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Vertical reaction forces and kinematics of backward walking underwater

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ABSTRACT

The aim of this study was to compare the first and second peaks of the vertical ground reaction force (VGRF) and kinematics at initial contact (IC) and final stance (FS) during walking in one of two directions (forward $\times$ backward) and two environments (on land $\times$ underwater). Twenty-two adults (24.6 ± 2.6 years) walking forward (FW) and backward (BW) on a 7.5 m walkway with a central force plate. Underwater immersion was at the height of the Xiphoid process. Ten trials were performed for each condition giving a total of 40 trials where the VGRF and kinematic data were recorded. Two-way repeated measures analysis of covariance was used with a combination of environment and direction of walking: FW on land, FW underwater, BW on land and BW underwater (entered as between-subjects factor) and repeated measures of VGRF peaks (first and second) or angles (at IC and FS). Walking velocity was included as a covariate. Both VGRF peaks were reduced when participants walked underwater compared to on land ($p < .001$). For BW, in both environments, the second peak was lower than the first ($p < .001$; for both). During BW at IC the ankle is more dorsiflexed and the knee is more flexed, both on land and underwater. At FS, there was no difference between the ankle angle for FW and BW in both environments. At IC, in FW and BW the knee and hip are more flexed underwater. BW underwater involves a lower VGRF and more knee and hip flexion than BW on land.

1. Introduction

Hydrotherapy has been investigated as a form of treatment for various conditions including osteoarthritis [1], post-operative recovery after total hip-replacement surgery [2], chronic back pain [3] and coronary artery disease [4]. Similarly, its use has been studied for the prevention of physical changes accompanying the ageing process [5].

Numerous exercises have been proposed in widely varying programs of hydrotherapy, among them backward walking (BW), which is included in some rehabilitation protocols [1–5]. Walking backward on an underwater treadmill has been shown to elicit more electromyogram (EMG) activity in the paraspinal muscles compared to BW on land. When compared to forward walking (FW) on an underwater treadmill, BW elicits more paraspinal, vastus medialis and tibialis anterior activity as well as higher physiological and perceived exertion responses [6–8].

The aquatic environment presents the advantage of reducing weight bearing due to buoyancy, but this varies with the immersion level [9–11] and velocity of movement [12]. Despite reduction in vertical ground reaction forces (VGRF) in FW underwater, Barela et al. [11] did not find significant differences in the range of motion of the ankle, knee or hip joints comparing the FW kinematics on land and in water.

On land, several authors have explored BW kinematics [13–17] and EMG patterns during BW compared to FW [14–16]. Some studies have explored the temporal–spatial characteristics of BW [18], but few authors appear to have investigated the kinetics of backward walking [19] or running [20] on land.

In the case of rehabilitation, it is necessary to determine the load that the patient can tolerate based on the injury suffered; this load can then serve as a foundation for the prescription of walking underwater [21]. However, little is known about the loads generated on the locomotor apparatus during BW in an aquatic environment.

Forward walking (FW) has been studied for longer than BW and its characteristics are already well defined. The shape of the force $\times$ time curve for the VGRF recorded during FW on land resembles an "M", which demonstrates the presence of two clear force peaks with a deflection between them. The first force peak (FFP) of VGRF arises from the contact of the foot with the ground. The second force peak (SFP) corresponds to the propulsion phase of walking [22]. In the case of walking underwater the peaks are not as distinct and the curve takes the form of a trapezoid [9–11].

The physiological and biomechanical demands of BW and FW differ [15]. In BW the VGRF in the contact phase with the toes on the ground (FFP) is greater than the phase of foot lift (SFP) [19].

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To our knowledge, to date no studies have examined the dynamometry or angle kinematics of BW in an aquatic environment.

