motion capture systems are expensive, complicated, and limited to laboratory settings. Therefore, their availability and application in clinical and practical settings are restricted. In addition, as the refractory index differs between air and water, light travels differently in the two mediums. Thus using systems relying on infrared cameras in water remains challenging.

The use of isoinertial sensors, such as accelerometers and gyroscopes, is gaining popularity amongst researchers in attempts to track human motion in non-laboratory settings. Studies have confirmed the accuracy of these sensors during walking, the timed-up-and-go test, and the sit-to-stand test. However, only sagittal plane data, peak velocities and power were reported. Thus, future research should aim to examine the use of isoinertial sensors in non-sagittal plane human motion, as this could further establish their role in biomechanical research. Research into the effectiveness of isoinertial sensors for tracking human movement in aquatic environments would provide valuable and exciting additions to current knowledge and research methodologies.

LACKING PROTOCOLS

To date, the consensus on the biomechanical and physiological effects of aquatic based activity are lacking. A likely reason for reported contradictions is differences in methodological protocols, including differences in water depth, temperature, activity and intensity (Table 1). These factors are all known to impact biomechanical and physiological responses to exercise. Caution is therefore warranted when comparing studies reporting on effects of aquatic-based exercise, and target population and exercise specifications should be considered. Establishment of guidelines for water temperature and depth would also be beneficial for aquatic-based exercise and research.
COMPARATIVE STUDIES – LAND VERSUS WATER

There are numerous systematic reviews and meta-analyses published assessing the differences in water- and land-based rehabilitation for patients with lower limb OA, fibromyalgia, chronic obstructive pulmonary disorder, asthma and stroke. However, these reviews agree that previous research is of poor quality and fails to show significantly different outcomes between the two environments. These reviews highlight the need for high quality comparative studies in this domain.

Much of the research in this domain relies on outcome measures, typically including subjective pain scales, functional tests with hand-held stopwatches, isolated muscle strength testing using non-specific hand-held dynamometers and isolated ROM tests. Although scientifically validated in clinical settings, research has questioned the application of these measurements in comparative research. Hatfield et al. (2011) highlighted that subjective reports are insensitive and likely produce skewed results. Further research has reported that pain is not necessarily reflective of functional outcomes and so the use of pain scales as an assessment tool may not be a valid measure of performance. The reliability of ROM tests have also been questioned following total knee replacement (TKR) surgeries, as ROM may be affected by several factors including the prosthetic design, preoperative motion and surgical technique.

An objective alternative to the outcome measures in question is the use of motion capture systems to determine pre- and post-intervention changes in kinematics. Although motion capture testing comprises several known limitations, it provides objective information on human movement that subjective data cannot provide. A recent literature review by Komnik et al. (2015) showed that motion capture is a common method to identify differences in kinematics following TKR. The review highlighted several lingering alterations in kinematics following surgery, including asymmetries between the limbs, and have provided useful information on the use of rehabilitation programmes following TKR surgery. However, this review was limited to include studies assessing kinematics following only land-based rehabilitation protocols.

Surprisingly, despite providing no empirical evidence to support these claims, highly regarded medical research foundations such as the Cochrane Collaboration and BioMed Central have indicated that aquatic-based rehabilitation is comparable to conventional land-based protocols. However, at the time of this review no published studies have investigated biomechanical differences between the two media using empirical methods such as motion capture. Research comparing pre- and post-rehabilitation kinematics of individuals following land- or water-based rehabilitation programmes would provide new information on the roles of aquatic therapy in rehabilitation and its effect on human movements.

SUMMARY

Aquatic therapy can aid in the rehabilitation of musculoskeletal, cardiovascular and neurological conditions as it offers a safe and social alternative to common land-based protocols. The physical properties of the water including buoyancy, viscosity and hydrostatic pressure has beneficial effects on joint loading, pain perception and blood flow. Studies have assessed the effectiveness of water based rehabilitation programmes for management of various medical conditions. However, these studies relied on subjective or clinical outcome measures. Although the subjective experience is an important aspect of rehabilitation, its scientific validity has been questioned.

Further, previous research into the biomechanical and physiological effects of water-based rehabilitation present contradicting results and a consent on practices such as water depth and temperature have not been established. Additionally, the current limitations in motion tracking methodologies adds further complexities to this research area, as it is possible that exercises
performed in the aquatic environment has biomechanical implications that remain unknown. This literature review identifies several gaps in the current knowledge and highlights possible pathways for future research. By bridging the gaps and gaining new knowledge in the roles of aquatic therapy in rehabilitation, we can establish protocols and procedures to ensure optimal recovery for individuals with injuries and pathologies.

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10.2. Publication 2 - Quantifying kinematic differences between land and water during squats, split squats, and single-leg squats in a healthy population.

Quantifying kinematic differences between land and water during squats, split squats, and single-leg squats in a healthy population

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Abstract

Aquatic exercises can be used in clinical and sporting disciplines for both rehabilitation and sports training. However, there is limited knowledge on the influence of water immersion on the kinematics of exercises commonly used in rehabilitation and fitness programs. The aim of this study was to use inertial sensors to quantify differences in kinematics and movement variability of bodyweight squats, split squats, and single-leg squats performed on dry land and whilst immersed to the level of the greater trochanter. During two separate testing sessions, 25 active healthy university students (22.3±2.9 yr.) performed ten repetitions of each exercise, whilst tri-axial inertial sensors (100 Hz) recorded their trunk and lower body kinematics. Repeated-measures statistics tested for differences in segment orientation and speed, movement variability, and waveform patterns between environments, while coefficient of variance was used to assess differences in movement variability. Between-environment differences in segment orientation and speed were portrayed by plotting the mean difference ±95% confidence intervals (CI) throughout the tasks. The results showed that the depth of the squat and split squat were unaffected by the changed environment while water immersion allowed for a deeper single leg squat. The different environments had significant effects on the sagittal plane orientations and speeds for all segments. Water immersion increased the degree of movement variability of the segments in all exercises, except for the shank in the frontal plane, which showed more variability on land. Without compromising movement depth, the aquatic environment induces more upright trunk and shank postures during squats and split squats. The aquatic environment allows for increased squat depth during the single-leg squat, and increased shank motions in the frontal plane. Our observations therefore support the use of water-based squat tasks for rehabilitation as they appear to improve the technique without compromising movement depth.
Introduction

The benefits of aquatic-based exercise constitute its common practice in rehabilitation, recovery, and fitness [1–3]. The reduced joint loading and external resistance provided by the buoyancy and viscosity are easily modifiable by manipulation of immersion depth [4], and practitioners can adjust the degree of offloading and resistance to progress exercises in a safe manner. Further, researchers suggest that viscosity slows movements and therefore prolongs the time an individual has to regain postural control and that buoyancy provides additional support [5, 6], which suggest that balance in the aquatic environment also is likely affected by water depth [7, 8]. The adaptability of aquatic exercise protocols means that they are suitable for exercise and rehabilitation of individuals with injury and pathology, as well as older and obese populations, where full gravitational loading might be inappropriate [4]. Previous research has indicated differences in muscle activity, joint angles, and movement speeds when walking and running in water [9, 10] and during isolated knee flexion-extension tasks [11], but the influence of the aquatic environment on closed-chain exercises often prescribed for rehabilitation and fitness programs has not been well researched. This has left practitioners without a comprehensive understanding of kinematic implications of water immersion on prescribed exercises, which potentially reduces their ability to ensure optimal efficacy of water-based exercise.

The squat exercise (and its variants) is common to numerous aquatic and land-based rehabilitation programs, with these movements described as functional, closed-chain exercises that involve all major muscles and joints of the lower body [12, 13]. In addition to the traditional squat, research supports the prescription of the split squat (SS) and single-leg squat (SLS), and their land-based kinematics are well documented in the literature [13, 14]. It is likely that squat kinematics differs, as is the case with walking and running [9, 10], when performed in water rather than on land. However, despite the significant body of literature on the land-based kinematics of these exercises, their water-based kinematics are not well investigated. To provide practitioners with the understanding to ensure optimal application of aquatic exercises, further examination of how the two environments affect squat kinematics is needed.

The aquatic environment is often considered a safer exercise setting than land, based on the fact that the density of the water slows movement speeds [5, 15], and thereby has been suggested to improve control and stability of movements [9]. Further, researchers have shown that slower squatting speeds reduce shear and compressive joint loads on the spine and knees [16, 17]. Additionally, it is important to control and monitor movement speeds during the ascending and descending phases of an exercise as they induce different muscular responses [18, 19], and biomechanics [20, 21]. In water, the buoyancy force decreases the loading during the descending phase, and during the ascending phase, it provides lifting assistance [22], while the viscosity also provides additional resistance [23]. Accordingly, water immersion likely affects the kinematics of the phases differently, although at the time of submission this has not been reported in the scientific literature, and increased understanding of these implications would be useful practitioners when employing the aquatic environment.

