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Abstract

Objective To quantitatively assess measures of static balance and limits of stability (LOS) in an aquatic environment compared to on land. **Methods** Fifteen healthy, young adults (23 ± 2 years) performed 90 s static balance trials on land and aquatic immersion at two different depths (greater trochanter, xiphoid process). Measures of 95% ellipse area and center of pressure (CoP) mean velocity were computed from the force data. Additionally, participants completed a visual analog scale (VAS) of perceived stability for each environmental condition. Following the static balance trials, participants performed anterior-posterior and medial-lateral LOS assessments. **Results** Significant differences in 95% ellipse area and CoP mean velocity were observed for the aquatic environments compared to on land ($p < 0.05$). VAS data revealed significant differences in perceived balance in an aquatic environment compared to on land ($p < 0.05$). LOS assessments revealed a significant difference in maximum CoP excursions in an aquatic environment compared to land ($p < 0.05$). **Conclusion** When participants performed a quiet double-leg stance task, measures of balance and perceived stability were inferior when the task was performed in water than on land. Additionally, participants achieved greater CoP maximum excursions in the water compared to on land. Although future research is needed to assess factors influencing balance in the water, the added instability in the water is clinically relevant. Results of

this study further highlight the importance of considering the inclusion of aquatic training as part of a comprehensive training / rehabilitation program.
Keywords:
Static Balance, Postural Sway, Center of Pressure, Aquatic, Water

1. Introduction

Balance is a key measure of human neuromechanical function that describes the capacity to maintain line of gravity within a base of support. Control of balance is reliant on interaction and integration of sensory input from the visual, vestibular, and proprioceptive systems. Contribution of individual sensory systems in maintaining balance during a movement task is variable and dependent on a multitude of factors including the explicit physical demands of the task, external environment, pathological impairment, and age [1, 2, 3]. Balance plays an important role in mitigating fall risk and subsequent injury in the elderly and is positively associated with improved performance and reduced risk for injury in athletic populations [4].

Assessments of static and functional (dynamic) balance are common in various populations including athletic post-injury, individuals experiencing impaired sensorimotor function, and the elderly. Balance under static conditions accentuates the capacity to minimize line of gravity sway within a defined, unchanging base of support [5]. Consequently, a static balance assessment typically requires an individual to stand as still as possible under varying conditions including support (double, single, or tandem leg stances) and visual (eyes open or closed) while the magnitude of postural perturbation or sway is noted. Individuals that display poor balance, relative to their age-matched peers, are often prescribed balance training programs.

The balance training literature contains a plethora of exercises that purport to improve measures of balance. Standing on one foot, walking backwards, standing on foam or ankle discs, walking on toes, and balance-specific lower extremity muscular strengthening are just a few examples of exercises that may improve balance [6]. The majority of balance interventions are performed on land, which is fitting given the terrestrial nature of humans. Few studies have utilized water as an environment for balance exercises [7]. This is noteworthy since those who may benefit most from balance training (e.g. athletic post-injury and elderly populations) are also those who may benefit from other exercise prescriptions performed in an aquatic environment.

While there is some evidence indicating that various aquatic exercise modalities may improve balance characteristics (e.g. center of pressure range and variability) on land [7, 8], there is no evidence indicating how water immersion itself influences measures of balance. Thus, the aim of this study was to quantify the effect of aquatic immersion on selected static balance measures, perceived balance, and limits of stability (LOS) during unperturbed standing. Findings of this study offer a fundamental understanding of environmental influences on static balance. Knowledge gained from this study adds to the balance literature by further assessing the effectiveness and applicability of aquatic immersion as a means to improve balance, especially for special populations commonly prescribed aquatic exercise modalities.

2. Methods

2.1. Subjects

Fifteen healthy, young participants took part in the study (Male = 9, Female = 6; age = 23 ± 2 yrs.; height = 172 ± 11 cm; weight = 729 ± 185 N). Participants were recruited from university and community settings and were excluded if they presented a lower extremity injury, sensory dysfunction (neural, vestibular, visual), or a concussion in the 12 weeks prior to the study. Prior to the study, participants were required to sign an informed consent form approved by the university Institutional Review Board. There was no participant attrition for the duration of the study.