As a result, the motor behavior of BW both on land and in an aquatic environment needs to be better described so that health care professionals have a scientific foundation on which to base their prescription of this activity as a therapeutic exercise. The main aim of this study was to compare the magnitudes of the FFP and SFP of the VGRF and the ankle, knee and hip angle at initial contact (IC) and final stance (FS) corresponding to the FFP and SFP, under four walking conditions: combining two directions (forward $\times$ backward) and two environments (on land $\times$ underwater).

2. Methods

2.1. Participants

Twenty-two able-bodied adults (11 males and 11 females), with an average age of 24.6 ± 2.6 years, height of 1.71 ± 0.79 m, mass of 66.8 ± 11.2 kg, and Xiphoid process height of 1.20 ± 0.62 m participated in the study. Inclusion criteria were age between 20 and 30 years and familiarity with a water pool through aquatic exercise or swimming. Exclusion criteria were: presenting a neurological or musculoskeletal disorder at the time of the study; presenting a loss of balance; reporting pain in the lower limbs during walking. No subjects had to be excluded and all participants signed consent forms approved by the institution's Ethics Committee (protocol 159/2008).

2.2. Force plate

The kinetics data for walking were acquired through an extensometric force plate (dimensions 400 mm $\times$ 400 mm $\times$ 100 mm) developed based on Roesler [23] and constructed using electrical resistance gages (strain gages) with a sensitivity of 2 N, error less than 1%, a native frequency of 300 Hz and maximal load of 4000 N.

The force platform was connected to an ADS2000-IP system for data acquisition, conditioning, transformation and signal processing (AC2122, Lynx Tecnologia Eletrônica LTDA), consisting of a 16-channel multiplexed conditioning board, with a Wheatstone bridge; a 16-bit analog–digital converter with a maximum limit of 60 kHz; AqDados 7.02 software; and a portable microcomputer. A sampling frequency of 1200 Hz was selected for the data acquisition, with a gain of 2000 and a 1200 Hz hardware filter.

2.3. Data collection

Anthropometric measurements were taken by determining the body mass, subject height and height of the Xiphoid process. Reflective markers are placed at the fifth metatarsal head, lateral malleolus, femoral epicondyle, greater trochanter, and 5 cm below the lateral projection of the Xiphoid process. To collect the kinematic data underwater, black markers were fixed on the skin using waterproof adhesive tape (Farmafix) (Fig. 1C). The participants then familiarized themselves with the instruments of measurement and the experimental environment, particularly with the walkway. They were considered adapted when they could maintain their balance and exhibited a constant walking speed on backward walking, and stepped on the platform in the correct way. The number of trials required for the familiarization was between four and eight. A force platform was fixed to a wooden support at the center of the walkway (7.5 m in length and 0.5 m in width) so that it was at the same height as the walkway (Fig. 1A and B). Kinematic data were recorded with a Sanyo Xacti VPC-CA65 at 30 Hz. Subjects performed 10 valid trials, at a self-selected comfortable speed and walking barefooted in both environments. The trials were considered valid when subjects placed one of their feet on the force plate, without looking downward or reducing the rhythm of the movement. The number of valid trials required was determined in a pilot study [24]. For the underwater tests they walked in a water depth corresponding to the Xiphoid process height. Subjects walked forward and backward along a walkway with the arms crossed at the chest [19]. Data were collected on two differed days using the same procedures. For each group of subjects the first environment tested (land or water) was randomized. The room and water temperatures were controlled at 25 ± 1 °C and 30 ± 1 °C, respectively, during the data collection.

2.4. Data analysis

For each subject and each condition the following variables were analyzed for all 10 trials: FFP and SFP of the VGRF and the kinematic characteristics. In FW the FFP corresponds to the highest value registered on the first half of the force $\times$ time curve acquired from the force platform. The SFP is represented by the highest value recorded on the second half of the curve. The VGRF values were normalized to the body weight of the subject outside of the water. Following the acquisition of dynamometric data, these were exported to be treated using Scilab software (INRIA). The data were also passed through a *Butterworth* type low-pass filter using a cut-off frequency of 20 Hz and 3rd order.

