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ORIGINAL RESEARCH

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The Effect of Water Walking on the Lower Limb Motion of Older Adults

Adriana M. Degani and Alessander Danna-dos-Santos

The authors investigated the lower limb movements of older adults walking at their preferred speed in shallow water to obtain information to help professionals prescribe exercises in a pool. The 8 participants presented (a) similar hip and thigh motions in water and on land, although a reduced thigh velocity was observed in the water; (b) increased knee flexion at the beginning of the walking cycle and reduced knee extension throughout the walking cycle in water; (c) reduced ankle motion throughout the walking cycle and plantar flexion during the swing phase in water; (d) reduced shank motion and velocity in water; and (e) different intralimb coordination resulting from a different relative phase between the shank and thigh segments. These results support the use of water as an environment for gait training in older adults. Water resistance and buoyancy seem to be the major forces to overcome when walking in shallow water, so the authors suggest paying special attention to immersion level and movement velocity when prescribing aquatic exercises.

Key Words: gait, biomechanics, lower limb coordination, range of motion, aquatic exercise, adapted aquatics

Regular physical activity can enhance physical adaptability, mobility, balance, and coordination in older adults, all of which contribute to an enriched life in old age. Many older adults are not able to exercise easily or safely on land. As a result, they limit their daily activities because of the fear of possible injury, and the consequent deconditioning and reduced fitness can progressively limit their functional mobility and social independence. The normal aging effect often is observed, for example, on the walking gait. The slower and shortened walking patterns often demonstrated by older adults have been related to regressive changes in their balance, range of motion, joint moments, response-execution time, muscle strength, and motor control (Kerrigan, Todd, DellaCroce, Lipsitz, & Collins, 1998; Nigg, Fisher, & Ronsky, 1994; Patla et al., 1993; Polcyn, Lipsitz, Kerrigan, & Collins, 1998; Prince, Corriveau, Hérbert, & Winter, 1997; Winter, Patla, Frank, & Walt, 1990).

Although land exercises are helpful for preventing or reducing age-related changes in gait function (DiBenedetto et al., 2005), the exercises can be difficult or uncomfortable for older adults. Aquatic exercises such as gait training are rec-

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ommended as a physical activity to either maintain or improve cardiorespiratory fitness, muscle strength, range of motion, balance, and motor control for older adults (Chu et al., 2004; Douris et al., 2003; Fujishima & Shimizu, 2003; Hansen, 1996; Heyneman & Premo, 1992; Lord, Mitchell, & Williams, 1993; Ruoti, Marsden, & Thompson, 1994; Shono, Fujishima, Hotta, Ogaki, & Masumoto, 2001; Simmons & Hansen, 1996). Walking in water is influenced by the mechanical properties of the immersion, such as buoyancy, water resistance, hydrostatic pressure, turbulence, and viscosity (Degani, 1998; Ruoti, Morris, & Cole, 1997). These properties can facilitate, support, or resist limb movement depending on the direction and speed of the movement. In general, the body's immersion in water reduces the weight-bearing forces, thus reducing friction between joint surfaces, allowing a larger range of movement without excessive strain, increasing the resistance against limb movements, challenging upright balance, changing the patterns of muscle activation, changing the cardiovascular responses, and providing different somatosensory information (Broman et al., 2006; Geigle, Cheek, Hunt, & Shafiq, 1997; Harrison & Bulstrode, 1987; Harrison, Hillman, & Bulstrode, 1992; Masumoto, Takasugi, Hotta, Fujishima, & Iwamoto, 2004; Miyoshi, Nakazawa, Tanizaki, Sato, & Akai, 2006; Ruoti et al., 1997; Yano, Nakazawa, & Yamamoto, 1995).

Older adults present a slower gait, slower cadence, and smaller stride length but a similar percentage of the walking cycle for both stance and swing phases (40% and 60% on average, respectively) in shallow water compared with walking on land (Degani & Danna-dos-Santos, 2006). The reduced walking velocity has also been described for young adults as being caused by the water's resistance to moving the body forward (Newman, Alexander, & Webbon, 1994; Wickman, & Luna, 1996).

