Journal of Biomechanics 44 (2011) 1170–1175

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Joint forces and torques when walking in shallow water

Maria Isabel Veras Orselli, Marcos Duarte*

Institute of Physics and School of Physical Education and Sport, University of São Paulo, São Paulo, Brazil

ARTICLE INFO

Article history:
Accepted 12 January 2011

Keywords:
Biomechanics
Kinematics
Kinetics
Gait
Movement

ABSTRACT

This study reports for the first time an estimation of the internal net joint forces and torques on adults' lower limbs and pelvis when walking in shallow water, taking into account the drag forces generated by the movement of their bodies in the water and the equivalent data when they walk on land. A force plate and a video camera were used to perform a two-dimensional gait analysis at the sagittal plane of 10 healthy young adults walking at comfortable speeds on land and in water at a chest-high level. We estimated the drag force on each body segment and the joint forces and torques at the ankle, knee, and hip of the right side of their bodies using inverse dynamics. The observed subjects' apparent weight in water was about 35% of their weight on land and they were about 2.7 times slower when walking in water. When the subjects walked in water compared with walking on land, there were no differences in the angular displacements but there was a significant reduction in the joint torques which was related to the water's depth. The greatest reduction was observed for the ankle and then the knee and no reduction was observed for the hip. All joint powers were significantly reduced in water. The compressive and shear joint forces were on average about three times lower during walking in water than on land. These quantitative results substantiate the use of water as a safe environment for practicing low-impact exercises, particularly walking.

1. Introduction

Walking in water is commonly used as a low-impact exercise for training and rehabilitation (Heyneman and Premo, 1992; Prins and Cutner, 1999). From a biomechanical point of view, there are two principal reasons why walking in water may be beneficial: the decreased apparent body weight due to the buoyant force and the increased resistance to movement due to the drag force exerted by the water on the human body. Indeed, the apparent body weight in water (the gravitational force minus the buoyancy force) decreases to about one-third of the body weight when subjects walk in chest-deep water and to one-half in waist-deep water (Barela and Duarte, 2008; Barela et al., 2006; Harrison et al., 1992; Nakazawa et al., 1994). In addition, subjects are $2-3$ times slower when walking in water than when walking on land at comfortable speeds in both environments (Barela and Duarte, 2008; Barela et al., 2006).

However, quantitative and detailed evidence is scarce concerning the decrease of the internal mechanical loads on the musculoskeletal system when walking in water compared with land activity. The main obstacle to this type of quantification is that the procedure necessary to estimate the internal loads commonly employed in gait analysis requires the use of a force plate and video cameras under the water. Another obstacle to an accurate estimation of the internal mechanical load is that the drag force acting on each segment during movement must be estimated. To our knowledge, only Newman (1992) estimated the mechanical loads while taking into account the drag forces during walking and running in water. In fact, Newman studied completely submerged subjects walking on a treadmill and she was concerned with energetic estimation and did not calculate joint forces and torques. Other authors estimated the joint torques during the stance phase of walking in shallow water, but they did not take into account the water drag forces (Miyoshi et al., 2005). Bearing in mind this limitation, they determined that the ankle, knee, and hip torques were considerably lower when walking in water compared with walking on land at comfortable speeds.

Given the lack of information related to internal loads when walking in shallow water, the goal of this study is to estimate the internal net joint forces and torques on the lower limbs and pelvis when walking in shallow water compared with walking on land. We hypothesize that the internal net joint forces and torques are decreased when walking in shallow water compared with walking on land. This quantitative analysis will contribute to understand the actual mechanical demands of exercise training and rehabilitation in an aquatic environment.

2. Methods

2.1. Subjects

Ten young adults (six females, four males) volunteered for this study. All of them practiced physical activities at least twice a week and were free from known musculoskeletal, neurological, cardiac, or pulmonary illnesses. Their mean ± SD age, height, and mass were 24 ± 3 years, 168 ± 7 cm, and 63 ± 8 kg, respectively.

* Correspondence to: Escola de Educação Física e Esporte, Universidade de São Paulo, Av. Prof. Mello de Moraes, 65, São Paulo/SP 05508-030, Brazil.
Tel.: +55 11 3091 8735; fax: +55 11 381 35921.
E-mail addresses: mduarte@usp.br, mduartex@gmail.com (M. Duarte).

0021-9290/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2011.01.017

All participants signed an informed consent agreement previously approved by the local ethics committee.

