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Biomechanical characteristics of adults walking in shallow water and on land

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Abstract

Although water environment has been employed for different physical activities, there is little available information regarding the biomechanical characteristics of walking in shallow water. In the present study, we investigated the kinematics, ground reaction forces (GRF), and electromyographic (EMG) activation patterns of eight selected muscles of adults walking in shallow water and on land. Ten healthy adults were videotaped while walking at self-selected comfortable speeds on land and in water (at the Xiphoid process level). In both conditions there was a force plate embedded in the middle of each walkway to register the GRF components. Reflective markers were placed over main anatomical landmarks and they were digitalized later to obtain stride characteristics and joint angle information. In general, walking in water was different to walking on land in many aspects and these differences were attributed to the drag force, the apparent body weight reduction, and the lower comfortable speed during walking in shallow water. The joint range of motions (ROM) were not different, the segment ROM, magnitudes of GRF components, impact force, and impulse were different between the two conditions. The present results will contribute to a better understanding of this activity in the context of training and rehabilitation.

Keywords: Gait; Physical activity; Ground reaction force; Kinematics; Electromyography

1. Introduction

Lately, the water environment has been employed for different physical activities other than swimming, such as walking and running [2,13,14]. From a mechanical point of view, there are two main reasons for this: the lower apparent body weight due to the buoyant force (the larger the submersed part of the human body, the lower the apparent body weight), and the increased resistance to movement due to the drag force exerted by water on the human body (the larger the frontal area and faster the movement of the body, the larger the resistance to movement). Thus, it seems easier to support the body in water than on land, movements are typically performed slowly in water with a longer time to control them, and the impact forces on the musculoskeletal system are diminished.

Even though walking in water has been an effective way of practicing such activities as both training and rehabilitation [13,14], there are few empirical data about their effectiveness. A biomechanical characterization of walking in shallow water could be helpful for a better understanding, for example, of the mechanical loads on the human body, on how humans behave and adapt to such a different environment, and consequently, to contribute to a more appropriate prescription of walking in water as part of training and rehabilitation programs.

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So far, few studies have been conducted to describe some aspects of walking in water and none of these studies provided a full description of the gait characteristics of a complete gait cycle [4,8–11]. Therefore, the purpose of this study was to qualitatively and quantitatively characterize a complete gait cycle of adults walking in shallow water and compare this to them walking on land. Specifically, we analyzed temporal and spatial gait parameters, kinetics (vertical and anterior–posterior ground reaction force components), kinematics (joint and segmental angles), and electromyographic activation patterns of selected muscles.

2. Methods

Ten healthy adults (4 males, 6 females) without any known physical or mental illnesses volunteered for this study. The participants' mean age, height, and mass (± 1 standard deviation) were 29 ± 6 years, 1.65 ± 0.10 m, and 63 ± 10 kg, respectively. Before their participation, they signed an informed consent form that was approved by the local ethics committee of the University of São Paulo.

The participants walked at self-selected comfortable speeds on ten occasions in bare feet, first on a walkway in the laboratory (land condition), and on ten occasions, on a walkway in the swimming pool (water condition). In the water condition, the participants kept their arms on the water surface. The walkway in the swimming pool was set according to the participants' height in such a way that they all walked with the water at the Xiphoid process level (Fig. 1). The experimental setup was designed to perform a bi-dimensional gait analysis of one stride, which consisted of the event between two successive right foot contacts to the ground per trial of the participants' walking. In addition, calibration trials were acquired, during which participants were requested to stand upright on the force plate for 30 s in both conditions.

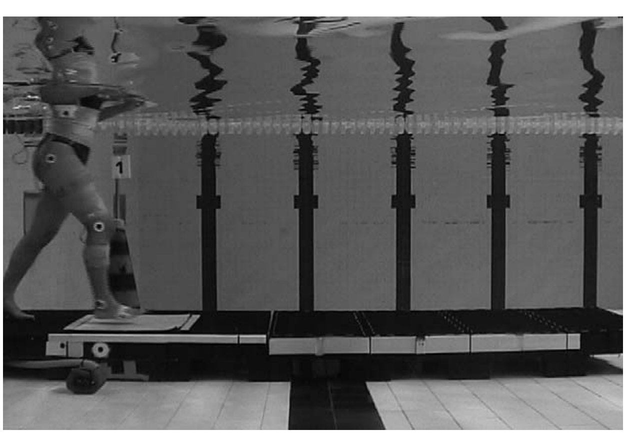

Fig. 1. Partial view of a participant walking in water condition with the water at the Xiphoid process level.