Gait stride was cut using WinProducer (InterVideo® 3 DVD 3.1 version). In forward walking the stride begins with heel contact and finishes with the renewed contact of the same foot. In backward walking successive foot retractions are

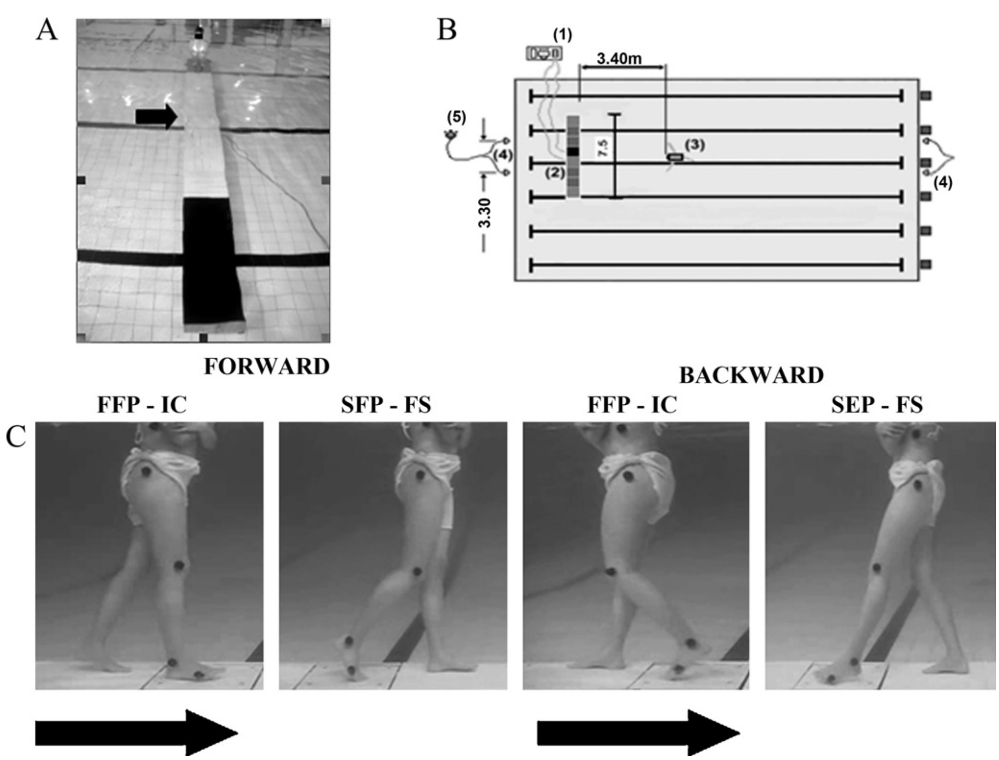

Fig. 1. (A) Walkway in which the force platform was inserted, indicated by the arrow. (B) Diagram to illustrate the data collection system in the aquatic environment: (1) acquisition system, (2) walkway, (3) video camera, (4) photocells, and (5) chronometer. (C) First force peak (FFP) and second force peak (SFP) with corresponding events related to initial contact (IC) and final support (FS), respectively, during forward and backward walking.

considered to cut a stride [19]. Markers in the video were digitized using APAS software (Ariel Dynamics, Inc.) and then kinematic data were low-pass filtered at 6 Hz using a Butterworth digital filter. Ankle, knee and hip joint at initial contact (IC) and final stance (FS) were identified by statistic analysis. Ankle angle was subtracted from the angular value in the neutral position [11].

