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Features of Acceleration and Angular Velocity Using Thigh IMUs during Walking in Water

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Cover Page Footnote

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Abstract

Ten participants were assessed while walking in water and on land with wearable inertial measurement units (IMUs) attached to the right thigh. Longitudinal acceleration, anterior-posterior acceleration, and frontal axis angular velocity were measured at 100 Hz, matched with video analysis sampled at 25 Hz during the walking trials. The longitudinal acceleration showed almost 1 g from initial heel contact to 70% of one cycle, and the anterior-posterior acceleration showed a sinusoidal pattern, synchronizing the approximate posture of the thigh in water. The frontal axis angular velocity fluctuated less while walking in water compared with on land, because thigh motion speed was slower in water than on land. The acceleration and angular velocity in water were stable and did not fluctuate. Walking exercises in water may be effective in individuals with knee- or thigh-related medical issues.

Keywords: gait, immersion, health promotion, exercise therapy, underwater, wearable inertial sensor

Introduction

Walking is the most fundamental mode of locomotion for humans. Current research has revealed the mechanics of walking in children, elderly, and disabled persons (Gil-Agudo et al., 2013; Grabiner et al., 2001; Shultz et al., 2010). The most common method for investigating mechanics of walking is by using a motion analysis system and infrared cameras (Lee et al., 2013). This technique is highly reliable, produces minimal error about the target point, and captures human motion in almost real time. Although this system has merits for investigating human motion, the measurement environment is restricted to the capture area and the system is very expensive (Mayagoitia et al., 2002). In addition, the small zone of capture of such a system limits the analysis of walking to the participant using a treadmill machine or using a small number of cycles (Lee et al., 2010). Research has reported differences between walking over ground and treadmill walking (Lee & Hidler, 2008). As such, a motion monitoring system not limited by a small capture area is needed for measuring multiple cycles of walking.

Currently, wearable inertial measurement units (IMUs) containing an accelerometer, gyroscope, and magnetometer have been used for monitoring and evaluating human motion. The IMUs are portable, being small and light in weight. This technology enables the measurement of human movement without the restricted capture area due to the wireless connection and/or logging system in the IMUs. The IMUs have been used in research for walking event identification (Lau & Tong, 2008; Saremi, et al., 2006), counting walking steps (Fortune et al. 2014), motion classification (Little et al., 2013), and estimating energy expenditure during daily life activities (Crouter et al., 2006). Thus, research focus has been able to move from the traditional laboratory to the open field.

Swimming and walking in the water also were researched using IMUs (James et al., 2011; Ohgi et al., 2014; Kaneda et al., 2014; Fantozzi et al., 2015). James et al. (2011) tried to develop a monitoring system for swimming which would be useful for swimmers and coaches providing stroke events such as wall push offs, turns, and lap times by attaching IMUs to the sacrum of swimmers. Ohgi et al. (2014) reported a stroke classification method using IMUs attached to the chest of swimmers. With respect to walking research, our team has also published an algorithm for the estimation of energy expenditure during walking in water from the acceleration data attached on the head of participants (Kaneda et al., 2014). Another research report described three-dimensional kinematic gait analysis in the water environment using IMUs (Fantozzi et al., 2015). The buoyancy and viscosity derived from water density affects human movement during exercise. To date, research has identified the biomechanical and kinesiological characteristics during walking in water in a similar manner to motion capture by video camera (Barela et al., 2006; Degani & Danna-dos-Santos, 2007), ground reaction force (Barela et al., 2006; Roesler et al. 2006), joint torque (Orselli & Duarte, 2011), and muscle activities (Barela et al., 2006; Miyoshi et al., 2006). As mentioned earlier, only one article has reported the use of IMUs for walking in water. It calculated a joint and segmental kinematic movement pattern (Fantozzi, et al., 2015). The raw data of acceleration from IMUs and gyroscope during walking in water has not been matched with video data analysis as used in previous studies (Barela et al., 2006; Degani & Danna-dos-Santos, 2007). In those previous studies, evaluations were made by targeting lower extremity motion during walking, and some differences were detected between walking on land versus in water. Therefore, using raw data from IMUs and targeting lower extremities may be effective in developing tools to monitor exercise or to evaluate motion for the prescription of health and rehabilitation training in water.

