PATTERN MATCHING ANALYSIS OF LOWER-LIMB GAIT MOTION IN WATER AND ON LAND AND ITS RELATIONSHIP TO JOINT MOTION

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This study applied dynamic time warping (DTW) to lower-limb gait motion in water with a slow to fast pace compared with those on land at a comfortable pace; this was done for 15 participants to examine if the result obtained would be similar to previous study irrespective of gait pace in water. The correlation between the DTW results and the joint angle difference in the two environments was also investigated to clear the reason for the result of DTW. Consequently, DTW detected incomplete motion in the water at any pace in the hip joint just before the toe-off, which moderately correlated (r = 0.59) with the peak extension angle difference of the hip joint between the two environments. Therefore, an increasing extension motion in the hip joint just before the toe-off during gait in the water would be suggested for simulating gait motion on land.

KEYWORDS: underwater, walking, DTW, normalization, correlation.

INTRODUCTION: Gait in shallow water without using a floating device is a fundamental form of exercise used for both health promotion and rehabilitation training. In studies examining joint motion during gait in water, joint motion has typically been normalized from 0% to 100% over time (Miyoshi, Shirota, Yamamoto, Nakazawa & Akai, 2004; Degani & Danna dos Santos, 2007). However, normalizing a time-series waveform over the entire duration may introduce distortions. The much longer duration of one gait cycle in water than that on land (Barela, Stolf & Duarte, 2006) indicates a considerably slower gait motion in water. Therefore, to enhance our comprehension of the characteristics of gait in water, time-series data analysis should include both time and motion alterations.

Dynamic time warping (DTW) was introduced for comparing two time-series waveforms without time normalization (Sakoe & Chiba, 1978). Ohgi (2006) demonstrated that DTW could be used to identify similarities between two different time-series waveforms, suggesting that the DTW process could identify similar and different phases in two time-series waveforms. The authors of this study applied DTW to analyze lower-limb angular displacement patterns in six participants during gait in water and on land at a comfortable pace (Kaneda, McKean, Ohgi & Burkett, 2012). The results indicated that the angular displacement pattern of the hip joint in water was not comparable to that on land around the toe-off. However, no further investigation has explored the effect of gait paces or examined the relationship to joint motion to determine the reason for the findings.

As a gait practice for health or rehabilitation in water, wherein some paces are used as its program, whether joint motion simluates normal gait in daily life would be an essential topic. Thus, this study aimed to investigate the characteristics of lower-limb angular displacement during gait in water from slow to fast paces and compare them with those on land at a comfortable pace using DTW. The investigation also included a correlation analysis between the DTW results and the angular displacements observed in the two environments to comfirm the impact of joint motion difference between the two environments. This study suggests an effective instruction point for gait practice in health or rehabilitation in water.

METHODS: Six men (age: 27.7 ± 7.7 yr, height: 182.7 ± 7.1 cm, and mass: 82.3 ± 10.5 kg) and nine women (age: 34.8 ± 7.6 yr, height: 171.3 ± 4.7 cm, and mass: 66.3 ± 8.5 kg) were recruited for this study. The participants provided informed consent before participation in the experiment, which was approved by the Human Research Ethics Committee of the University of the Sunshine Coast.

The participants completed three gait trials along a 7–10-m track both on land at a self-selected comfortable pace and in the water at self-selected slow, comfortable, and fast paces. The pool depth was 1.35 m. A digital video camera (DCR-TRV900 3CCD, SONY Co., Tokyo, Japan), with the camera lens at a height of 1.0–1.2 m, was positioned on the right side of the participant to capture one complete 2D (the vertical (gravitational) and horizontal (gait track) axes) gait cycle on land. In the water, an underwater digital video camera system (Orca Swim Tracker, Design Sciences LLC, Colorado, USA) was used; the camera lenses above and under the water were about 1.0–1.2 m high and 0.2–0.4 m deep, respectively. Both cameras operated at a frame rate of 25 Hz. To determine angular displacements of the ankle, knee, and hip joints in the sagittal plane for both environments, body markers were placed on the right side of the participant at the head of the fifth metatarsal, lateral malleolus, femoral epicondyle, greater trochanter, and midpoint of the iliac crest. A Butterworth low-pass filter with a cutoff frequency of 6 Hz was applied to the manually digitized kinematic data by using Frame-DIAS V (Q'sfix Co., Tokyo, Japan). For analysis, data from a single gait cycle from one-foot contact to the subsequent foot contact of the same leg during the third trial of each environment and pace were used. Then, DTW was applied to compare the angular displacements of each joint between land and water at each pace.
In the DTW analysis, the angular displacements on land and in water at each pace were used as the ordinate and abscissa axes, respectively. The initial moment of heel contact (time = 0) was established at the intersection of the axes. According to the DTW results, a diagonal search path indicated that the joint angular displacements under the two conditions were similar (Fig. 1, circle A). A horizontal search path indicated that the joint exhibited additional angular displacement during gait in water compared with that on land (Fig. 1, circle B). A vertical search path indicated that the joint experienced incomplete angular displacement during gait in water compared with that on land (Fig. 1, circle C).
This study was considered significant when the duration exceeded 0.2 s in the vertical search path, which was based on the valid time length of the low-pass filter (6 Hz) of 0.17 s and the sampling rate of the video camera (25 Hz) of 0.04 s. Specifically, this study focused on determining whether a longer vertical search path in the hip joint around the toe-off, indicating dissimilarity in the angular displacement pattern of the hip joint between water and land, would be observed irrespective of the gait pace in water. Therefore, the Pearson product–moment correlation coefficient between the time length of the vertical search path in the hip joint (over 0.2 s) and the difference in peak extension angles in the two environments was computed around the toe-off.