Another parameter that characterizes the human gait is the lower limb coordination pattern, which one can describe as the mobility of the joints and segments in a complete walking cycle. Although there is a lack of information about joint mobility for older adults walking in water, some researchers have studied young adults. One study (Yamamoto, Nakazawa, & Yano, 1995) compared the range of the lower limb joint motion during the stance phase for adults walking on land and at different speeds (normal, fast, and slow) in a pool (1.20-m depth). The range of the knee and ankle motion for the fast speed condition in water was different from that used on land, whereas the hip-joint motion was similar among all conditions. The main difference occurred at the moment of foot strike, when knee flexion and ankle flexion occurred in water as compared with walking on land. A larger range of ankle motion during the stance phase also was reported for adults walking in water than when walking on land (Gehm, Becker, Martinez, & Loss, 2003). Another study, performed in a water depth adjusted for each participant's height to reduce body weight by 80%, revealed a smaller range of knee motion in water and a similar range of hip and ankle motion for both environments (Miyoshi, Shirota, Yamamoto, Nakazawa, & Akai, 2004). For all three joints, a lower moment throughout the stance phase in water was reported than when walking on land. The differences among studies can be explained by the different water depths and walking velocities used.

Considering the gait changes expected because of normal aging, as well as the popularity of gait training in water, specific studies are needed to clarify where the movement pattern alters when individuals walk while partially immersed. The purpose of the present study was to investigate the effect of shallow-water walking on the lower limb movement-coordination patterns for older adults to help professionals prescribe more appropriate aquatic exercises.

Methods

Participants

Eight older adults (mean age 62.5 years, mean height 1.67 m) with no musculoskeletal or neurological impairment participated in this study. All procedures were explained to the participants, and each provided written informed consent before data collection. Participants were asked to be barefoot and to wear swimming suits for the testing.

Procedure

Four reflective markers (1 cm in diameter) were placed on specific anatomical marks on the right lower limb: the fifth metatarsophalangeal joint, the lateral malleolus at the ankle, the lateral surface of the knee joint, and the greater trochanter at the hip. Four black markers (1 cm in diameter) were placed on top of the reflective markers before filming the participants in the swimming pool because the reflective markers did not present a good contrast for digitizing the data collected underwater.

Data collection consisted of filming the participants as they walked forward on a walkway on land and as they walked forward in a pool (1.10-m depth). According to the mean height of the participants, the water depth selected corresponded, approximately, to a partial immersion at the xiphoid-process (sternal) level. Aquatic exercises usually use this water depth, and it corresponds to 28% and 35% of land weight-bearing force for women and men, respectively, in a quiet standing posture (Harrison & Bulstrode, 1987). It is important to remember that the percentage of weight bearing increases when walking in water over that of quiet standing in water (Harrison et al., 1992; Roesler, Haupenthal, Schütz, & Souza, 2006).

A camcorder (Gradiente GCP-165CR, 1/2000 shutter speed) with 60 Hz of frequency was used to videotape the right side of all participants walking at their preferred speed in the two conditions: walking on land (WL) and walking in shallow water (WW). The videotaping protocol for both conditions was identical except that the camcorder was situated in a waterproof filming box fixed to a table for the WW trials. A period of familiarization was provided for participants before data collection, during which they walked for a few minutes as “naturally” as possible. After the familiarization period, each participant performed 10 trials for each condition. They walked at their preferred speed, with resting periods of 15 s between trials to prevent fatigue. All participants performed the 10 trials of the walking task on land first and then the 10 trials in the pool. We thought that there would be no effect of condition order because of the well-learned nature of the walking task.

