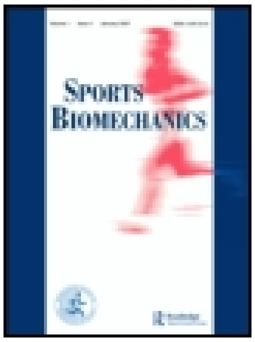

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The influence of water depth on kinematic and spatiotemporal gait parameters during aquatic treadmill walking

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ABSTRACT
The purpose of this study was to investigate kinematic and spatiotemporal variables of aquatic treadmill walking at three different water depths. A total of 15 healthy individuals completed three two-minute walking trials at three different water depths. The aquatic treadmill walking was conducted at waist-depth, chest-depth and neck-depth, while a customised 3-D underwater motion analysis system captured their walking. Each participant's self-selected walking speed at the waist level was used as a reference speed, which was applied to the remaining two test conditions. A repeated measures ANOVA showed statistically significant differences among the three walking conditions in stride length, cadence, peak hip extension, hip range of motion (ROM), peak ankle plantar flexion and ankle ROM (All p values < 0.05). The participants walked with increased stride length and decreased cadence during neck level as compared to waist and chest level. They also showed increased ankle ROM and decreased hip ROM as the water depth rose from waist and chest to the neck level. However, our study found no significant difference between waist and chest level water in all variables. Hydrodynamics, such as buoyancy and drag force, in response to changes in water depths, can affect gait patterns during aquatic treadmill walking.

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Aquatic gait analysis; water immersion; gait biomechanics; joint kinematics

Introduction

Gait training with partial weight bearing (PWB) or an anti-gravity system is widely utilised for rehabilitation of acute injury, post-operation and chronic medical conditions. The general assumption behind this method is that the partial support of patients' body weight during walking will alleviate the level of stress and pain applied on the lower extremity joints (Murray, Hunter, Paper, Kelsey, & Murray, 1993). It can also allow patients to train gait in early rehabilitation when they may have deficiencies in muscle strength, postural control and gait (Hassid, Rose, Commisarow, Guttry, & Dobkin, 1997; McCain et al., 2008). The benefits of gait rehabilitation with PWB have been well documented in various populations including older adults and people with gait impairments (Dodd & Foley, 2007; Kyvelidou,

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Kurz, Ehlers, & Stergiou, 2008; Mao et al., 2015; Miyai et al., 2002; Wilson, Powell, Gorham, & Childers, 2006). The PWB system is often used with an instrumented treadmill, which tends to be costly and not readily available in a typical rehabilitation setting or community fitness centre.

The benefits of PWB can be obtained by walking in water thanks to the unique characteristics of the water properties (Mercer, Applequist, & Masumoto, 2014). Buoyancy of water decreases the vertical ground reaction force and supports body weight, which can eventually reduce the level of pain and stress on the lower extremity joints during walking (Dolbow, Farley, Kim, & Caputo, 2008; Nakazawa, Yano, & Miyashita, 1994). Walking in water offers additional benefits related to hydrostatic pressure, viscosity, water temperature and drag force. The hydrostatic pressure and viscosity provide postural support for individuals with balance and gait impairments (Simmons & Hansen, 1996). Moreover, drag force and viscosity of water can provide an ideal opportunity to perform functional strength training while exercising in water (Mercer et al., 2014). In addition, warm temperature of water (86–94°F or 30–34.4 °C) and lack of a harness can help increase the level of comfort during training in water when compared to PWB gait training overground (Hall, Swinkels, Briddon, & McCabe, 2008; Norman, Pepin, Ladouceur, & Barbeau, 1995). These water properties are generally utilised in rehabilitation settings to benefit not only the older adults but also the populations with various disabilities for their gait training.

Buoyancy is well known to reduce the vertical ground reaction force, which allows less body weight bearing while walking in water (Nakazawa et al., 1994). In addition, manipulating the level of water immersion demonstrated different influence of body weight bearing on the lower joints. It is estimated that 50% of the body weight is supported when water is at the waist level, 70–75% at the chest and 90% at the neck (Koury, 1996). Significant increases in stride length, double limb support time and angular movement in lower extremity joints of healthy adults have been documented when the level of PWB support was set at 50 and 70% compare to 10% (Threlkeld, Cooper, Monger, Craven, & Haupt, 2003). However, limited studies have examined the influence of water depths on biomechanical gait variables.

