Energy Consumption and Observational Biomechanical Analysis of Human Gait at Different Water Depths

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Abstract*–Natural disasters such as hurricanes, tsunamis, and severe flooding present extreme environmental constraints that significantly disrupt normal human locomotion. During pedestrian emergency evacuations, rising water levels impose physical burdens on the human body, including hydrodynamic drag resistance, buoyancy, and postural instability. This study investigates the energetic and biomechanical performance of human gait across varying water immersion depths as a follow-up to previous work on this topic. Four healthy adult participants completed controlled dynamic walking trials across four environmental conditions: baseline (no water), ankle depth, knee depth, and waist depth. Energy consumption, specifically oxygen consumption (VO2) and completion velocity, was measured using a wireless portable spirometer (VO2 Master). Synchronized dual-plane underwater and surface video recordings were captured and analyzed using observational gait analysis to assess lower-limb motion adaptations. Results indicate an inverse relationship between immersion depth and walking velocity. While velocity progressively decreased in deeper water (dropping from an average of ~93.7 ft/min in dry conditions to ~71.7 ft/min at waist depth), oxygen consumption spiked at intermediate depths (knee level averaging ~22.0 ml/kg/min compared to ~10.8 ml/kg/min on dry ground), then dropped, repeating the behavior observed in the previous work. Kinematic visual analysis revealed distinct compensatory adaptations, including increased knee flexion, hip circumduction, and shortened gait cycles. These findings provide empirical data on human physical thresholds during flood evacuations, offering critical insights for disaster management strategies, urban evacuation modeling, and aquatic rehabilitation design.

***Keywords*—Biomechanics, Tsunamis, Oxygen Consumption, Observational Gait Analysis.**

I. Introduction

Movement is a fundamental characteristic of human life, arising from coordinated muscle activity acting upon the skeleton under central nervous system control. In unconstrained terrestrial environments, human walking is a highly optimized, energy-efficient motor pattern. However, catastrophic natural hazards alter environmental conditions and severely impair normal locomotion. Island territories such as Puerto Rico, situated near the active subduction zone of the Puerto Rico Trench between the Caribbean and North American tectonic plates, face heightened exposure to earthquakes, tsunamis, and severe weather events. Tropical cyclones, hurricanes, and heavy rainfall frequently trigger widespread urban and riverine flooding, creating hazardous wading conditions for vulnerable populations during emergency evacuations [1], [2].

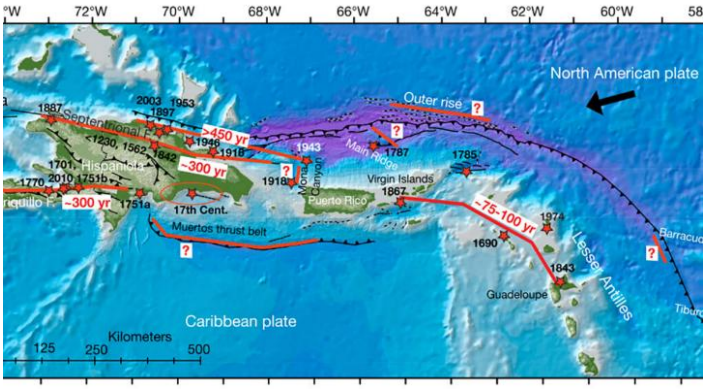


Fig. 1. Map of the North American-Caribbean tectonic plate boundary [2].

When individuals navigate flooded pathways, partial water immersion introduces fluid forces that modify normal gait mechanics. Hydrodynamic drag opposes limb advancement during the swing phase, while hydrostatic pressure and buoyancy reduce effective body weight and foot-ground traction during the stance phase. To overcome these opposing physical constraints and maintain dynamic balance, individuals adjust their stepping behavior. Recent studies demonstrate that increasing water depth decreases walking speed, shortens stride length, and increases lateral trunk oscillations [3]. However, a critical need remains to quantify the exact physiological energy expenditure and kinematic compensations associated with progressive water levels during simulated disaster scenarios.