The purpose of this study was to assess and compare the motion of walking in water with the motion of walking on land using data from IMUs attached to the thigh with the simultaneous data from a video camera.

Method

Participants

Six men and four women ages 30 ± 6 years were recruited for this study. All participants were free from orthopedic conditions that might have affected the walking motion. Participants provided informed consent prior to participating in the research which was approved by the Human Research Ethics Committee at the University of the Sunshine Coast.

Procedures

The participants performed walking in water (WW) and on land (LW) at three walking speeds at their self-determined slow, moderate (comfortable) and fast pace. They walked along a 10 m walkway three times at each speed, and the first and second trials were treated as practice, with the data from the third trial used for analysis. The experiments were carried out at the outdoor swimming pool at the university. The WW was conducted in the swimming pool. The depth of the swimming pool was 1.35 m which was between the levels of the xiphoid and the clavicle of each of the participants. The LW was conducted on the swimming pool deck.

The IMUs, containing a tri-axial accelerometer, gyroscope, and magnetometer (LP-WS0904, 9DoF Wireless Motion Logger, Logical Product Co., Japan), were attached to the participant's front side of the right thigh at the mid-point. The IMUs measured acceleration and angular velocity at a sampling rate of 100 Hz. The IMUs were waterproofed using a zip lock package and were attached to the thigh by adhesive double-sided tape and kinesio-tape. The video cameras used for each trial were DCR-TRV900 3CCD (SONY, Japan) for LW and Orca Swim Tracker) (Design Science, USA) for WW. Each camera was set at the right side of the participant with a sampling rate of 25 Hz. The cameras were set to capture the latter part of the walking trial. Using the accepted standard protocol (Miyoshi et al., 2004; Miyoshi et al., 2006), vinyl tape markers were attached on the lateral malleolus, lateral epicondyle, greater trochanter, and midpoint of the iliac crest of the participant's right side to detect body position for analyzing the video files.

From the acquired files, one walking cycle of the latter part of the third trial was identified based on one complete action between consecutive heel strikes. The hip and knee angles (from the lateral epicondyle to the midpoint of the iliac crest via the greater trochanter for hip angle and from the lateral malleolus to the greater trochanter via the lateral epicondyle for knee angle) of the sagittal plane were calculated by a two-dimensional direct linear transformation method. The digitization of the marker sets was processed manually, then the angle of the thigh segment (from the lateral epicondyle to the greater trochanter) relative to the vertical (gravitational) axis of the sagittal plane also was calculated. The data from IMUs allowed acceleration and angular velocities of a given walking cycle to be calculated. In this study, the longitudinal and anterior-posterior acceleration (L-A and AP-A, respectively) and frontal axis angular velocity (F-AV) were used for analysis as the video data captured motion only in the sagittal plane. The thigh sensor was placed such that the positive value was delivered when standing stationary in L-A, when elevating the thigh (hip joint flexion) in AP-A, and when moving counterclockwise rotation (hip joint flexion) in F-AV.

The IMUs and video data were synchronized with participant heel strike motion by viewing the frames on video camera and the acceleration spikes on the IMUs. After one cycle, video and IMU data were low-pass filtered at 6 Hz and normalized with one cycle from 0-100% based on the heel strike during walking. The data were then configured with LW and WW in each parameter. Walking speed was calculated from the greater trochanter data of the video data and then averaged for one cycle. The toe-off moment was also determined from video data and calculated the ratio of the stance phase.

Analysis

The normality of each data set was confirmed using a two-way ANOVA with Tukey's post-hoc test applied to investigate any differences in the walking speed and the ratios of the stance phase. When significant interactions were not observed after two-way ANOVA analysis, a one-way ANOVA with Tukey's post-hoc test was performed comparing the pace difference in each condition. The difference between WW and LW was tested using a paired t-test. The α was set at $p < 0.05$.

Results

Figure 1 showed the result of the walking speed and stance ratio in each trial. As expected, the statistical analysis revealed that walking speeds were significantly faster on land than in water, and the speed was gradually faster in accordance with a pace set faster in both conditions. The stance ratio was shorter in the water. In addition, the ratio was shorter in accordance with a pace set faster in both conditions.

