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RESEARCH ARTICLE

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Aquatic treadmill walking at three depths of water in people with traumatic brain injury

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Abstract

Objective: The purpose of this study was to analyse kinematic and spatiotemporal gait characteristics of aquatic treadmill walking among three different depths of water in individuals with traumatic brain injury.

Methods: A total of 13 individuals with traumatic brain injury participated in the study and completed walking trials at three different depths as follows: waist, chest, and neck level, which was adjusted by a movable floor pool. A self-selected comfortable walking speed at the waist level was used as a matched speed for all walking trials. Participants completed three aquatic treadmill walking trials under each of the three water depths. Each participant's gait was captured by a customized underwater motion analysis system and processed by a two-dimensional motion analysis software.

Results: The repeated measures analysis of variance showed significant differences in spatiotemporal and joint kinematic variables across three conditions: stance swing ratio (p = .023), peak hip flexion (p = .001), hip range of motion (p = .047), and peak ankle dorsiflexion (p = .000). Various water properties in conjunction with motor impairments might have contributed to alterations in gait kinematics.

Conclusion: Our findings suggest that walking in neck-depth water may not be ideal for gait training as it appears to limit hip flexion and ankle dorsiflexion. It is recommended that waist to chest-depth water be used to provide an accommodating environment for aquatic gait rehabilitation.

KEYWORDS
Aquatic treadmill, gait kinematics, partial weight bearing, traumatic brain injury

1 | INTRODUCTION

Individuals who have sustained traumatic brain injury (TBI) often demonstrate gait impairments that are associated with paralysis, muscular atrophy, compromised motor control, and muscular contracture (Acuña, Tyler, Danilov, & Thelen, 2018; Lorenz, Charrette, O'Neil-Pirozzi, Doucett, & Fong, 2018; Perez, Green, & Mochizuki, 2018). Limited mobility can also affect the independence of activities of daily living and quality of life (Cheng, Chi, Williams, & Thompson, 2018; Ptyushkin, Cieza, & Stucki, 2015).

Individuals with TBI demonstrate a shorter stride length, excessive hip flexion, limb instability, and equinovarus foot during stance phase; insufficient limb clearance, hip hike during swing phase, and lack of knee extension in terminal swing phase (Chou, Kaufman, Walker-Rabatin, Brey, & Basford, 2004; Perez et al., 2018; Williams, Schache, & Morris, 2013). Gait deficits can be associated with impaired balance, poor neuromotor control and abnormal muscle activation (Acuña et al., 2018; Williams et al., 2013). Treadmill-based gait training has shown effectiveness in restoring gait of people with various disabilities (Ambrus, Sanchez, & Fernandez-del-Olmo, 2019; Mao et al., 2015). It has been documented that treadmill walking in combination with a partial weight bearing (PWB) system can contribute to improving gait in people with TBI (Brown et al., 2005; Seif-Naraghi & Herman, 1999). Gait training in water can provide similar PWB effects due to buoyancy, which can help ease joint pain and promote independence of movements (Barela, Stolf, & Duarte, 2006; Foley, 2003).

It has been documented that gait rehabilitation in water is effective in individuals with neurological impairment (Jung, Ozaki, Lai, & Vrongistinos, 2014; Salem et al., 2011; Vivas, Arias, & Cudeiro, 2011); however, it has not been documented which depth is ideal for aquatic gait training in people with TBI. Although it did not involve individuals with TBI, Jung, Kim, Lim, and Vrongistinos (2018) investigated walking patterns of healthy individuals at different depths of water and found that significant differences exist when water becomes deeper. However, to our knowledge, no other studies have investigated the biomechanical gait patterns in people with TBI at various water depths. Therefore the purpose of this study was to examine kinematic and spatiotemporal gait parameters of aquatic treadmill walking at three different depths of water (waist, chest, and neck) in people with TBI. We hypothesized that there will be differences in gait patterns among three depths of water.