2.5. Statistical analysis

Walking speeds were compared using one-way ANOVA with the Tukey post hoc test. The kinetic and kinematic characteristics of the two environments were compared using two-way repeated measures analysis of co-variance (ANCOVAs), considering as factors the four combinations of environment/direction of walking: FW land, BW land, FW underwater, BW underwater (entered as between-subjects factor) and repeated measures of peaks (FFP and SFP) or angles (at IC and FS). Since the ground reaction forces covaried with walking speed and this variable varies depending on both the environment (underwater and land) and walking direction (FW and BW), walking speed was controlled by including it as a covariate in the ANOVA design. When interactions occurred, an appropriate ANCOVA was separately applied followed by pairwise comparisons. Bonferroni adjustments were used during the post hoc analysis.

3. Results

3.1. Walking speed

Walking speed differed according to the conditions ($F_{3,\ 87} = 314.5$; $p < 0.001$). Tukey post hoc analysis showed that on land the speed for FW (1.22 ± 0.15 m/s) was greater than that for BW (0.70 ± 0.13 m/s; $p < 0.001$) and both of these were greater than the speed underwater (0.40 ± 0.07 and 0.32 ± 0.06 m/s, respectively, for FW and BW; $p < 0.001$ for both). Underwater there were not significant differences between FW and BW speeds.

3.2. First and second peaks of VGRF

Significant differences were observed in the peaks relating to the different walking conditions ($F_{3,\ 83} = 602.11$; $p < 0.001$). Overall, both peaks were lower underwater for both walking directions, with these decreases exceeding 66% (from 66% to 69%; Fig. 2).

Because the interaction observed between conditions and peaks ($F_{1,\ 83} = 122.15$; $p < 0.001$) a separate analysis was carried out for each environment. On land we found main effect of peak ($F_{1,\ 41} = 4.11$; $p = 0.04$) and direction ($F_{1,\ 41} = 15.45$; $p < 0.001$) and also there was an interaction between peak and direction ($F_{1,}\ 41 = 99.96$; $p < 0.001$). On land, for FW the FFP was smaller than the SFP (by ~8%) whereas for BW the FFP was larger than the SFP (by ~21%; $p < 0.001$; Figs. 2 and 3).

Underwater, no main effect was found in peaks or direction. However, since there was an interaction between peak and direction ($F_{1,\ 41} = 21.3$; $p < 0.001$) pairwise comparisons were made which showed that the FFP and SFP were similar for FW but different for BW. Underwater for BW the FFP was larger (~12%) than the SFP (post hoc, $p < 0.001$; Figs. 2 and 3).

3.3. Angles at initial contact (IC) and final stance (FS)

Qualitatively the ankle angular profiles for FW and BW differed, and to a lesser extent there were differences between environments (Fig. 4 – dashed lines compared with continuous lines). Because there was an interaction effect between ankle angle at IC and FS and walking direction ($F_{1,\ 81} = 18.3$; $p < 0.001$), a separate analysis was carried out for the IC and FS phases. At IC ankle angle