This study, conducted through an interdisciplinary collaboration between the Department of Biomedical Engineering and the Department of Civil Engineering at the Polytechnic University of Puerto Rico under the HSI STEM Program, evaluates human metabolic performance and gait biomechanics across four water immersion levels: no water (baseline), ankle level, knee level, and waist level. By measuring oxygen consumption (VO2), walking speed, and joint kinematics through observational gait analysis, this research aims to generate scientific evidence to improve pedestrian evacuation modeling and support public safety infrastructure design.

II. Referential Markup

A. Human Gait Cycle and Kinematics

The human gait cycle is defined as the time interval between two successive initial contacts of the same foot. It comprises two primary phases: the stance phase (~60–65% of the cycle), where the foot remains in contact with the supporting surface, and the swing phase (~35–40% of the cycle), where the foot is elevated and advances forward [4]. These phases are further categorized into eight functional subphases: initial contact (foot or heel contact), loading response, midstance, terminal stance, preswing, initial swing, midswing, and terminal swing [5].

Under dry conditions, these subphases coordinate smooth forward movement of the body's center of mass (COM). In aquatic environments, fluid resistance creates forces proportional to the square of limb velocity and frontal surface area. During the swing phase, fluid drag severely inhibits leg swing, forcing compensatory joint movements to achieve clearance [6].

B. Metabolic Parameters and Oxygen Consumption

Physiological energy expenditure during locomotion is directly linked to muscular exertion and metabolic substrate oxidation. Indirect calorimetry measures oxygen consumption (VO_2, expressed in ml/kg/min) to determine aerobic energy expenditure. While VO_2 measures the rate of energy expenditure per unit of time, Oxygen Cost (eq. 1) assesses functional efficiency per unit of distance traveled (ml/kg/m):

$$Oxygen\ Cost = VO_2 / Walking\ Velocity \quad (1)$$

A higher oxygen cost reflects reduced gait efficiency, indicating that a person expends greater metabolic energy to travel a given distance. In flooded environments, fluid drag forces subjects to exert more muscular work at lower speeds, increasing oxygen cost and accelerating fatigue.

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C. Observational Gait Analysis

Every biomechanical analysis of human movement begins with observing the movement to be studied and identifying the events, phases, and characteristics that will later serve as references for numerical studies. This first phase of observation allows initial inferences about the origin and causes of movement, the reasons for its patterns, and the internal and external factors influencing body segment arrangements during movement [5].

In human gait, observational analysis has made it possible to describe the different events, phases, and sub-phases of the gait cycle, infer muscular activity, and understand the interaction with the ground reaction force that drives it. Together, these factors, along with the external environment, make it possible to define the requirements and prerequisites of normal gait.

Various protocols have been developed for gait analysis [7] from video observation [8], as shown in Figure 2; this work uses Observational Gait Analysis (OGA) [5]. This method uses a video recording of a study subject walking in a straight line, with sagittal and coronal planes superimposed on a single screen and progressive close-ups from full-body to detailed views of the feet. See Figure 3.



Fig. 2 Observational analysis camera setup [5].



Fig. 3 Observational analysis using 2-camera (sagittal and coronal plane) video recording [5].

This video recording is used as a source of information for a questionnaire that starts from the contact of the foot with the ground to the general aspect of the trunk in full body, and where the questions include interaction between planes and some estimates of angle values that are then contrasted with those expected in normal gait. The analysis that comes out of the conclusions and findings of the questions asked in the method results in a first approximation to the description of kinematics and spatiotemporal variables of the gait pattern under study, and that is complemented, to the extent necessary, with the results of instrumented motion capture (MOCAP) systems [5].

D. Previous work

This work continues a first part in which we carried out a case study to evaluate oxygen consumption behavior for a single subject and refine the methodology [6], which was presented at the 2026 edition of this conference.