The averaged knee, hip, and thigh angle patterns are depicted in Figure 2. The knee joint in water showed a more flexed position compared to that on land at the heel contact phase, and after the heel contact, while the knee joint tends to extend more, with this tendency being larger at the faster pace. In the swing phase, the knee angle was also more flexed in the water than on land. After that, the knee joint moved to extend toward to the heel contact. There was a peak extension phase near 95% of one cycle on the land. The hip joint was always in a flexed position throughout the cycle in the water compared with that on land, and the difference of the flexion peak in the swing phase between two conditions became larger at the faster pace. The angle of the thigh segment was almost the same at the heel contact between the two conditions. However, more angle fluctuation was observed in the water than on land.

The L-A, AP-A, and F-AV patterns are shown in Figure 3. The L-A in the water showed mostly 1 g (gravitational acceleration) up to 70% of the cycle, and slightly decreased before moving back to 1 g toward the heel contact phase. This decrease becomes larger when walking at the faster pace. The AP-A in the water was negative after around 10% of the cycle, crossed the 0 g to positive around 60%, then maintained the positive value to the end of the cycle. The pattern of the L-A and AP-A were very different between the two conditions, especially regarding the high g around the end of the cycle on land, which was not observed in the water. The negative F-AV was larger on land than in water in the stance phase, and the difference became larger when walking at the faster pace, and a larger positive F-AV was observed in the swing phase. There was no fluctuation across 0°/s in the water during the last part of the cycle.