2.2. Procedures and data acquisition

The experimental setup was designed to perform a two-dimensional gait analysis of one stride (gait cycle) of the participants walking. The experimental setup and procedures used to collect the data were similar as those reported elsewhere (Barela and Duarte, 2008; Barela et al., 2006). The participants walked on 10 occasions in bare feet at self-selected and comfortable speeds on a walkway in the laboratory (the land condition) and on a walkway in the swimming pool (the water condition). In the water condition, the participants walked in water at their chest level (Xiphoid process) and were instructed to keep their arms out of the water. The water temperature was maintained at 30 °C.

Passive reflective markers were placed on each participant's right side at the following points: head of the fifth metatarsal, calcaneous, lateral malleolus, knee joint interline, greater trochanter, iliac creast, and 5 cm below the lateral projection of the Xiphoid process. The participants' movement in the sagittal plane was recorded at 60 Hz with a digital video camera (GRDVL-9800U, JVC, Wayne, US). The ground reaction forces (GRF) were recorded at 100 Hz using a force plate embedded in each of the walkways (OR6-WP-1000, AMTI, Watertown, US). The videos were later digitized using the APAS software (Ariel Dynamics, Inc., Trabuco Canyon, US). The real coordinates were reconstructed using a direct linear transformation (DLT) algorithm in the land condition and a localized DLT algorithm to account for refraction in the water condition (Kwon, 1999) implemented in the Matlab 7.5 software (Mathworks Inc., Natick, US).

2.3. Inverse dynamics

Using inverse dynamics, we estimated the joint forces and torques at the ankle, knee, and hip on the right side of the body. We modeled the human body as a rigid body model in the sagittal plane with five segments (foot, leg, thigh, lower trunk, and middle trunk) and three hinge joints (ankle, knee, and hip). The equations of motion for the model were solved using the Newton – Euler formulation. We considered the following net forces (F) and torques (M) acting on the body segments: proximal and distal joint forces (F_{pj} and F_{dj}, respectively) and joint torques (M_{pj} and M_{dj}, respectively), force of gravity (F_G), GRF (acting only on the foot during the support phase), buoyancy (F_B), and drag (F_D) forces due to the environment (air or water, but these forces are negligible on the air) and their respective torques with respect to the proximal joint. From the Newton–Euler equations for the sagittal plane analysis, the general forms of the proximal joint force and torque are

$$\vec{F}_{pji} = m_i \vec{a}_i - \vec{F}_{dji} - \vec{F}_{Gi} - \vec{F}_{Bi} - \vec{F}_{Di}$$

$$\vec{M}_{pji} = I_i \vec{\alpha}_i - \vec{M}_{dji} - \vec{M}_{Gi} - \vec{M}_{Bi} - \vec{M}_{Di}$$

where the subscript i refers to the segment; m and I denote the mass and moment of inertia, respectively; a and α denote the linear and angular acceleration, respectively. For the foot segment, the distal joint force is the GRF and the distal joint torque is the torque due to GRF. To calculate the body segment parameters' mass, center of gravity, and moment of inertia of each segment, we used Zatsiorsky – Seluyanov's anthropometric model (Zatsiorsky, 2002) with the adjustments proposed by de Leva (1996).

2.4. Estimation of the drag force

For the estimation of the drag force on the subjects' foot, leg, and thigh of the right side and on the submerged part of their trunk, we modeled the body – fluid interaction as a stationary flow and we ignored any non-inertial effects such as added-mass terms. In addition, for the estimation of the drag force, we neglected the drag due to friction between the skin and water, and we only considered the pressure drag. Accordingly, the drag force (F_D) was modeled as

$$\vec{F}_D = -\frac{C_D \rho_m A_\perp v^2}{2}\hat{v}$$

where v^2 is the square of the segment velocity, $A_\perp$ is the projection of the frontal area in a plane perpendicular to the segment velocity, ρ_m is the water density, C_D is the drag coefficient, and $\hat{v}$ is a unitary vector in the direction of the segment velocity. We employed the strip theory to compute the drag force (Newman, 1977). In the strip theory, each body is divided into many thin strips on which the drag can be calculated, and the total drag is given as the sum of these individual drags. Accordingly, each solid used to model the body segment was divided in transverse sections in relation to the longitudinal axis. For each strip of frontal area $dA_\perp$, the infinitesimal drag force $d\vec{F}_D$ is given by (Fig. 1)