Data Processing

For each trial, MGI VideoWave SE Plus software (version 1.5) captured a complete walking cycle at 30 Hz. As standardized, the period between two consecutive ipsilateral foot strikes defined a complete walking cycle. The first ipsilateral foot strike will be referred as time zero ($t_0 = 0$), and it was used to align all walking cycles. The four markers were digitized using the Ariel Performance Analysis System (APAS, version 1.4) and transformed into x and y coordinates for each frame. These coordinates were filtered at 4 Hz by a low-pass, fourth-order, zero-lag Butterworth digital filter.

Throughout all trials, the relative and apparent angles of the right lower limb in a complete walking cycle were defined as shown in Figure 1. The variables of interest were grouped into three categories: the joint displacement, the lower limb segment displacement, and the intralimb coordination pattern.

The joint-displacement category analyzed the relative angles among the lower limbs' segments in the sagittal plane (Figure 1). The hip, knee, and ankle angles were computed for each walking cycle as the angle between the thigh and vertical axis, the thigh and shank, and the shank and foot, respectively. For each joint, the maximum and minimum angles were selected, the total range of motion was computed, and the joint angle at specific moments of the walking cycle was selected.

The apparent angles of the shank and thigh for each walking cycle described the movement of the lower limb segments. The shank and thigh angular positions were defined as the angle between the horizontal axis and the shank and thigh segments, respectively (Figure 1). The range of the angular position and the angular-velocity peak were computed for both shank and thigh segments (Winstein & Garfinkel, 1989). The difference between the maximum and minimum angular positions in a walking cycle defined the range of the angular position, and the average between the absolute values of the maximum and minimum angular velocities defined the angular-velocity peak.

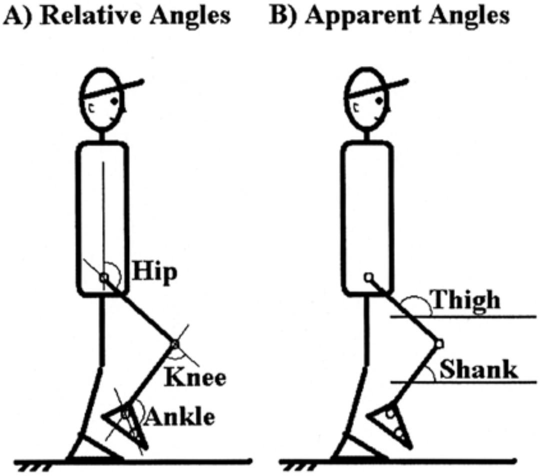
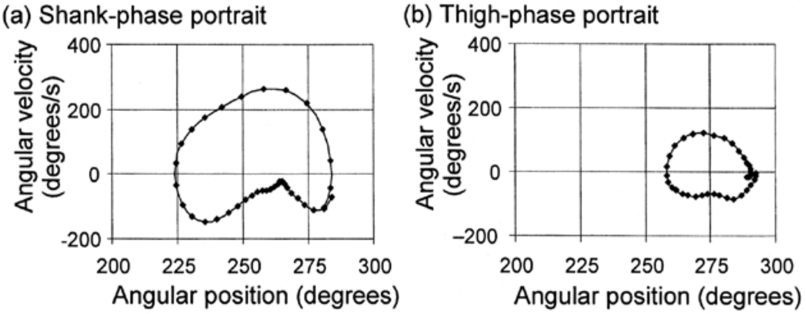


Figure 1 — An illustrative representation of the position of the four markers (fifth metatarsophalangeal joint, lateral malleolus at the ankle, lateral surface of the knee joint, and greater trochanter at the hip) on the right side of a participant.