Aquatic treadmill walking (ATW) demonstrated decrease in cadence when compared to overground treadmill walking (OTW) in healthy adults (Hall, Macdonald, Maddison, & O’Hare, 1998; Masumoto, Shono, Hotta, & Fujishima, 2008; Shono et al., 2007). Previous study reported increased cadence during ATW with horizontal water flow when compared to without horizontal water flow (Masumoto, Hamada, Tomonaga, Kodama, & Hotta, 2012). Young adults showed decreased cadence during ATW as the water depths increased (Pohl & Mcnaughton, 2003). In addition, physiological analysis of ATW at different water depths reported decreased metabolic cost in association with an increase in water depth (Alkurdi, Sadowski, Paul, & Dolny, 2010; Benelli et al., 2014; Gleim & Nicholas, 1989). However, to our knowledge, no study specifically examined the influence of different water depths on kinematic gait variables of ATW. Therefore, the purpose of this study was to investigate spatiotemporal and kinematic gait parameters of ATW at three different water depths in healthy adults. It was hypothesised that the increase of water depth would alter both spatiotemporal and kinematic gait variables of ATW.

Methods

Participants

A total of 15 adults (25–60 years, 9 males/6 females, mean age 37.1 ± 10.9 years) participated in this study. Participant's mean height and mass were as follows: height (170.0 ± 9.6 cm), mass (74.7 ± 16.2 kg). All participants were able to walk without a walking aid, cooperate with the testing procedures and had no surgery within the last six months. Participants were excluded if they had any musculoskeletal injuries, neurological disorders, cardiopulmonary conditions or fear of water. The study was approved by California State University, Northridge Institutional Review Board. Informed consent was obtained from each participant prior to data collection.

Experimental protocol

Aquatic treadmill walking was performed in a university-based aquatic therapy facility. The water temperature was maintained at 34 °C. Participants walked on an aquatic treadmill (AquaGaiter, FERNO, Willington, OH, USA). No horizontal water flow or artificial current was used during the aquatic treadmill walking. The water depths were adjusted to the waist [Anterior superior iliac spine], the chest [Xiphoid process] and the neck [Cervical 7] level by using a movable floor pool (CmbH & Company, Wilhelmshaven, Germany) (Figure 1).

Before data collection, 15 waterproof reflective markers (10 mm in diameter) were attached to the bony landmarks of the lower extremities by using the Helen Hayes lower-limb marker set model (Kadaba, Ramakrishnan, & Wootten, 1990). The markers were attached to the sacrum and bilaterally on the anterior superior iliac spine (ASIS), the midpoint of the lateral femur, the lateral femoral epicondyle, the midpoint of the lateral tibia, the lateral malleolus, the calcaneus and the second metatarsal head.

The 3-D trajectories of the lower-limb motions were captured via six waterproof underwater lenses (60 Hz) connected to six digital video recorders out of the water (Figure 2). The six underwater lenses were positioned 1.5 m away from the aquatic treadmill with approximately 60° of separation among them. A digital music player was used to synchronise video clips from the six cameras with sound.

Participants were asked to change into tight fitting shorts over their swimsuits. They wore the same type of aqua-shoes for all test conditions on the aquatic treadmill. Barefoot walking was not feasible due to the friction generated by the moving treadmill belt. The general

Figure 1. Underwater views of a participant walking at three water depths. Neck level, chest level and waist level from the left.

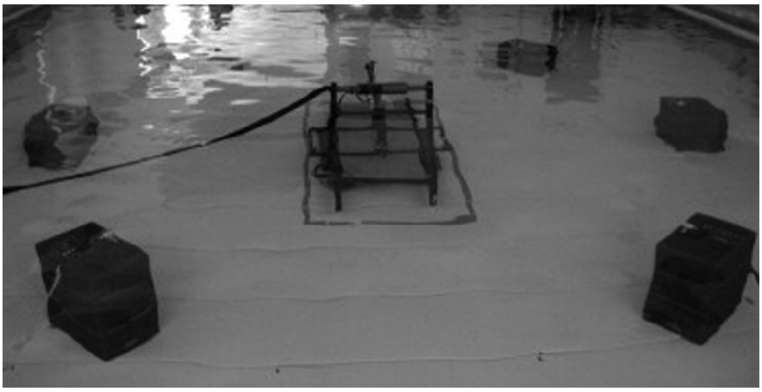

Figure 2. Instrument setting: 3-D underwater motion analysis system and aquatic treadmill in the moveable floor pool.