$$d\vec{F}_D = -\frac{C_D \rho_m v^2}{2} dA_\perp \hat{v}$$

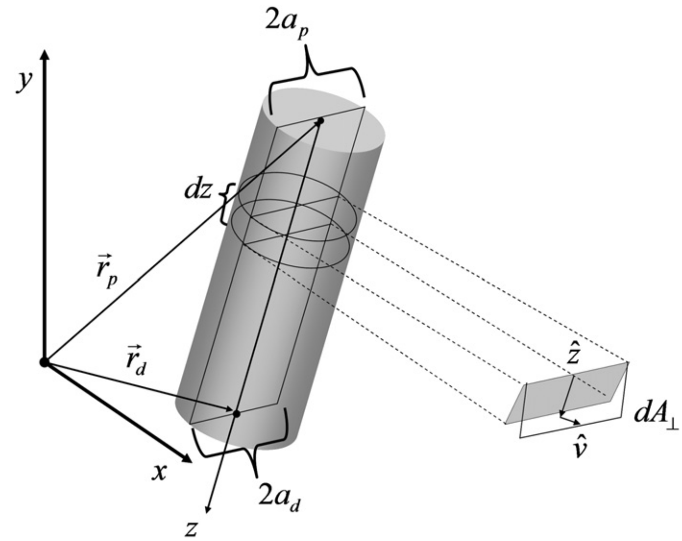

Fig. 1. Representation of a segment modeled as a truncated circular cone moving in space. $dA_\perp$ represents the projection of the frontal area perpendicular to the velocity $\hat{v}$ on that point of an infinitesimal strip. The x and y axes are given in the laboratory coordinate system and the z axis is the longitudinal axis in the local coordinate system with its origin at the proximal joint (the point around the torque is calculated for the distal segment).

It can be shown that the resultant drag force and torque acting on the segment are given by (see the Supplementary Material for more details)

$$\vec{F}_D = -\int_0^L C_D \rho_m \left[\frac{(a_d - a_p)z + a_p L}{L}\right] \left|\hat{z} \times \vec{v}(z)\right| \vec{v}(z) dz$$

$$\vec{M}_D = -\int_0^L C_D \rho_m z \left[\frac{(a_d - a_p)z + a_p L}{L}\right] \left|\hat{z} \times \vec{v}(z)\right| (\hat{z} \times \vec{v}(z)) dz$$

For the C_D coefficient, we adopted the value of 1. For the water density (ρ_m), we adopted the value of 1000 kg/m^3.

To verify the accuracy of the method for estimating the drag force, we compared the mechanical impulse on the body at the anterior–posterior direction due to the estimated total drag force (F_{Dap}) with the impulse of the anterior–posterior component of GRF (GRF_{ap}), adopted as the reference, in relation to the actual change of the body's momentum due to these forces (see the Supplementary Material for more details). If the estimation of the total drag force is accurate, we expect to find at the anterior–posterior direction an identity relation between the absolute value of the impulse due to the drag force and the impulse due to the GRF minus the change in the bodies' momentum.

2.5. Data analysis

We analyzed one gait stride per trial for each participant for a total of five strides in each condition. The data were digitally filtered and differentiated using a Savitz–Golay smoothing filter with appropriate window lengths. From the position data of the anatomical markers, we calculated position, velocity, and acceleration of the center of mass of each segment and of each joint at the sagittal plane. Joint angular displacements were referenced by the participants' neutral angles as measured during quiet standing trials in each condition. All the stride cycles were normalized in time from 0 to 100% in steps of 1%. These cycles were then averaged across trials to obtain the mean cycle for each participant and the same process was repeated to obtain the mean cycle among participants.

The following physical quantities are reported: the anterior–posterior and vertical components of GRF and angular displacement and velocity, joint power, internal net joint torque, and force at the ankle, knee, and hip. Joint power was calculated as the product of the torque and angular velocity of the joint. Positive joint power indicates that energy is generated and negative joint power that energy is absorbed by the joint. Force and joint power were normalized by the subjects' body weight (BW) measured during the quiet standing trial on land, and torques were normalized by the subjects' BW times leg length (LL). The following variables were calculated for the three joints in order to compare subjects' performance in both environments: range of motion, peak of absolute angular velocity, peak of flexor and extensor joint torques, peak of generation and absorption joint power, peak of joint force components, peak of vertical GRF component, and impulse due to the anterior posterior GRF component. In addition, stride period, length, and velocity were computed.

Paired t tests were employed to determine the differences due to the effect of the environment. The result of this test is reported together with the Cohen's d effect size. A significance level of 0.05 was adopted for all statistical tests.

3. Results

While standing still in chest-high water the subjects had an apparent weight of 214 ± 37 N, which represented 34.7 ± 3.2% BW. In water compared with on land, the subjects had similar stride lengths, but a significant longer stride period; consequently, they walked significantly slower in water than on land (Table 1). In relation to the stride cycle, the support phase was significantly shorter in water than on land. The peak of the vertical GRF was significantly lower in water. Of note, the pattern of the anterior–posterior GRF was qualitatively different in water than on land; in water, this component was always positive (meaning the subjects' force on the ground was always being applied backwards) and, as a result, the impulse of anterior–posterior component of GRF during support was significantly higher in water than on land (Table 1 and Fig. 2).