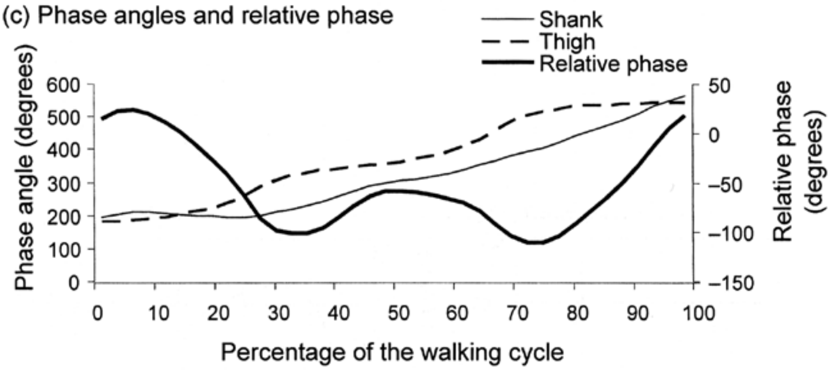
The relative phase (RP) between the shank and thigh segments for each walking cycle characterized the intralimb coordination pattern. In order to compute the RP, phase portraits and phase angles for both shank and thigh segments were calculated (Clark, Truly, & Phillips, 1990; Kelso, Saltzman, & Tuller, 1986). The phase portrait is a graphical representation of the segment's motion as a function of time. It was obtained by plotting the angular position on the *x* axis and the angular velocity on the *y* axis. The normalized phase portrait from –1 to +1 was transformed into equivalent polar coordinates, creating the phase angle: Phase angle = $\tan^{-1}(x/y)$. Finally, the RP was computed as the difference between the shank- and thigh-phase angles. Figure 2 illustrates the phase portrait, phase angle, and RP in a representative participant walking on land.

The maximum, minimum, and amplitude of the RP for each walking cycle were computed. The RP values at specific moments, such as the walking events (ipsilateral foot strike, contralateral toe-off, contralateral foot strike, and ipsilateral toe-off) and the joint reversals, were selected. These reversals were defined by peaks and valleys identified along the RP trajectory as R1, R2, R3, and R4, respectively.



(a) Shank-phase portrait

(b) Thigh-phase portrait



(c) Phase angles and relative phase

Figure 2 — Phase portraits, phase angles, and relative phase of the lower limbs' segments in an individual trial of a representative participant walking on land. Panels (a) and (b) show the shank- and thigh-phase portraits, respectively. Panel (c) shows the shank- and thigh-phase angles and the relative phase between the shank and thigh.

Data Analysis

The relative and apparent angles and the RP between the shank and thigh as time series were normalized to a percentage of the total cycle time. Descriptive statistics, such as the average and standard error, were computed for all variables. Student's *t* tests for similar samples were used to compare WL and WW. In all analyses, the MINITAB Student program (version 14) was used, and the level of significance was set at $p < .01$ to control for a potentially inflated experimentwise Type 1 error rate.

Results

All participants accomplished the task of preferred speed in WW. They compensated for the aging factor and the challenge of the hydrodynamic properties by changing some of their walking parameters. In general, the sequence of the joint motion during WW was similar to that used in WL. The hip moved from a flexed to an extended position and then to a flexed position again. The knee began flexed, realized a small extension, flexed again, and extended at the end of the walking cycle. The ankle dorsiflexed, followed by plantar flexion and another dorsiflexion. Figure 3 shows the hip-, knee-, and ankle-angle displacements as time series for older adults' WL and WW as an average across all participants.

Walking in water had no significant effect on hip movement for the participants (Figure 3). The means and standard errors for the amplitude of hip motion in a complete walking cycle were 34.2° ± 2.7° and 37.1° ± 2.3° for WW and WL, respectively. The hip began the walking cycle flexed (19.5° ± 0.8° and 23.2° ± 2.0° for WW and WL, respectively). During the stance phase, the hip joint moved from a flexed to an extended position. The neutral hip position (0°) was achieved at about the moment of the contralateral foot strike for both WW and WL. The hip achieved its maximum extension (–9.7° ± 1.7° and –13.9° ± 3.0° for WW and WL, respectively) at the beginning of the swing phase and then moved from an extended to a flexed position. The maximum hip flexion during the swing phase was 23.6° ± 3.0° and 17.6° ± 2.1° for WW and WL, respectively. The *t* tests conducted confirmed similar hip motion for older adults in WW and WL ($p > .01$).