In the previous work (see Figure 4), a drop in oxygen consumption and cost of O2 was observed when the water was at waist level (light blue), which was contrary to what was expected given a progressive increase in VO2 & cost of O2 and a decrease in walking speed as the water level rose (see orange -baseline-, grey -ankle-, and yellow -knee- in Figure 4).

The subject reported gait compensations, which prompted a repeat of the study, incorporating video recording to observe underwater gait and infer walking kinematics. To improve the repeatability of the results and in accordance with the recommendations, the number of subjects was increased.

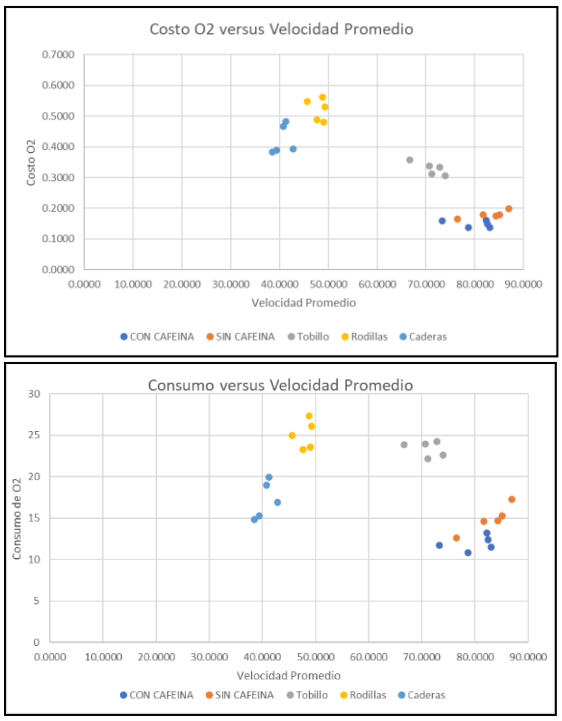


Fig. 4 Oxygen consumption (VO2) (top) and cost of O2 (bottom) vs. gait velocity for the subject of previous work [6].

III. Methodology

A. Participant Recruitment

Four healthy Biomedical Engineering students (two female, two male; ages 20-23 years) participated voluntarily after providing informed consent. We recorded anthropometric measurements to determine appropriate immersion depths for each participant and standardize experimental conditions.

B. Experimental Setup

Testing was conducted in a controlled swimming pool environment under four walking conditions (see Figure 5): baseline (no water), ankle-depth, knee-depth, and waist-depth water. Throughout the experiment, a portable VO_2 Master metabolic analyzer, synchronized video cameras, a measuring tape, and a stopwatch were used throughout the experiment.



Fig. 5 Example of the 4 walking conditions (levels), mimicking different flood levels: (A) No Water, (B) Ankles, (C) Knees, and (D) Waist [6].

C. Walking Protocol

Each participant completed a standardized Six-Minute Walk Test (6MWT) consisting of one minute seated, one minute standing, six minutes of walking, and eight minutes of recovery. The VO_2 for each test was obtained as the average of the readings given by the spirometer in the last 3 minutes of the walking phase, since these are in the steady-state zone of the oxygen consumption curve according to the kinetic equation for physical performance at sustained loads [9]. Figure 6 illustrates the 6MWT protocol.

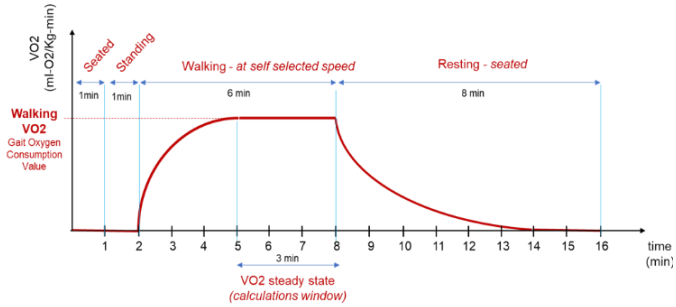


Fig. 6 6MWT protocol and the timing of its phases [5].