Figure 1

Walking speed and stance ratio in each condition and speed setting

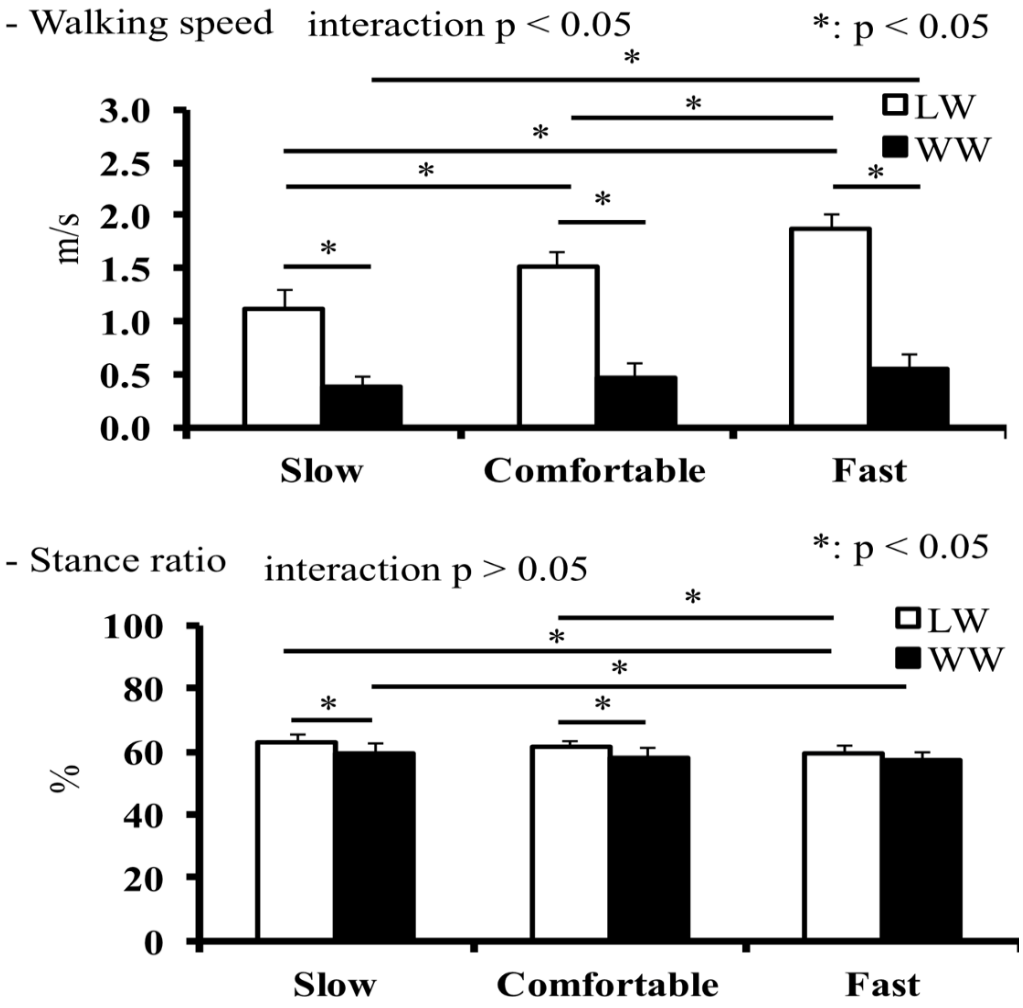

Fig. 1

LW: walking on land, WW: walking in water.

Figure 2

Knee, hip, and thigh angle in each condition and speed setting

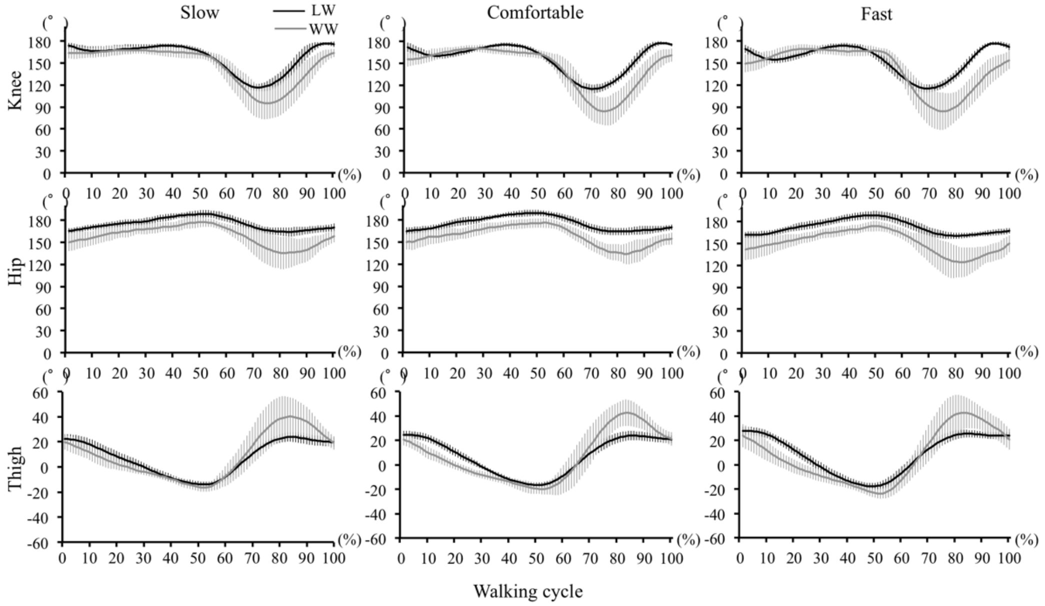

Fig. 2

LW: walking on land, WW: walking in water. The solid line curve indicates mean value of all participants and shaded area indicates SD.

Discussion

This study investigated the characteristics of acceleration and angular velocity of the lower limbs especially in the thigh segments during walking in water and on land using IMUs synchronized to video analysis. This study is the first to express raw data of acceleration and angular velocity from IMUs synchronized with video analysis during walking in water.