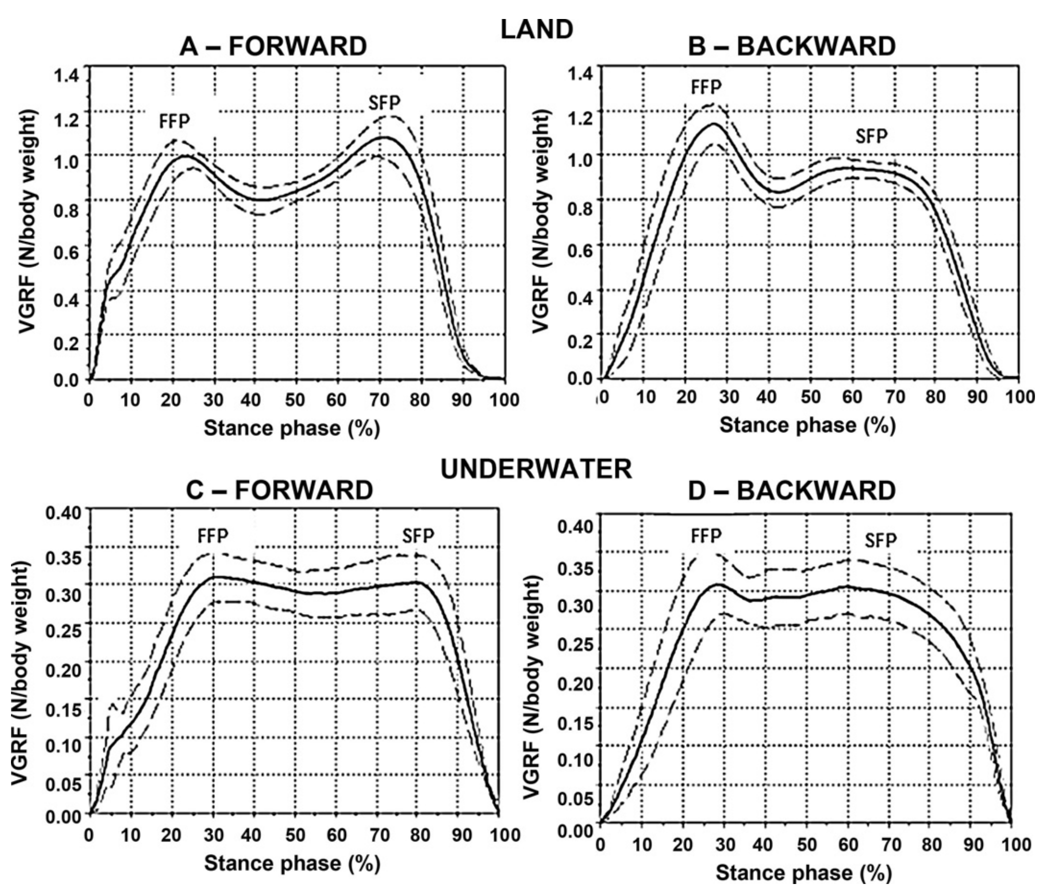

Fig. 2. Mean and standard deviation curves of vertical ground reaction forces (VGRF) on land and underwater: A and C in forward and B and D in backward direction. First force peak (FFP) and second force peak (SFP). Note the difference in the scales between on land and underwater, to enable comparison of the shape of the curves.

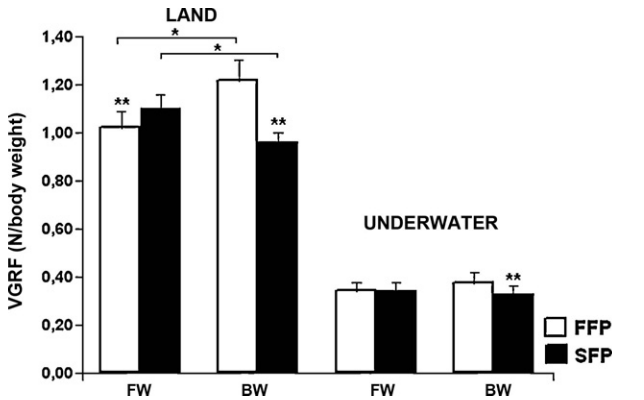

Fig. 3. Mean and standard deviation of vertical ground reaction forces (VGRF) in Newtons (N)/body weight: First force peak (FFP) in white and second force peak (SFP) in black. Forward (FW) and backward (BW) directions on land and underwater. *Significant differences between directions (FW × BW); **significant differences between peaks (FFP × SFP).

showed a greater dorsiflexion during BW ($F_{1,\ 81}$ = 18.4; $p < 0.001$) compared FW, without significant differences between environments (Table 1). At FS no differences were found for ankle angle for the different directions or environments.