The complete protocol was repeated five times under every experimental condition to improve measurement reliability.

Throughout all sessions, participants wore casual clothing and sports shoes, and each subject used the same set for all water levels.

D. Data Acquisition

Physiological variables including oxygen consumption (VO_2) and oxygen cost were continuously recorded during the MWT. Simultaneously, frontal and lateral video recordings were captured (GoPro video cameras) using a special camera mount on a mobile setup designed for use in the pool (as shown in Figure 7) to enable observational gait analysis of gait cycle phases, subphases, and descriptive kinematics.

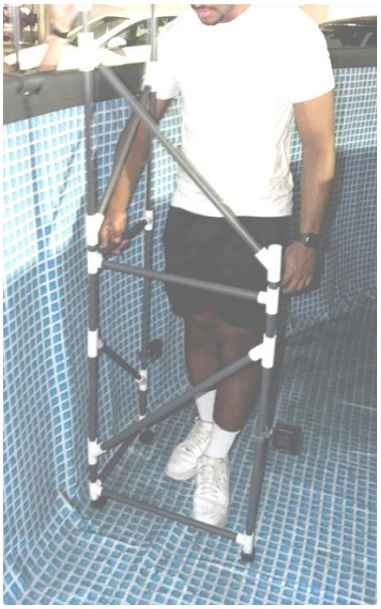


Fig. 7 Camera mounting.

E. *Data Analysis*

Descriptive statistics were used to compare metabolic and spatiotemporal variables across immersion levels. Observational gait analysis identified compensatory movement patterns associated with increasing water depth, allowing relationships between water immersion and locomotor performance to be established.

IV. Analysis and Results

A. *Walking Speed and Velocity Trends*

The experimental data demonstrated a clear inverse relationship between water depth and self-selected walking velocity across all four participants. As summarized in Table I, average walking velocity decreased progressively from dry baseline conditions to deeper water levels (consistent with Rivera [6] and Dias [3]). As shown in Figure 8. Shows the behavior of average VO2, repeating the findings of Rivera [6].

TABLE I
AVERAGE METABOLIC AND SPATIAL-TEMPORAL PERFORMANCE ACROSS WATER DEPTH

Water Depth Condition	Average Velocity (ft/min)	Average VO_2 (ml/kg/min)	Average Cost O_2 (ml/kg/ft)	Relative Velocity Reduction (%)
No Water (Baseline)	93.7	10.8	0.115	0.0%
Ankle Level	81.2	10.0	0.123	-13.3%
Knee Level	72.1	22.0	0.305	-23.1%
Waist Level	71.7	19.7	0.275	-23.5%

Participants achieved their highest speeds on dry ground (~93.7 ft/min). Walking speed dropped by 13.3% at ankle depth (~81.2 ft/min) and reached a threshold reduction at knee (~72.1 ft/min) and waist levels (~71.7 ft/min), representing a ~23.5% overall velocity decline.