The ranges of motion of the ankle, knee, and hip joints were similar (p's > 0.05) in both environments, while the angular velocities were significantly lower in water than on land (p's < 0.05) for all three joints (Fig. 3 and Table 2).

With regards to the kinetic variables, significant differences between environments were found at the peak of the ankle flexion torque, peak of the ankle and knee extension torque, and at the peak of generation and absorption power for the three joints (p's < 0.05; Fig. 3 and Table 2). Peak values for compressive and shear joint forces occurred on the stance phase in both environments, and were significantly higher on land than in water for the three joints (p's < 0.05; Fig. 4 and Table 2).

The absolute value of the impulse due to drag force ($|I_D|$) and the impulse due to ground reaction force (I_{GRF}) minus the change in the body's momentum (Δp) at the anterior–posterior direction are similar (Fig. 5). The adjusted linear regression between these two terms suggests an identity relation: $|I_D| = [0.97 \pm 0.18(I_{GRF} - \Delta p) + 7.4 \pm 7.5]$ N s, with $\chi^2 = 9.9$ and adjusted $R^2 = 0.78$, $p < 0.001$. In addition, the angular coefficient was not statistically different from 1 ($p = 0.87$), and the linear coefficient was not statistically different from 0 ($p = 0.36$).

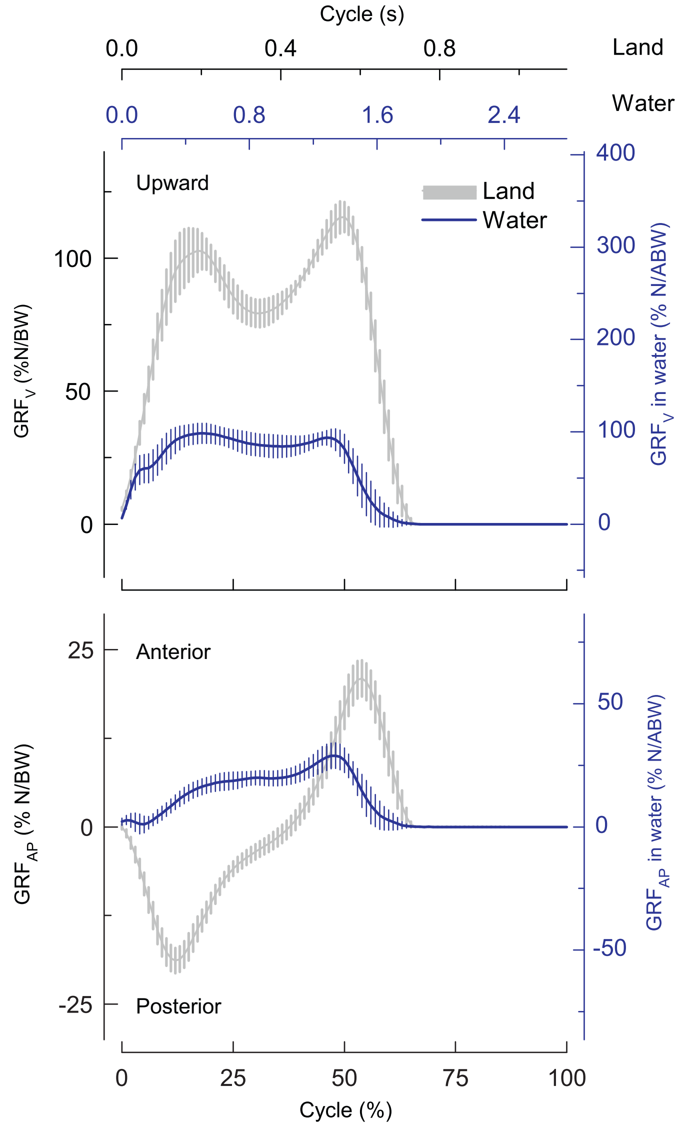

Fig. 2. Mean and standard deviation across subjects of the vertical (GRF_V) and anterior–posterior (GRF_{AP}) ground reaction forces while walking on land and in water. The right axis indicates the forces normalized by "apparent body weight" (ABW, body weight minus buoyancy force) and the top axes show the mean duration of a stride on land and in water in absolute units of time.