Water-based exercise creates numerous eddies, waves, and currents around the body, causing the accompanying forces to change constantly in response to body movements and water depth. According to the concepts described in dynamical systems theory [24], exercising immersed in this ever-changing environment will require the body to adapt and thus increase its movement variability. While research in this area is still relatively new, exercises that increase movement variability are probably beneficial as reduced variability linked to overuse injuries [25]. Further, as injured populations commonly portray reduced adaptability [24], increased movement variability is likely advantageous for rehabilitation programs. However,
despite research on movement variability have espoused its roles in athletic performance and rehabilitation, its impact in the aquatic environment has received little attention and remains largely unreported.

The growing use of aquatic exercises in training and rehabilitation, coupled with the relative absence of objective research on the influence of the aquatic environment on movement patterns for squats and squat based exercises were the key motivations for this study. Accordingly, this study aims to (1) quantify differences in segmental orientation and speed between land- and water-based squats, SS and SLS during the ascending and descending phases, and (2) examine whether the aquatic environment affects the degree of movement variability of the exercises when performed by individuals without previous exposure to water-based squats. It was hypothesized that water immersion would change the segmental orientations and reduce the speeds compared to land, and that the degree of movement variability would increase due to unfamiliar environmental constraints.

Materials and methods

Participants

Twenty-five healthy university students (11 females: 1.64±0.06 m, 59.2±10.3 kg, 21.6±2.3 yrs., and 14 males: 1.77±0.08 m, 75.3±10.5 kg, 22.6±3.3 yrs.) volunteered for participation in this study. The participants were healthy at the time of testing and had at least 3 years’ experience in gym-based activity with no prior exposure to aquatic-based exercise. Inclusion criteria ensured that participants were without any past lower limb surgeries and injury free at the time of testing. Self-reported leg dominance was recorded (left = 2, right = 22) by determining participants preferred kicking leg, and written informed consent was obtained prior to any testing in accordance with the approval from the University of the Sunshine Coast Human Research Ethics Committee.

Instrumentation

The use of inertial sensors for biomechanical analyses provide an accurate and portable method for analyzing segmental kinematics and has the advantage of being readily adaptable for use both on land and in water [26, 27]. Few researchers have used inertial sensors to assess underwater kinematics, however a recent study reported sagittal and frontal plane kinematics for the lower limbs and trunk during underwater gait [28]. The inertial sensors used in this study were waterproof and contained tri-axial accelerometers and gyroscopes (100 Hz) (Nanotrax, Catapult sports, Docklands, VIC). Each sensor has its own internal coordinate system and with the direction of segmental rotations differing both between left and right sides and between segments during the exercises (i.e. in the sagittal plane, the left thigh and right shank rotated in an anticlockwise direction during the ascending phase, whilst the left shank and right thigh rotated in a clockwise direction), the individual sensors differed in recording positive or negative values. Therefore, the data was adjusted so recordings from all sensors complied with a global coordinate system with the positive Y-axis directed anteriorly, the positive X-axis directed from left to right and the positive Z-axis pointing vertically. Four sensors were attached bilaterally to the participant’s lateral mid-thigh and shank, half-way between the proximal and distal joint centers and one sensor was positioned over the spinous process of the third thoracic vertebra. The allocation of the sensors was measured to be at equal distance from the proximal and distal joint centers and one sensor was positioned over the spinous process of the third thoracic vertebra. The allocation of the sensors was measured to be at equal distance from the proximal and distal joint centers for the lower body segments to ensure consistency, although researchers have highlighted that a considerable advantage of portable systems is that they are less sensitive to exact placement on the segments [26]. To measure squat depth, one additional sensor was attached to the sacrum, at equal distance from the posterior superior
iliac spines. Before each exercise, a static calibration was performed with the participant standing still in an upright posture for ten seconds to establish $0^\circ$ orientations for the sensors and identify any offset in sensor allocations [28]. Each sensor was attached to the participant using 38mm rigid sports tape, and to avoid any intra-sensor bias, the same sensor was allocated to the same segment for all participants.

**Experimental protocol**

Each participant attended two testing sessions; one land-based and one water-based, both with identical testing protocols and occurring within one week of each other. Following a self-selected warm up that included a few minutes of aerobic activity, stretches and between five and ten practice repetitions of each exercise for familiarization of the protocols and environments, the participants performed ten repetitions of the exercises; squat, SS, and SLS. All unilateral exercises were performed on both legs however, to avoid any bilateral asymmetries associated with leg dominance [29], the dominant leading leg data is presented. In order to capture each participants’ natural technique, and to ensure consistency between environments, no instructions were provided concerning foot positions or depth of the exercises [30]. Participants were instructed to maintain their elbows extended, palms facing down, arms straight and horizontal during all exercises, and during the SLS, the contralateral leg was flexed at the knee to between 70–90˚, and kept behind the participant during the task. Participants performed all exercises to a tempo indicated by a metronome [31, 32] set at 100 beats per minute with four beats during the ascent and four beats during the descent, and were allowed between one and two minutes rest between the exercises. No randomization of the order of the exercises was used to allow the same task familiarization for each participant, and due to the natural sequencing progression of the movements. Also, as this was an inaugural study on kinematics the traditional approach is to use a homogeneous sample to begin with and future research should assess other populations. We based this on the current needs and demands of the local population to make the study relevant and practical.

The second testing session occurred at an outdoor pool complex and took place within one week of the first session. To ensure a consistent water depth and allow between-subject comparisons, participants performed the exercises on a platform of adjustable height, which was set so the water depth was level with the greater trochanter on each individual participant. The pool was of Olympic standard that was 1.35 meters deep without the platform, and had lane-ropes in place to reduce water turbulence, and the water temperature was maintained at 29.1˚C±1.0 during the testing period.

**Data processing**

The data from the inertial sensors was imported using Catapult Sprint (version 5.1; Catapult sports, Docklands, VIC), and the raw data from the gyroscopes (angular velocity in three spatial dimensions) was extracted into a comma-separated value (.csv) file. Each of the three gyroscope datasets were integrated and any gyroscopic drift was quantified with linear regression; the raw datasets were corrected for the drift and integrated again to yield non-drifting datasets of angular displacement as a function of time. The start and completion times of each repetition were identified from the minima and maxima of the dataset which had the largest amplitude of motion. This dataset was smoothed with a custom, variable-width, non-weighted box-smoothing algorithm, so that all true minima and maxima (peak angles) were correctly identified and false peaks due to noise were ignored, with a minimum amount of smoothing (excessive smoothing has potential to slightly “shift” maxima and minima). The individual repetitions in each of the three datasets were extracted, collated into sets, and processed. The
data was processed so that the start of each cycle occurred at the bottom of the movement where the peak angle was most obvious, so for the analysis, the start of the movement (0%) represented the bottom of each task (the point of peak knee flexion), and subsequently, the top of the movement (point of peak knee extension) occurred around 50% (Fig 1). Further, the

Fig 1. Exercise protocol. Participant performing the three exercises during immersion to highlight the top (0 and 100%) and bottom (50%) position of the three exercises.

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accelerometer data from the sacral sensor was used to determine its vertical displacement, which indicated movement depth [20].

Data analysis
The data for each of the ten repetitions was time-normalized to 1000 data points and imported to Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) for comparison and analysis. As previous research has questioned the accuracy of transverse plane data recorded with inertial sensors [27, 28], only sagittal and frontal plane kinematics was analyzed in this study. All statistical analyses were performed with IBM SPSS software version 22 (IBM, New York, NY). Absolute values were used for all velocity data to allow comparisons between environments throughout both the ascending and descending phases, so it is portrayed as non-directional speed of movement. To identify differences between the phases of movement, time series data for displacements and speeds were divided into four phases; the early ascent (0–25%), late ascent (25–50%), early descent (50–75%) and late descent (75–100%). Kinematic variables of interest included the average angular displacement and speed for each phase, total range of motion, and peak velocities. The movement depths were tested for covariance, and all kinematic variables were tested for compliance with the assumptions of an analysis of covariance. Wherever the assumptions were met, an analysis of covariance determined significant differences between the environments, and elsewhere, a repeated measures one-way analysis of variance was used.