2.2. Procedures

2.2.1. Static Balance

Participants were invited to attend a single testing session, lasting approximately one hour. Data collection took place in a climate-controlled room in an athletic training facility. Air temperature and water temperature were regulated to 24,° C and 30 °C, respectively.

During the testing session, participants were asked to perform a single 90 s static balance trial on a force platform (Advanced Mechanical Technology, Inc. (AMTI), model OR6-WP, Watertown, MA, USA) under varying environmental and visual conditions. The three environmental conditions were land and water immersion at the greater trochanter and xiphoid process depths. The two visual conditions were eyes open and eyes closed. Visual conditions were randomized but external environments were not. Participants performed the land trial first, followed by the greater trochanter water depth, and lastly the xiphoid process water depth. This order was selected to produce a thermoneutral environment that minimized shivering and its effect on spurious balance scores.

For all conditions, participants were given the verbal cue "hands on hips. . . stand as still as possible" immediately prior to triggering the 90 second data acquisition. For the eyes open trials, participants were instructed to focus on a white strip of tape, placed at eye level, on a wall 1.8 m from the edge of the pool. For the eyes closed trials, to ensure consistent head position between visual conditions, participants were instructed to focus on the same strip of tape and then to close their eyes. Water-resistant chalk was used to place target marks on the force plate surface. This was done to ensure consistency of foot placement, minimizing variability in base of support geometry across conditions.

All aquatic and land balance trials were performed in the same standing location. The force platform was positioned on an adjustable floor of an aquatic treadmill (HydroWorx 2000TM, Middletown, PA) one meter from the edge of the pool. The force platform and acquisition hardware were calibrated according to manufacturer guidelines. External vibration and fluid current, manifested from the aquatic treadmill machinery, were suppressed for the balance trials and LOS trials by powering down the pool pump system during data acquisition.

Participants also completed a visual analogue scale (VAS) for all balance conditions. Immediately following each static balance trial, participants were asked to make a pen mark on a 117 mm continuous, solid line representing perceived level of stability ranging from "very stable" (0 mm) to "very unstable" (117 mm). This continuum measure was included to provide self-reported perception of static, unperturbed balance and thereby serving as a secondary, quantitative assessment of balance between land and water environments.

2.2.2. Limits of Stability

Participants were asked to perform anterior-posterior and medial-lateral LOS excursions to better understand how the environment influences volitional sway capacity and to better interpret any static balance differences between environments. The LOS assessments were performed in the same order and immediately following each static balance test. Participants were instructed to "keep both feet flat on the force plate", "lean like a tree three times in each direction", and "lean as far as possible without making a step". Prior to the trials, participants were given time to practice the movement requirements. Practice was given for the land and water conditions. Participants were given ninety seconds to perform three maximum excursions in each of the four directions.

2.3. Data Analysis

Static balance and LOS kinetic data obtained via the waterproof force platform were recorded and analyzed using NetForce data acquisition software (AMTI). Kinetic data for all trials were sampled at 25 Hz. It is generally considered in the balance literature that the majority of the CoP displacement signal is contained in low frequencies [9, 10, 11, 12] (e.g. < 2 Hz). Since CoP signals acquired in an aquatic environment are currently foreign to the literature, a more conservative sampling frequency of 25 Hz was considered appropriate for the present study. Sampling duration of 90 s was selected based on previous studies indicating that longer sampling durations boost the capability to capture low CoP signal frequencies not otherwise detectible when using shorter sampling durations [9, 13] (e.g. 15-30 s). Mean center of pressure (CoP) over the 95% ellipse area (EA, cm^2) and mean CoP velocity (MV, $cm * s^{-1}$) for each 90 s collection served as the dependent measures for the balance tests. For the LOS trials, three maximum and minimum (x,y) CoP excursions were obtained from the CoP data. The rectilinear distance between the maximum or minimum CoP excursions served as the LOS dependent measure. In each excursion direction, the mean of three trials was used for statistical analysis.