4. Discussion

This study reports for the first time an estimation of the joint forces and torques on the lower limbs and pelvis during a complete cycle of walking in shallow water, taking into account the drag forces generated by the movement of the body segments in water. The investigated subjects walked in chest-high water and at a comfortable speed resulting in an apparent weight in water of about 35% of their weight on land and they were about 2.7 times slower in the water than on land. We confirmed our initial hypothesis of a decrease in the internal net joint forces and torques on the lower limbs and pelvis when walking in shallow water compared with walking on land, with the exception of the hip joint torque, which presented similar values in both environments.

While walking in water, if on one side the buoyancy force reduces the apparent body weight leading to a reduction of the support forces, then on the other side the water drag leads to an increase of the forces necessary to propel the body forward against the water's resistance. Consequently, locomotion in water will not necessarily result in lower internal musculoskeletal loads in comparison to locomoting on land. The water's depth and moving velocity will mostly determine what will happen to the internal musculoskeletal loads. In the present study, walking in chest-high water at a comfortable speed resulted in a significant decrease in the internal musculoskeletal loads on the ankle, knee,

Table 1
Mean and standard deviation across subjects of spatio-temporal and ground reaction force (GRF) variables (normalized by body weight, BW) for walking on land and in water and the statistics for the comparisons between environments.

Variable	Environment		Statistics
	Land	Water	Effect size; p value
Stride length (m)	1.38 ± 0.08	1.28 ± 0.15	0.8; 0.079
Stride period (s)	1.12 ± 0.08	2.79 ± 0.30	7.5; < 0.001
Stride velocity (m/s)	1.23 ± 0.10	0.46 ± 0.04	10.3; < 0.001
Support phase duration (%)	63 ± 1	57 ± 3	2.3; < 0.001
Vertical GRF peak (% N/BW)	117 ± 6	37 ± 4	16.8; < 0.001
Impulse of anterior–posterior GRF (%N · s/BW)	−0.4 ± 0.5	9 ± 1	11.9; < 0.0001

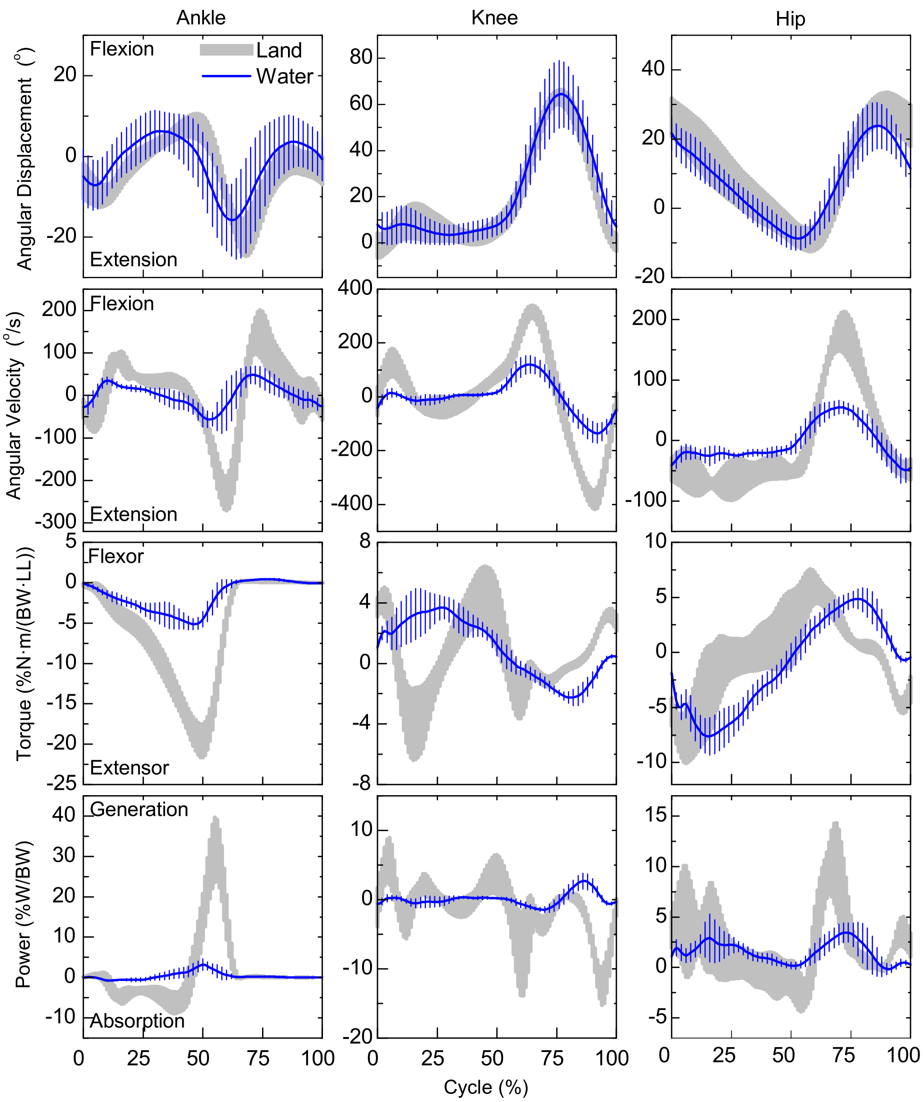

Fig. 3. Mean and standard deviation across subjects of the angular displacement, angular velocity, joint torque, and joint power of the ankle, knee, and hip joints at the sagittal plane while walking on land and in water.