The results showed an interaction effect between knee angle at IC and FS and walking direction ($F_{1,\ 81}$ = 534.9; $p < 0.001$). At IC the knee is more flexed during BW ($F_{1,\ 81}$ = 195.1; $p < 0.001$) compared FW, and also more flexed underwater compared to on land ($F_{1,\ 81}$ = 14.5; $p < 0.001$; Fig. 4 continuous and dashed lines). At FS the knee is more flexed during FW ($F_{1,\ 81}$ = 299.5; $p < 0.001$) compared to BW, and there were no significant differences between environments (Table 1).

For the hip angle an interaction effect was present between the IC and FS moments and walking direction ($F_{1,\ 81}$ = 3.11; $p < 0.001$). At IC, the hip angle was lower during BW compared to FW ($F_{1,\ 81}$ = 67.2; $p < 0.001$), and also was more flexed underwater compared to on land ($F_{1,\ 81}$ = 4.77; p = 0.03). At FS the hip angle was greater during BW ($F_{1,\ 81}$ = 81.8; $p < 0.001$) compared to FW.

4. Discussion

The objective of this study was to compare the first and second peaks of the VGRF and angular displacements of the ankle, knee and hip at initial contact and final stance in forward and backward walking on land or underwater.

On land walking speed was lower during BW compared to FW, but underwater the difference between the walking speeds during BW and FW was not significant, which is consistent with