The range of knee motion and maximum knee flexion in a complete walking cycle in water presented values similar to those during WL (Figure 3). There was a total range of motion of 47.4° ± 3.9° and 49.7° ± 1.4° for WW and WL, respectively, and a maximum knee flexion of 56.6° ± 3.7° and 54.3° ± 2.0° for WW and WL, respectively. The knee, however, initiated the walking cycle more flexed in water (19.3° ± 2.7° and 9.3° ± 1.8° for WW and WL, respectively). The knee presented a smaller extension throughout the walking cycle (9.2° ± 1.8° and 4.6° ± 1.7° for WW and WL, respectively) and an larger flexion at the end of the swing phase (17.8° ± 2.5° and 5.1° ± 1.7° for WW and WL, respectively) in water than on land. These results were confirmed through *t* tests, which indicated differences between WW and WL conditions for the knee angle at the moment of the ipsilateral foot strike ($p < .01$), minimum knee angle ($p < .01$), and minimum knee angle during the second half of the swing phase ($p < .002$).

The ankle joint presented an overall smaller range of motion (15.4° ± 1.6° and 24.4° ± 1.8° for WW and WL, respectively) and a smaller plantar flexion during

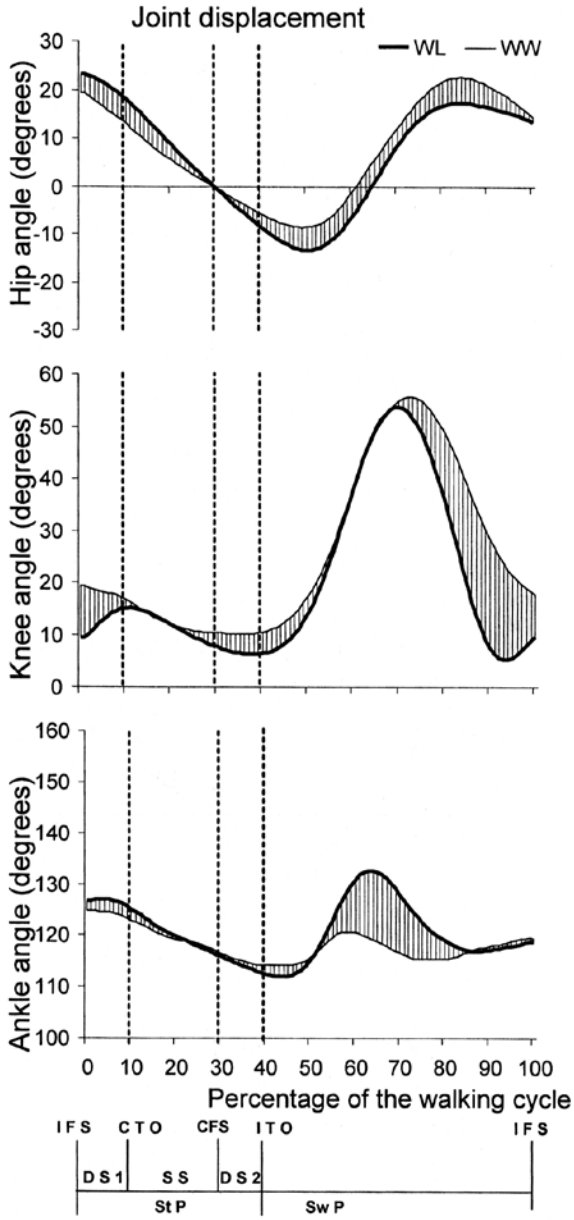


Figure 3 — Average across participants of the hip-, knee-, and ankle-angle displacements as time series in a complete walking cycle for older adults walking on land (WL) and in shallow water (WW). IFS = ipsilateral foot strike; CTO = contralateral toe-off; CFS = contralateral foot strike; ITO = ipsilateral toe-off; DS1 = first double support; SS = single support; DS2 = second double support; StP = stance phase; SwP = swing phase.

the swing phase (123.2° ± 2.5° and 133.4° ± 1.8° for WW and WL, respectively) in WW than in WL. Figure 3 shows the ankle displacement as a time series. Results of *t* tests confirmed the differences between WW and WL conditions for ankle range of motion ($p < .004$) and maximum angle during the swing phase of the walking cycle ($p < .007$).

