PHYSIOMECHANICAL MODEL OF SHALLOW WATER WALKING: DRAG AND BUOYANCY FORCES AFFECTING THE COST OF TRANSPORT

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Although the physiologic and biomechanical responses of shallow water walking (SWW) have been studied extensively, a physiomechanical model aiming to define the mechanical determinants of cost of transport (C) of SWW is lacking. Therefore, we investigated the SWW by healthy men at different speeds (0.2, 0.4, 0.6 m/s) and depths (knee, hip, umbilical, xiphoid). The objectives of this study were 1) to analyze the C response during SWW by healthy men and 2) to propose a physiomechanical model of SWW by determining the C response and its correlation with drag force and buoyancy forces during SWW. The C had a minimal value at intermediary speeds only in the knee depth, while in the other deeper depths, the C presented a monotonic rise with the speed increase. A minimum C was found at hip depth during 0.2 m/s, suggesting an optimization between the effects of buoyancy and drag forces at this condition. These findings could be applied in the exercise prescription of SWW for different populations, as indicators of the relative importance of hydrostatic and hydrodynamic forces effects on energy expenditure during SWW.

KEYWORDS: locomotion; physiomechanics; human aquatic locomotion; water immersion.

INTRODUCTION: Land activity is associated with a high incidence of injuries of various body regions and tissues (Parkkari, Kujala & Kannus, 2001). The aquatic exercise is a popular type of exercise to promote rehabilitation to the healing process and return to activity. One prevalent water exercise is shallow water walking (SWW).
The literature points out physiological and biomechanical alterations during SWW compared to dry land walking (Ivaniski-Mello et al., 2020). During the SWW the human body is under the effects of buoyancy and drag forces. These forces interact with the locomotor system affecting the physiological and biomechanical parameters of SWW.
One paramount parameter to comprehend the walking physiomechanics is the Cost of Transport (C) (Saibene & Minetti, 2003), a variable related to the energy expended to move a mass unit by a distance unit. The C - affected by the walking speed and task constraints - is strictly related to the inverted pendulum energy-saving mechanism in human species. The inverted pendulum mechanism is a mechanical energy transfer between body center of mass mechanical energies during stride cycle, which allows metabolic energy saving (Saibene & Minetti, 2003). Therefore, a physiomechanical understanding of speed and depth influence on SWW energy expenditure response could help to substantiate the practical application of this exercise.
The objectives of this study were 1) to analyze the C response during SWW and 2) to propose a physiomechanical model of SWW by determining the C response and its correlation with DrF and buoyancy forces during SWW at different walking speeds (0.2, 0.4, 0.6, 0.8 m/s) at different water immersion depths (knee, hip, umbilical, xiphoid) by healthy adult men.

METHODS: Nine men (28 ± 8 years, 77.7 ± 9.2 kg, 1.78 ± 0.04 m) were analyzed during the walking in shallow water. All subjects were healthy, without any neurological or musculoskeletal condition that could impair their walking ability. This study was approved by the local institutional ethics committee. All subjects were aware of the potential risks of the experimental protocol and gave their written informed consent. We registered the project at Open Society Foundations (DOI: 10.17605/OSF.IO/JFYXN).

The subject walked on the pool floor at four immersion depths (knee, hip, umbilical, xiphoid) at four fixed speeds (0.2, 0.4, 0.6 m/s) in each depth, randomly chosen. We also acquired anthropometric data from lower limb and trunk measures of lengths and perimeters. The walking speed was controlled by a timed audible stimulus and marked positions every 2.5 m on the border of the pool. We instructed the individual to perform the displacement from one marker to another accordingly to the audible stimulus synchronization.
The kinematic data were collected using a waterproof GoPro Hero 5 (GoPro Inc., San Matea, USA) at 60 Hz. Anatomical markers in the subjects' skin were marked. A rectangular calibrator of 2.1 x 1.6 m dimensions was used to calibrate the movement area. The videos were manually digitalized in SkillSpector v. 1.2.3 (Video4Coach, Copenhagen, Denmark) software. The position per time matrix were processed in a MATLAB (2012b, Mathworks Inc., Natick, Massachusetts, USA) routine (https://github.com/andreivaniskimello/Gait-Analysis). The kinematic data were filtered with a low-pass Butterworth filter of 4-5 Hz, second order. Five strides per subject in each speed condition were analyzed.
The O2 consumption and CO2 production were collected by a K5 wearable metabolic system (COSMED, Rome, Italy) in breath-by-breath mode, calibrated accordingly to manufacturer instructions. The respiratory gases response in rest orthostatic posture was collected during a five minutes period at each depth. The respiratory gases were collected during all the five minutes of walking, but only the last two minutes of the walking test was used for posterior analysis. The C (J/kg/m) was estimated by indirect calorimetry from the K5 data (Kipp, Byrnes & Kram, 2018).
Physiomechanical model: The physiomechanical model was developed from physiologic collected and kinetic estimated data during SWW. The physiologic data was C. The kinetic data was estimated from kinematic and anthropometric data collected experimentally. The kinetic variables were: drag force and mean vertical ground reaction force during stride cycle (mV-GRF).
The drag force (N) was estimated from the model of Orselli and Duarte (2011) using anthropometric and kinematic data. The drag force was calculated during all stride (contact and swing phases). We estimated the buoyance effect for each walking condition by predictive equations of mV-GRF (N) at each immersion depth. The mV-GRF, in turn, was determined considering it as equal to the subject weight (Minetti, 1998) and calculating the apparent body weight (% of dry land weight) for each depth (Kruel, 1994).
The results are presented as mean and 95% confidence interval (95% CI). A correlation was used to verify the relation between C with kinetic parameters (DrF and mV-GRF) in SPSS v.26 (IBM, Chicago, Illinois, USA).