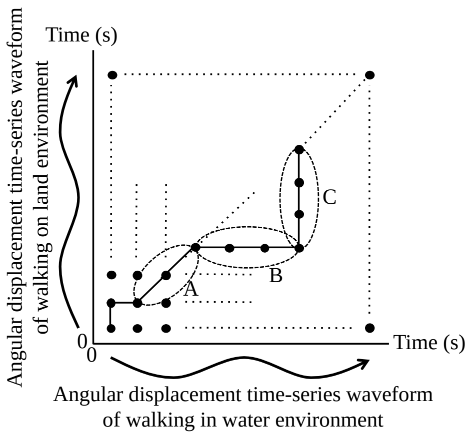

Fig. 1. Example of dynamic time warping analysis.

RESULTS: Figure 2 illustrates typical examples (n = 2) of the search path for each joint and pace. The main finding indicated a significant vertical search path (over 0.2 s) detected in the hip joint just before the toe-off in 11 (73.3%), 9 (60%), and 11 (73.3%) participants at slow, comfortable, and fast paces in the water, respectively, when compared with the comfortable pace on land. In the ankle and knee joints, some participants exhibited a significant vertical search path; however, these results were not consistent across participants.

As a significant vertical search path was detected just before the toe-off in the hip joint, the Pearson product–moment correlation coefficient was calculated between the time length of the vertical search path and the difference in the peak extension angles of the two environments just before the toe-off (Table 1). The correlation coefficients were 0.77, 0.42, and 0.44 for slow, comfortable, and fast paces in the water, respectively. If all the paces were combined, the correlation coefficient was 0.59 (Figure 3).