2 | METHODS

2.1 | Study design

The study was conducted at a university-based aquatic therapy facility using a therapeutic pool set at 34°C. Participants were required to complete treadmill walking in three different conditions as follows: waist-depth, chest-depth, and neck-depth water in 1 day. The water depths were adjusted by a movable floor pool (KBE Bauelemate, GmbH & Co., Wilhelmshaven, Germany, 2002) to each participant. Waist depth was defined as the level of anterior superior iliac spine, chest depth was defined as the level of the xiphoid process, and neck depth was defined as the level of cervical 7.

2.2 | Participants

A total of 15 individuals with TBI were recruited in this study using convenience sampling. All participants were recruited by word of mouth and through issuance of flyers at a university-based aquatic therapy center. The mean age of participants was 43.2 (range: 27 and 64 years), and average years after TBI were 12.67. All participants had bilateral paresis, seven participants used no walking aid, seven participants used a walker, and one participant used a walker with ankle foot orthotics on both legs. All participants had previous experience of aquatic exercise including the use of an aquatic treadmill. Participant characteristics are summarized in Table 1. Inclusion criteria consisted of (a) diagnosis of TBI by a physician, (b) ability to walk with or without an aid for 10 minutes, (c) the ability to follow the test protocol, and (d) no surgery within the last 6 months. Exclusion criteria consisted of (a) recent surgery within the last 6 months, (b) orthopaedic or peripheral nerve injuries to their lower limbs, (c) severe cognitive and/or behavior disorder that would interfere with study participation, (d) severe uncontrolled seizures, (e) nonambulatory, and (f) acute illness. Prior to the study, participants were informed of the purpose, protocol, and risks of the study. The research protocol was approved by the University's Institutional Review Board, and informed consent was obtained from all participants.

2.3 | Procedure

All participants were asked to walk on the aquatic treadmill (AquaGaitor, Hudson Aquatic, Angola, IN, 2002) at three different water levels. Prior to the trials, anthropometric data were obtained, and participants were asked to wear tight fitting shorts over their swimsuits and the same type of aquatic-shoes for all test conditions. A total of 15 waterproof markers (8 mm in diameter) were attached to bony landmarks of the lower extremities for two-dimensional motion analysis. Marker attachments included the sacrum, anterior superior iliac spine, the midpoint of anterior superior iliac spine and posterior superior iliac spine, greater trochanter, lateral femoral condyle, lateral malleolus, calcaneus, and fifth metatarsal head. To minimize possible errors, a single researcher performed marker attachment. A 5-minute familiarization time at waist depth was given to all participants prior to testing trials. During familiarization, participants self-selected a comfortable walking speed that was later applied to subsequent testing conditions. Participants completed three test trials of 2-minute treadmill walking at each condition with a 2-minute resting period between each trial. The specific order of water depths was randomized for all participants.

All participants held onto an aquatic parallel bar (AquaSprint, San Luis Obispo, CA, 2002) to eliminate arm movement that could interfere with camera view during treadmill walking. A previous study

TABLE 1 Participant characteristics

Characteristic	Value
Gender (M/F)	12/1
Age (years)	43.23 ± 12.04
Height (cm)	174.68 ± 9.4
Weight (kg)	80.77 ± 15.03
Post-TBI (years)	12.67 ± 10.59
Walking aids (No aids/Walker)	7/6

Note. Mean ± standard deviation (range).
Abbreviations: F, female; M, male; TBI, traumatic brain injury.

validated that the elimination of arm movement has no significant effect on gait kinematics during treadmill walking (Stephenson, De Serres, & Lamontagne, 2010). Two digital video cameras (Canon GL, Melville, NY, 2002) with 60 Hz and a shutter speed of 1/15,000 s were placed into underwater housings (Equinox, Galesburg, MI, 2001) and positioned 2 m away from both sides of the aquatic treadmill. To synchronize the two video cameras, a red flashlight was used during the trials. Captured data were imported to a two-dimensional motion analysis software (eHuman, HMA Technology, Inc, Ontario, Canada, 2003), manually digitized, and reconstructed for two-dimensional coordinates.