and hip joints with no changes in their angular displacements. The observation that the subjects walked in water with the same kinematic pattern and range of motion of the ankle, knee, and hip joints is consistent with findings in the literature (Barela et al., 2006). However, due to the reduced walking speed, the subjects presented significant lower angular speeds for these joints in comparison to walking on land.

The flexor torques were similar for the knee and hip joints, while the extensor torques were considerably reduced for the ankle and knee joints, but not for the hip joint when the subjects walked in water versus walking on land. Joint powers were considerably reduced for all three joints when the subjects walked in water compared with walking on land. This reduction in joint power was due to the decrease in the joint torque and mainly to the decrease in angular speed. The alterations in joint torque patterns and the reduction in power are consistent with the alterations in muscle activity typically observed during walking in water at a comfortable speed (Barela et al., 2006; Masumoto and Mercer, 2008). For a detailed discussion in this topic, see the Supplementary Material.

The reduction in the joint torques was related to the water's depth. The greatest reduction was observed for the ankle and then the knee and no reduction was observed for the hip. This pattern suggests that the reduction is related to the relative change from land to water of the amount of apparent weight each joint should support. Similarly, the reduction in joint power was also larger for the ankle joint. The largest reductions of joint torque and power for the ankle joint during the support phase than for the other joints in the water compared with being on land are consistent with the understanding that the major role of the ankle joint is to support the body rather than to push the body forward during walking (Sutherland et al., 1980). The buoyancy force diminished the need for the ankle joint to provide support in water.

Despite the fact that the subjects walked slower in water than on land, the hip torque peaks did not differ between walking on land and in water during the support phase. Considering that the major function of the hip joint is to propel the body forward (Riley et al., 2001), the drag force during walking in water demanded more from the hip joint in order to execute its function, and this would explain why the hip torque peaks were similar in water and on land. These results and interpretations for the joint torques are partially in agreement with the work of Miyoshi et al. (2005) who also estimated the joint torques during walking in shallow water but only for the support phase and did not take into account the water drag forces.

Table 2
Group mean and standard deviation across subjects of the kinematic and kinetic variables for walking on land and in water and the statistics for the comparisons between environments.

Variable	Environment	Joint		
		Ankle	Knee	Hip
Range of motion (°)	Land	30 ± 5	65 ± 3	37 ± 4
	Water	30 ± 7	66 ± 15	37 ± 5
Effect size; *p* value		0.02; 0.93	0.08; 0.86	0.05; 0.88
Absolute angular velocity peak (°/s)	Land	242 ± 42	392 ± 32	183 ± 34
	Water	93 ± 21	157 ± 29	72 ± 16
Effect size, *p* value		4.5; < 0.001	7.6; < 0.001	4.1; < 0.001
Flexor torque peak (%N · m/(BW · LL))	Land	0.22 ± 0.10	5.3 ± 1.1	6.5 ± 1.8
	Water	0.49 ± 0.10	4.6 ± 1.0	5.4 ± 1.0
Effect size; *p* value		2.7; < 0.001	0.62; 0.21	0.78; 0.15
Extensor torque peak (%N · m/(BW · LL))	Land	19.8 ± 2.0	4.7 ± 1.8	8.4 ± 2.1
	Water	5.9 ± 0.7	2.5 ± 0.4	8.1 ± 1.7
Effect size; *p* value		9.3; < 0.001	1.7; < 0.01	0.21; 0.67
Generation power Peak (%W/BW)	Land	38.2 ± 8.2	7.3 ± 2.8	12.4 ± 3.6
	Water	4.6 ± 1.5	3.2 ± 1.2	5.0 ± 1.8
Effect size; *p* value		4.8; < 0.001	1.9; < 0.001	2.6; < 0.001
Absorption power Peak (%W/BW)	Land	8.4 ± 1.4	14.5 ± 2.9	4.5 ± 2.5
	Water	1.2 ± 0.3	2.0 ± 0.3	0.7 ± 0.3
Effect size; *p* value		7.3; < 0.001	6.2; < 0.001	2.1; < 0.01
Compressive joint Force peak (%N/BW)	Land	114 ± 6	106 ± 6	94 ± 5
	Water	38 ± 4	37 ± 4	36 ± 4
Effect size; *p* value		16.5; < 0.001	13.0; < 0.001	13.8; < 0.001
Shear joint force peak (%N/BW)	Land	34 ± 7	36 ± 5	23 ± 5
	Water	13 ± 4	9 ± 1	10 ± 3
Effect size; *p* value		4.0; < 0.001	8.3; < 0.001	3.0; < 0.001