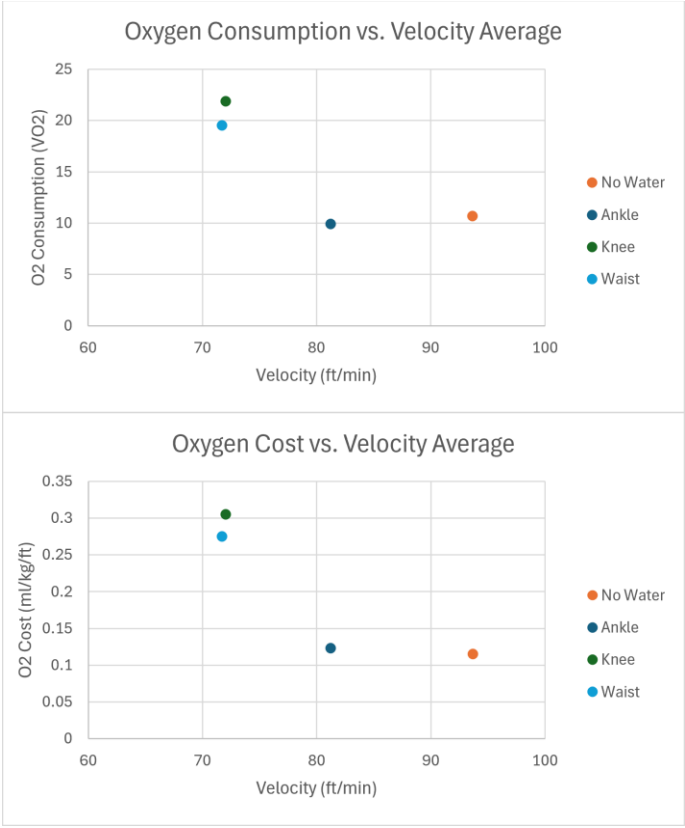


Fig. 8 Average oxygen consumption (VO2) (top) and cost of O2 (bottom) vs. gait velocity.

B. *Metabolic Oxygen Expenditure Trends*

Oxygen consumption (VO_2) exhibited non-linear physiological responses across immersion levels:

Baseline & Ankle Levels:

Metabolic demand remained relatively low and stable, averaging ~10.8 ml/kg/min on dry land and ~10.0 ml/kg/min at ankle depth. At ankle depth, subjects maintained efficient forward momentum with minimal fluid resistance.

Knee Level Peak:

VO_2 spiked sharply at knee depth, reaching an average peak of ~22.0 ml/kg/min (more than double the baseline demand). At this depth, fluid drag directly resists lower-leg swing without providing enough buoyancy to support body weight, forcing high muscular exertion.

Waist Level Adjustment:

At waist depth, average VO_2 slightly decreased to ~19.7 ml/kg/min compared to knee level, while velocity remained low (~71.7 ft/min). Hydrostatic buoyancy at waist depth partially unloaded body mass, offsetting a portion of the metabolic work required for weight bearing, though high drag continued to restrict forward speed.

Because walking speed dropped significantly while VO_2 remained elevated at knee and waist depths, the calculated *Oxygen Cost* (VO_2 / Velocity) increased substantially in deeper water, indicating a severe drop in locomotor efficiency.

C. Biomechanical and Kinematic Adaptations

Underwater observational gait analysis tracking revealed distinct kinematic adaptations as water level increased (see Figures 9 and 10; example in foot contact). Below is a description summarizing the observations common to the subjects and levels:

Baseline:

Typical observational gait pattern. See Figure 9. Although the environment did not change the free-walking pattern, the sports shoes had extended heel parts, so the loading response was slightly faster than when walking barefoot.

This detail is negligible for this analysis, and differences in shoe type were not part of the work.

Ankle level:

Sagittal plane: Typical gait pattern, slight hip flexion to lift the thigh and make heel contact slightly in knee flexion. Foot in slight dorsiflexion in swing. The pattern is modified to keep the limb out of the water, especially the foot.

Coronal plane: Slight separation between the legs throughout the gait cycle.

Knee level:

Sagittal plane: Initial contact sometimes in the 2nd rocker (contact with the sole). Greater knee flexion at initial contact compared to water at the ankles. Neutral foot during swing. The effort to walk is noticeable due to water resistance, with an impressive reduction in speed but an increase in step length compared to the ankles.

Coronal plane: an increased length between the feet in average swing is observed compared to the previous level. During the swing, interacting with the transverse plane, a circumduction (outward swing) is observed that quickly returns inward when it is going to be done in heel contact.

The subjects reported that when they started walking and tried to reach a constant walking speed, the shoes tended to skid due to water resistance. After walking for a while, they reported feeling pushed by the volume of water, which formed a current in the direction of displacement because of the same drag produced by the legs.

Waist level:

See Figure 10. At this water level, the previous pattern was again observed: the shoes skate at the beginning of the route, then the water pushes at the end of the walk.