The participants' movement on the sagittal plane (the main plane of movement) was recorded at 60 Hz with digital cameras (GRDVL-9800U, JVC), and one was enclosed in a waterproof housing (#6010.90, Ikelite), in order to obtain kinematic measurements. Passive reflective markers were placed on the participants' right side of the following bony landmarks: fifth metatarsal head, lateral malleolus, femoral epicondyle, greater trochanter, and 5 cm below the lateral projection of the Xiphoid process. The digitalization of all markers was performed using the Ariel Performance Analysis System (APAS) software (Ariel Dynamics, Inc.) and the reconstruction, filtering, and posterior analyses were performed using the Matlab software (Mathworks, Inc., version 6.5). The reconstruction of the real coordinates was performed using the direct linear transformation (DLT) procedure on land, and using a localized two-dimensional DLT procedure in water to account for refraction in the underwater video [7].

We registered the surface electromyographic activity (EMG) from eight muscles on the body's right side: tibialis anterior (TA), gastrocnemius medialis (GM), vastus lateralis (VL), long and short head of the biceps femoris (BFLH and BFSH, respectively), tensor fasciae latae (TFL), rectus-abdominis (RA), and erector spinae (ES) at the first lumbar vertebrae (L1 level) during the task. For such, we used passive disposable dual Ag/AgCl snap electrodes with a 1 cm diameter of each circular conductive area and a 2-cm center-to-center spacing (dual electrode #272, Noraxon). The electrodes were placed on the belly of each muscle along the muscle fiber direction after the skin area was shaved and cleansed with gauze soaked in alcohol. Extreme care was necessary to insulate electrodes for the water condition trials. For this, we used transparent dressing (Tegaderm, 3 M) placed over the electrode and the cable connection near the electrodes. The body segments near by the electrode areas and cables were slightly bandaged with elastic bands to avoid cable movement. The EMG signals were registered with an 8-channel telemetric EMG system (Telemyo 900, Noraxon), which had a gain of 1000 times, bandwidth (-3 dB) of 10–500 Hz, and common mode rejection ratio >85 dB.

We recorded the vertical and the anterior–posterior components of the ground reaction force (GRF) using force plates (OR6-2000, AMTI, on land, and a waterproof OR6-WP-1000, AMTI, in water). GRF and EMG signals were sampled at 1000 Hz using the APAS software and these signals were synchronized to the video images by a homemade trigger.

2.1. Data analysis

All data analyses were performed using the Matlab software. All the data were digitally filtered using a 4th order and zero-lag Butterworth filter. Kinematics data were low-pass filtered at 8 Hz for the trunk and hip markers and at 10 Hz for the knee, ankle, and foot markers, GRF data were low-pass filtered at 50 Hz. The EMG data were band-pass filtered at 20–400 Hz, and subsequently full-wave rectified and low-pass filtered at 5 Hz to obtain the linear envelope. Kinematics data were referenced by the participants' neutral angles measured during the calibration trial on land. GRF data were normalized by the participants' own body weight in each condition, also measured during the calibration trials (for the water condition, the measured vertical GRF during quiet standing in water is a result of the body weight minus buoyancy and it will be termed 'apparent body weight' from now on). The EMG data of each muscle were normalized by the mean value of the EMG data during the gait cycle in order to obtain the average pattern across participants. All the gait cycles were normalized in time from 0% to 100%, with a step of 1%. Then, these cycles were averaged to obtain the mean cycle for each participant and the same process was repeated to obtain the mean cycle among participants.

From the kinematics data, the following variables were obtained: stride length, duration, speed, support phase duration, ankle, knee, and hip joints range of motion (ROM), and foot, shank, thigh, and trunk segments ROM during each stride. From the GRF vertical component, we investigated the reduction of apparent body weight from land to water, the magnitudes of the two peaks and the valley, and the impact force, calculated as the slope of a linear fit by least squares of the first 100 ms of the vertical GRF versus time curve. From the anterior–posterior component, the impulse was calculated as the area under the force versus time curve during the support phase.