To allow comparison of environmental differences in displacements and movement speed throughout the tasks, the differences between the group mean waveforms ±95% confidence limits (95% CI) were plotted as a time series [33, 34] for the full movements (0–100%). The 95% CI was calculated using the critical t-value and degrees of freedom, and wherever it (shaded areas on figures) did not include zero, the environments were considered to have a significant effect on the variable. The mean differences were calculated as the land-based values less the aquatic-based values, thus a shaded area above zero indicated a trend of higher recorded values on land, and vice versa. Variability of the individual waveforms was analyzed by calculating the coefficient of variance (CV), with additional calculations analyzing variability in pattern (CV_p) and offset (CV_o) [35] in both environments. The latter two techniques have been applied successfully to cyclical data and have been shown to be more sensitive to changes in movement patterns than the more traditional CV analysis techniques [35, 36]. To portray the influence of the changed environment on variability, the differences between environments are presented as the land-based percentage less the pool-based percentage. Effect sizes were calculated and ranked using the method developed by Cohen [37], with scores d> 0.2 considered small, d> 0.5 moderate and d> 0.8 considered large effect. The alpha level was set at p<0.05.

Results
The analysis showed that immersion in water did not significantly affect the depth of the squat (land: 0.43±0.18 m, pool: 0.45±0.15 m, p = 0.700, d = 0.12) and SS (land: 0.34±0.06 m, pool: 0.38±0.09 m, p = 0.091, d = 0.53). However, the environment had a significant effect on the depth of the SLS (land: 0.22±0.09 m, water: 0.31±0.11 m, p = 0.006, d = 0.89).

The analysis of the angular displacement time series showed that water immersion had moderate and large effects on all segments in the sagittal plane during at least one exercise (Fig 2 and S1 Fig). Though, only the movements of the shank segment were effected in the frontal plane (Fig 3 and S2 Fig). Moderate and large effects were also observed in the movement speeds in the both planes of motion in all three exercises (Fig 4 and Fig 5). The waveforms also
revealed differences in both orientation and speeds that differed between the phases when performing these exercises immersed in water.
The CV analysis showed several moderate and large significant effects on the segments movement variability in both planes of motion, with CV values often larger in the aquatic environment (Table 1). Only the shank segment portrayed more variability on land in the frontal...
plane during the SLS. The individual CV values for each segment in the two environments are provided in the supplementary material (S1 Table). The overall range of motion and peak velocities were also affected by the changed environment, with the data presented in the supplementary material (S2 Table, and S3 Table).

Discussion
Our study shows that immersion in water alters squat, SS, and SLS trunk and lower body kinematics in young, healthy adults. These results support previous research on the influence of immersion in water on gait kinematics [9, 28]. To the best of our knowledge, this is the first study to use inertial sensors to compare the kinematics of squat variations on land and in water. A key finding is that water immersion to the greater trochanter does not limit the depths of squats and SS, and allows participants to maintain a range of movement similar to that they typically use on land. However, the aquatic environment does allow performers increased squat depth during the SLS.

During squats and SLS, the sagittal plane orientation of the thorax was particularly affected by the immersion protocols (Fig 2). These changes were indicative of a more vertically aligned trunk posture throughout the movements, being particularly apparent closer to the bottom position of both tasks (0–25% and 75–100% in Fig 2). This is a positive find as research highlights the important role that maintaining an upright trunk during squats and lifting tasks has in minimizing spinal compressive loads and shear forces [16, 38], and decreasing reliance on passive structures for support [39]. The more vertically aligned trunk posture in the aquatic environment is most likely an indication of the added support provided by the water coupled with the influence of the buoyant force acting up through the thorax. Further, the forward inclination of the trunk during squats performed on land is no doubt a strategy to maintain balance, and the participants might feel unstable if they attempt to employ a more vertical trunk posture, as it shifts their center of mass backwards [40]. Therefore, it appears the gravitational offloading and viscosity of the water reduces the performers’ reliance on their body position for stability and allows them to use a more upright trunk posture. Theoretically, the trunk posture employed in the aquatic environment during squats and SLS reduces spinal forces.
beyond what is already achieved with buoyancy, and provides a more stable movement with less reliance on the individuals’ balance skills. Our study assesses kinematic variables, so future research is needed to examine kinetic implications of water immersion during these exercises to provide additional understanding of the mechanical aspects of water-based exercise. However, it remains important for practitioners to understand the kinematic implications of water immersion to assist in the prescription of exercises. For example, researchers have highlighted increased forward trunk inclination during squats in older populations and individuals with lower back pain [41, 42], so the upright posture in the aquatic environment is likely beneficial for these populations. These results suggest that practitioners can employ the aquatic environment to improve squatting depth while simultaneously minimize spinal loads and improving trunk orientation. Further, although the analysis showed moderate and large effect sizes on the frontal plane speed of the trunk during the squat between the environments, these differences are probably too small to be of clinical importance.

The additional support in the aquatic environment is also evident in more vertically aligned shanks during the squats and SS, especially during the deeper phases of the tasks as the performer can ‘sit back’ in the movement without compromising balance. Again, this is a positive find as the upright shank positions are associated with reduced strain on the knees [43]. Contrary to the other exercises, the SLS had a slight, temporary increase in sagittal plane shank inclination in the aquatic environment during the ascending phase, which probably was associated with balance. On land, participants employ a forward trunk inclination to maintain the center of mass within the base of support, but the supportive and offloading properties of the water allow them to maintain vertical trunk posture and instead shift their entire body forward (i.e. increasing their shank inclination), without compromising balance. The buoyant force provided by the water would both reduce joint loading and offer lifting assistance during the ascending phase [22]. Combined, this means that participants probably were less limited by muscle strength and balance when they performed SLS in water and were thus able to squat deeper. Research have previously reported different muscle activation patterns between land and water and suggested that the offloading and reduced movement speeds dictated the muscular responses [44]. Future research is needed to assess muscle activity and kinetics during water-based squat tasks to determine neuromuscular responses to water immersion. Unsurprisingly, our examination revealed faster sagittal plane movement speeds for the segments in the environment with larger movement range (Fig 4). However, when the ranges are similar, the speeds appear highly individual and the environmental effects differ throughout the movement phases, particularly for the thigh and shank. Although, there seems to be some tendency for faster speeds in water during the late ascent, which could be explained by the buoyancy force adding to the muscular force providing an upthrust [45]. These preliminary findings could indicate that practitioners can employ the aquatic environment to train movements their clients might be unable to perform on land, likely as a part of early rehabilitation. A reduced restriction of strength and balance would allow clients to perform exercises such as SLS will full range earlier in the water than what is possible on land.

Our data also reveal more frontal plane movements of the shank in the aquatic environment during the SLS and the descending phase of the squat (Fig 3). While the frontal plane speeds of both lower body segments show similar trends to the sagittal plane, few differences are large enough to be of clinical interest (Fig 5). Nevertheless, lower body mediolateral alignment is an important consideration during squat performance as increased translation is linked to knee instability and injury [14]. Despite the aquatic environment often is considered unstable [46], it is possible that the properties of water can benefit balance through a few different features: First, the offloading reduce limitations by muscular strength for stability, second, slower movements provide increased time for postural corrections [5, 6], and third, it is
possible that density and viscosity of the fluid can provide some support. The combination of these aspects could explain the increased frontal plane shank movements employed by our participants as they utilized the water for improving their balance. Previous research suggests that the aquatic environment reduces muscle activity of prime movers due to gravitational offloading [47], and similar trends are likely occurring in the stabilizing muscles, although further research is needed for confirmation. The practical implications of the increased frontal plane movements during water-based SLS require further examinations of whether it affects the leg muscle activity, and whether any changes are beneficial for rehabilitation.

Reduced reliance on muscle force for stability can also explain the increased movement variability in the aquatic environment. Increased movement variability indicates that the performer adapts to the constant movements of the surrounding water. Previous research suggests that injury and pain changes movement patterns by reducing movement variability [48], leaving the individual with decreased ability to adapt to surroundings and consequently, reduced functionality [24]. The increased movement variability during these squat exercises in the aquatic environment can potentially assist in restoring the adaptability in an injured population, further supporting its use in rehabilitation. Interestingly, during the SLS the shank portrays less variability in the frontal plane while in water but maintains a larger movement range. This could be linked to the strategy of using the vicious fluid for balance that we proposed earlier. Performers would not be able to apply this strategy on land under full gravitational loading as no additional support is provided by the air. It is also possible that the balance strategies employed on land are more variable than those applied in water, however future research should examine this further. Comparative research on movement variability in aquatic settings is lacking, thus preventing further comparisons and conclusions regarding its clinical significance.