The VAS scales were analyzed by measuring the distance from the left of the scale to the vertical mark drawn by each participant. This distance measure (mm) for each static balance test served as the dependent measure and was used for subsequent statistical analysis.

2.3.1. Repeatability Testing

To assess multiple-trial stability of the balance measures used in this study, coefficients of variation were obtained for both the 95% ellipse area and mean CoP velocity using an unbiased estimator, $\hat{C}_{V*} = (1 + \frac{1}{4n}) \times \hat{C}_V$. While coefficients for both measures were within acceptable limits (MV: 0.01–0.04, EA: 0.17–0.34), these reliability data suggest that CoP mean velocity has a tighter distribution in terms of trial-to-trial variability than the measure of 95% ellipse area. Recent research on traditional balance CoP measures support the use of mean CoP velocity and regard it to be the most reliable parameter [13]. These same authors also recommend the use of both 95% ellipse area and mean CoP velocity as they offer a more diverse picture of static balance.

2.4. Statistical Analysis

Ninety five percent ellipse area, mean CoP velocity, and VAS scores were analyzed using a 2 (vision) X 3 (environment) Repeated Measures Analysis of Variance (ANOVA) with vision as an independent factor ($p = 0.05$). If a main effect was observed, pairwise comparisons were obtained for the environment factor using a LSD post-hoc assessment.

CoP distances in the anterior-posterior and medial-lateral directions were analyzed using a one-way Repeated Measures ANOVA (= 0.05). Succeeding any significant main effects, pairwise comparisons were made using a LSD post-hoc adjustment. Effect sizes (ES) were computed to appreciate the meaningfulness of any significant differences.

3. Results

3.1. Static Balance

Regarding the 95% ellipse area, there was a significant main effect for the environment factor (F = 54.2, p = 0.000), but no effect was observed for vision (p = 0.136), or the interaction between vision and environment (p = 0.143) Pairwise comparisons for environment revealed the 95% ellipse area was statistically different between land and water conditions and between water depths (p = 0.000, ES = 0.8–1.6, See Figure 1). For instance, compared to land values, 95% ellipse area increased by 155% and 317% for the greater trochanter and xiphoid conditions, respectively. The CoP mean velocity measure displayed the same trend between conditions as the 95% ellipse area. That is, there was a significant main effect for the environment factor (F = 132.9, p = 0.000), but no effect was observed for vision (p = 0.942) or the interaction between vision and environment (p = 0.923). Pairwise comparisons for the environment factor displayed significantly different velocity scores between land and water and between water depths (p = 0.000, ES = 1.0–1.7, See Figure 2). For instance, compared to land values, mean CoP velocity increased by 74% and 209% for the greater trochanter and xiphoid conditions, respectively.

In general, the VAS results mirrored the force platform measures of 95% ellipse area and mean CoP velocity. For example, there was a significant main effect for the environment factor (F = 35.07, p = 0.000) but there was no effect for vision (p = 0.127) or the interaction (p = 0.118). Pairwise comparisons revealed that participants perception of balance was different between land and both water conditions and between water depths (p = 0.000–0.002, ES = 0.4–0.9, See Table 1).

3.2. Limits of Stability (LOS)

The ANOVA was significant (F = 3.13–5.24, p = 0.02–0.05) and follow-up comparisons revealed the anterior-posterior and medial-lateral excursions were significantly different between land and both water conditions (p = 0.001–0.049, ES = 0.3–0.7, See Table 2). For example, compared to land values, LOS excursions increased in all directions for the greater trochanter (9–13%) and xiphoid (7–12%) conditions. There was no significant difference between the greater trochanter and xiphoid process water depths (p = 0.464–0.896, ES = -0.3–0.1).