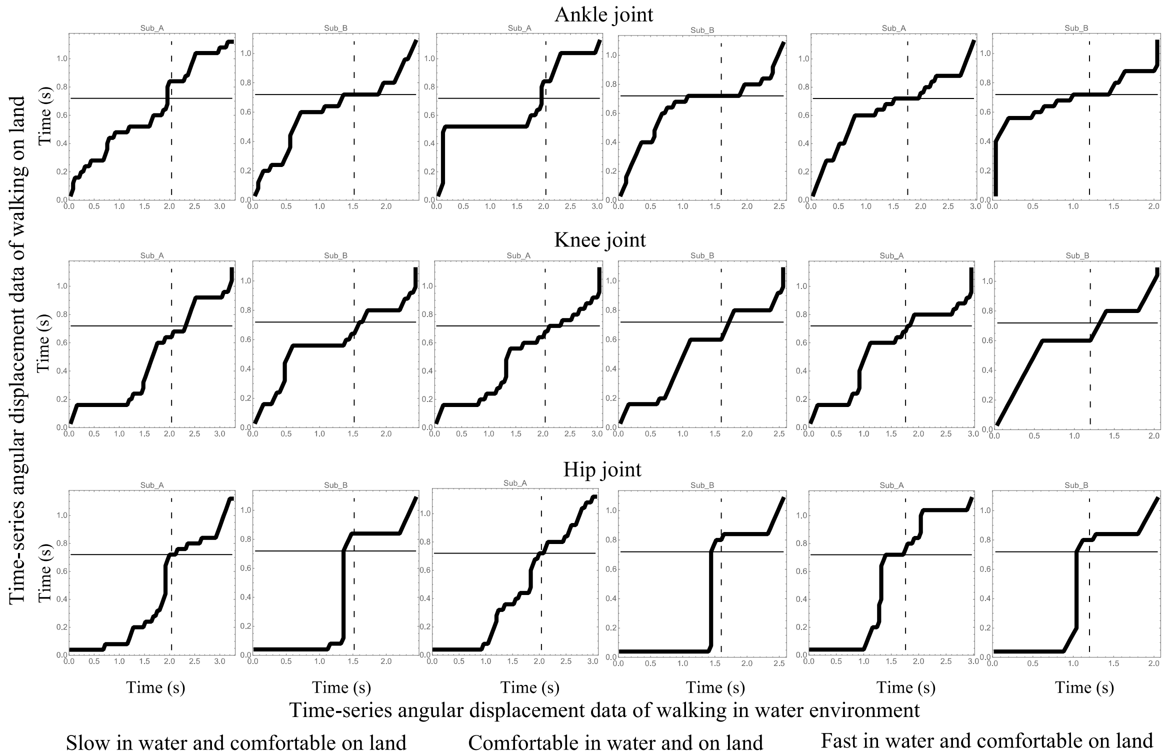

Fig. 2. Search path results based on dynamic time warping for each joint.
Solid and long horizontal straight lines indicate the toe-off on land. Dashed and long vertical straight lines indicate the toe-off in water.

Table 1: Correlation coefficients of the vertical search path and peak extension angle difference at the hip joint.

	r value	p-value
Slow in water and comfortable on land (n = 11)	0.77	<0.01
Comfortable in water and on land (n = 9)	0.42	0.27
Fast in water and comfortable on land (n = 11)	0.44	0.18
All combined (n = 31)	0.59	<0.01

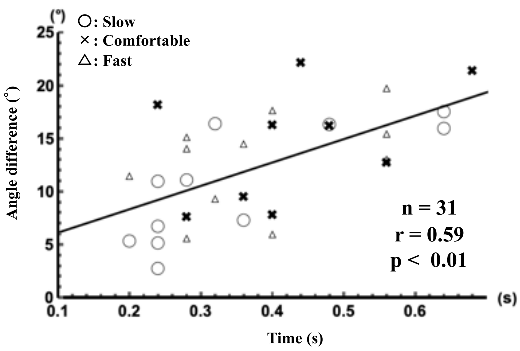

Fig. 3. Correlation of the vertical search path and peak extension angle difference at the hip joint with all paces in water.

DISCUSSION: A significant vertical search path was detected by DTW, particularly around the toe-off in the hip joint, when comparing gait in the water with that on land at a comfortable pace (Kaneda et al., 2012). In this study, a similar search path just before the toe-off in the hip joint was observed in many participants, irrespective of the gait pace in water when compared with the comfortable pace on land. In this study, the identification of a vertical search path implies an incomplete angular displacement during gait in water compared with that in air. A previous study reported a flexed joint angle (approximately 8°) during the stance phase in water compared with that in air (Miyoshi et al., 2004), along with the smaller extension peak at the hip joint around the toe-off (Miyoshi et al., 2004; Degani & Danna dos Santos, 2007). Consistent with these findings, this study investigated the correlation between the time length of the vertical search path and the difference in the extension peak at the hip joint in the two environments. The results revealed a moderate correlation when all paces were combined in water, indicating that the smaller extension motion at the hip joint just before the toe-off during gait in water influenced the vertical search path detected by DTW in this study. The results suggested that increasing hip extension motion just before the toe-off during gait in water would render the motion more similar to that in air. This would be useful information for health or rehabilitation in water to simulate the motion of normal gait in daily life for enhancing or regaining gait ability.

In the ankle and knee joints, some vertical search paths emerged; however, these were not consistent among participants. This was not observed in the previous study (Kaneda et al., 2012). There are reports showing disagreement of joint usage at ankle and knee joints during gait in water compared with that in air (Miyoshi et al., 2004; Barela et al., 2006; Fantozzi, Giovanardi, Borra, & Gatta, 2015). This study would likely contribute to the vertical search path in the ankle and knee joints. Further research is required to elucidate these points.

One limitation of this study is that only participants who were nondisabled with respect to their gait were recruited. Another limitation is that this study analyzed sagittal plane motion; however, gait is composed of three-dimensional motion. Thus, further studies are required for better suggestions for health or rehabilitation in water.

CONCLUSION: In this study, DTW was applied to compare the angular displacements of the lower-limb joints during gait in water with a slow to fast pace and those on land at a comfortable pace. The results confirmed that hip joint motion during gait in water was characterized by incomplete extension motion just before the toe-off compared with that in air. Thus, increasing the hip extension motion during gait in water just before the toe-off may induce motion similar to that in air. This would be useful information for health and rehabilitation in water for enahancing or regaining normal gait ability in daily life.

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