The thigh and shank segments' motion presented some differences between WW and WL conditions (Figure 4). Despite no significant effect of water for the range of thigh motion (35° ± 3° and 38° ± 2° for WW and WL, respectively), the range of shank motion decreased in water as compared with WL (47° ± 3° and 66° ± 2°, respectively). For both segments, the velocity peak decreased in water (13°/s ± 2°/s and 11°/s ± 5°/s for the thigh and shank, respectively) as compared with WL (30°/s ± 4°/s and 80°/s ± 6°/s for the thigh and shank, respectively). These results were confirmed by *t* tests ($p < .001$).

The intralimb coordination represented by the RP is illustrated in Figure 5. The positive values mean larger phase angle (PhA) for the shank than for the thigh, and the negative values mean the opposite. The reversals along the RP trajectory represented by valleys and peaks mean that the difference between the shank and thigh PhAs increased and decreased, respectively. Older adults presented two peaks and two valleys for both WW and WL conditions. The first and second joint reversals (R1 and R2) occurred at the beginning and end, respectively, of the stance phase, and the third and fourth joint reversals (R3 and R4) occurred during the swing phase.

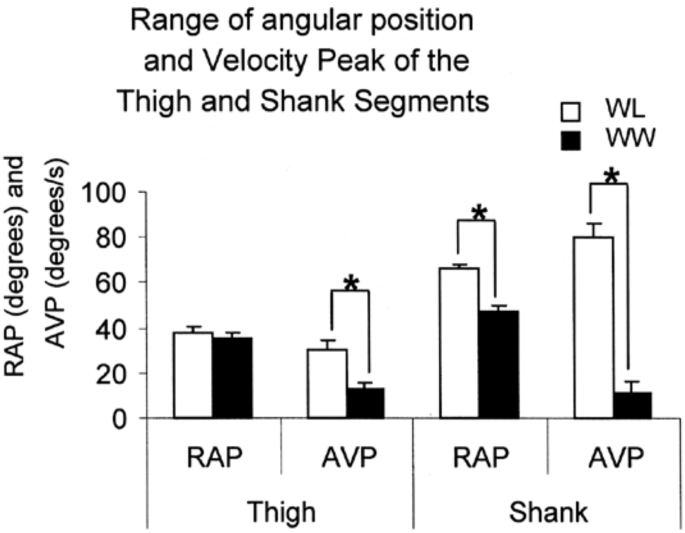


Figure 4 — Average across participants and standard-error bars of the range of angular position (RAP) and the angular velocity peak (AVP) for the thigh and shank segments in a complete walking cycle for older adults walking on land (WL) and in shallow water (WW). *$p < .01$ due to *t* test for similar samples.