Four multivariate analyses of variance (MANOVA), having as factors one group and two conditions, the last factor considered as a repeated-measure, and as dependent variables stride length, duration, speed, and support phase duration for the first MANOVA; ankle, knee, and hip joints ROM for the second MANOVA; foot, shank, thigh, and trunk segments ROM for the third MANOVA; and first peak, second peak, valley, and impact force for the fourth MANOVA were employed. Two univariate analyses of variance (ANOVA), having as factors one group and two conditions, the last factor considered as repeated-measure, and as dependent variables body weight (apparent body weight for the water condition) and impulse were employed. An alpha level of 0.05 was used for all statistical tests, which were performed using the SPSS software (version 10.0).

3. Results

All participants were able to walk on land and in shallow water at the Xiphoid process level at self-selected comfortable speeds. Table 1 presents the mean (±1 SD) values of the temporal and spatial gait parameters. MANOVA revealed the difference between conditions, Wilks' Lambda = 0.004, $F(4,6) = 377$, $p < 0.001$. Univariate analyses indicated differences for stride duration, $F(1,9) = 414$, $p < 0.001$, and speed, $F(1,9) = 414$, $p < 0.001$. There was no difference for stride length, $F(1,9) = 4.10$, $p > 0.05$, and support phase duration, $F(1,9) = 3.72$, $p > 0.05$.

Table 1
Mean values (±1 SD) of temporal and spatial gait parameters during the stride cycle on land and in shallow water ($N = 10$)

	Land (mean ± SD)	Water (mean ± SD)
Duration (s)*	0.95 ± 0.01	2.41 ± 0.25
Length (m)	1.32 ± 0.13	1.19 ± 0.15
Speed (m/s)*	1.39 ± 0.14	0.50 ± 0.07
Support phase duration (%)	61.9 ± 1.9	60.4 ± 2.2

* $p < 0.001$.

The mean values (±1 SD) of body weight on the land condition and apparent body weight in the water condition were 556 ± 85 and 205 ± 32 N, respectively, which is significantly different (ANOVA, $F(1,9) = 404$, $p < 0.001$). The mean (±1 SD) apparent body weight reduction was 63.2 ± 1.9% across all participants.

Following are the results of joint and segmental angles patterns, GRF components, and respective variables, and EMG patterns. In order to compare stride duration in both conditions, additional horizontal axes were also added in each figure (upper portion) to indicate the mean non-normalized values of stride duration in each condition.

3.1. Joint and segmental angles

Fig. 2 depicts the mean (±1 SD) stride cycle of ankle, knee, and hip joint angle patterns of all participants walking on land and in water. Qualitatively all the joints seemed to have roughly similar patterns in both conditions. The ankle was more plantar flexed in water during the support phase (the first 60% of the stride cycle approximately) and at the end of the swing phase (the remaining 40% of the stride cycle approximately) than on land (Fig. 2, upper panel). The knee joint in water presented a reduced flexion during about the first 15% of the stride cycle (known as the weight acceptance phase during walking) compared to on land, and as a result, the knee was more extended in water than on land during the support phase (Fig. 2, middle panel). The hip joint in the water condition was similar to the condition on land with the exception of a flexion peak at the swing phase that was observed during walking in water (Fig. 2, bottom panel).

Fig. 3 shows the mean (±1 SD) stride cycle of the foot, shank, thigh, and trunk segmental angle patterns

