A COMPARISON OF LOWER LIMB JOINTS ANGULAR DISPLACEMENT BETWEEN LAND AND WATER-WALKING USING DYNAMIC TIME WARPING

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The purpose of this study was firstly to compare lower limb joints angular displacement between land and water-walking by dynamic time warping. Six subjects (age 30.0±5.3 yr) performed 10 m land and water-walking at self-selected speed. Ankle, knee and hip joint angular displacements were calculated from video (25Hz) and compared to the two wave forms from the dynamic time warping procedure. Results showed the ankle and knee joints demonstrated warping periods in water-walking, when compared with land-walking. However, the warping periods around toe-off was seen at the hip joint in land-walking, compared with water-walking. Overall the ankle and knee joints motion in water walking were comparable to land-walking motion. However, the hip joint kinematics during water walking were not always comparable with land walking kinematics.

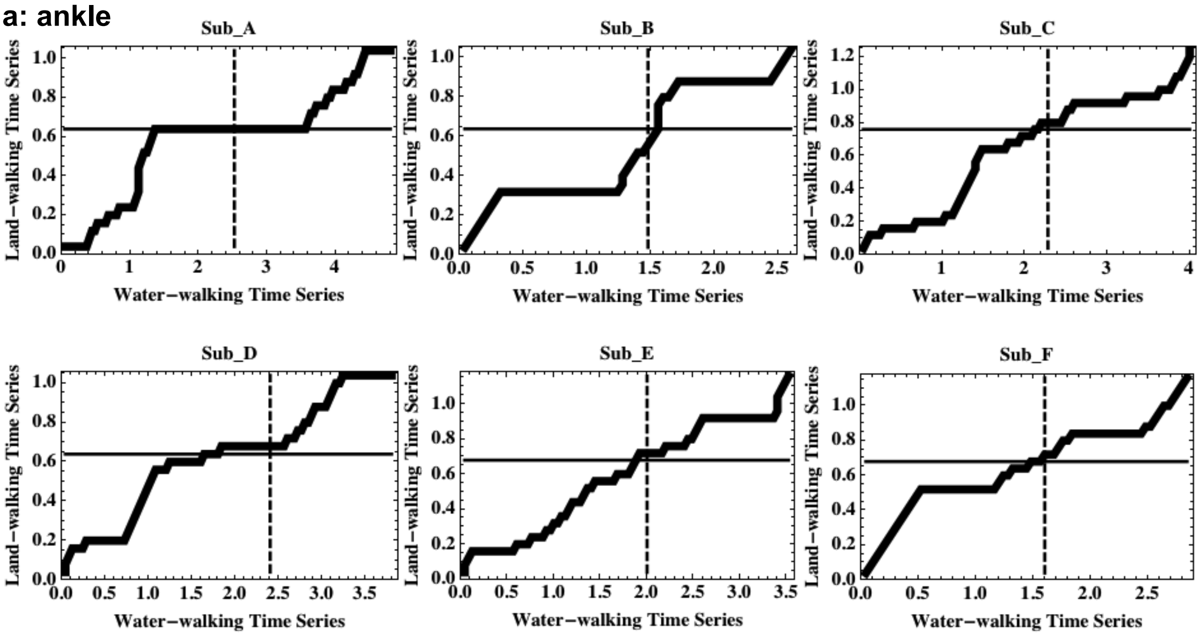
KEY WORDS: aqua exercise, DTW, similarity, time distortion, normalization.

INTRODUCTION: Aqua exercise has become increasingly popular for both fitness enhancement and rehabilitation training, especially for people who have difficulty performing land based exercise such as the frail elderly people (Sato, Kaneda, Wakabayashi & Nomura, 2007). Comparisons of lower limb joints angular displacement have been made between land and water-walking by normalizing (0-100%) each stride period from heel contact to the next heel contact (Miyoshi, Shirota, Yamamoto, Nakazawa & Akai, 2003; Barela, Stolf & Duarte, 2006; Barela & Duarte, 2008). However, applying normalization for one stride period can change the time series of the actual stride. In analysing the characteristics of walking, it should include both the lower limb joints angular displacement as well as changing of movement speed as this is a key feature of water-walking. To achieve this, dynamic time warping is suggested to measure similarity between two signals without the usual time normalization (Sakoe & Chiba, 1978). Initially, dynamic time warping was applied for word recognition (Sakoe & Chiba, 1978), and recently it has been used to differentiate human walking technique (Muscillo, Conforto, Schmid, Caselli & D'Alessio, 2007). The aim of this study was to compare lower limb joints angular displacement between land and water-walking by applying dynamic time warping, and to clarify the time series characteristics of water-walking without time normalization.