Figure 3

Acceleration and angular velocity in each condition and speed setting

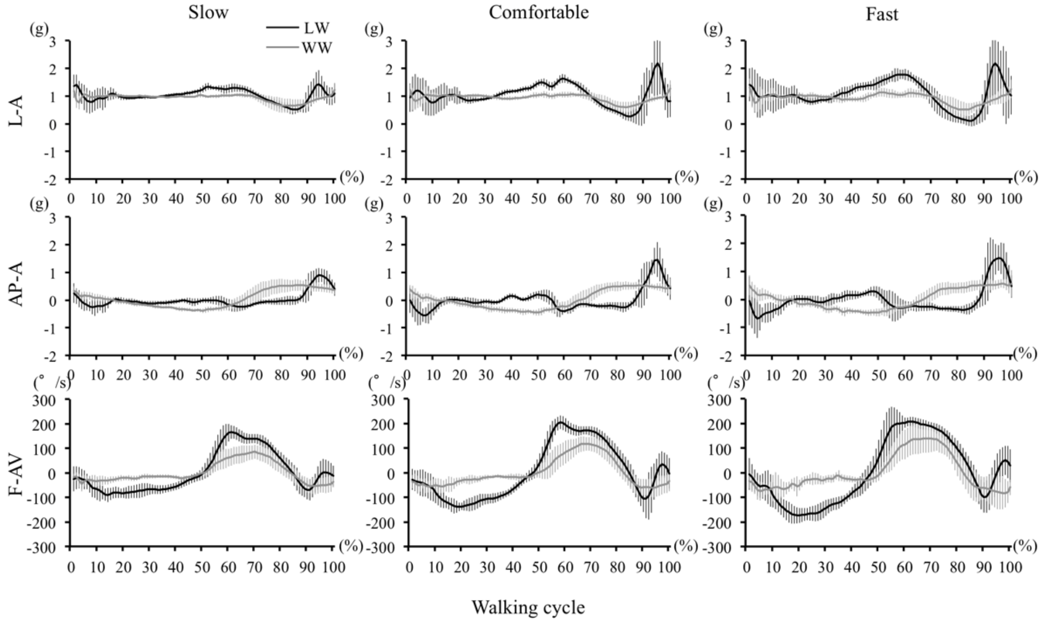

Fig. 3

LW: walking on land: WW: walking in water; L-A: longitudinal acceleration: AP-A: anterior-posterior acceleration: F-AV: frontal axis angular velocity. A solid line curve indicates mean value of all participants and shaded area indicates SD.

The walking speed in the water was similar to that reported by Roesler et al. (2006). Other studies conducted by Barela et al. (2006) and Orselli & Duarte (2011) showed similar walking speeds both in water and on land. The stance time ratios decreased when the walking speed was faster and for water compared with on land (Kato et al., 2002; Kaneda, et al., 2008). The knee angle was also more flexed at the heel contact phase for the water than on land (Kaneda, et al., 2008; Miyoshi, et al., 2004). The fluctuation after the heel contact at the knee joint commonly called the “double knee action” almost disappeared in the water (Barela, et al., 2006;

Miyoshi, et al., 2004). A larger peak knee flexion angle in water than on land was observed at the swing phase (Degani & Danna-dos-Santos, 2007). A greater hip flexion angle for the water at the stance phase and a larger peak flexion angle in the swing phase were seen in the water than on land (Barela, et al., 2006; Degani & Danna-dos-Santos, 2007). Further, the L-A, AP-A, and F-AV on land showed very similar patterns to that described in previous studies (Bussmann et al., 2000; Lau & Tong, 2008; Saremi, et al., 2006). Therefore, the analyzed data obtained in this study was generalized to previous studies.

This study mainly focused on examining the acceleration and angular velocity in relation to the sagittal plane; L-A, AP-A, and F-AV were analyzed. A key outcome observed was that the L-A in the water showed 1 g up to around 70% of the cycle in all speeds although the thigh posture by video analysis fluctuated more than on land. There may be some reasons for these variations. First, the double knee action observed during LW almost disappeared for WW. This did not generate any fluctuation influencing thigh posture around the initial part of the cycle. Second, the faster speed trials resulted in faster pushing off the ground on land than in water through the stance phase which may create increased centripetal or centrifugal force. It has been said gravitational acceleration, translational acceleration, centrifugal acceleration, and tangential acceleration are included within the acceleration data (Koyanagi & Ohgi, 2010). Therefore, it was speculated that the acceleration force from the thigh segment was reduced during walking in water. The decrement of the L-A in both conditions by 70-90% of the cycle would be mostly affected by the flexed hip joint where the gravitational effect was reduced. The smaller decrement of the L-A in the water than on land may be due to the slower motion speed in water than on land as seen in the F-AV in this study.