One limitation of our study is that although our sensor allocation was thorough, there is a risk of slight discrepancies in sensor positions between testing sessions and participants. However, our method of landmark identification is the same as is used in practical settings and previous research and the risk of errors should be further reduced with the static capture [28]. Further, the sensors we used did not contain magnetometers, which potentially increased their susceptibility to internal drift [27], but the analysis compared only data recorded with the same sensor in the two environments, and any drift remaining after the filtering should be the same within each sensor. Additionally, we acknowledge that the greater variability in the water might be attributed to the participants performing the exercises in a novel environment. All participants were experienced in performing the exercises on land, but had not performed the exercises in water prior to the day of testing. It is possible that the inexperience of the participants increased their movement variability in the water. Future research should assess if habituation decreases the movement variability in the aquatic environment to further the research into this area. Further, researchers have shown kinematic differences between males and females during squatting tasks [49], and changing the depth of immersion can potentially also affect the kinematics of the exercises [46]. However, the small sample size of this study did not allow for analysis of differences between sexes and we limited our analysis to one depth however, we highlight that future research should assess if water immersion affects the kinematics differently between sexes, and quantify implications of different water depths on kinematics.

Conclusion

This study reveals several kinematic differences between land and water when healthy adults perform bodyweight squats, SS and SLS. Our data shows that immersion in water to the greater trochanter does not limit the overall movement range or depth during the squat and SS, while it allows performers to achieve greater depth during the SLS. The aquatic environment
encourages more vertically aligned trunk and shank segments with an overall smaller range of motion, which consequently decreases the speed of the segments. We also observe increased motions in the frontal plane during water-based SLS, and that all three exercises show increased movement variability in water. This study also highlights the need for further research into the applications of water-based squatting tasks in order to provide practitioners with a more comprehensive understanding of movement mechanics in water. Combined, the findings of our study highlight the suitability of aquatic-based squats, SS and SLS for lower body rehabilitation as water immersion emphasizes improved technique without changing the overall movement pattern.

Supporting information

S1 Fig. Displacement waveforms of sagittal plane movements for the three segments between land- and aquatic-based squats. Average sagittal plane displacement on land (solid line) ±95% confidence limits (green area), and in water (dashed line) ±95% confidence limits (blue area) for thorax, thigh, and shank segments during the squat, split squat, and single leg squat. Vertical lines indicate the start and end of each phase; early ascent (0–25%), late ascent (25–50%), early descent (50–75%) and late descent (75–100%).

S2 Fig. Displacement waveforms of frontal plane movements for the three segments between land- and aquatic-based squats. Average frontal plane displacement on land (solid line) ±95% confidence limits (green area), and in water (dashed line) ±95% confidence limits (blue area) for thorax, thigh, and shank segments during the squat, split squat, and single leg squat. Vertical lines indicate the start and end of each phase; early ascent (0–25%), late ascent (25–50%), early descent (50–75%) and late descent (75–100%). Positive values indicate valgus movements at the thigh and shank.

S1 Table. Movement variability (%) for the three segments in the environments. CV–Coefficient of variance, CV_p–Coefficient of variance for pattern, CV_o–Coefficient of variance for offset

S2 Table. Mean (SD) range of motion and the movement variability (%) between the two environments during the concentric phase of the movement. CV, coefficient of variability

S3 Table. Mean (SD) peak velocity between the two environments during the concentric phase of the movement. X, Extension Y, Abduction Z, External rotation.

Positive percentages indicate larger movement variability in the aquatic environment, and negative percentages indicates larger movement variability on land.

* indicates significant difference between environments at P<0.05.
α –indicates large effect size at Cohen’s d >0.8.
β –indicates moderate effect size at Cohen’s d>0.5.
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References


10.3. Publication 3 - Limb symmetry during double-leg squats and single-leg squats on land and in water in adults with long-standing unilateral anterior knee pain; a cross sectional study.

Limb symmetry during double-leg squats and single-leg squats on land and in water in adults with long-standing unilateral anterior knee pain; a cross sectional study

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Abstract

Background: The presence of pain during movement typically results in changes in technique. However, the physical properties of water, such as flotation, means that water-based exercise may not only reduce compensatory movement patterns but also allow pain sufferers to complete exercises that they are unable to perform on land. The purpose of this study was to assess bilateral kinematics during double-leg squats and single-leg squats on land and in water in individuals with unilateral anterior knee pain. A secondary aim was to quantify bilateral asymmetry in both environments in affected and unaffected individuals using a symmetry index.

Methods: Twenty individuals with unilateral knee pain and twenty healthy, matched controls performed body weight double- and single-leg squats in both environments while inertial sensors (100 Hz) recorded trunk and lower body kinematics. Repeated-measures statistics tested for environmental effects on movement depths and peak angles within the anterior knee pain group. Differences in their inter-limb symmetry in each environments was compared to the control group using analysis of variance tests.

Results: Water immersion allowed for greater movement depths during both exercises (double-leg squat: +7 cm, \( p = 0.032 \), single-leg squat: +9 cm, \( p = 0.002 \)) for the knee pain group. The double-leg squat was symmetrical on land but water immersion revealed asymmetries in the lower body frontal plane movements. The single-leg squat revealed decreased hip flexion and frontal plane shank motions on the affected limb in both environments. Water immersion also affected the degree of lower limb asymmetry in both groups, with differences also showing between groups.

Conclusions: Individuals with anterior knee pain achieved increased squat depth during both exercises whilst in water. Kinematic differences between the affected and unaffected limbs were often increased in water. Individuals with unilateral anterior knee pain appear to utilise different kinematics in the affected and unaffected limb in both environments.

Keywords: Inertial sensors, Asymmetry, Kinematics, Aquatic exercise
Background

Anterior knee pain (AKP) is an umbrella term for pain around the anterior aspects of the knee that is aggravated by physical activity [1] and common tasks in daily life such as descending stairs and squatting [2]. It is one of the most common conditions presenting in physiotherapy clinics [1, 3], and may present as a unilateral or bilateral condition [4]. AKP has been linked to lower body malalignments and deficits in strength, flexibility, and neuromuscular function [5]. Prolonged pain has been suggested to change muscular function and disrupt inter-muscular coordination [6], so it is not surprising that previous research has reported compromised muscle functions in individuals with AKP [2, 7]. Similarly, research indicates that these individuals employ compensatory movement strategies during exercises like single-leg squats (SLS) and running [8, 9]. Common strategies include increased pelvic obliquity, lateral trunk lean, and valgus alignment [10], which probably contributes to the continued aggravation of AKP [2, 3, 9].

Rehabilitation programs often target hip and gluteal function and include double-leg squats (DLS) and SLS to improve strength, balance, and coordination [1, 5]. Despite AKP frequently presenting unilaterally [4], most biomechanical studies compared affected individuals with healthy controls and failed to discuss bilateral differences [8, 9]. This is troubling, as research has reported bilaterally different kinematics following unilateral knee injuries [4, 7, 11, 12]. It is likely that long-standing unilateral AKP also result in bilaterally asymmetrical kinematics, and further examinations are needed to map compensatory movements. Water-based rehabilitation is anecdotally effective for AKP, and although previous research supports its application for rehabilitating degenerative knee conditions [13], research on its efficacy on AKP is limited. The aquatic environment reduces loading [14, 15], improves strength [16, 17], and supports balance [18, 19], thus providing a suitable alternative to land-based rehabilitation for AKP. Aquatic therapy is also known to reduce pain and increase range of motion [16, 20], which are important benefits for rehabilitation [1]. Importantly, previous research has highlighted that water immersion encourages different kinematics compared to land due to buoyancy, viscosity, and density [15, 20, 21]. Particularly, water-based squat tasks portrayed increased movement depths and different trunk and lower body kinematics compared to squats performed on land [20]. Previous research has not quantified kinematic impacts of water immersion on individuals with AKP. Such information would be useful for practitioners when programming for water-based rehabilitation.

Bilateral differences in kinematics are often quantified in injured populations as their kinematics can reflect compensatory movements, and affect the efficacy of rehabilitation programs [11]. Few published reports have assessed asymmetry in water, but a recent analysis highlighted increased asymmetries in water for healthy individuals during gait [22]. Despite only assessing spatial-temporal implications, the authors highlighted that symmetry can provide important insights into movement control. No published research has quantified kinematic asymmetries during DLS and SLS between land and water at the time of submission.

Traditionally, symmetry index (SI) calculations rely upon discrete data and are not applicable to time series data [23, 24], but this issue was addressed by Nigg, et al. [24] who developed an SI calculation for continuous data sets. This method has not been used to quantify bilateral asymmetry in individuals with AKP compared to healthy controls. An increased understanding of the effects of water immersion on symmetry in individuals with AKP would clarify the roles of aquatic therapy for rehabilitation further.