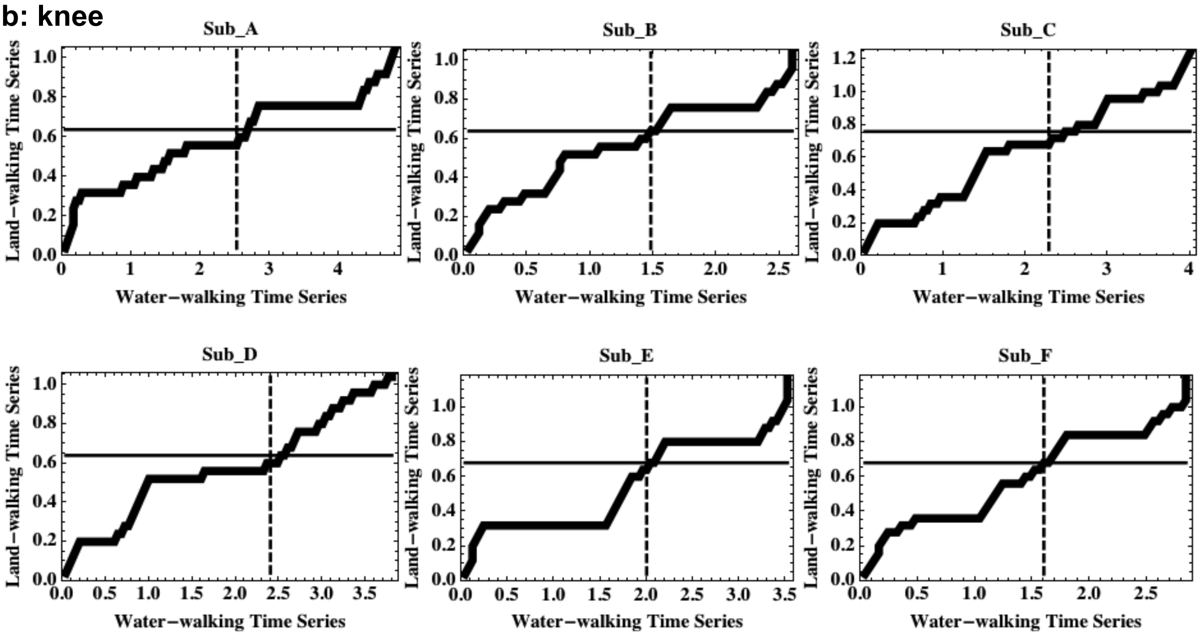
METHODS: Four males and two females were recruited (30.0 ±5.3 y; 173.6 ±4.2 cm; 70.1 ±10.5 kg). Subjects provided informed written consent before the experiment, which was approved by the University of the Sunshine Coast Human Research Ethics Committee. The movement task required participants to walk along a 10 m walkway both on-land and in-water at their self-selected pace three times for each condition. The in-water movement task was conducted in a 27°C outdoor swimming pool with a constant depth of 1.35 m. The kinematics of the right lower limb during one complete gait cycle was recorded on-land using a digital video camera (25Hz; Mini DV Handycam Vision, DCR-TRV900E, Sony, Australia) and underwater using an underwater digital video camera system (25Hz; Orca Swim Tracker, Design Science, USA). To detect ankle, knee and hip joint angular displacement in sagittal plane, body markers were placed on the right side of the subject at the fifth metatarsal head, lateral malleolus, lateral femoral epicondyle, greater trochanter, and midpoint of the iliac crest. A Butterworth low pass filter with cut-off frequency of 10Hz (Barela et al., 2006; Barela & Duarte, 2008) was applied to the kinematic data. Dynamic time warping (Sakoe & Chiba, 1978) was applied to compare the joint angular displacement between on-land and in-water walking between heel-contact to the next heel-contact. The first and second trials were treated as familiarization trials and the third trial of each condition was analyzed using dynamic time warping. This method determines the optimal cost path from the beginning to the end of two signals, which is expressed by the summation of the distance of the each data point between the two signals in the similarity matrix. The kinematics of a horizontal line is represented by a single point in land walking. This horizontal line is the result of dynamic time warping showing that water-walking continues or warps ahead to a point where both movements become more similar again. Similarly the kinematics of a vertical line is represented by a single point on water-walking. A diagonal line indicates similarity between the water and land walking movements and no warping. Further details of dynamic time warping are described elsewhere (Sakoe & Chiba, 1978).