Spatiotemporal and kinematic gait variables were measured in this study. The spatiotemporal gait variables included cadence, stride length (meter), and stance/swing time ratio. Kinematic gait variables included peak sagittal plane angles and range of motion (ROM) of the hip, knee, and ankle joints. The spatiotemporal and lower-limb kinematic gait parameters were averaged from three trials at each water depth for data analysis. All data were examined for normality of distribution, equal variance, and independence of each observation in order to establish the statistical assumptions of analysis of variance (ANOVA). A repeated measures ANOVA was used to compare gait variables across three test conditions. When ANOVA yielded a significant difference across the conditions, post hoc comparisons with least significant differences were used to identify any significant interactions and mean differences between specific levels of water depths. The significant level was set to.05. All statistical analyses were performed by using SPSS v.22.0 software.

3 | RESULTS

Thirteen out of 15 participants were able to complete the self-selected comfortable walking trial at three depths of water. Two individuals could not perform aquatic treadmill walking safely and were excluded from the data. The results of repeated measures ANOVA showed significant differences in spatiotemporal and kinematic gait variables across three conditions as follows: stance swing ratio (p = .023), peak hip flexion (p = .001), hip ROM (p = .047), and peak ankle dorsiflexion (p = .000). No significant differences were found in hip extension, knee kinematics, ankle plantar-flexion, and

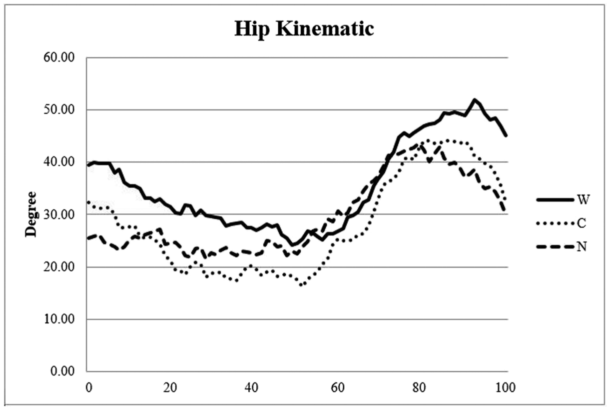

FIGURE 1 Hip kinematic. Values expresses as means. C, chest-water level; N, neck-water level; W, waist-water level

TABLE 2 Spatiotemporal and kinematic gait variables

Measure	Water depth W	C	N	p value
SL	0.36 ± 0.17	0.41 ± 0.33	0.42 ± 0.28	.246
ST	2.74 ± 0.78	2.87 ± 0.64	2.92 ± 0.47	.516
S/S	2.34 ± 0.60	1.93 ± 0.56[a]	1.97 ± 0.72	.023
CD	48 ± 17.87	44 ± 9.72	42 ± 6.47	.287
Hip Flex	55.91 ± 14.80	50.77 ± 14.30[a]	47.41 ± 15.87[b]	.001
Hip Ext	14.51 ± 14.99	12.80 ± 17.33	14.97 ± 14.70	.639
Hip ROM	41.41 ± 10.31	37.96 ± 9.47	32.44 ± 15.72[a]	.047
Knee Flex	64.26 ± 13.31	63.06 ± 16.20	61.35 ± 17.09	.496
Knee Ext	15.16 ± 10.73	14.50 ± 10.48	17.76 ± 10.29	.440
Knee ROM	49.10 ± 16.26	48.55 ± 17.91	43.59 ± 11.95	.241
Ankle DF	12.16 ± 6.99	15.66 ± 7.78[a]	22.24 ± 10.02[b,c]	.000
Ankle PF	47.38 ± 13.88	49.61 ± 11.27	53.22 ± 15.87	.312
Ankle ROM	35.22 ± 11.40	33.95 ± 12.17	30.98 ± 8.67	.499

Abbreviation: C, chest; CD, Cadence; DF, dorsiflexion; PF, plantar-flexion; ROM, range of motion; SL, stride length in meters; S/S, stance swing ratio; ST, stride time in seconds.
[a]Significantly different than waist (p < 0.05).
[b]Significantly different than waist(p < .01).
[c]Significantly different than chest (p < .01).