Sagittal plane: initial contact similar to the water level at the knee. Marked knee flexion at initial contact compared to previous levels. Foot sometimes in neutral or slight dorsiflexion during swinging. Effort to walk due to water resistance and thrust (buoyancy), with evidence of reduced speed and increased stride length.

Coronal plane: distance between the feet is greater than at the previous levels, with interaction with the transverse plane resulting in marked circumduction in swing and forward pelvic rotation to complete circumduction for heel contact.

In summary:

Gait Cycle reduction:

Participants exhibited shorter stride lengths and shortened gait cycle durations in deeper water.

Joint Flexion & Circumduction:

Participants showed exaggerated knee flexion and hip circumduction at knee and waist depths as they lifted their legs to clear fluid resistance during the swing phase.

Circumduction movements and changes in standing progression near foot contact, along with pelvic advancement, could indicate greater transverse-plane involvement in adaptations subjects make to minimize energy expenditure.

Postural Instability:

Greater lateral trunk tilt and arm displacement were recorded in deeper water, reflecting compensatory movements to maintain balance against buoyancy and fluid resistance.

Increasing water depth affected both metabolic and biomechanical gait performance. Deeper immersion was associated with reduced walking speed, increased metabolic demand, and more pronounced gait adaptations, including greater knee flexion and changes in stepping patterns. These results align with previous findings and highlight the

importance of considering water depth when evaluating human mobility during flood and tsunami evacuation scenarios.



Fig. 9 Sagittal (left) and coronal (right) views of baseline gait cycle – initial contact.



Fig. 10 Sagittal (left) and coronal (right) views of waist-level gait cycle initial contact.

An important observation, along with the attitude of the trunk to seek stability, is the use of the upper limbs. The subjects, without exception, tended to pull their arms out of the water and make movements of the scapular girdle against rotation with respect to the pelvis; that is, internal rotation of the ipsilateral pelvis and sternal shoulder girdle, and vice versa on the lateral side. This phenomenon is striking and should be addressed for a better analysis.

V. Conclusions and Recommendations

Increasing water depth affected both the metabolic and biomechanical performance of human gait. Deeper immersion was associated with reduced walking speed, increased metabolic demand, and more pronounced gait adaptations, including greater knee flexion and changes in stepping patterns. These results align with previous findings and highlight the importance of considering water depth when evaluating human mobility during flood and tsunami evacuation scenarios.

Future research should expand the number and diversity of participants to strengthen the applicability of the findings. Additionally, given the effect of shoe slippage when starting the walks with considerable levels of water (knee up) and then the push of the water in the direction of the walk, it may also incorporate controlled moving-water conditions to simulate realistic flood and tsunami environments better and evaluate their effect on metabolic demand and gait stability.

When a shoe slips in tsunami or flood conditions, evacuation becomes more difficult. Shoe slippage relates to sole-floor adhesion (the sole-floor interface) under pushing and dragging forces from water. This study assumes that different surface and shoe types will have distinct adhesion and anti-slip patterns, providing criteria for selecting floor materials and textures that facilitate evacuation in urban areas at risk of tsunamis and floods.

To build on the previous analysis of shoe slipperiness, it is recommended to include a study that examines water levels at intermediate points between the ankle and the knee, and between the knee and thigh, for a better characterization of the findings of this work and other possible factors that affect evacuations in the event of a tsunami depending on the water level.

Incorporating kinematic information was useful for the analysis and seems related to the reduced energy consumption at higher water levels. It is recommended to incorporate spatiotemporal parameter analysis and adapt the system to enable distance measurements. It is also recommended to incorporate angle measurements for future studies.

It is recommended to evaluate the interaction between the sagittal and coronal planes and to consider a variation of the montage to incorporate a superior view for the observation of the transverse plane, which is presumed to be important in the compensatory responses instinctively performed by the subjects. In addition, the incorporation of the trunk and upper limbs in the analysis.

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