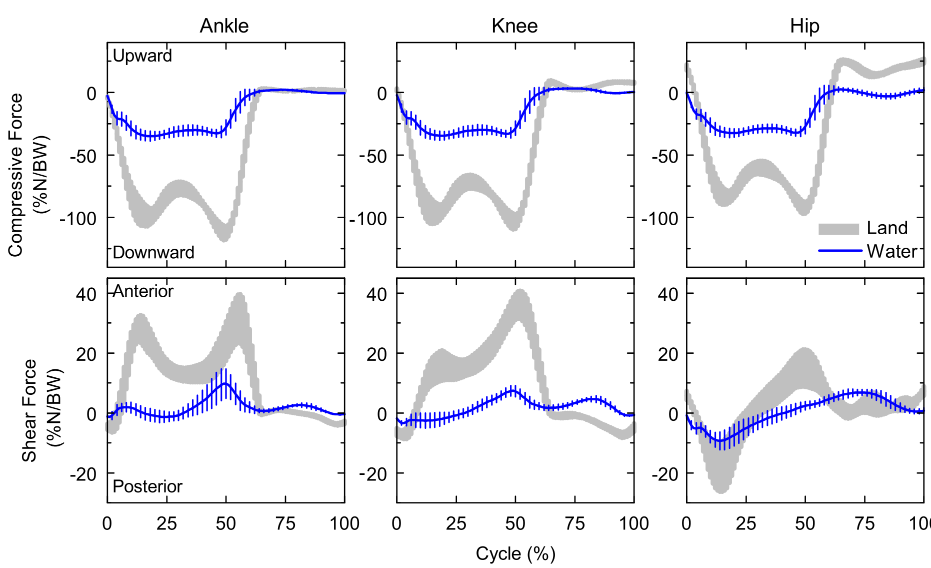

Fig. 4. Mean and standard deviation of the ankle, knee, and hip joint forces while walking on land and in shallow water. The components were calculated in the local frame of the distal segment and are decomposed in compressive and shear forces.

Both compressive and shear forces at the ankle, knee, and hip joints were significantly lower when the subjects walked in water than when they walked on land. The joint force peaks were about 3 times lower during walking in water than on land. The joint forces were larger and with similar patterns in the support phase of walking in both environments. At the swing phase, there were changes in the sign of both compressive and shear joint forces because of the almost zero apparent weight of the submerged segments in water and the need to move against the resistance of water. When the joint forces in water are normalized by the apparent body weight (which is about 35% of the weight on land), the forces on all joints in both environments become very similar (see Fig. 6 in the Supplementary Material), illustrating once more the effect of buoyancy force in reducing mechanical loads on the muscle–skeletal system. Of note, one could expect that the water drag force could have increased these mechanical loads, particularly the shear joint forces. Such an increase was not observed because when the subjects walked at comfortable speeds in both environments, they walked about 2.7 times slower in the water than on land, diminishing the drag force and its effect.

Concerning the limitations of this study, we estimated the internal mechanical loads during walking in water by employing a two-dimensional analysis at the sagittal plane. Certainly a three-dimensional analysis would provide a more accurate description of walking in water. However, we think the present study is justified, given the lack of information about this issue and the technical

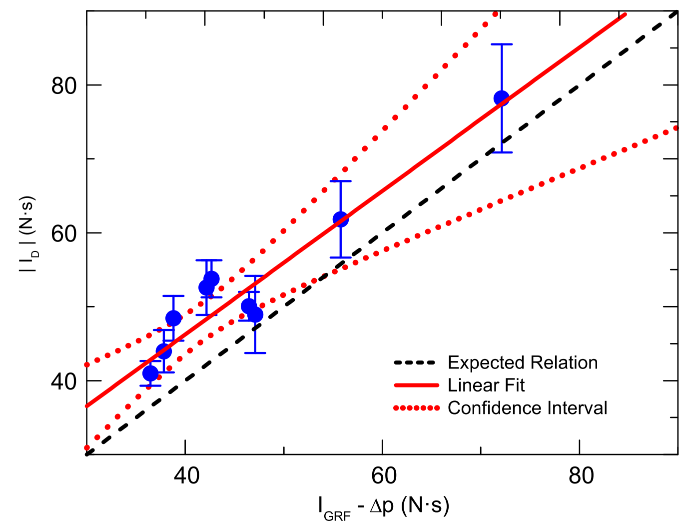

Fig. 5. Absolute value of impulse due to drag force ($|I_D|$) versus the impulse due to GRF minus the change in a body's momentum ($I_{GRF}-\Delta p$) at the anterior–posterior direction during the single support period of walking in shallow water.