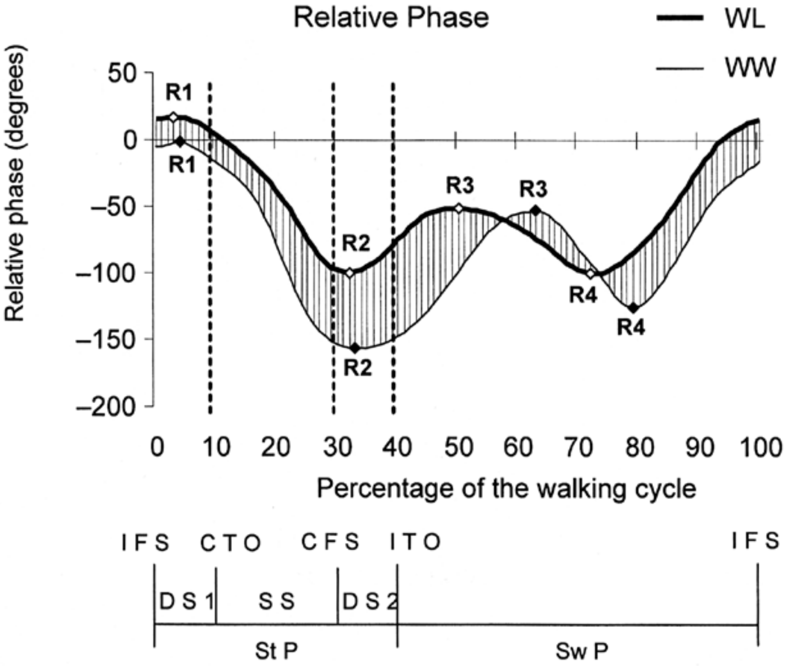


Figure 5 — Average across participants of the relative phase between the shank and thigh segments as time series in a complete walking cycle for older adults walking on land (WL) and in shallow water (WW). IFS = ipsilateral foot strike; CTO = contralateral toe-off; CFS = contralateral foot strike; ITO = ipsilateral toe-off; DS1 = first double support; SS = single support; DS2 = second double support; StP = stance phase; SwP = swing phase. R1, R2, R3, and R4 stand for the four reversals in the relative-phase trajectory.

As shown in Figure 5, the beginning of the walking cycle showed a smaller RP for the WW condition (–5.3° ± 1.7° and 15.1° ± 1.7° for WW and WL, respectively). This occurred because the shank PhA was smaller than the thigh PhA in water, whereas the opposite was true on land. In addition, the difference between the shank and thigh PhAs was larger in water than during WL. During the rest of the stance phase, the shank PhA was smaller than the thigh PhA for both WL and WW. The difference between the shank and thigh PhAs was larger in WW than in WL. It can be observed (see Figure 5) that there was a smaller RP at the R2 moment in water (–159.1° ± 2.1° and –102.2° ± 2.9° for WW and WL, respectively). Note that the first and second reversals happened at the same time in a walking cycle for both WW and WL (3.6% ± 0.5% and 33.0% ± 1.0% for the R1 and R2 moments in water and 3.0% ± 0.4% and 32.6% ± 0.7% for the R1 and R2 moments on land, respectively).

During the swing phase, the difference between the PhAs for the shank and thigh decreased, increased, and decreased again for both WW and WL conditions (Figure 5). Despite similar relationships between the shank and thigh PhAs at the moment of the third reversal (–43.5° ± 5.6° and –48.2° ± 3.0° for WW and WL, respectively), R3 happened later in water than on land (64.9% ± 1.9% and 49.8% ± 1.3%, respectively). At the end of the walking cycle, a fourth reversal occurred. The difference between the PhAs of the shank and thigh during the swing phase was larger, and it happened later in water than in the WL condition. It can be observed by the RP at the R4 moment (–131.6° ± 4.8° and –101.7° ± 4.2° for WW and WL, respectively) and by the moment of the R4 in a walking cycle (79.0% ± 1.1% and 73.1% ± 0.6% for WW and WL, respectively).

Furthermore, the total amplitude (minimum value subtracted from the maximum value) of the RP was larger in water (158.7° ± 3.5° and 126.0° ± 4.2° for WW and WL, respectively). The RP results were confirmed by *t* tests, indicating differences between WW and WL conditions for the RP at the R1, R2, and R4 moments ($p < .001$); the moments of R3 and R4 in a walking cycle ($p < .002$); the RP at the moment of the walking events ($p < .002$); and minimum, maximum, and range values of the RP ($p < .001$).

Discussion

Despite hydrodynamic properties and the normal aging effects, all of our older adult participants were able to walk in shallow water by changing some walking parameters they used on land. In general, the sequence of the lower limb movements in the sagittal plane was roughly similar for the WW and WL conditions. These similarities do not mean that either the muscle activation or the joint positions were the same. Some studies have described these different muscle activities and joint displacements for young adults for water- and land-walking tasks (Masumoto et al., 2004; Miyoshi et al., 2006, 2004; Yano et al., 1995).

