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The influence of the aquatic environment on the center of pressure, impulses and upper and lower trunk accelerations during gait initiation

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ABSTRACT

Gait initiation is defined as the transition from stationary standing to steady-state walking. Despite the frequent use of therapy pools for training walking in early stages of rehabilitation, none have been reported on the effects of immersion on gait initiation. We aimed to analyze the center of pressure (COP) trajectories, the vertical and anteroposterior impulses and upper and lower trunk accelerations during anticipatory (APA) and execution phases of gait initiation. In the COP trajectory, the execution (EXE) phase was further subdivided in two phases: predominantly mediolateral (EXE1), and predominantly anteroposterior (EXE2). Able-bodied participants initiated gait while standing on a force plate and walked approximately 4 steps following a visual cue. The participants were wearing three inertial sensors placed on the lower and upper trunk, and on the stance shank. Individuals performed 10 trials each on land and in water, in two consecutive days. The lengths and velocities of COP trajectories increased in water compared to land during APA, while the COP length increased and the COP velocity reduced in water during EXE2. The anteroposterior impulses increased in water during EXE. Lower trunk acceleration was smaller in water while the upper trunk acceleration did not differ, resulting in the larger ratio of upper to lower trunk acceleration in water during EXE. Overall, immersion in water increases COP length during gait initiation, and reduces COP velocity during EXE2, indicating a new postural strategy in water. The aquatic medium may be favorable for individuals who need weight support, gradual resistance and a longer time to execute gait initiation.

1. Introduction

Gait initiation is a common functional task defined as the transition from stationary standing to steady-state walking [1]. Gait initiation is frequently divided in two phases, the anticipatory postural adjustment (APA) phase and the execution of the first step [2–4]. The APA phase is known to generate the forward momentum [3] and to control the mediolateral (ML) stability [2] for the execution of the first step (EXE).

Effects of various sensorimotor and environmental conditions, such as with different speeds [2], different step lengths [5], stepping over obstacles [6], and changing initial stance position [7], on gait initiation have been investigated. However, to date, gait initiation has been underexplored in the aquatic environment, even though gait training in the aquatic environment is a common and effective approach for rehabilitation in people with various gait and balance impairments [8]. The physical properties of water appear to benefit people with low-functioning performance by providing body offloading due to buoyancy and moderate resistance due to water viscosity [9,10].

In our previous study [11], we demonstrated that the aquatic environment affects the center of pressure (COP) trajectory, the impulse

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exerted by the body, and kinematics of lower limbs during gait initiation. However, as only the lower body segment receives resistance due to water viscosity and the upper body segment is left to move freely, the relation of movements between upper and lower body segments in water can be different from that on the land. Thus, in the current study, we investigated the relation of movements between upper and lower body segments in addition to the COP trajectory and impulses.

Further, in the current study, we propose to divide the EXE phase into two phases to differentiate two events on the execution phase of the COP, i.e., in one the COP predominantly moves in ML direction (EXE1) and in the other the COP predominantly moves in anteroposterior (AP) direction (EXE2). In this way, we were able to identify the trajectory that corresponds to the weight-transferring to the stance limb (the ML COP trajectory, EXE1) and one corresponding to stepping forward (the AP COP trajectory, EXE2). The aquatic medium may affect these COP trajectories differently in AP and ML directions due to the effects of water resistance and buoyancy when body moves during weight transfer and stepping forward in water. Under the support of buoyancy, the ML COP trajectory in EXE1 would increase due to a longer weight transfer and the AP trajectory during EXE2 would increase because individuals could take a longer first step or lean more forward. In other words, we hypothesize that the EXE1 trajectory would be predominantly longer in ML direction and EXE2 trajectory would be predominantly longer in AP direction. Furthermore, the water resistance would increase the duration of the trajectories as the COP velocity during EXE2 would decrease.

Therefore, the aim of the present study was to investigate the kinematics and kinetics of posture during gait initiation in water, focusing on trunk acceleration and with newly proposed divisions of COP. We first hypothesized that the aquatic medium would increase the length of COP trajectory during APA and execution phases, and would decrease velocity while individuals are stepping forward. Second, we hypothesized that a greater mean AP force would be required during the first step, in order to overcome water resistance. Third, we hypothesized that the ratio between upper and lower trunk accelerations in AP direction would increase (acceleration of upper trunk > acceleration of lower trunk) in water during execution phase compared to on land walking, due to greater resistance that the lower trunk and legs experience in water.