The AP-A pattern for the water also showed sinusoidal behavior with a gradual decreasing and increasing curve throughout one cycle, whilst familiar patterns were observed on land as reported in a previous study (Bussmann et al., 2000). This could also be due to the slower walking speed and motion that identified the F-AV in this study. Bussmann et al. (2000) reported a computed gravitational component for the thigh during walking on land, and this was very similar to the AP-A pattern in water in this study. Thus, the AP-A could be a useful measure to monitor the posture of the attached segment in walking in the water.

The common point in the L-A and AP-A was that of the high g around the end of the cycle on the land. This finding was not observed in the water. The peak acceleration observed on the land was also reported in previous studies (Bussmann, et al., 2000; Lau & Tong, 2008; Saremi, et al., 2006). Bussmann et al. (2000) suggested that the acceleration peak toward the end of the cycle (97% of the cycle) could be associated with the moment of heel strike (i.e. due to impact). In the present study, these were observed at 94% or 95% of the cycle. Interestingly, the knee extension peaks around the end of the cycle in the slow, comfortable, and fast pace were 95%, 97%, and 97% respectively. In addition, the F-AV crossed 0°/s at 95%. These phenomena would indicate that there was an impact on the thigh segment by the swing motion of the shank segment where the segment stopped acutely at the peak extended position of the knee joint and then prepared for the shock absorption at the heel contact phase. Such an impact at the end of the cycle is a problem in people with a prosthetic leg and this is known as a "terminal impact" (Furse et al., 2011). In the water, the impact just before heel contact phase was not observed. This may be due to the high viscosity in the water environment where the motion of the shank swing was very slow and did not reach full extension and the knee joint was more flexed compared to the land (Barela, et al., 2006; Degani & Danna-dos-Santos, 2007; Kaneda, et al., 2008). The authors suggested there was no need to prepare for the impact force absorption while walking in the water due to the buoyancy effect and changes in lower limb speed (Miyoshi, et al., 2004). Therefore, the excess load for the knee joint can be reduced during walking in water.

The F-AV in the water was slower than on the land. The water viscosity influenced the motion speed and it was significantly slower in water than on land (Kaneda, et al., 2008; Roesler, et al., 2006). The end phase of a cycle transitioned smoothly for water but fluctuated across 0°/s on the land. This would strongly relate to the shank swing speed with the extended knee joint and an impact phase on land as mentioned previously in the L-A and AP-A discussions. The integration of angular velocity in three-dimensions may show a similar pattern with hip and/or thigh angles. Indeed, Fantozzi et al. (2015) calculated hip, knee, and ankle angle patterns from IMU data and indicated a similar tendency as reported by previous studies involving video capture data. Taking into account that water has been widely reported as an effective environment for rehabilitation training with less fear of crucial accidents during exercise (Sato et al. 2007), the authors believe this new research contributes to re-constructing human motion during walking during such rehabilitation training.

From the results and discussions in the present study, we suggest that walking exercises in water may be applicable for persons who have reduced motion or pain in their knees or thighs. During walking in water, acceleration and impact force, which burden the thighs or knees just before the heel contact, are reduced. This suggests that walking in water may also be applicable for individuals who have a lower extremity prothesis because walking in water reduces the “terminal impact”. The present study did not have subjects with a prosthetic leg, and further studies are required to expand the observations for this population.

Limitations

A limitation of this study was the stated discrepancy of the sampling rate between IMUs and videos. The authors believe this would only reinforce our results and discussion made in the present study. Analyzing consecutive cycles of the walking motion which is presently out of the scope of the camera may also provide additional value.

Conclusion

This study investigated acceleration and angular velocity during walking in water and on land using IMUs attached on the participant's thigh. The pattern of data of one cycle in relation to the sagittal plane was analyzed and compared with video analysis. The following conclusions have been made: 1) acceleration of the longitudinal axis during water walking showed almost 1 g from heel contact to 70% of one cycle, 2) acceleration of the anterior-posterior axis showed a sinusoidal pattern which may follow thigh posture, and 3) the acceleration force and excess force observed at the thigh segment or knee joint was reduced during walking in water. The present study suggested that walking exercises in water might benefit individuals who have hip or knee issues. Finally, the motion during walking in water can be characterized accurately by IMUs matched to video cameras.

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