procedure of this investigation required all participants to walk on the aquatic treadmill at three different water depths in a random order. A five-minute practice trial was given at the waist level of water that allowed them to get familiarised with aquatic treadmill walking. During the practice trial, participants selected their comfortable walking speed, which was applied across all test conditions as a matched walking speed. Participants completed three test trials of two-minute treadmill walking for each test condition. To minimise fatigue, a two-minute rest period was provided after each test trial. All participants were asked to keep their hands on an aquatic parallel bar in order to eliminate propelling movements by using their arms and prevent their arms from interfering with the camera view (AquaSprint, San Louis Obispo, CA, USA, 2005). Previous study reported that eliminated arm movements have no influence on the joint kinematics of the lower limbs during treadmill walking (Stephenson, De Serres, & Lamontagne, 2010).

Biomechanical gait variables were categorised into spatiotemporal and kinematic parameters. Spatiotemporal variables were stride length in metres and cadence (number of steps per minute). Stride length is defined as the distance between two successive foot placements on the same side. Stride length was measured from heel to heel of the same foot. Gait cycle was manually processed based on the visual identification of foot strike (heel contact) for the start of the stride and foot-off (toe-off) for the end of the stride. Kinematic variables included sagittal plane joint kinematics of the low extremity (peak hip flexion/extension, hip range of motion (ROM), peak knee flexion/extension, knee ROM, peak ankle dorsi-/plantar flexion and ankle ROM). Angular reference for all kinematic variables is based on the anatomical position with flexion described in positive direction and extension in negative (For ankle kinematic variables, ankle dorsi-flexion is described as positive direction and ankle plantar flexion is described as negative).

Data acquisition and analysis

Captured data were imported to Vicon Peak Motus software v9.2, digitised and reconstructed for 3-D coordinates. All raw data were low-pass filtered digitally (at 6 Hz) by using a fourth-order 0-lag Butterworth filter. The spatiotemporal and lower-limb kinematic gait parameters were processed and averaged from two full gait cycles at each water depth for data analysis. The spatiotemporal parameters were normalised by using the formula explained by Hof (1996).

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). Repeated measures ANOVA was used to compare gait variables across three test conditions. Dependent variables for this investigation included spatiotemporal and sagittal plane kinematic data in the lower extremities while independent variable was the level of water depths. When ANOVA yielded a significant difference across the conditions, Post hoc comparisons with least significant difference (LSD) were used to identify any significant interactions and mean differences between the specific levels of water depths (waist vs. chest, waist vs. neck and chest vs. neck). All statistical analyses were performed by using SPSS v.22.0 software.

Results

All participants were able to complete the self-selected comfortable walking trials at waist-depth, chest-depth and neck-depth water (mean speed of 0.46 ± 0.13 m/s, 0.46 ± 0.10 m/s and 0.45 ± 0.09 m/s, respectively) without any falls or injuries. Spatiotemporal and joint kinematic variables showed significant differences across three conditions specifically in stride length ($p = 0.009$), cadence ($p = 0.035$), peak hip extension ($p = 0.012$), hip ROM ($p = 0.003$), peak ankle plantar flexion ($p = 0.008$) and ankle ROM ($p = 0.037$). However, no significant differences were found in the sagittal plane knee joint kinematics (Table 1).

Post hoc analysis showed a significant increase in stride length and decrease in cadence as the water depth increased. The participants increased stride length by approximately 9% from the waist to the neck (0.75–0.82 m; $p = 0.007$) and 7% from the chest to the neck (0.76–0.82 m; $p = 0.002$). They decreased cadence by approximately 8% from the waist to the neck (74.26–68.26 steps/min; $p = 0.015$) and 7% from the chest to the neck (73.66–68.26

Table 1. Spatiotemporal and kinematic variables for treadmill walking among three water depth conditions (mean ± SD) and *p* values.