2. Methods

2.1. Participants and location

Ten able-bodied volunteers (5 females, age 19–35 years, weight 46–81 kg, height 164–178 cm, and body mass index 17–26), without contraindication to immersion in thermal water, participated in this study. Participants reviewed and signed a written informed consent. Ethical approval was obtained.

Tests in water and on dry land were conducted in the hydrotherapy pool area. The water temperature was set around 35 °C. Tests on dry land were performed at the pool side in order to avoid any environmental difference other than immersion in water.

2.2. Instrumentation

A 9.80 m × 4.90 m × 1.10 m therapy pool was used for the water experimental condition. The water flow/pump of the pool was turned off to minimize water turbulence. In both environments, we used an aluminum custom-made walking pathway (2.80 m × 0.51 m × 0.08 m). A waterproof force plate (ORP-WP-1000, AMTI, USA) was placed in level with the aluminum pathway to align both surfaces. The force plate recorded ground reaction force (GRF) components and moments at a sampling frequency of 1000 Hz.

Three wireless body-worn inertial sensors (Physilog, GaitUp, Switzerland) sealed in waterproof bags were firmly attached to the lower trunk region (L5/S1 vertebrae), upper trunk region (head of sternum) and on the shank of first stance limb using waterproof medical adhesives. Each inertial sensor contained a 3D-accelerometer and a 3D-gyroscope. The accelerometer had a range of ± 11 *g* for each of three directions. The inertial sensors recorded data synchronously on memory cards at a sampling frequency of 500 Hz.

We analyzed data from the trunk inertial sensors synchronized by means of a mechanical strike applied on a waterproof force sensitive resistor switch placed over the upper trunk inertial sensor, before and after each trial. This strike was used for synchronization of the force plate and the inertial sensor data *a posteriori*.

2.3. Experimental procedure

A feet contour was drawn on the force plate on land in comfortable position one day prior to the gait initiation experiment to assure the same standing position between both conditions. We also determined the preferred leg for the first step as the one chosen at least twice in three trials of gait initiation.

Gait initiation was performed after the assessment of quiet standing posture which was the first part of our study published elsewhere [12]. During tests on land and in water, following 5–10 s of standing, participants were instructed to initiate gait with their preferred leg at a self-selected speed as soon as the visual cue (a light positioned about 3.5 m anterior to the participants' eye level) turned on. They continued walking up to 4 steps until the end of the pathway. In water, participants walked at approximately 1 m deep and were asked to maintain upper limbs just above the water without touching the water surface. The same arm posture that was used during walking in water was adopted during dry land trials. Participants were allowed to practice gait initiation twice before the actual experiments, to help participants select their comfortable walking speed and to learn how to maintain consistent posture of the arms.

Data from 10 trials were acquired both in water and on dry land. The experiments in water and on dry land were conducted on two consecutive days, and the order of the experiments was randomized among the participants.

2.4. Data analysis

Data analysis was performed using *Matlab* (R2015b, Mathworks, USA). First, all signals were filtered using a second-order Butterworth filter with a cut-off frequency of 10 Hz for the COP and forces, and a cut-off frequency of 30 Hz for the acceleration.

The COP mean position during 2-s quiet standing was calculated in relation to the ankle line and to the lateral borders of the feet. We calculated a ratio of the distance between the mean COP position to the left foot border over the distance of the mean COP position to the right foot border (COP-ML symmetry). The borders of the feet were taken from the feet contour drawn on the force plate.

Fig. 1 illustrates the time series of the COP trajectories, normalized GRF components, upper and lower trunk acceleration and the free vertical moment (FVM), with events of gait initiation (1, 2, and 3) of a representative single trial from a single subject. The events of gait initiation cycle were the following:

1. Onset of APA phase, defined on the COP trajectory in ML direction as the time when the COP increased more than 2 standard deviations of its mean value during 2-s of quiet standing [13,14].
2. End of APA phase, which corresponds to the point where the peak of COP in ML direction returns to the baseline [13]. This point approximates to the heel-off event and was used to set the beginning of step execution in all signals.
3. End of Execution phase determined as the heel-strike of the swing limb, which was identified as the negative peak of FVM [15].

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