RESULTS: Figures 1-a, b and c shows the results of the dynamic time warping for each joint's angular displacement of each subject.

a: ankle



b: knee



c: hip

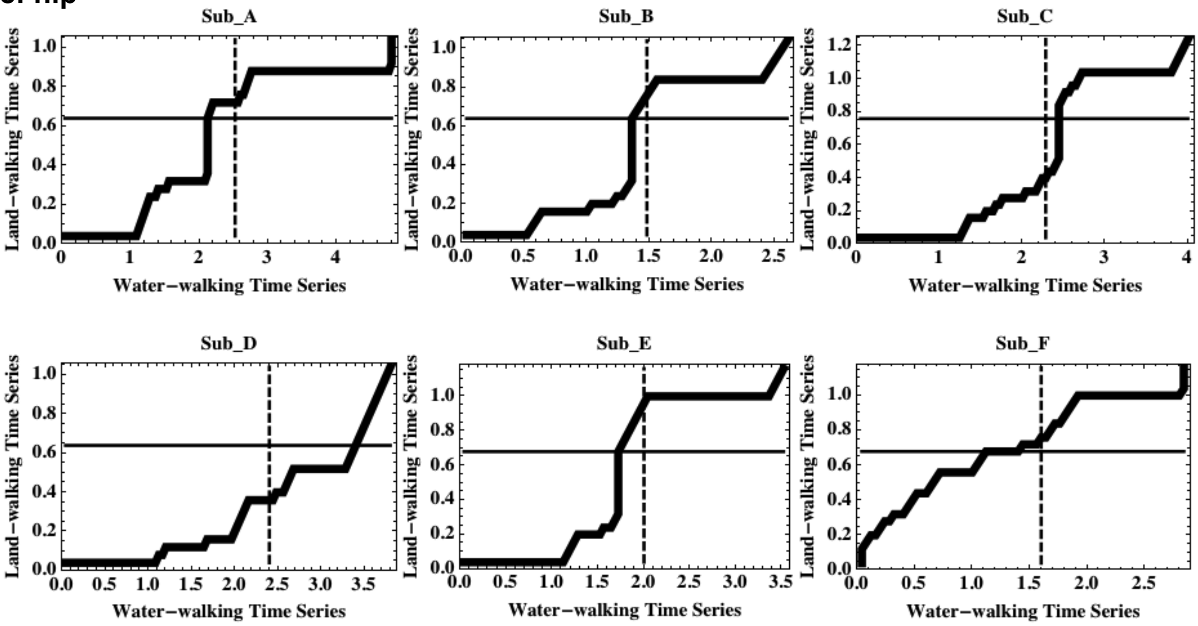


Figure 1: The results of DTW applied to the each joint (a: ankle, b: knee, c: hip). Diagonal line represents similar joint kinematics between conditions, and horizontal or vertical line represents different kinematics against the intended condition.