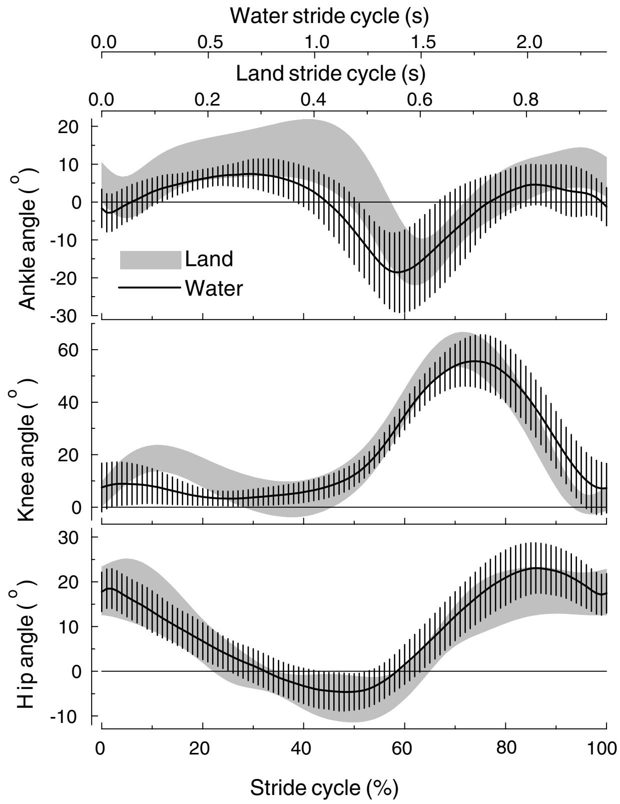

Fig. 2. Mean (±1 SD) stride cycle of ankle, knee, and hip joint angles for the participants walking on land (grey area) and in water (line). Positive values mean ankle dorsiflexion, knee and hip flexion, negative values mean ankle plantar flexion, knee and hip extension ($N = 10$).

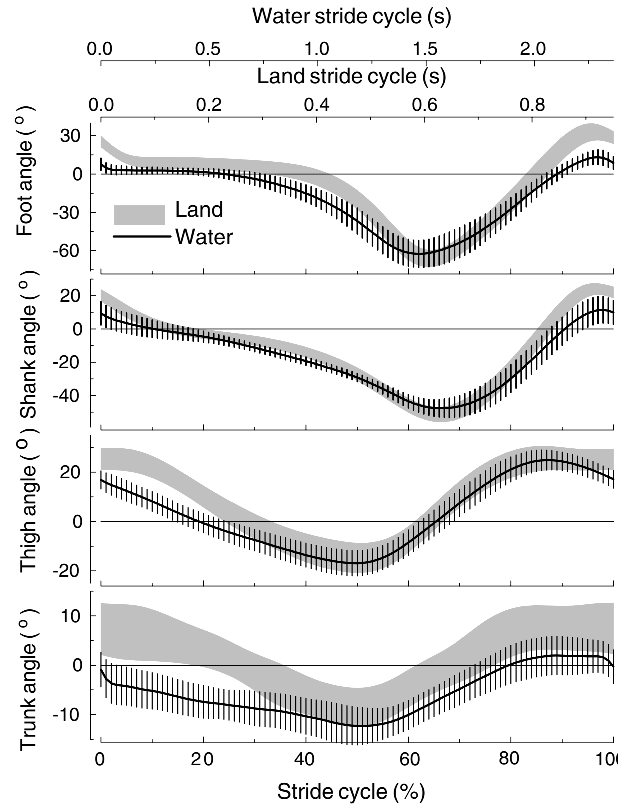

Fig. 3. Mean (±1 SD) stride cycle of the foot, leg, thigh, and trunk segmental angles for the participants walking on land (grey area) and in water (line). Positive values mean counter-clockwise (backward) rotation of the segments and negative values mean clockwise (forward) rotation of the segments ($N = 10$).

of all participants walking on land and in water. Qualitatively all the segments also seemed to have roughly similar patterns in both conditions with the difference that in water, the segments were more counterclockwise (backward) rotated throughout the entire stride cycle, particularly for the beginning and ending phases of the cycle, i.e., during the beginning and ending phases, the segments had a posture closer to neutral (the posture during the quiet standing trial).

Table 2 presents the mean values (±1 SD) for ankle, knee, and hip joint ranges of motion (ROM) and for foot, shank, thigh, and trunk segmental ROM. Regarding the joint ROM, participants presented the same ROM for all the three joints on land and in water (MANOVA, Wilks' Lambda = 0.400, $F(3,7) = 3.50$, $p > 0.05$) and regarding the segmental ROM, MANOVA showed a difference between conditions, Wilks' Lambda = 0.145, $F(4,6) = 8.83$, $p < 0.05$. Univariate analyses indicated differences for foot, $F(1,9) = 25.7$, $p < 0.005$, shank, $F(1,9) = 23.9$, $p < 0.005$, and trunk segments, $F(1,9) = 6.41$, $p < 0.05$.