Older adults appear to modify some joint parameters to adapt their gait in water. The knee began the walking cycle more flexed in water and did not extend as much throughout the walking cycle as it did on land. We suggest that the smaller weight-bearing forces in water resulting from upward buoyancy decreased the load for the lower limbs, and the knee did not have to extend as it does on land. The ankle also adapted to the water's properties. The ankle joint decreased its range of motion and presented a smaller plantar flexion during the swing phase. The ankle changes seemed to be related to both reduced ground-reaction force (vertical component) and water resistance (Miyoshi et al., 2004; Nakazawa, Yano, & Myashita, 1994; Roesler et al., 2006; Yamamoto et al., 1995). The smaller apparent corporal weight in water reduces the ground-reaction force at the moment of toe-off to move the body forward. Because there is no need for a larger plantar flexion to produce forward impulse, the ankle joint can reduce its range of motion. In addition, the drag force tends to keep the ankle plantar flexed throughout the swing phase. The dorsiflexion observed in water during the swing phase, however, seemed to be an adaptation to avoid dragging the foot on the bottom of the pool. This dorsiflexion is not necessary on land, because the knee of the contralateral leg is more extended, the leg weight is higher, and the dorsiflexion on land is only the minimum required to avoid dragging the foot on the ground.

The water resistance against the thigh moving forward during the swing phase was not enough to change the thigh segment's motion, although the thigh-velocity peak was lower in water than on land. This slower motion in water seems not to be related to aging because the reduced velocity of movement in water is documented across all ages (Degani & Danna-dos-Santos, 2006; Newman et al., 1994; Wickman & Luna, 1996). Furthermore, both shank displacement and velocity were influenced by water properties. The range of the shank motion and its velocity were lower in water than on land, as would be expected. The smaller range of shank motion can be attributed not only to the water resistance but also to the shorter stride length in water (Degani & Danna-dos-Santos).

Because the parameters of thigh and shank motion appear to modify in water, we also expected the RP between the thigh and shank to be influenced by the water's properties. These two segments changed their coordinative organization to move the body forward in water. The participants initiated the gait cycle on land with the shank moving in its position and velocity trajectory ahead of the thigh; they changed to the thigh being ahead after the contralateral toe-off and just passing the shank ahead of the thigh again at the end of the cycle. Nevertheless, the participants walked in water with the thigh moving through its phase trajectory ahead of the shank throughout the entire cycle.

The participants showed four reversals throughout the RP trajectory for both WW and WL. The RP at the moment of some reversals and their moments in water differed somewhat from WL. In addition, there was a larger difference between the shank and thigh PhAs in WW than in WL. Interjoint coordination also changed for young adults when walking in water (Miyoshi, Shirota, Yamamoto, Nakazawa, & Akai, 2005).

The results of this study suggest that changes in lower limb coordination for older adults seem to be more related to water properties than to aging, because similar results were found in studies comparing young adults walking on land and in shallow water (Miyoshi et al., 2005; Newman et al., 1994; Yamamoto et al., 1995; Yano et al., 1995). The reduced weight, ground-reaction forces in the vertical axis, movement velocity, and stride length resulting from hydrodynamic properties seem to evoke gait adaptations such as reduced ankle motion and knee extension, reduced shank motion, reduced shank and thigh velocities, and different relationships between shank and thigh movement.

Because water resistance and buoyancy both seem to be the major forces to overcome when older adults walk in shallow water, we suggest that special attention be given to the immersion level and movement velocity during exercise in water. Different levels of immersion and different movement velocities can challenge older adults in terms of upright balance, movement resistance, somatosensory information, and postural control. The ideal level of immersion and exercise velocity will depend on the goal of the exercise.

Based on these findings, we support using water as an alternative exercise environment for older adults, especially when they exercise at their own preferred pace and degree of rigor. Findings from the present study might be helpful for professionals who wish to prescribe activities in the pool.

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