Accordingly, this study aimed to assess kinematic implications of water immersion on individuals with AKP during DLS and SLS by (1) quantifying differences in frontal and sagittal plane peak joint and segment angles and, (2) compare the environmental impacts on bilateral asymmetry with healthy controls. It was hypothesised that individuals with AKP would utilise different kinematics in water than on land, and that water immersion would increase the degree of asymmetry in this population compared to the uninjured control group.

Methods

Participants

Twenty young adults with chronic AKP (10 males and 10 females) and 20 healthy age- and gender-matched adults volunteered for participation (AKP group 22.8 ± 4.0 y, 71.2 ± 13.0 kg, 1.72 ± 0.09 m, control group 22.2 ± 2.9 y, 67.6 ± 13.4 kg, and 1.72 ± 0.10 m). The AKP group reported unilateral pain for at least three months (3–48 months) but were otherwise healthy. All participants were physically active and had at least three years’ experience with body weight exercises, and no prior exposure to water-based exercise. Self-reported leg dominance was determined as the participants’ preferred kicking leg (right: 18, left: 2 in each group). In accordance with the Human Research Ethics Committee approval, any participant with knee pain during stair descent was excluded from participation. Informed written consent was obtained before testing.

Experimental design

This study used inertial sensors, which have successfully been used to record underwater sagittal and frontal plane kinematics [20, 21]. Four sensors (100 Hz) (Nanotrack, Catapult sports, Docklands, VIC) were allocated bilaterally...
to the lateral thighs and shanks, halfway between the proximal and distal joint centres (Fig. 1). One sensor was positioned over the third thoracic vertebra and another was attached to the sacrum. To ensure consistency in sensor allocation, the same person attached the sensors at each testing occasion. A ten-second static calibration was performed before each exercise in the anatomical position to establish 0° orientations for the sensors [21]. To avoid intra-sensor bias, the sensor allocations were consistent throughout testing.

Each participant attended two testing occasions; the first in a motion laboratory and the second at a pool complex within one week of the first session. A platform of adjustable height ensured a water depth to the greater trochanter on each participant (87 ± 5 cm). The Olympic standard pool had a water temperature of 29.1 °C ± 1.0 during the testing.

Both sessions started with a self-selected warm up of two to three minutes of aerobic activity and five to ten practice repetitions of the exercises for familiarization [18], followed by ten DLS and ten SLS on each leg. During the SLS, the contralateral limb was flexed at the knee to 70–90° and positioned behind the body. The arms were maintained outstretched in front during both exercises. No instructions were provided concerning stance width and squat depth [11], and the tempo was dictated by a metronome (100 bpm). The participants completed one repetition over eight beats, four to descend, and four to ascend. Two minutes’ rest was allowed between the exercises, and no randomization was used to allow the same task familiarization for each participant.

Data processing
The raw data from the ten repetitions were smoothed with a custom, variable-width, non-weighted box-smoothing algorithm and the slope for any internal drift was quantified using linear regression and subtracted. A more in-depth description of the data processing can be found in Severin, et al. [20]. The smoothed data were integrated to yield segmental displacements and the ten repetitions were identified based on peak sagittal plane angles. The segmental angles from the shank, thigh, sacrum, and trunk were used to calculate the relative angles [21], which was done using the following equations:

$$\theta_{knee} = \theta_{shank\ sensor} + (180 - \theta_{thigh\ sensor})$$

(1)

$$\theta_{hip} = \theta_{sacral\ sensor} + (180 - \theta_{thigh\ sensor})$$

(2)

$$\theta_{trunk} = \theta_{thoracic\ sensor} + (180 - \theta_{sacral\ sensor})$$

(3)

To allow comparisons between the individual sensors, and to calculate joint angles, all data were adjusted to comply with standard Euler conventions, with flexion, adduction, and internal rotation portrayed as positive rotations [25]. The data were time normalized to 1000 data points in order to simplify comparisons. Data from the sacral sensor determined the vertical displacement of the pelvis to indicate squat depth [26]. The variables of interest included bilateral peak sagittal angles and SI-scores of the shank, thigh, and thorax segments as well as knee, hip, and trunk angle.

Data analysis
This study followed the convention of limiting analyses to the sagittal and frontal planes [20, 21] due to questioned accuracy of internal sensors in the transverse plane [27]. Statistical analyses were performed on all kinematic variables using IBM SPSS version 22 (IBM, New York, NY). Bilateral differences in kinematics in the AKP group were assessed by comparing peak angles for segments and joints between environments. The SI-scores determined bilateral asymmetry between the affected and unaffected limb in the AKP group, and between the dominant and non-dominant limb in the control group. An SI score of zero-score indicated...
perfect symmetry [24]. The SI score was calculated with the calculation used by Nigg, et al. [24]:

\[
SI = \int_{t=t_1}^{t_2} A \ | \ x_r(t) - x_l(t) \ | \ dt
\]

\[
A = \frac{2}{\text{range}(x_r(t)) + \text{range}(x_l(t))}
\]

Where the value of a specific variable at the time \( t \) for the right limb is represented by \( x_r(t) \), and \( x_l(t) \) represents the same variable for the left limb.

The movement depths between environments were tested for covariance and the kinematic variables were tested for compliance with the assumptions of an analysis of covariance. Wherever the assumptions were met, an analysis of covariance determined significant differences between the environments, and elsewhere, a Wilcoxon Singed-rank test was used. The SI-scores for both groups were tested for normality using a Shapiro-Wilk’s tests, and whenever it was violated, a Mann-Whitney U test was used to determine differences between groups. Where normality was indicated, an analysis of variance was used to test for between-group differences in SI-scores. Effect sizes were calculated and ranked using the method developed by Cohen [28], with scores \( d > 0.2 \) considered small, \( >0.5 \) moderate and \( >0.8 \) considered large effect. The alpha level was set at \( p < 0.05 \).

Results

The analysis showed that water immersion affected the maximal depth for the AKP group both during the DLS (land: \( 33 \pm 8 \) cm, pool: \( 40 \pm 11 \) cm, \( p = 0.032, d = 0.70 \)) and the SLS (affected limb: land: \( 20 \pm 7 \) cm, pool: \( 29 \pm 10 \) cm, \( p = 0.002, d = 1.06 \), unaffected limb: land: \( 19 \pm 6 \) cm, pool: \( 27 \pm 9 \) cm, \( p = 0.003, d = 1.00 \)). Participants in the AKP group verbally reported that water immersion reduced any sensation of pain or discomfort during both exercises.

The analysis revealed that the limbs reached different peak angles in the two environments during the exercises, although it was more evident during the SLS. Water immersion increased the frontal plane peak angles of the affected limb during the DLS, but did not affect it sagittal plane motions (Table 1). The unaffected limb did not show any statistically significant differences between the environments in either plane of motion. For the SLS, water immersion increased the sagittal plane peak angles of both limbs, and decreased those of the thorax segment and trunk angle (Table 2). The changes in the frontal plane were less congruent during the SLS, as some peak angles increased, while others decreased or remained unaffected by immersion. Similarly, the kinematic differences between the limbs generally increased in the sagittal plane, whereas the differences in the frontal plane were less consistent.

Water immersion also affected the degree of asymmetry in both groups during the exercises, as was indicated by the SI-scores (Table 3). The SI analysis revealed that the groups were affected differently by the changed environment, although no obvious trends indicated whether water immersion increased or decreased the degree of symmetry in either group. For example, during the SLS, the AKP group had increased SI-scores for hip flexion and decreased scores for anterioposterior trunk motion in water. Meanwhile, the control group showed increased SI-scores for knee and hip abduction during DLS, and reduced scores for hip abduction during the SLS when the exercises were performed in water.