	Water depth			
Variables	Waist	Chest	Neck	*p*
Stride length (m)	0.75 ± 0.12^{c}	0.76 ± 0.12^{c}	0.82 ± 0.12^{a,b}	**0.009**
Cadence (steps/min)	74.26 ± 8.73^{c}	73.66 ± 10.74^{c}	68.26 ± 12.43^{a,b}	**0.035**
Peak hip flexion (°)	23.90 ± 6.02	20.08 ± 5.36	19.81 ± 5.25	0.261
Peak hip extension (°)	2.25 ± 2.29^{c}	0.43 ± 2.24^{c}	4.22 ± 2.27^{a,b}	**0.012**
Hip ROM (°)	21.65 ± 4.24^{c}	19.65 ± 3.19^{c}	15.59 ± 3.30^{a,b}	**0.003**
Peak knee flexion (°)	70.37 ± 5.24	69.65 ± 7.26	67.76 ± 8.97	0.463
Peak knee extension (°)	11.10 ± 5.15	9.99 ± 5.55	10.10 ± 4.96	0.290
Knee ROM (°)	59.27 ± 4.32	59.66 ± 6.32	57.66 ± 9.25	0.686
Peak ankle dorsi-flexion (°)	8.76 ± 6.74	6.29 ± 4.46	0.83 ± 4.83	0.758
Peak ankle plantar flexion (°)	−29.90 ± 5.76^{c}	−32.20 ± 6.05^{c}	−44.33 ± 5.90^{a,b}	**0.008**
Ankle ROM (°)	38.66 ± 5.72^{c}	38.49 ± 4.04^{c}	45.16 ± 4.50^{a,b}	**0.037**

Notes: SD = standard deviation; ROM = range of motion.
p values are bold when significant.
[a] Significantly different than waist ($p < 0.05$).
[b] Significantly different than chest ($p < 0.05$).
[c] Significantly different than neck ($p < 0.05$).

steps/min; $p = 0.009$). However, no significant differences in spatiotemporal variables were found between the waist and the chest levels.

In regard to kinematic changes, the participants significantly decreased peak angle of hip extension and ROM as the water depth increased. Hip ROM decreased by approximately 28% from the waist to the neck (21.65°–15.59°; $p = 0.001$) and 21% from the chest to the neck (19.65°–15.59°; $p = 0.001$) (Figure 3). In addition, ankle ROM increased by 14% from the waist to the neck level (38.66°–45.16°; $p = 0.015$) and by 15% from the chest to the neck level (38.49°–45.16°; $p = 0.015$) (Figure 4). There was no significant difference in kinematic variables between the waist and the chest level.

Discussion and implications

The aim of this study was to investigate biomechanical gait variables during ATW among three different water depths in healthy individuals. Spatiotemporal and joint kinematic variables were analysed to compare gait parameters across three water depths: waist, chest and neck levels.

Our results showed that there were significant differences in spatiotemporal gait variables during ATW among three water depths. The participants demonstrated increased stride length and decreased cadence when the water became deeper to the neck level from the waist or the chest levels. However, spatiotemporal variables did not show significant changes from waist to chest level.

Our findings in spatiotemporal gait variables can be explained in association with the properties of water. The effect of increased buoyancy may have contributed to longer stride length as water became deeper. The increased buoyancy at the neck level provide greater weight support, which appears to enhance dynamic balance allowing participants to have longer single-leg stance time (Baezner et al., 2008). The increase in single-leg stance time helped participants have a longer swing time and an increased step length on the

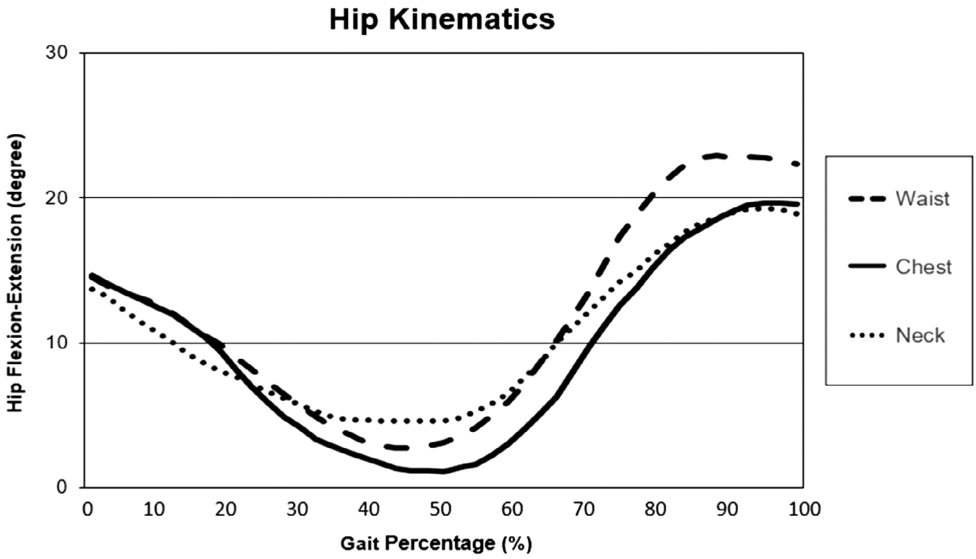

Figure 3. Hip kinematics during aquatic treadmill walking among three water depths.