difficulty of performing such an investigation. Furthermore, the observed differences between walking in water and on land were very large, and we do not expect to see any significant discrepancy of a three-dimensional analysis with the present results. In addition, even with the low speeds investigated in this study, it is worth investigating the contribution of inertial terms (added-mass terms) for a more accurate estimation of the drag force in water.

We verified the accuracy of the water drag force estimation by comparing the change in the whole body momentum, estimated by the total drag force acting on the body, and the one measured by the force plate (adopted as reference). We obtained a good agreement between these values, suggesting that the approximations taken for the calculus of the water drag force are valid. However, this procedure only compared the total value of the water drag force, and is not a validation of the drag force estimation acting on each segment at each instant.

As a whole, the present results confirm the use of water as a safe environment for practicing low-impact exercises, particularly for walking. There was no change in ankle, knee, and hip range of motion, but there was a considerable decrease in the joint force and torques on the ankle and knee joints. Although we did not observe a significant decrease in the hip joint torque, there was a significant decrease in the hip joint forces and so the present results also support the idea that patients with problems in their hip and pelvis structures could benefit from exercising in a water environment. However, all these results depend on the walking speed and water depth and these factors must be investigated for a greater understanding of the effect of the water environment on the human gait.

5. Conflict of interest statement

There are no conflicts of interest.

Acknowledgments

This work was made possible by a grant from Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP/Brazil) awarded to M. Duarte (08/10461-7) and by a scholarship from Conselho Nacional de Desenvolvimento e Pesquisa (CNPq/Brazil) to M. I. V. Orselli.

Appendix A. Supplementary Material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jbiomech.2011.01.017.

References

Barela, A.M., Duarte, M., 2008. Biomechanical characteristics of elderly individuals walking on land and in water. J. Electromyogr. Kinesiol. 18, 446–454.
Barela, A.M., Stolf, S.F., Duarte, M., 2006. Biomechanical characteristics of adults walking in shallow water and on land. J. Electromyogr. Kinesiol. 16, 250–256.
de Leva, P., 1996. Adjustments to Zatsiorsky–Seluyanov's segment inertia parameters. J. Biomech. 29, 1223–1230.
Harrison, R.A., Hillman, M., Bustrode, S., 1992. Loading of the lower limb when walking partially immersed: implications for clinical practice. Physiotherapy 78, 164–166.
Heyneman, C.A., Premo, D.E., 1992. A 'water walkers' exercise program for the elderly. Public Health Reports 107, 213–217.
Kwon, Y.-H., 1999. Object plane deformation due to refraction in 2-dimensional underwater motion analysis. J. Appl. Biomech. 15, 396–403.
Masumoto, K., Mercer, J.A., 2008. Biomechanics of human locomotion in water: an electomyographic analysis. Exerc. Sport Sci. Rev. 36, 160–169.
Miyoshi, T., Shirota, T., Yamamoto, S., Nakazawa, K., Akai, M., 2005. Functional roles of lower-limb joint moments while walking in water. Clin. Biomech. (Bristol., Avon.) 20, 194–201.
Nakazawa, K., Yano, H., Miyashita, M., 1994. Ground reaction forces during walking in water. Med. Sport Sci. 39, 28–34.
Newman, D.J., 1992. Human locomotion and energetics in simulated partial gravity. Unpublished Thesis Ph. D. Massachusetts Institute of Technology.
Newman, J.N., 1977. Marine Hydrodynamics. MIT Press, Cambridge, Mass.
Prins, J., Cutner, D., 1999. Aquatic therapy in the rehabilitation of athletic injuries. Clin. Sports Med. 18, 447–461.
Riley, P.O., Della Croce, U., Kerrigan, D.C., 2001. Propulsive adaptation to changing gait speed. J. Biomech. 34, 197–202.
Sutherland, D.H., Cooper, L., Daniel, D., 1980. The role of the ankle plantar flexors in normal walking. J. Bone Joint Surg. Am. 62, 354–363.
Zatsiorsky, V.M., 2002. Kinetics of Human Motion. Human Kinetics, Champaign, IL.