RESULTS: The polynomial regression curve estimated from C at knee depth has presented a U-shaped pattern (Figure 1), distinctly from all other depths, which showed a monotonic C increase with the speed increase (not presented here). This minimal point at intermediary speed in knee depth is similar to dry land condition (Saibene & Minetti, 2003). Nevertheless, the minimum C at knee depth (2.6 J/kg/m, 0.32 m/s) occurred at a much slower walking speed than in dry land (3.89 J/kg/m, 1.02 m/s).
Our results also indicate a increase of C and drag force and a reduction of mV-GRF accompanying the depth increase (Figure 2). The correlation analysis showed a positive correlation of C with drag force ($r = 0.89$, $p < 0.001$), and negative correlation of C with mV-GRF ($r = -0.39$, $p < 0.001$). It should be noted also that the overall minimum point of C was at hip depth during 0.2 m/s walking (Figure 2A).

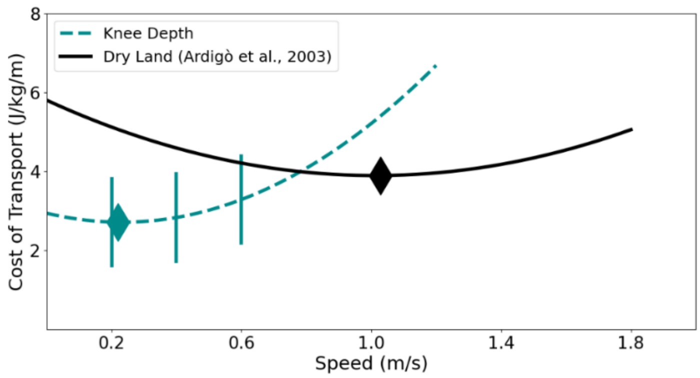

Figure 1: Cost of transport (J/kg/m) as a function of walking speed (m/s) at knee depth during SWW (blue) in comparison to dry land walking (black). The SWW data were collected experimentally with second order polynomial fit curve. The dry land data are from a polynomial function by Ardigò, Saibene & Minetti (2003). The diamonds are the minimum points of cost of transport for each condition. The vertical bars are the 95% CI for each speed condition obtained from experimental data.