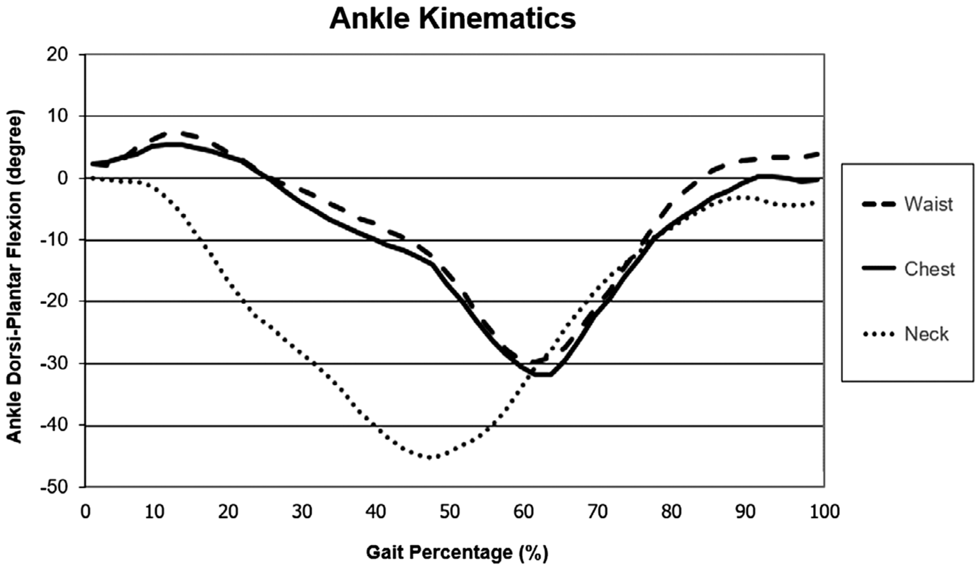

Figure 4. Ankle kinematics during aquatic treadmill walking among three water depths.

contralateral leg. As a result, participants demonstrated longer stride length while walking on the aquatic treadmill at neck level water depth. The significant increase in stride length might have affected our findings of decreased cadence. At a constant speed, stride length and cadence are inversely related (Nilsson, Thorstensson, & Halbertsma, 1985; Nilsson & Thorstensson, 1987; Zijlstra & Hof, 2003). Our participants showed significantly decreased cadence when the water depth became deeper to the neck level. The participants seemed to have difficulty in making frequent steps while propelling their limbs against the water resistance in neck-depth water.

The results are consistent with previous studies which examined the influence of PWB on spatiotemporal gait variables during OTW. It was documented that there was a significant decrease in cadence and increase in stride length when body weight support increased from 10 to 50 and 70% during body weight support treadmill walking in healthy individuals (Threlkeld et al., 2003). As the water depth increased, body weight support increased accordingly. Approximately 50% of body weight is supported at waist level, 70–75% at chest level and 90% at neck level (Koury, 1996; Driver, O'connor, Lox, & Rees, 2004). Moreover, ATW study has revealed that increased level of water immersion showed decrease in cadence, possibly due to the increased duration of the gait cycle which might have been affected by drag force of water (Hall et al., 1998). An increase in step length was reported during the ATW as well as a progressive decrease in cadence (Benelli et al., 2014). However, a previous study by Pohl and Mcnaughton (2003) found that cadence was similar among land-based, thigh-deep and waist-deep walking conditions. A possible explanation for the inconsistent findings is that our study immersed the participants in a deeper water level which provides increased water resistance on the surface of the body.

Our findings showed significant changes in kinematic gait variables during ATW at different water depths. Hip and ankle joints demonstrated significant alterations as the water depth increased, whereas the knee joint did not seem to be affected much. Increased peak ankle plantar flexion and ROM were identified as the water level became deeper to neck level from chest and waist level. The increased buoyancy at neck level water depth supported participant's body weight substantially and made it difficult to plant their heels down. The visual assessment and kinematic analysis confirmed that participants did not have a clear heel strike during the early stance phase and walked on their toes throughout the stance phase. The belt of the treadmill seemed to drag their foot backward at the toe-off phase contributing to an increase of peak plantar flexion. In addition, as transitioning to the swing phase of gait cycle, the drag force and water resistance appeared to force the ankle joints further into plantar-flexed position resulting in a significant increase of peak plantar flexion. This increase of peak plantar flexion eventually affected the increase of ankle ROM.