4. Discussion

The aim of this study was to evaluate the effect of aquatic immersion on static balance and LOS. The data revealed a greater challenge to static balance in an aquatic environment compared to on land as evidenced by greater 95% ellipse area, mean CoP velocity, and perceived balance (VAS) measures in the former environment. There is a prospective multi-component model underlying these balance findings between aquatic and land environments. However, the level of contribution of specific mechanisms is not effusively clear.

Land measures of 95% ellipse area and mean CoP velocity for the current study (e.g. 2.3 cm^2, 7.8 $cm * s^{-1}$, respectively) were consistent with values reported in previous research using similar methods [14] (EA (1.8–2.4 cm^2), MV (6.9–9.4 $cm * s^{-1}$).

The mechanical effect of buoyancy may explain why balance measures in this study were inferior in water than on land. Previous research examining aquatic therapy revealed that buoyant forces unloaded ones body weight by as much as 50–75% when submerged to the xiphoid process [15]. In support of the data by Harrison et al., post hoc assessments of our vertical ground reaction force data revealed that participants were, on average, unloaded by 68 ± 3% at the xiphoid depth and 39 ± 4% at the greater trochanter depth. This unloading of body weight effectively raises the whole body center of gravity [15] which, theoretically, reduces stability and is likely the foremost contributor to the inferior balance scores observed in the present study.

Aside from the mechanical mechanism of buoyancy, neural mechanisms may also have influenced balance in the aquatic environment. For example, there is conjecture that, in reference to a land environment, certain properties of aquatic fluid dynamics (e.g. hydrostatic pressure, fluid viscosity) stimulate ancillary input from somatosensory and vestibular systems. These fluid properties, which provide resistance to movement, are thought to enhance balance by increasing error detection and correction time [16]. Conversely, the current study discovered that balance was worse in the water compared to land. This observation was supported by the VAS scores, which revealed that participants perception of stability was also lower for the water conditions.

Evidence from previous research comparing reflex responses between environments (water versus land) observed a substantial reduction in the soleus Hoffman reflex during water immersion [17] and others have observed a substantial reduction in lower extremity muscle activity during gait [18] and trunk muscle activity during postural exercises [19] performed in water compared to on land. Remarkably, this suggests a reduction in muscle activation and reflex response when immersed in water despite a decrease in balance as evidenced in the current study. It is likely the case that immersion in water challenges static balance but also, due to unloading of body weight, reduces the corrective lower extremity and trunk torque requirements to maintain balance or accomplish other movement tasks.

It should also be noted that vision had no effect on balance measures (Figure 1 and 2) and no interaction was observed between vision and environment, suggesting the environmental effect of water immersion was not influenced by vision. Indeed, the protocol used in this study (e.g. double foot pressure for equilibrating proprioception, control of head position and visual focus, and large base of support area) was designed to accentuate results based on changes in environmental surroundings and to limit reliance on visual stimuli. Also, the lack of reliance on visual stimuli observed in the current study has been previously noted by researchers examining young, healthy participants using similar experimental setups [20, 21]. Winter et. al observed no significant differences in CoP measures between eyes open and eyes closed trials when participants performed a quiet, double-leg, hip-width stance task. Additionally, it has been noted that reliance on the integration of visual stimuli to does not influence youths ability to maintain limb load symmetry during a quiet, double-leg stance [20]. However, it becomes more critical for populations commonly linked with compromised control of balance [20] (e.g. elderly). Aside from vision, somatosensory, and proprioceptive mechanisms, it is possible that anticipatory mechanisms that effected balance on land were not pre-tuned for the water environment. Previous research has indicated that expectation is a significant factor influencing static balance [22] and since humans are terrestrial by nature it would be expected that any pre-programed responses for a static balance task on land may not be appropriate for the same task performed in an aquatic environment. For instance, the anticipatory muscle response required to adjust and maintain posture on land is likely going to be different in water because of the aforementioned fluid properties that essentially support body weight.