3.2. Ground reaction force components

Fig. 4 presents the mean (±1 SD) stride cycle of vertical and anterior–posterior GRF components for all participants walking on land and in water during the stride cycle. The magnitudes of the data were normalized by the respective participant's body weight or the apparent body weight (water condition). The data from the water condition were also normalized by the body weight and are indicated in Fig. 4 by the right vertical axis.

Table 2
Mean values (±1 SD) of ankle, knee, and hip joint angles range of motion (ROM) and foot, shank, thigh, and trunk segmental angles ROM, during the stride cycle on land and in shallow water ($N = 10$)

	Land (mean ± SD)	Water (mean ± SD)
Joint angle ROM		
Ankle (°)	32.9 ± 4.1	32.3 ± 11.6
Knee (°)	61.4 ± 4.6	56.4 ± 8.7
Hip (°)	29.3 ± 7.0	29.6 ± 3.5
Segmental angle ROM		
Foot (°)*	100.7 ± 7.2	78.5 ± 14.3
Shank (°)*	76.8 ± 6.0	60.9 ± 6.7
Thigh (°)	42.4 ± 5.9	42.7 ± 3.9
Trunk (°)**	18.8 ± 3. 9	15.9 ± 4.1

* $p < 0.005$.
** $p < 0.05$.

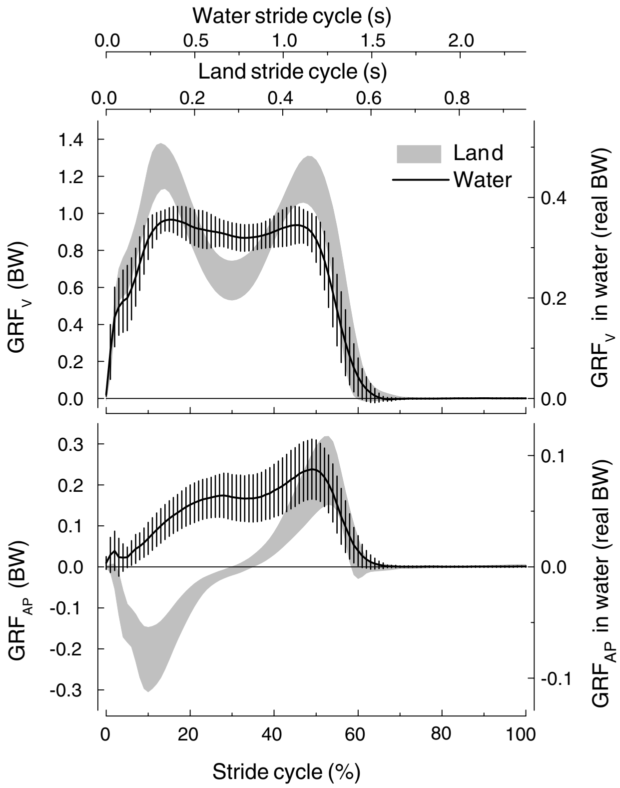

Fig. 4. Mean (±1 SD) stride cycle of the vertical (GRF$_V$) and anterior–posterior (GRF$_{AP}$) ground reaction forces for the participants walking on land (grey area) and in water (line). The left axis indicates the forces measured in units of body weight (BW) (apparent body weight for the water condition). The right axis indicates the forces in water measured in units of real body weight ($N = 10$).

Regarding the vertical GRF component pattern, one can observe in Fig. 4 (top panel) a typical pattern of two well-defined peaks and a valley when participants walked on land and a flatter curve with almost no distinction between the two peaks and the valley when they walked in water. The anterior–posterior GRF component patterns were also different between land and water conditions. The typical anterior–posterior GRF pattern observed during walking on land (Fig. 4, bottom panel) consisting of one negative phase followed by one positive phase, each with about the same areas, was not observed in the water condition. Instead, an always-positive curve was observed.