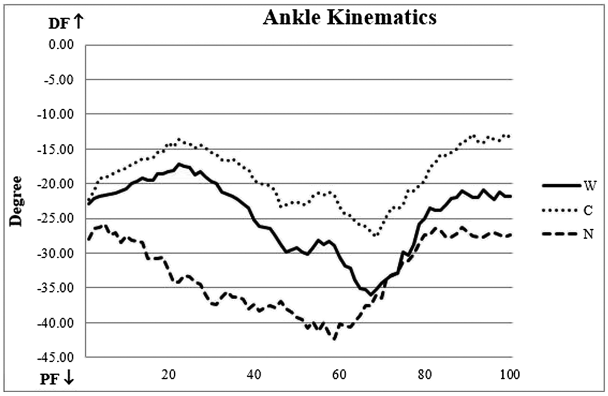

FIGURE 2 Ankle kinematics. Values expresses as means. C, chest-water level; DF, dorsi-flexion; N, neck-water level; PF, plantar-flexion; W, waist-water level

ankle ROM. The means and standard deviations of spatiotemporal and gait kinematic variables are presented in Table 2.

The results from the post hoc analysis were summarized by the change of water depths. From waist to chest-level water depth, hip flexion decreased by 9% (55.91 to 50.77 degrees; p = .049). Mean sagittal plane kinematics of hip is presented in Figure 1. In addition, dorsiflexion decreased by 28% (−12.16 to −15.66; p = .001; Figure 2) and stance/swing ratio decreased by 17.5% (2.34 to 1.93; p = .023). From chest to neck-level water depth, we found a decrease in dorsiflexion by 29.6% (−15.66 to −22.24 degrees; p = .000). Lastly, from waist to neck-level water depth, we found decreases in hip flexion by 15.1% (55.91 to 47.41 degrees; p = .000), hip ROM by 21.7% (41.41 to 32.44 degrees; p = .013) and dorsiflexion by 45% (−12.16 to −22.24 degrees; p = .000).

4 | DISCUSSION

The purpose of this study was to determine the biomechanical differences in aquatic treadmill walking among three different water depths in individuals with TBI. It was revealed that there are significant differences in kinematic and spatiotemporal variables among the three depths of water. Participants showed significant changes in stance swing ratio, peak hip flexion, hip ROM, and peak ankle dorsiflexion, whereas they demonstrated no significant differences in hip extension, knee kinematics, ankle plantar-flexion, and ankle ROM across the three depths of water.

Decreased peak dorsiflexion may be associated with the increased buoyancy effect when water becomes deeper. A previous study has shown that PWB with a harness system elicited early onset plantar-flexion during midstance phase and full body weight support further exacerbated plantar-flexion throughout the stance phase (Ferrarin et al., 2018). A similar weight support effect can be achieved through the buoyancy of water. At neck-level water depth, individuals are bearing only 10% of their body weight (Bates & Hanson, 1996), which evidently induces excessive floatation of the lower extremity making it difficult to perform heel strike. Jung et al. (2018) also found similar results in individuals without disability in walking at different water depths. Participants demonstrated toe walking throughout the gait cycle as water depth increased from chest to neck level. The findings indicate that deep water, particularly at neck depth, does not allow individuals to walk with proper ankle kinematics. Our results confirm it and suggest that neck-level water may not be an ideal environment for people with neurological disabilities to train gait with optimal ankle–joint kinematics.