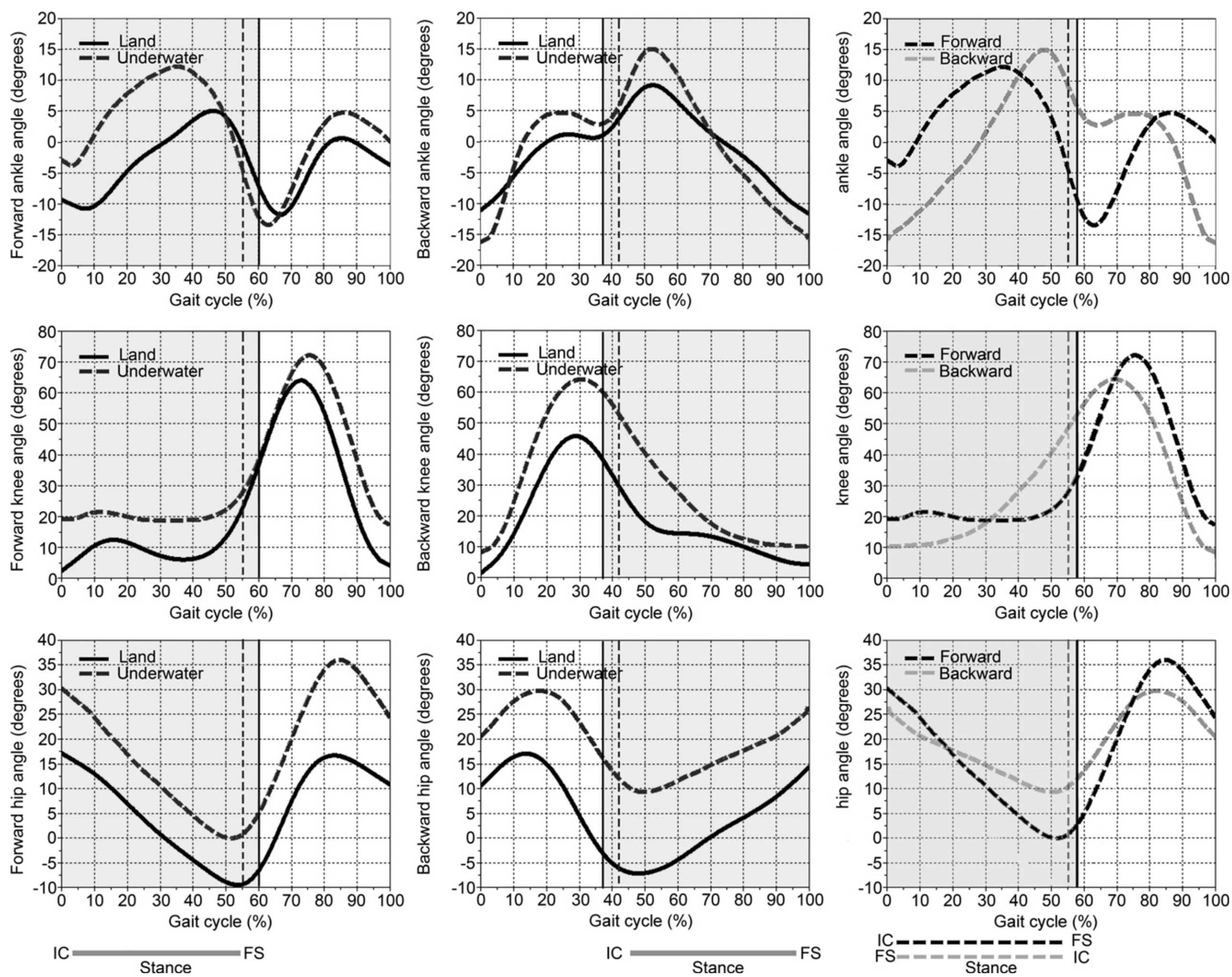

Fig. 4. Mean angular displacement for ankle (first line), knee (middle line) and hip (last line). Walking forward – FW (first column) and backward – BW (middle column) in the two environments. Continuous line represents walking on land and the dashed line walking underwater. Vertical lines indicate the moment when the final stance (FS) for FW and initial contact (IC) for BW occur, since the stride cut-off for BW was considered as the foot withdrawal. Last column: FW (black dashed line) and BW (gray dashed line) underwater. The BW data were plotted in the reverse direction, from right to left, to facilitate the comparison. Stance phase is colored in gray.

Table 1
Angular values at initial contact (IC) and final stance (FS) corresponding to the moments in which occurs first force peak (FFP) and second force peak (SFP) of vertical ground reaction forces in forward and backward direction on land and underwater.

	Forward				Backward			
	FFP-IC		SFP-FS		FFP-IC		SFP-FS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
On land								
Ankle (°)	−9.1*	3.6	−7.7	3.9	2.3	4.8	−11.1	11.5
Knee (°)	2.6*	2.1	39.9*	6.7	36.1	8.4	1.4	2.5
Hip (°)	17.2*	5.1	−5.8*	4.7	−3.9	9.8	10.1	6.1
Underwater								
Ankle (°)	−2.6*	9.1	−8.1	10.8	5.5	5.7	−15.1	12.3
Knee (°)	17.9*,**	8.6	28.8*	6.5	50.7**	8.4	7.0	3.5
Hip (°)	30.2*,**	8.4	1.3*	4.8	10.0**	6.8	19.5	5.6

* Significant differences for direction.
** Significant differences for environment.

previously reported results [25]. Differences between the walking speeds for FW and BW on land can be explained by BW being less practice than FW [15]. Also, subjects are more careful during BW on land, where the lack of forward vision can be challenging in terms of balance [7]. The absence of a difference between FW and BW speeds underwater may be related to the resistance offered by the water [25].

Despite the growing use of aquatic BW as a training resource [1–5,26], apart from velocity [25], neuromuscular parameters (EMG) [6,7], and spatiotemporal parameters [8], no previous studies have analyzed the ground reaction forces or angular kinematics of this activity.

Underwater, the force–time curve, representing the VGRF observed during FW, was similar to those described in the literature [9–11]. Both the FFP and SFP of the VGRF were lower underwater compared to on land. Reduction in walking speed and apparent body weight in water may be related to the flat shape of this curve during FW underwater [11].

The speeds for walking underwater were 33% and 46% of those for walking on land, respectively, for FW and BW. The speed for FW was similar to those observed in other studies [11,25]. The decreases of 67% and 69%, respectively, for the FFP and SFP of the VGRF during FW underwater compared with on land, are similar to values reported in the literature [9–11]. Barela et al. [11] found a comparative 60% reduction in the VGRF for the same immersion levels in water.