The SI scores also differed between the groups. Although the analysis often indicated higher scores for the AKP in both environments, the control group showed

| Table 1 Peak angles (±SD) for double-leg squats between the limbs of the AKP group in both environments |
|---------------------------------|---------------------------------|---|---------------------------------|---------------------------------|---|
|                                | Land                            | Pool |                                | Unaffected                      | Affected                       | d  | Unaffected                      | Affected                       | d  |
|                                | Shank angle (°)                 |      |                                | 21.3 ± 8.0                      | 21.8 ± 8.0                     | 0.05| 18.3 ± 8.4                      | 22.0 ± 6.3                     | 0.50|
|                                | Thigh angle (°)                 |      |                                | 59.6 ± 27.9                     | 62.6 ± 22.6                    | 0.12| 65.4 ± 22.5                     | 68.9 ± 21.9                    | 0.16|
|                                | Knee flexion (°)                |      |                                | 94.4 ± 16.7                     | 90.2 ± 19.5                    | −0.23| 95.2 ± 10.4                     | 91.6 ± 13.4                    | −0.27|
|                                | Hip flexion (°)                 |      |                                | 73.8 ± 17.0                     | 71.7 ± 31.1                    | −0.08| 77.8 ± 19.7                     | 75.5 ± 15.8                    | −0.10|
|                                | Shank medial deviation (°)      |      |                                | 9.2 ± 5.3                       | 8.2 ± 5.7                      | −0.20| 10.0 ± 5.0                      | 11.9 ± 4.2^b                    | 0.42|
|                                | Thigh lateral deviation (°)     |      |                                | 10.3 ± 8.5                      | 13.6 ± 9.4                     | 0.37| 12.4 ± 10.4                     | 20.6 ± 9.0^b                    | 0.84^*|
|                                | Hip adduction (°)               |      |                                | 60.0 ± 8.5                      | 3.6 ± 5.6                      | −0.33| 4.1 ± 3.8                       | 3.0 ± 3.1                      | −0.32|
|                                | Knee adduction (°)              |      |                                | 17.2 ± 12.8                     | 20.0 ± 13.7                    | 0.21| 19.8 ± 13.0                     | 30.3 ± 11.6^a                    | 0.85^*|
|                                | Hip abduction (°)               |      |                                | 12.0 ± 9.0                      | 12.7 ± 9.9                     | 0.07| 10.8 ± 8.0                      | 18.8 ± 10.2^b                    | 0.85^*|
|                                | Knee abduction (°)              |      |                                | 3.8 ± 3.1                       | 2.1 ± 2.5                      | −0.58| 3.4 ± 2.8                       | 3.7 ± 3.7                      | 0.08|

*a* indicates significant difference between limbs at \( p < 0.05 \)

*b* indicates large within-limb effect size between environments at Cohen’s \( d > 0.8 \)

*c* indicates moderate within-limb effect size between environments at Cohen’s \( d > 0.5 \)
Table 2 Peak angles (±SD) for single-leg squats between the limbs of the AKP group in both environments

<table>
<thead>
<tr>
<th></th>
<th>Land</th>
<th>Pool</th>
<th>Cohen’s d</th>
<th>Land</th>
<th>Pool</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank angle (°)</td>
<td>260 ± 10.0</td>
<td>24.0 ± 5.8</td>
<td>-0.25</td>
<td>25.8 ± 8.4</td>
<td>27.8 ± 7.7b</td>
<td>0.25</td>
</tr>
<tr>
<td>Thigh angle (°)</td>
<td>36.1 ± 14.7</td>
<td>36.2 ± 11.8</td>
<td>0.00</td>
<td>51.3 ± 9.0a</td>
<td>49.1 ± 8.6a</td>
<td>-0.25</td>
</tr>
<tr>
<td>Thorax angle (°)</td>
<td>23.8 ± 11.5</td>
<td>23.2 ± 9.8</td>
<td>-0.06</td>
<td>17.9 ± 11.2b</td>
<td>16.2 ± 8.6b</td>
<td>-0.16</td>
</tr>
<tr>
<td>Knee flexion (°)</td>
<td>65.0 ± 13.5</td>
<td>61.6 ± 10.4</td>
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<td>78.1 ± 13.4a</td>
<td>76.0 ± 12.1a</td>
<td>-0.17</td>
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<td>Hip flexion (°)</td>
<td>42.8 ± 12.9</td>
<td>33.7 ± 11.4</td>
<td>-0.75*</td>
<td>59.8 ± 11.3a</td>
<td>42.5 ± 9.6a</td>
<td>-1.37*</td>
</tr>
<tr>
<td>Trunk flexion (°)</td>
<td>20.6 ± 13.4</td>
<td>19.6 ± 11.2</td>
<td>-0.08</td>
<td>21.1 ± 9.4</td>
<td>12.4 ± 7.4b</td>
<td>-1.03*</td>
</tr>
<tr>
<td>Shank medial deviation (°)</td>
<td>2.4 ± 2.3</td>
<td>7.5 ± 4.8</td>
<td>1.35*</td>
<td>10.4 ± 6.7a</td>
<td>11.3 ± 7.4b</td>
<td>0.13</td>
</tr>
<tr>
<td>Thigh lateral deviation (°)</td>
<td>5.2 ± 4.1</td>
<td>6.3 ± 5.7</td>
<td>0.22</td>
<td>8.7 ± 8.5c</td>
<td>9.7 ± 7.3b</td>
<td>0.13</td>
</tr>
<tr>
<td>Thorax lateral deviation (°)</td>
<td>5.0 ± 6.0</td>
<td>3.5 ± 2.9</td>
<td>-0.31</td>
<td>3.5 ± 2.8</td>
<td>2.6 ± 2.6</td>
<td>-0.34</td>
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<tr>
<td>Hip adduction (°)</td>
<td>9.4 ± 8.7</td>
<td>6.1 ± 4.2</td>
<td>-0.49</td>
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<td>4.9 ± 2.9</td>
<td>-0.51</td>
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<tr>
<td>Knee adduction (°)</td>
<td>9.5 ± 7.7</td>
<td>12.3 ± 7.9</td>
<td>0.36</td>
<td>19.0 ± 13.2a</td>
<td>19.7 ± 12.3b</td>
<td>0.05</td>
</tr>
<tr>
<td>Hip abduction (°)</td>
<td>7.4 ± 6.3</td>
<td>5.7 ± 5.8</td>
<td>-0.28</td>
<td>7.8 ± 7.5</td>
<td>11.1 ± 8.1b</td>
<td>0.42</td>
</tr>
<tr>
<td>Knee abduction (°)</td>
<td>4.2 ± 2.6</td>
<td>2.2 ± 1.6</td>
<td>-0.89*</td>
<td>7.8 ± 6.3b</td>
<td>2.3 ± 2.2</td>
<td>-1.18*</td>
</tr>
<tr>
<td>Trunk lateral tilt (°)</td>
<td>5.3 ± 4.8</td>
<td>8.2 ± 4.4</td>
<td>0.63*</td>
<td>4.3 ± 2.4</td>
<td>3.6 ± 3.0a</td>
<td>0.23</td>
</tr>
</tbody>
</table>

*indicates significant difference between limbs at p < 0.05
indicates large within-limb effect size between environments at Cohen’s d > 0.8
indicates moderate within-limb effect size between environments at Cohen’s d > 0.8

more asymmetry in knee and hip abduction during both land- and water-based DLS. They also showed higher SI-scores for knee flexion during water-based SLS.

Discussion

Primary findings from this study were that participants with AKP employed different kinematics in the affected and unaffected limbs during DLS and SLS performed on land and in water. Immersion appear to increase kinematic differences between the limbs, perhaps because of the more dynamic environment [29]. Further, although the aquatic environment seemingly affected the SI-scores both in individuals with AKP and in uninjured controls, the analysis showed no obvious trends towards more or less asymmetry in either environment.

The results from this study suggested that water immersion allows individuals with AKP to achieve greater squat depth during both DLS and SLS, compared to when performing the exercises on land. The increased depth during the SLS was reflected in increased peak hip and knee flexion angles. During the DLS, increased depth occurred most likely due to several non-significant increases in joint angles in the lower body. The reduced loading in water no doubt allowed greater movement depth without resulting in discomfort or pain at the knee. Water immersion can therefore improve knee joint range of motion during squat tasks in this population. Re-establishing knee joint range of motion is a primary goal in early rehabilitation for AKP [1], and practitioners are encouraged to recognize the benefits of increased squat depth during rehabilitation for this population.

Interestingly, the AKP group showed similar peak angles during land-based DLS in both limbs in the sagittal and frontal motions. These observations support previous research that reported comparable flexion angles during DLS in individuals with previous ACL injury [11, 30]. However, the authors stressed that kinetic differences existed between the limbs, and cautioned that compensatory movements may not be reflected in the kinematics. The authors also highlighted that it often is difficult for practitioners to identify joint substitutions without access to kinetic measurements. It is possible the AKP group in this study employed compensatory movement strategies that would have been evident on land during kinetic assessments, despite appearing symmetrical during the kinematic analysis.