Despite a reduction in static balance measures and VAS, results of the LOS tests indicated participants had a greater capacity to volitionally displace their CoP in water compared to on land. This again may be due to fluid properties of an aquatic environment (e.g. hydrostatic pressure, increased viscosity), a reduction in ankle stabilizing torque requirements due to buoyancy, or possibly a reduction in perceived consequence associated with falling in the water compared to falling on land. This latter conjecture is commonly reported in the literature [23, 24, 25] but, to the knowledge of the authors, has not been formally tested.

In terms of the clinical applications of this study, the added instability in an aquatic environment may be beneficial to populations who are commonly prescribed aquatic exercise modalities (e.g. post-injury, pathologically impaired, and the elderly). Developing stability through exercises that are characteristically instable improves neuromuscular coordination and postural control strategies which lead to improvements in physical function and reduced risk for falls for special populations [26, 27, 28, 29, 30] (e.g. elderly, those with impaired neuromuscular function).

In conclusion, when healthy, young participants performed a quiet, double-leg stance task, measures of balance and perceived stability were inferior when the task was performed in water at two different depths (hip and chest) than on land. Future research is needed to better understand how factors influencing balance differ in aquatic environment and to investigate adaptations in neuromuscular coordination and postural control strategies as a consequence of aquatic balance training prescriptions.

5. References

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Table 1: VAS of Perceived Stability (mm)

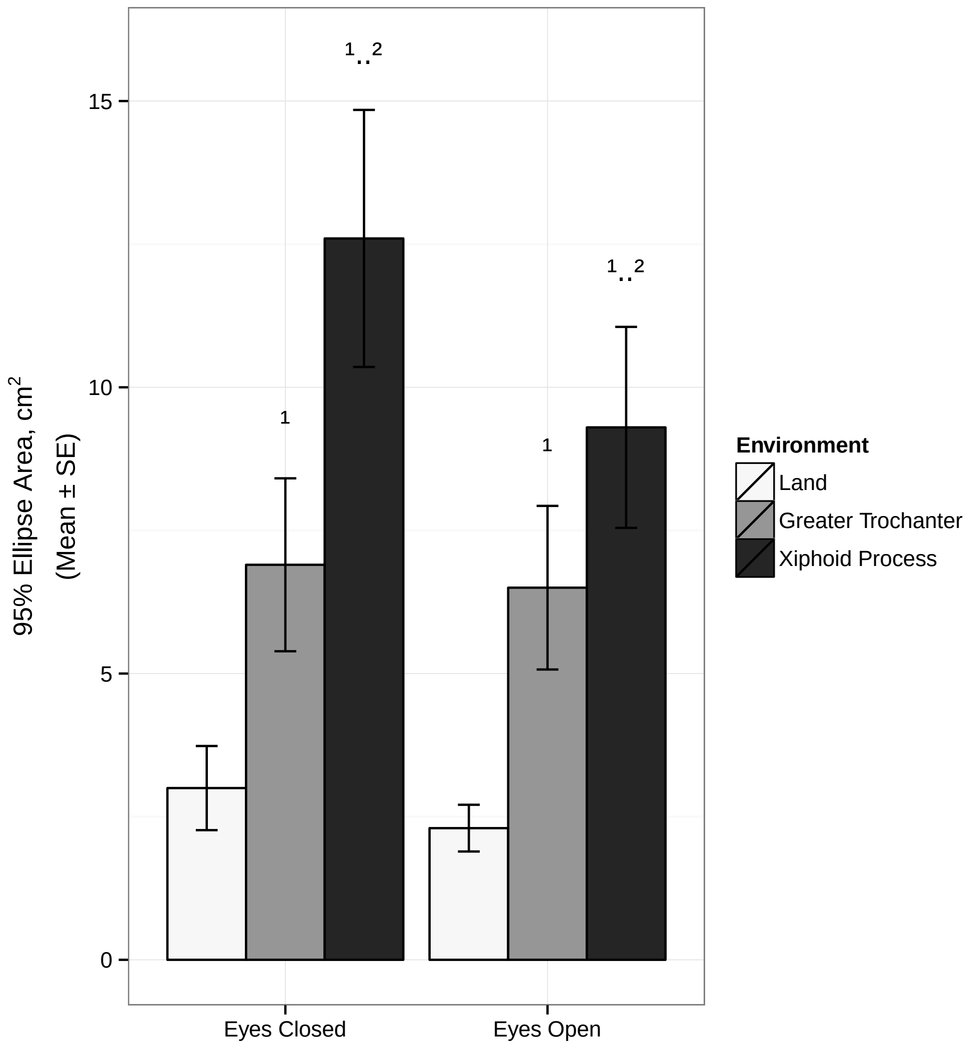
Environment	Mean	SD
Land	12.43	9.58
Greater Trochanter	16.47	10.42
Xiphoid Process	29.57	18.15