Compared to on land, the same effects are observed for BW underwater, that is, the environment reduces the VGRF by around 67%. As happens for FW underwater [11], for BW underwater the peaks are attenuated due to the reduction in apparent body weight and possibly a reduction in the speed of motion.

The second peak of the VGRF is lower than the first peak during BW in both environments. On land, for BW, the FFP is caused by loading with body weight and is greater than the SFP caused by the foot-off. This increase in the magnitude of the FFP during BW may be related to a more abrupt discharge of the ipsilateral limb at IC, since the center of mass appears to be already displaced to the back [19]. Also, while in FW the SFP at final support is related to a strong contraction of the plantar flexors for propulsion, during BW the force necessary for propulsion during FS (SFP) is generated mainly by the knee extensor musculature [15]. In BW the *plantigrade–digitigrade* sequence normally observed in FW is reversed and the first contact with the ground is made by the toes, while loss of contact can be through a heel-off or toe-off.

At IC during BW the ankle is more dorsiflexed (positive values) that during FW, irrespective the environment. On land other authors also found differences between FW and BW in terms of the ankle angle [15].

At final stance the ankle did not show differences according to walking direction, both on land and underwater. During BW some subjects left the force plate with the heel and others with the toes. Winter et al. [15] reported that the medial gastrocnemius shows an extra-activity burst immediately before the heel-off or toe-off. Although during BW the power has to be achieved by the dorsiflexors, instead of the plantar flexor, it may be that some subjects leave the ground with the toes due to biomechanical restrictions. Schneider et al. [27] observed an increase in the amplitude of the soleus H-reflex during the mid-swing phase of BW and proposed that this finding was related to the task. Underwater loss of contact at the end of stance phase can also be achieved by a heel-off or toes-off. Studies on the muscle activity during BW underwater have shown that the tibialis anterior and, at moderate speed, the gastrocnemius have an increase in activity [7], but this study did not analyze the kinematics and the significance of these findings is thus unclear.

As previously reported for walking on land [13–18], the differences in the kinematics of FW and BW underwater are mostly related to the ankle angle, with the knee and hip showing a reversed pattern with differences in amplitude.

Despite large differences between the ankle patterns for the two directions, for both FW and BW the waveform of the ankle is similar in the two environments. During FW the ankle angle at IC (or at FS) is similar when comparing on land with underwater. Barela and Duarte [28] found significant differences between walking on land and in water in relation to the ankle. They also observed differences in relation to the knee but not the hip, as was the case in our study. In the present study, at IC, during FW the knee is in a neutral position on land and semi-flexed underwater and the hip is more flexed underwater compared to on land. Also, for BW both the knee and hip are more flexed at IC underwater compared to on land. Differences in the results may also be related to differences in the age groups of the study subjects.BW on land has also been studied in a neurological population [29,30]. Since the water viscosity provides postural support [21] BW underwater can be safer than BW on land for use in a neurological population with balance problems. The applicability of BW underwater in cases of Parkinson disease and for stroke rehabilitation merits further study.

5. Conclusions

The reduction in the VGRF previously reported for FW underwater was also observed for BW underwater. Also, analysis of the differences between the first and second peaks in the VGRF showed that during BW underwater the forces are greater on contact compared to at push-off, as described for BW on land. Compared to FW, BW is associated with more dorsiflexion and knee flexion at IC both on land and underwater. Qualitatively, the overall kinematics waveform for BW on land is preserved underwater. However, underwater both the knee and hip are more flexed through the gait cycle. The additional information provided by this paper on the VGRF and kinematics during BW underwater may be of use to therapists in selecting the treatment strategies for patients.

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Conflict of interest statement

The authors of this study have no conflicts of interest to disclose.

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