Kinematic differences appeared between the limbs during DLS performed in water that were not evident on land. Interestingly, while the unaffected limb appeared to maintain its kinematics in both environments, increased hip abduction in the affected limb indicated a wider stance in water, while the body remained over the unaffected limb. Perhaps this strategy indicated a shift in loading towards the unaffected limb, but kinetic analyses are needed for confirmation. Previous research has suggested that water immersion changes balance demands [18, 19], and the wider stance was perhaps a balance strategy. However, the effects of changed balance demands on exercise performance and outcomes has not been well-documented in the literature. Research on effects of water immersion on kinematic symmetries is scarce, but similar to the results from this study, increased asymmetries has been reported.
by one previous study [22]. The authors suggested that the increased asymmetry probably reflected pre-existing functional differences due to greater instability in water. It is possible the asymmetries that appeared during water-based DLS were reflections of compensatory movement strategies revealed by the aquatic environment.

The gravitational offloading [14], decreased pain [31], and altered proprioception [19] in water likely changed the demands of the exercises, perhaps to the extent where established movement strategies were disrupted and asymmetries were revealed. Currently, not enough research has been conducted on the topic to determine whether the different kinematics between the affected and unaffected limbs in water were associated with compensatory strategies. Future research should assess kinetic profiles and quantify environmental effects on compensatory movements. The possibility that water immersion may reveal existing kinematic differences is exciting as it provides practitioners with a useful movement assessment tool that is not currently available.

Kinematic differences between the limbs also existed during the SLS in both environments and were evident both the sagittal and frontal planes of motion. Land-based SLS on the affected limb showed decreased hip flexion, increased varus alignment and lateral trunk lean. The reduced hip flexion probably indicated a strategy with less hinging from the hip, which shifts the centre of mass posteriorly, and reduces the demand of the gluteal muscles [10]. This increases the demand of the quadriceps, and consequently the compressive loads of the patellofemoral joint [32], which potentially contributes to the continued aggravation of AKP. Research has also suggested this might contribute the weak gluteal muscles that are often reported in this population [7, 10]. The compensatory movements employed by the AKP group on land may therefore aggravate their condition further. Importantly, this adaptation was not reduced in water, despite the considerable offloading.

The increased lateral trunk lean on land during SLS on the affected limb supported previous research that reported increased frontal plane movements in individuals with AKP [2, 9]. The reduced trunk lean in water suggested that immersion may provide some support to the trunk.

Table 3 Asymmetry index score (±SD) between the groups in both environments

<table>
<thead>
<tr>
<th></th>
<th>Land</th>
<th>Control</th>
<th>d</th>
<th>Pool</th>
<th>Control</th>
<th>d</th>
</tr>
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<tr>
<td><strong>Double-leg Squat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank AP (*)</td>
<td>5.9±1.1</td>
<td>5.4±1.2</td>
<td>0.40</td>
<td>5.9±1.6</td>
<td>5.8±1.4</td>
<td>0.06</td>
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<tr>
<td>Thigh AP (*)</td>
<td>5.3±0.7</td>
<td>5.0±1.4</td>
<td>0.33</td>
<td>5.3±0.5</td>
<td>5.1±1.7</td>
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<td>1.3±1.3a</td>
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<td>0.76a</td>
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<tr>
<td>Hip flexion (*)</td>
<td>1.4±0.8</td>
<td>1.3±0.7</td>
<td>0.11</td>
<td>1.6±1.1</td>
<td>1.7±1.7</td>
<td>−0.09</td>
</tr>
<tr>
<td>Shank ML (*)</td>
<td>1.9±1.3</td>
<td>2.3±1.7</td>
<td>−0.26</td>
<td>2.7±2.1</td>
<td>2.2±2.7</td>
<td>0.20</td>
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<tr>
<td>Thigh ML (*)</td>
<td>2.9±2.1</td>
<td>3.0±2.2</td>
<td>−0.06</td>
<td>3.6±2.0</td>
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<td>Knee abduction (*)</td>
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<td>4.8±1.5</td>
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<td>3.3±2.5</td>
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<td>−1.26*</td>
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<tr>
<td>Hip abduction (*)</td>
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<td>4.6±2.1</td>
<td>−0.91*</td>
<td>3.0±1.9</td>
<td>7.4±2.6a</td>
<td>−1.87*</td>
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<table>
<thead>
<tr>
<th></th>
<th>Land</th>
<th>Control</th>
<th>d</th>
<th>Pool</th>
<th>Control</th>
<th>d</th>
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<tr>
<td><strong>Single-leg Squat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank AP (*)</td>
<td>5.3±1.4</td>
<td>5.1±1.3</td>
<td>0.15</td>
<td>6.3±1.7</td>
<td>6.3±1.3a</td>
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<td>Thigh AP (*)</td>
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<td>−0.13</td>
<td>4.8±0.9</td>
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<td>0.85*</td>
<td>1.3±0.7a</td>
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<td>Trunk flexion (*)</td>
<td>3.4±1.9</td>
<td>2.3±1.2</td>
<td>0.69*</td>
<td>2.4±1.5b</td>
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<td>1.04*</td>
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<td>Thigh ML (*)</td>
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<td>0.96*</td>
<td>2.8±1.4a</td>
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<td>Thorax ML (*)</td>
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<td>0.84*</td>
<td>5.3±4.0a</td>
<td>5.8±3.8</td>
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<td>5.0±1.8</td>
<td>0.64*</td>
<td>7.1±3.1</td>
<td>6.0±2.9</td>
<td>0.37</td>
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<tr>
<td>Hip abduction (*)</td>
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<td>7.3±4.6</td>
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<td>5.1±3.0</td>
<td>0.45</td>
<td>11.5±9.4</td>
<td>6.6±4.1</td>
<td>0.67</td>
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</table>

*p* indicates significant difference between environments at *p* < 0.05

*Indicates large within groups effect size between environments at Cohen’s d > 0.8

*Indicates moderate within groups effect size between environments at Cohen’s d > 0.5
Our results showed marginally reduced valgus alignment on the affected limb, although previous research has reported increased valgus in this population [2, 9]. The previous authors suggested that increased valgus was associated with hip-muscle weaknesses. The reason for this discrepancy with previous research remains unknown, but the knee abduction angles in the unaffected limb were similar to previous reports for healthy controls [9]. Interestingly, water immersion increased the knee abduction angles of the affected limb, while it increased the varus alignment in the affected limb. This was likely a positive observation, as increased valgus alignment is associated with decreased functionality and injury [3, 33]. Further research is needed to determine the functional effects of these frontal plane adaptations during the DLS.

The increased hip abduction angles during water-based SLS cannot be attributed to a wider stance, as it is unilateral exercise. Previous research have suggested that increased balance demands in water requires an increased reliance on frontal plane motions [20]. Increased lower body motions in the frontal plane is perhaps a normal response to the unstable nature of the aquatic environment. This study did not quantify balance so the implications of water immersion on postural control remain unknown, however, previous research reported improved land-based balance following water-based training [19, 34]. Although these studies did not measure balance during immersion. Research has reported increased postural sway in water during quiet standing [35], but did not assess dynamic movements. Future research should analyse ground reaction forces and perturbations in centre of pressure during water-based exercises to further the understanding water immersion on balance strategies.

The SI analysis showed that water immersion often affected bilateral asymmetries in both individuals with AKP and healthy controls. Regardless, practitioners should acknowledge that some asymmetry is normal even within a healthy population [22–24], although research is yet to determine the threshold for when asymmetrical movements should be considered undesirable. The SI-scores in this research ranged from 0.3 to 15.3, and researchers using the same SI method reported scores between 8 and 16, but did not refer to whether this should be considered normal [24]. Therefore, the practical implications of these values remain unclear.

Some SI-scores indicated more asymmetry on land, while others suggested more asymmetry in water. The observations of increased SI-scores in water agree with previous research [22], however, the implications of this are still unknown. Practitioners should consider that the emphasized asymmetries in water may be detrimental for rehabilitation. Asymmetrical motor patterns can reduce the efficacy of rehabilitation exercises [11], which highlights the need for close monitoring during rehabilitation. Further, prolonged asymmetrical motions at the knee joints has been suggested to increase the risk of osteoarthritis [11]. However, it is possible that gravitational offloading in water reduces long-term implications of asymmetrical loading. Additionally, the participants in this study had no prior experience with water-based exercise, so it is possible that habituation could change these results and reduce the degree of asymmetry during the water-based exercises. Regardless, the offloading constitutes a primary rationale for employing aquatic therapy for rehabilitation [16] as it allows for earlier return to partially loaded activities. Continuous movement assessments throughout a rehabilitation program can highlight asymmetries and potentially indicate the efficacy of the program.

Researchers have highlighted lacking understandings on implications of water immersion on movement symmetry [22], which deserves attention in future research. This study assessed kinematic effects of water immersion, and future research is still needed to assess the effects of water immersion on kinetic and neuromuscular profiles of individuals with AKP. This would provide practitioners with a clearer understanding of the roles of water-based rehabilitation for this population. Further, the transferability of movements between the environments has not been established and it is possible that any beneficial movement adaptations observed in water is confined to pool-settings. This necessitates that future research determines the degree of transferability between water and land to optimize current guidelines for practitioners.