The participants demonstrated significantly decreased hip ROM at the neck level of water compare to chest and waist level. This decreased hip ROM as a result of elevated water depth can be explained by the effects of increased buoyancy and water resistance. From the mid-stance to late stance, decrease of peak hip extension was detected. Increased water resistance made it difficult to transfer the weight over the base of support defined by the standing foot. In addition, increased up-thrust force due to buoyancy might have interfered with the body weight transfer during this particular phase of gait cycle when peak hip extension is typically observed. The significant decrease in the peak hip extension contributed to the decreased hip joint ROM.

The absence of significant changes in knee kinematics during the stance phase can be explained with the findings from previous research. The function of the knee joint movement during aquatic walking has been identified to be absorption of impact force during the gait cycle (Miyoshi, Shirota, Yamamoto, Nakazawa, & Akai, 2005). This functional role of knee joint explains why there were no significant changes found in knee kinematics in the present study. The changes in water depth do not appear to affect the role of the knee joint as a shock absorber at the foot strike. Moreover, during the swing phase, participants did not seem to have much difficulty in propelling the shank below the knee joint through increased water resistance as the water depth increased. The surface area of the shank is relatively smaller and streamlined as compared to the thigh, which could have contributed to minimal to no changes in the knee kinematics.

It is difficult to relate our findings to previous literature as no study investigated the influence of different water depths on kinematic gait variables. However, our results in kinematic variables are somewhat consistent with previous research which examined the influence of PWB on kinematic gait variables during OTW. Threlkeld et al. (2003) reported decreased hip ROM and increased ankle ROM/plantar flexion during the swing phase as greater PWB support was applied. The research group also reported significant changes in the knee kinematics as higher PWB support level was applied whereas our result showed no significant differences on knee kinematic. However, this inconsistent finding in the knee kinematic appears to be associated with environmental differences. Change of water depths does not only affects the level of PWB, but also alters the influence of water properties and hydrodynamics, such as water resistance, turbulence and drag force, on gait pattern during aquatic walking.

Future research is warranted to address some of our study limitations and additional questions. The present study used an aquatic treadmill to compare biomechanical gait variables at different water depths. However, aquatic treadmills are expensive and not readily available in community pool settings. Future studies should consider using pool floor walking to compare gait variables at different water depths. Secondly, our study analysed biomechanical gait differences at various water depths. Further investigation on physiological differences will help us obtain comprehensive understanding of gait mechanics and economy in response to various water depths. Moreover, the current study investigated changes in gait biomechanics only above the waist level. However, it would be interesting to compare any differences at the water level below the waist, such as thigh-depth or knee-depth. The present study used a video-based motion analysis system which required manual digitisation. Every effort was made to minimise errors and increase intra-rater repeatability. However, there must have been embedded human errors by using manual digitisation of underwater video footages. Our findings in gait kinematics might have been affected by the use of aquatic parallel bar. It was mostly used for comfort and safety during treadmill walking. Additionally, it was reported that the use of handrail has minimal to no influence on joint kinematics of the lower limbs during treadmill ambulation (Stephenson et al., 2010). Lastly, it should be rather clinically meaningful and relevant to examine the influence of water depths on gait biomechanics of people with mobility impairment.

Conclusion

Healthy adults demonstrated significant differences in gait biomechanics while walking on an aquatic treadmill at different water depths. We found that they walked with longer stride length, decreased cadence, greater ankle ROM and less hip ROM as the water depth increased from the waist to the neck levels, as well as from the chest to the neck levels. However, it is interesting to note that no difference in gait parameters were found between the waist and the chest levels. In addition, our kinematic results indicate that hip and ankle joint kinematics can be influenced by the change of water depth while the knee joint does not. Hydrodynamics, such as buoyancy and drag force, in response to the water depth change, appears to be one of the main factors for these differences. It is suggested that professionals in aquatic therapy and rehabilitation should consider our findings when determining appropriate pool depths for program participants. In particular, older adults have been documented to show shorter stride length and limited ankle kinematics during gait (Arnold, Mackintosh, Jones, & Thewlis, 2014; Judge, Davis, & Ounpuu, 1996). Our findings suggest that neck or chest depth of water is recommended for aquatic exercise and gait training of geriatric population in order to facilitate proper ankle movement and stride length.

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Disclosure statement

The authors declare that they have no financial conflicts of interest.

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