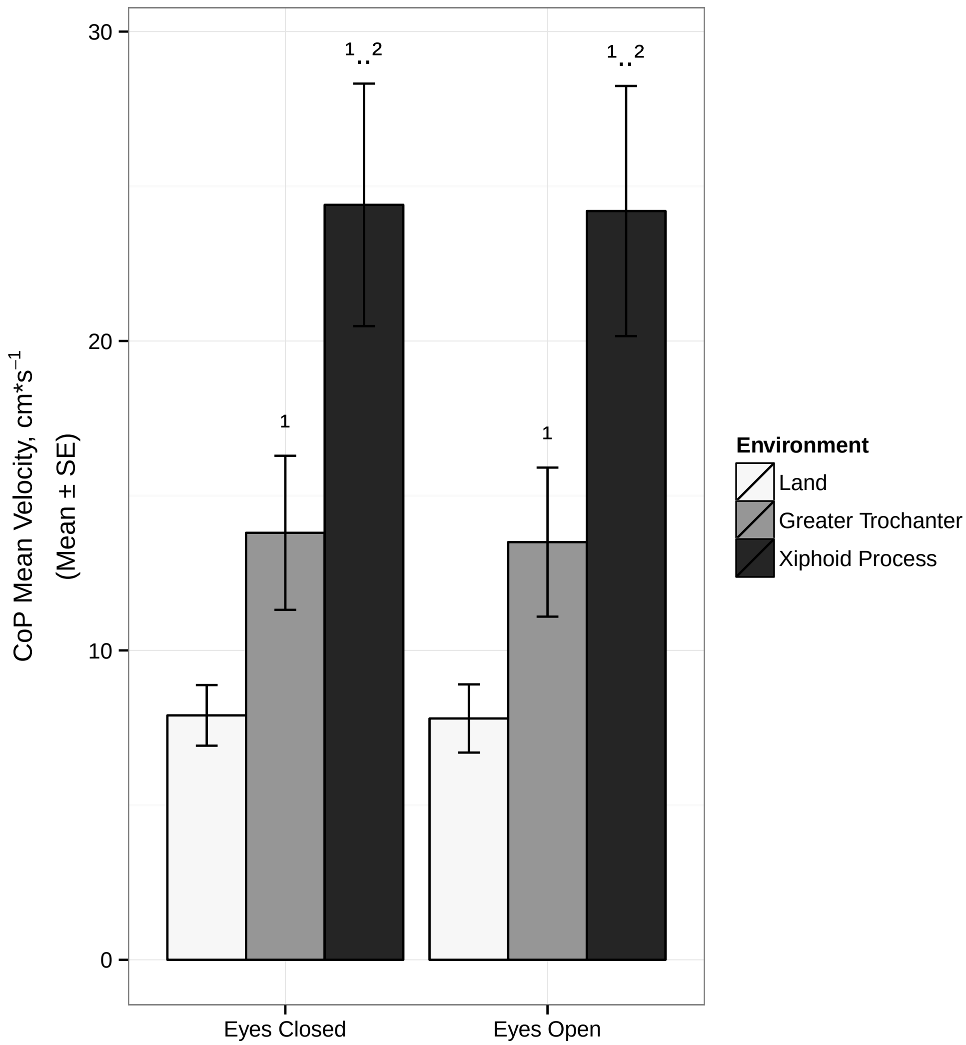
Table 2: Limits of Stability (cm)