The participants in our study showed a significant decrease in hip flexion at both chest and neck-water depths compared with waist level. According to Archimedes' principle of buoyancy ($F_b = pgV$), force of buoyancy (F_b) is affected by the density of the fluid (p), gravitational acceleration (g), and volume of the fluid displaced (V; Bates & Hanson, 1996). In this study, the density of the fluid and gravitational acceleration was constant. While walking in deeper depths of water, the participants' body was more fully immersed thus increasing the force of buoyancy applied to their center of mass. It appears that the increased buoyancy reduced the stability of the trunk compromising proximal control. The lack of proximal control can be associated with limited hip flexion, making it challenging for the lower extremities to advance during deep-water walking.

Decreased hip flexion and ROM can also be associated with instability of single-limb-stance phase in neck-depth water. In order to complete maximum hip flexion during the swing phase, it is essential to have stable single-limb support in the contralateral extremity. Furthermore, balance deficits in individuals with TBI appear to make the single-limb stance in neck-depth water more challenging, so that they could not achieve hip flexion at the terminal swing phase.

Participants showed a significant decrease in stance/swing ratio from waist to chest depth of.

Water, which means that our participants spent shorter time in stance phase and a longer time in swing phase as the water became deeper. An increase of upthrust force from buoyancy may have contributed to increasing the swing phase by eliciting earlier initiation of swing phase and delaying the terminal swing. Further observation of video revealed that participants were forced to prematurely lift the foot in the late stance phase and struggled to accomplish foot strike at the end of swing phase. Reestablishing foot strike at the terminal swing can be assisted by gravity during overground walking. However, it appeared to require concentric effort of knee flexors and hip extensors to achieve foot strike in this phase of gait cycle while walking in deep water depths.

No significant difference was found in peak ankle plantar-flexion among three depths of water. Due to toe walking being associated with the buoyancy effect, participants were already fixated in ankle plantar-flexion throughout the stance phase and ultimately retained this position during the swing phase. This ankle kinematic result could possibly explain why no significant differences were found in knee kinematics. The primary function of initial knee flexion during stance phase is to absorb the impact force during weight acceptance (Miyoshi, Shirota, Yamamoto, Nakazawa, & Akai, 2005). However, the buoyancy diminishes or even eliminates the need of shock absorption at foot strike during aquatic treadmill walking as seen in our participants. As when transitioning to swing phase, the knee flexion is also supported by the buoyancy of water. This buoyancy effect on knee joint kinematics seems to be applied similarly during both stance and swing phases regardless of water depths.

We acknowledge that there were limitations in this study. The sample size was relatively small consisting of 13 individuals with ambulatory TBI, which limits the ability to generalize our findings. No assessment was completed to determine the participants' cognitive ability. Future studies should include "inability to walk at all three conditions" as part of exclusion criteria. No energy expenditure, strength, or ROM data were collected, which could have provided more information. In addition, our study employed a two-dimensional underwater motion analysis system that did not allow us to investigate kinematic gait variables in the frontal and transverse planes. It is suggested that future research should utilize three-dimensional gait analysis and waterproof *electromyography* in order to acquire comprehensive perspectives of aquatic treadmill walking at various water depths. No preliminary data were collected on overground treadmill in this study. Future research should consider the use of a baseline measurement of gait kinematics using an overground treadmill to indicate normal kinematics for the group. Lastly, manual digitization had to be used for our underwater motion analysis study, which may have increased the possibility of researcher's errors. Every attempt was made to reduce potential errors such as designation of a single researcher who completed all marker attachments and digitization.

4.1 | Implications for physiotherapy practice

To our knowledge, this is the first study to compare gait kinematics in people with TBI among various water depths. Our results demonstrated that people with TBI alter spatiotemporal and kinematic gait variables as water depth changes. Our findings suggest that walking in neck-depth water may not be ideal for gait training because it appears to limit hip and ankle joint kinematics. It is recommended that waist to chest-depth water be used to provide an accommodating environment for aquatic gait rehabilitation.

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