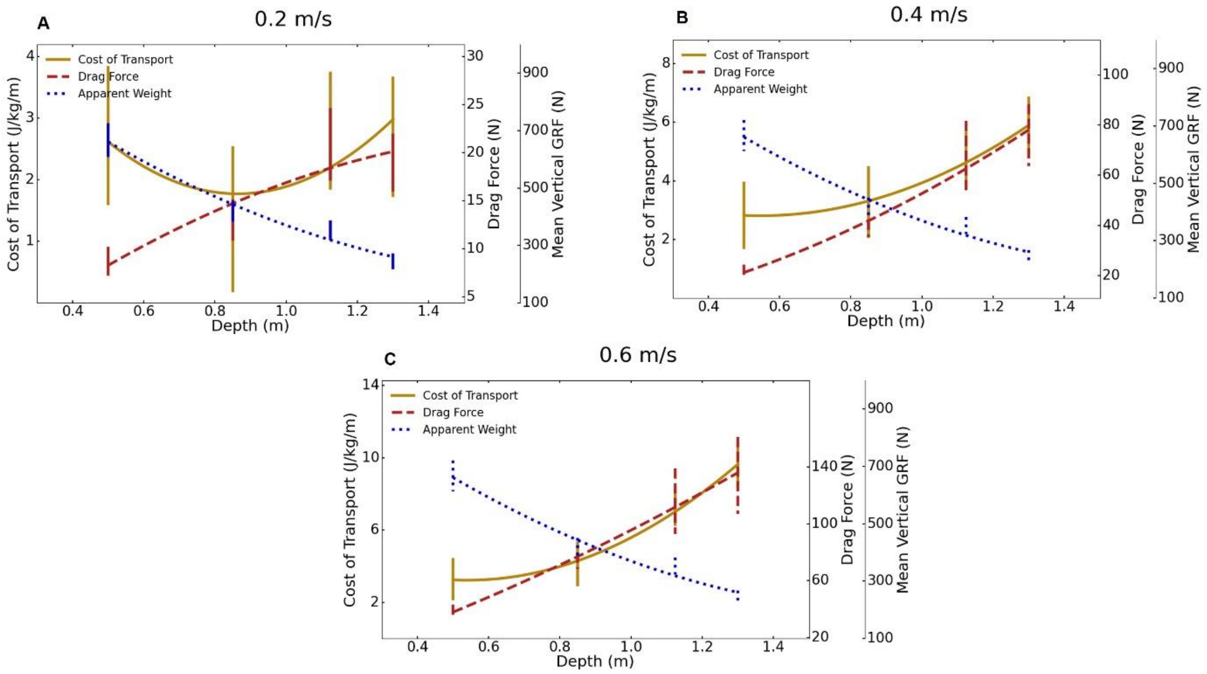

Figure 2: Cost of transport (yellow lines, J/kg/m), drag force (red lines, N) and mean vertical ground reaction force (blue lines, N) per depth of immersion (m) during shallow water walking at 0.2 m/s (A), 0.4 m/s (B), 0.6 m/s (C). The lines are plotted from 2º order polynomial fit calculated for each variable from experimental data. The vertical bars crossing the lines are the 95% confidence intervals for each depth condition obtained from experimental data.

DISCUSSION: The aims of the present study were to analyze the C response during SWW and to propose a physiomechanical model of SWW. The C during SWW had a minimal value at intermediary speeds only in the knee depth, while in the other deeper depths, the C presented a monotonic rise with the speed increase. Also, the C response in SWW seems to be related to the interplay between buoyancy and drag forces. It can be better observed by the minimum C point at hip depth during 0.2 m/s speed, suggesting an optimization between the effects of buoyancy and drag forces at this condition.

To our knowledge, this is the first study to propose a physiomechanical model of C response during SWW through a quantitative estimation of buoyancy and drag forces. We could observe an increase in similar trend of C curves along with drag force despite the mV-GRF reduction with depth increase (Figure 2). The higher correlation values of C corroborate this response more aligned with drag force than with mV-GRF (r=0.89 vs. r=-0.39, respectively). Therefore, the hydrodynamic characteristics of the SWW play a major role in C response than the attenuation of gravitational force effects due to buoyancy.

Despite the general trend of C rise accompanying the increase in both depth and speed, it is possible to observe a minimum point of C during SWW at hip depth at the 0.2 m/s. At hip depth, the apparent weight is reduced, facilitating the effort to move the body, while the magnitude of the drag force increase at this depth and speed is not large enough to provide such important dynamic resistance to the body segments movement. This optimal point of minimum C may not occur at faster speeds as a result of the stronger resistance of drag force. As could be observed by the findings of Pohl & McNaughton (2003), who found higher values for oxygen consumption during walking at thigh depth in comparison to waist level of immersion during walking at 1.1 m/s at underwater treadmill. Alkurdi et al. (2010) reported a reduction of energy expenditure with increasing immersion level above xiphoid; however, they evaluated SWW at underwater treadmill, which could be interpreted a biomechanical distinct condition from pool floor SWW (Gleim & Nicholas, 1989).

These findings could be applied in the exercise prescription of SWW for different populations as indicators of the relative importance of hydrostatic and hydrodynamic forces effects on energy expenditure during SWW.

CONCLUSION: Our results demonstrated that C had a minimal value at intermediary speeds only in the knee depth. In the other deeper depths, the C presented a monotonic rise with the speed increase. A minimum C point at hip depth during 0.2 m/s speed was found, suggesting an optimization between the effects of buoyancy and drag forces at this condition.

To our knowledge, this is the first study to develop a SWW physiomechanical model using C measures and drag and buoyancy forces estimation involved during SWW. Future studies testing this physiomechanical model in other depths, speeds, and populations are suggested.

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