Table 3 presents the mean values (±1 SD) for the first and second peaks, valley, impact force, and impulse in normalized units. Regarding the vertical GRF component, MANOVA showed a difference between the conditions, Wilks' Lambda = 0.006, $F(4,6) = 263$, $p < 0.001$. Univariate analyses indicated differences for the first peak, $F(1,9) = 36.3$, $p < 0.001$, the second peak, $F(1,9) = 21.5$, $p < 0.005$, the valley, $F(1,9) = 22.5$, $p < 0.005$, and the impact force, $F(1,9) = 298$, $p < 0.001$. Regarding the horizontal impulse, ANOVA revealed a difference between the conditions, $F(1,9) = 114$, $p < 0.001$.

Table 3
Mean values (±1 SD) of the first and second peaks, and valley, in units of body weight (apparent body weight for the water condition), BW, impact force and impulse during the stride cycle on land and in shallow water ($N = 10$)

	Land (mean ± SD)	Water (mean ± SD)
1st peak (BW)*	1.27 ± 0.13	1.03 ± 0.08
2nd peak (BW)**	1.20 ± 0.14	1.01 ± 0.10
Valley (BW)**	0.63 ± 0.11	0.82 ± 0.08
Impact (BW/s)*	10.3 ± 1.9	5.41 ± 1.70
Impulse (BW.s)*	0.00 ± 0.01	0.20 ± 0.06

* $p < 0.001$.
** $p < 0.005$.

3.3. Muscle activation pattern

Fig. 5 shows the mean (±1 SD) stride cycle of the surface electromyographic (EMG) activation patterns from the eight selected muscles. The EMG activation patterns were different for most of the investigated muscles in water and on land. Regarding the water condition, the GM muscle was the only one that presented a similar

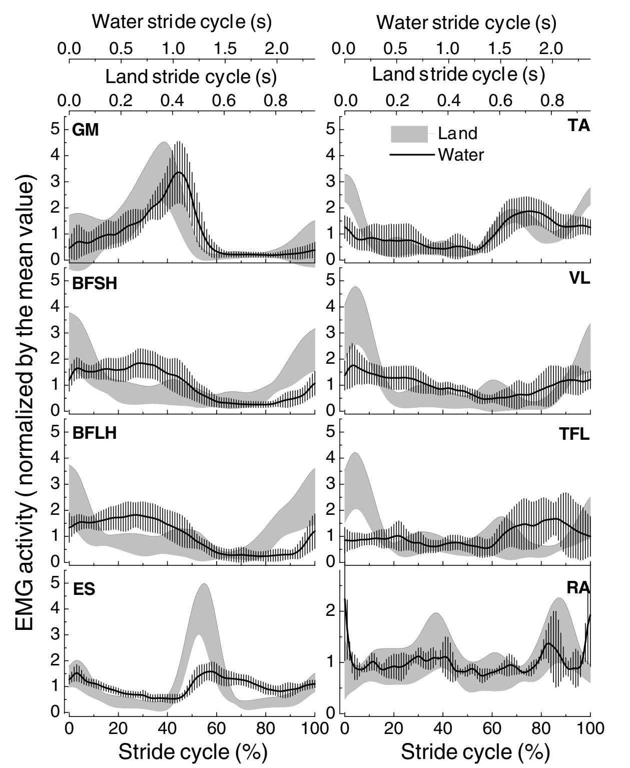

Fig. 5. Mean (±1 SD) stride cycle electromyographic (EMG) activity normalized by the mean value of the gastrocnemius medialis (GM), tibialis anterior (TA), short head of the biceps femoris (BFSH), vastus lateralis (VL), long head of the biceps femoris (BFLH), tensor fasciae latae (TFL), erector spinae at L1 level, and rectus-abdominis (RA) muscles for the participants walking on land (grey area) and in water (line) (for the water condition, $N = 3$ for RA and $N = 9$ for TFL; for the land condition, $N = 6$ for RA; and $N = 10$ for the remaining muscles in both conditions).

pattern to the land condition (but the peak activity in water was delayed at about 10% in relation to the on land condition). On one hand, the TA and TFL muscles were activated during the swing phase, and on the other hand, the BFSH, VL, and BFLH were activated during the support phase. The ES muscle was more activated at the end of the support phase and remained as such during the swing phase. The RA muscle seemed to be more activated at foot contact (extremes of the stride cycle); however, the present data was acquired only from three participants and in few trials for the water condition.