**Conclusions**

Water immersion allowed individuals with unilateral AKP increased depth during DLS and SLS, along with some increased flexion angles. The increased movement range catered to early rehabilitation goals for individuals with AKP. The exercise environment also affected the movement patterns differently between limbs. The degree of asymmetry was affected in both groups during the exercises, although the long-term implications of this remain unknown. Increased asymmetries during water-based exercises suggests that clinicians should pay close attention to their client’s technique and perhaps use verbal and visual feedback to minimise any movement compensations. This study suggests that practitioners should consider aquatic therapy as one component of a comprehensive treatment plan for participants with long-standing AKP, and use it in conjunction with established protocols.

**Abbreviations**

AKP: Anterior knee pain; DLS: Double-leg squat; SI: Symmetry index; SLS: Single-leg squat
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Availability of data and materials
The datasets (in anonymised form) used and/or analysed during the current study are available from the corresponding author on reasonable request.

Authors’ contributions
AS developed the study design, collected, analysed, interpreted the data and wrote the manuscript. BB and NW both contributed to study design and writing of the manuscript. MS contributed to study design, data interpretation and writing of the manuscript. AW contributed to data analysis and writing of the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate
This project was conducted in accordance to the approval by the Human Ethics Research Committee at the University of the Sunshine Coast, which approved the research protocol and data collection instruments (S/15/742). All participants signed a written informed consent prior to any data collection.

Consent for publication
A signed consent form was provided for the publication of Fig. 1.

Competing interests
The authors declare no competing interests.

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References


### 10.4. Additional information

Table 10.1. Peak angles for the squat across the three populations.

<table>
<thead>
<tr>
<th></th>
<th>Young healthy adults</th>
<th>Old adults</th>
<th>Anterior knee pain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land (*)</td>
<td>Pool (*)</td>
<td>p</td>
</tr>
<tr>
<td>Trunk extension</td>
<td>0.17 (8.9)</td>
<td>-1.36 (8.2)</td>
<td>0.575</td>
</tr>
<tr>
<td>Trunk flexion</td>
<td>37.28 (25.4)</td>
<td>30.77 (19.9)</td>
<td>0.377</td>
</tr>
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<td>Hip extension</td>
<td>1.16 (7.65)</td>
<td>1.10 (6.55)</td>
<td>0.138</td>
</tr>
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<td>Hip flexion</td>
<td>70.44 (22.17)</td>
<td>84.05 (24.42)</td>
<td>0.103</td>
</tr>
<tr>
<td>Knee extension</td>
<td>3.45 (5.75)</td>
<td>3.72 (6.80)</td>
<td>0.595</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>97.60 (14.71)</td>
<td>99.64 (14.13)</td>
<td>0.640</td>
</tr>
<tr>
<td>Trunk lateral flexion</td>
<td>1.58 (2.97)</td>
<td>0.77 (3.06)</td>
<td>0.122</td>
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<tr>
<td>Hip abduction</td>
<td>14.39 (9.38)</td>
<td>14.40 (9.38)</td>
<td>0.998</td>
</tr>
<tr>
<td>Hip adduction</td>
<td>0.40 (3.75)</td>
<td>-0.18 (5.39)</td>
<td>0.647</td>
</tr>
<tr>
<td>Knee abduction</td>
<td>0.08 (3.29)</td>
<td>-1.85 (4.61)</td>
<td>0.116</td>
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<tr>
<td>Knee adduction</td>
<td>23.45 (12.09)</td>
<td>29.42 (15.33)</td>
<td>0.151</td>
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</table>

\(d\) – Cohen’s \(d\) effect size
<table>
<thead>
<tr>
<th></th>
<th>Young healthy adults</th>
<th></th>
<th>Older adults</th>
<th></th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Land (°)</td>
<td>Pool (°)</td>
<td>p</td>
<td>d</td>
<td>Land (°)</td>
<td>Pool (°)</td>
</tr>
<tr>
<td>Trunk extension</td>
<td>2.55 (6.89)</td>
<td>1.39 (5.60)</td>
<td>0.555</td>
<td>0.18</td>
<td>0.41 (4.46)</td>
<td>1.88 (3.27)</td>
</tr>
<tr>
<td>Trunk flexion</td>
<td>14.49 (12.15)</td>
<td>16.83 (10.86)</td>
<td>0.511</td>
<td>-0.20</td>
<td>22.48 (12.32)</td>
<td>4.94 (5.84)</td>
</tr>
<tr>
<td>Hip extension</td>
<td>3.66 (7.18)</td>
<td>4.01 (7.21)</td>
<td>0.871</td>
<td>-0.05</td>
<td>5.67 (5.56)</td>
<td>2.66 (6.86)</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>51.70 (12.43)</td>
<td>60.37 (13.12)</td>
<td>0.028</td>
<td>-0.68</td>
<td>30.25 (12.41)</td>
<td>43.66 (12.65)</td>
</tr>
<tr>
<td>Knee extension</td>
<td>3.90 (7.18)</td>
<td>4.06 (7.21)</td>
<td>0.956</td>
<td>-0.02</td>
<td>5.75 (8.51)</td>
<td>5.53 (9.95)</td>
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<tr>
<td>Knee flexion</td>
<td>78.20 (16.41)</td>
<td>69.58 (13.57)</td>
<td>0.063</td>
<td>0.57</td>
<td>61.14 (14.94)</td>
<td>65.46 (16.14)</td>
</tr>
<tr>
<td>Trunk lateral flexion</td>
<td>-2.85 (4.13)</td>
<td>2.26 (7.32)</td>
<td>0.005</td>
<td>-0.86</td>
<td>4.44 (8.99)</td>
<td>2.35 (3.84)</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>16.23 (12.30)</td>
<td>25.46 (11.54)</td>
<td>0.013</td>
<td>-0.77</td>
<td>3.53 (4.69)</td>
<td>12.05 (9.68)</td>
</tr>
<tr>
<td>Hip adduction</td>
<td>1.85 (4.33)</td>
<td>0.79 (5.03)</td>
<td>0.451</td>
<td>0.23</td>
<td>3.68 (4.94)</td>
<td>0.31 (6.54)</td>
</tr>
<tr>
<td>Knee abduction</td>
<td>0.05 (4.64)</td>
<td>0.75 (3.47)</td>
<td>0.570</td>
<td>-0.17</td>
<td>1.72 (4.54)</td>
<td>0.20 (6.59)</td>
</tr>
<tr>
<td>Knee adduction</td>
<td>27.16 (13.87)</td>
<td>22.43 (11.73)</td>
<td>0.228</td>
<td>0.37</td>
<td>9.92 (9.03)</td>
<td>19.84 (10.43)</td>
</tr>
</tbody>
</table>

*d* – Cohen’s *d* effect size
### Table 10.3. Peak angles for the single-leg squat for the young healthy and anterior knee pain groups.

<table>
<thead>
<tr>
<th></th>
<th>Young healthy adults (dominant limb)</th>
<th>Anterior knee pain (affected limb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land (°)</td>
<td>Pool (°)</td>
</tr>
<tr>
<td>Trunk extension</td>
<td>1.34 (5.53)</td>
<td>5.18 (3.98)</td>
</tr>
<tr>
<td>Trunk flexion</td>
<td>11.94 (10.33)</td>
<td>4.49 (8.72)</td>
</tr>
<tr>
<td>Hip extension</td>
<td>2.87 (7.06)</td>
<td>2.94 (9.19)</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>30.53 (14.80)</td>
<td>52.85 (24.54)</td>
</tr>
<tr>
<td>Knee extension</td>
<td>0.74 (6.71)</td>
<td>0.24 (8.72)</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>65.46 (13.06)</td>
<td>83.23 (14.58)</td>
</tr>
<tr>
<td>Trunk lateral flexion</td>
<td>3.69 (3.87)</td>
<td>2.25 (7.97)</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>8.95 (7.92)</td>
<td>9.44 (10.08)</td>
</tr>
<tr>
<td>Hip adduction</td>
<td>1.27 (4.76)</td>
<td>1.35 (7.89)</td>
</tr>
<tr>
<td>Knee abduction</td>
<td>1.55 (2.87)</td>
<td>0.86 (5.45)</td>
</tr>
<tr>
<td>Knee adduction</td>
<td>13.46 (9.81)</td>
<td>10.97 (6.04)</td>
</tr>
</tbody>
</table>

*d* – Cohen’s *d* effect size