Envrironment		Front	Left	Back	Right
Land	Mean	10.13	13.53	9.65	14.26
	SD	2.56	1.94	2.13	1.88
Greater Trochanter	Mean	11.02	14.38	10.90	15.56
	SD	2.53	2.44	1.99	2.36
Xiphoid Process	Mean	11.28	14.47	10.82	15.21
	SD	2.45	2.11	2.67	1.36

Figure 1: 95% Ellipse Area. [1]Significantly different from the land condition ($p < 0.05$). [2]Significantly different from the greater trochanter condition ($p < 0.05$).

Figure 2: CoP Mean Velocity. [1]Significantly different from the land condition ($p < 0.05$). [2]Significantly different from the greater trochanter condition ($p < 0.05$).


95% Ellipse Area, cm2
(Mean ± SE)
15
10
5
0
1..2
1
1..2
1
Eyes Closed
Eyes Open
Environment
Land
Greater Trochanter
Xiphoid Process


30
20
10
0
CoP Mean Velocity, cm*s^{-1}
(Mean ± SE)
1 2
1
1 2
1
Eyes Closed
Eyes Open
Environment
Land
Greater Trochanter
Xiphoid Process

Appendix A. Sampling

Measures of CoP movement are not a true representation of center of gravity (CoG) sway. Rather, they signify neuromuscular activation responses used to regulate CoP displacement in reaction to CoG perturbations. There are many factors that influence the reliability of CoP sampling, which will be discussed in subsequent sections. Selection of appropriate methodology is both measure and protocol specific [13] and no standard procedures exist for the sampling of CoP measures. However, several recent studies provide a solid framework for balance methodology utilizing traditional CoP measures [9, 13].

Appendix A.1. Sampling Frequency

It is generally considered in the balance literature that during static balance, the majority of the CoP displacement signal is contained in low frequencies [9, 10, 11, 12] (e.g. < 2 Hz). Recent studies advise using a sampling frequency of 100 Hz filtered at a cutoff frequency of 10 Hz [11, 13]. Reduced reliabilities of CoP measures have been reported for frequencies below 10 Hz, however, using sampling frequencies above 10 Hz (e.g. 25 Hz and below) do not disturb the estimation of CoP parameters [11]. Since CoP signals acquired from static balance trials in an aquatic environment are currently foreign to the literature, a more conservative sample frequency of 25 Hz was considered appropriate for the present study.

Appendix A.2. Sampling Duration

Sampling duration of 90 seconds was selected based on previous studies examining the reliability of CoP measures under various sampling protocols [9, 13]. Carpenter et al. suggest using longer sampling durations (e.g. 60-120s) compared to those of shorter duration. These authors discovered that longer sampling durations improve measures of CoP signal reliability. In addition, longer sampling durations boost the capability to capture low CoP signal frequencies not otherwise detectible using shorter sampling durations (e.g. 15-30s).

Appendix A.3. Number of Trials

The literature is not as clear regarding the appropriate number of trials for static balance measures of CoP and entails striking a balance between total testing volume, trial duration, and number of trials [13]. Single trial design was employed for this particular study to limit the volume of balance testing required for each participant. Under this study design, participants were required to fully focus on balancing for a total of nine minutes in addition to completing three LOS tests. Also, a single trial design controlled for potential physiological responses due to prolonged exposure to an aquatic environment as participants were required to spend an appreciable amount of time immersed in water.

Appendix A.4. Other

Although this study provides a highly controlled assessment of static balance between land and water environments, it is recommended that future studies consider additional controls including: normalization of CoP measures to anthropometric / morphological characteristics of participants and base of support / pedal geometry [13].