4. Discussion

In the present study, we examined adults walking at self-selected comfortable speeds in two different environmental conditions: on land and in water at the Xiphoid process level. Kinematics, ground reaction forces (GRF), and electromyographic (EMG) data were investigated in order to compare walking in both conditions.

According to the results, walking in shallow water was different from walking on land and the observed differences may be attributed to the water drag force during movement, lower apparent body weight in water, and the lower comfortable walking speed the subjects selected in water. Consequently, some of the differences we observed are not only due to the different conditions, but also due to the different speeds the subjects walked at, hence it has been shown that for walking (on land) the speed evokes changes in walking characteristics [1,6]. Nevertheless, stride length and the percentage of the support phase duration in relation to the stride duration remained about the same for the two conditions. Typically, on land, the support phase duration decreases as the walking speed increases [1]. Although we are comparing two different walking conditions, it is interesting to note that the large difference in speeds did not affect the support phase duration. This finding may suggest that other biomechanical variables affect the support phase duration.

Regarding to joint and segmental angle patterns, the relationship between adjacent segments did not change during the stride cycle for land or water conditions since no difference was found for any joint range of motion (ROM) between both conditions. On the other hand, in terms of segmental angles, the ROMs were different between both conditions for the foot, shank, and trunk segments. This difference is due mainly to the different segmental postures adopted by the participants while walking in water. Instead of keeping a more forward leaning position in water as on land, the subjects adopted a closer to neutral position, which may be attributed to the water drag force.

The vertical and the anterior–posterior GRF curves in the present study were found to be in accordance with previous investigations during walking on land [12,15] as well as during walking in water [10,11]. The reduction of both the walking speed and apparent body weight, but most influenced by speed reduction, explains the flat shape of the vertical GRF during walking in water, with almost no distinction between the peaks and valley in the vertical GRF that are typically observed during walking on land at normal speed. The vertical GRF impact on each participant's body was lower during walking in water than on land. This result supports the notion that this activity generates less impact on the human body when it is performed in water than when it is performed out of it. This impact force reduction is also explained by the observed reduction in walking speed and in the apparent body weight.

The anterior–posterior GRF component showed a very distinct pattern during walking in water and this finding is in accordance with a previous investigation [10]. For walking on land, generally a zero total horizontal impulse means that there was no change in the speed between the end and the beginning of the support phase. However, for walking in water, even for maintaining a constant speed it is necessary to generate an impulse to overcome the drag force in the horizontal direction exerted by water on the body. We hypothesized that this was the reason for the always-positive anterior–posterior GRF pattern during the stance phase observed in the bottom panel of Fig. 4. We estimated the drag force during walking in water and we observed that the magnitude of the anterior–posterior GRF component was indeed proportional to the water drag force, confirming our hypothesis.

Different EMG activation patterns were observed during walking in water in comparison to walking on land for most of the investigated muscles. It has been shown that the EMG activation patterns during walking on land vary under different speeds [3] as well as under body weight support [5]. The EMG activation patterns presented well-defined peaks of activity (phasic pattern) during walking on land, and instead, a flatter (tonic pattern) of EMG activations were observed in the water condition. Probably, this tonic EMG pattern is due to the very slow walking speed and due to the necessary constant muscle activation to overcome the drag force during walking in water. In addition, the apparent body weight reduction decreased the intensity of the loading and propulsive events during walking in water, which also may have contributed to the tonic pattern.

In summary, the present study quantified many biomechanical aspects of walking in water and compared them to walking on land. Differences were found between the two conditions, although we should be reminded that these differences were not only affected by the different environmental conditions, but also by the different walking speeds.

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Marcos Duarte graduated in 1989 with a BSc in Physics at the University of São Paulo (USP), Brazil. He gained an MSc degree, in 1992, and a PhD in Sciences, in 1994, at the same University at the Institute of Energetic and Nuclear Research's Optoelectronic Materials Division. In 1995, he was hired as an Assistant Professor at the School of Physical Education and Sport at USP, where, since 2001, he is an Associate Professor and coordinates the Laboratory of Biophysics. From 1997 till 1999, he was with the Biomechanics Laboratory at The Pennsylvania State University as a post-doctoral fellow. His main areas of research are in the interface between Biomechanics and Motor Control of human movement.