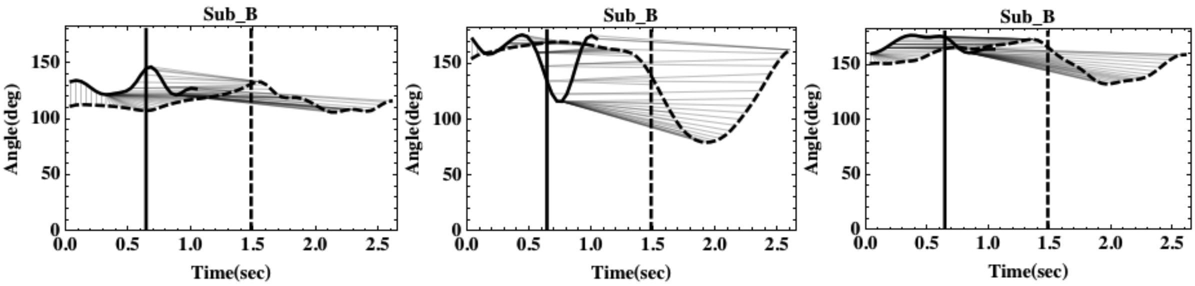


Figure 2: An example of joint angle displacement pattern in hip, knee, and ankle joint (Sub_B). Solid and dashed line represents land-walking and water-walking, respectively. Each vertical line represents toe-off moment. Thin gray line indicates correspondence between movement pattern for water and land walking using dynamic time warping.

The ankle joint seemed to be independent for each subject. Although four subjects displayed a horizontal line during stance and swing phase respectively, two showed a horizontal line around toe-off. At the knee joint, there were either two horizontal lines in former and latter part during stance phase or one comparably longer horizontal line during stance phase. Comparably longer horizontal lines were seen in four subjects during swing phase at the knee joint. Five subjects showed comparably longer horizontal lines in the early period of the stance phase at the hip joint. During the swing phase at the hip joint, a horizontal line was seen in all subjects immediately after the toe-off to just before the next heel-contact. Interestingly, four subjects showed comparably longer vertical lines just before the toe-off at the hip joint. An example of angular displacement pattern in each joint was showed in the Fig 2. The ankle joint was independent for subjects as well as the results of the dynamic time warping. At the knee joint, a double-knee action seen in land-walking during early time of stance phase tended to disappear in water-walking, and knee flexion was larger in water-walking than land-walking during swing phase. The hip joint pattern consistently showed a more flexed position throughout in-water-walking.

DISCUSSION: The current study showed a tendency toward subject-dependent results in the ankle joint kinematics, which is in conflict with results of previous research that reported either increased (Miyoshi et al., 2003; Kaneda, Wakabayashi, Sato, Uekusa & Nomura, 2008) or decreased dorsi flexion (Barela et al., 2006; Barela & Duarte, 2008) in water-walking. Joint range of motion was also reported with differing results (Miyoshi et al., 2003;

Degani & Danna-dos-Santos, 2007; Kaneda et al., 2008). At the knee joint, the horizontal line during stance phase particularly seen in the earlier phase was influenced by a reduced flexion motion attributed to absorbing impact forces seen in land-walking (Miyoshi et al., 2003). The horizontal line during swing phase, which indicates no coincident kinematics in land-walking compared with water-walking, may be due to a more flexed position in water-walking than land-walking seen in this study. The hip joint was more flexed in water-walking than land-walking throughout the cycle (Miyoshi et al., 2003), causing the horizontal lines to appear during early stance phase and most of swing phase. However, one subject (Sub_F) had a similar hip kinematics for both conditions during early stance phase and resulted in no horizontal line.

There was almost no vertical line in the DTW at the ankle and knee joints. This implies that most of water-walking motion for the ankle and knee joint was comparable with the land-walking motion. However, there was a definite vertical line at the hip joint in some subjects, indicating a warping period during land-walking compared with water-walking. In regard to hip joint angular displacement, water-walking was not always comparable to the land-walking movement and at this time, the authors can't determine the cause of this result. These results suggest an important application to aqua rehabilitation such as regaining or simulation training for land-walking, and further specific investigation into the joint kinematics of the hip would need to confirm the effectiveness of water-walking.

CONCLUSION: This study using dynamic time warping showed the water-walking movement was almost totally included in land-walking movements at the ankle and knee joint. However, the ankle joint behaviour was subject-dependent whereas the knee joint behaviour was more consistent between subjects. There was also a warped period around toe-off period in land-walking in some subjects at the hip joint compared to water-walking movement indicating water-walking was not always comparable with the land-walking movement.

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