Aquatic-Treadmill Walking: Quantifying Drag Force and Energy Expenditure

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Context: Quantification of the magnitudes of fluid resistance provided by water jets (currents) and their effect on energy expenditure during aquatic-treadmill walking is lacking in the scientific literature. Objective: To quantify the effect of water-jet intensity on jet velocity, drag force, and oxygen uptake (VO2) during aquatic-treadmill walking. Design: Descriptive and repeated measures. Setting: Athletic training facility. Participants, Intervention, and Measures: Water-jet velocities were measured using an electromagnetic flow meter at 9 different jet intensities (0–80% maximum). Drag forces on 3 healthy subjects with a range of frontal areas (600, 880, and 1250 cm²) were measured at each jet intensity with a force transducer and line attached to the subject, who was suspended in water. Five healthy participants (age 37.2 ± 11.3 y, weight 611 ± 96 N) subsequently walked (~1.03 m/s or 2.3 miles/h) on an aquatic treadmill at the 9 different jet intensities while expired gases were collected to estimate VO2. Results: For the range of jet intensities, water-jet velocities and drag forces were 0–1.2 m/s and 0–47 N, respectively. VO2 increased nonlinearly, with values ranging from 11.4 ± 1.0 to 22.2 ± 3.8 mL · kg⁻¹ · min⁻¹ for 0–80% of jet maximum, respectively. Conclusions: This study presented methodology for quantifying water-jet flow velocities and drag forces in an aquatic-treadmill environment and examined how different jet intensities influenced VO2 during walking. Quantification of these variables provides a fundamental understanding of aquatic-jet use and its effect on VO2. In practice, the results indicate that VO2 may be substantially increased on an aquatic treadmill while maintaining a relatively slow walking speed.

Keywords: aquatic rehabilitation, oxygen consumption, biomechanics

A review of literature for aquatic rehabilitation and conditioning reveals that aquatic treadmills, with adjustable belt speeds, water depths, and fluid resistances, are becoming an increasingly prevalent mode of exercise, possibly because of greater availability and benefits in terms of reduced joint loads.¹⁻⁴ There also appears to be a growing understanding of how belt speed,⁴ water depth,⁵,⁶ and their interaction⁷ influence oxygen uptake (VO2) during gait. What is not clear from the literature is an understanding of the magnitudes of fluid resistance produced by water jets (currents) and their effect on energy expenditure during gait.

As a person walks on an aquatic treadmill, current flow in the tank can be incrementally adjusted to increase the resistance experienced. Water-current flow can be generated by pressure, paddlewheel, or propeller mechanisms and can be directed toward the frontal plane of the subject. The flow rate or relative velocity of the fluid is an underlying factor in the determination of hydrodynamic drag forces as noted in the following equation:

\[ F_d = \frac{1}{2} C_d A \rho v^2 \] (Eq. 1)

where \( F_d \) = drag force, \( C_d \) = coefficient of drag, \( A \) = frontal area of immersed body, \( \rho \) = fluid density, and \( v \) = relative velocity of the fluid with respect to the body. Assuming that fluid density, drag coefficient, and frontal area remain constant, drag forces during aquatic-treadmill gait are proportional to the square of the relative velocity (\( v^2 \)). Velocity of a fluid can be quantified using flow probes commonly used in civil engineering to measure flows in open-channel streams, while drag forces can be measured using force transducers common in biomechanics laboratories.

Presumably, VO2 for a given water depth and walking speed will change according to the drag forces applied. A recent study by Greene et al.⁸ generally supported this premise by revealing a rise in VO2 with a rise in jet intensities above 50% of maximum. Others have also incorporated water jets into aquatic-treadmill training programs,²,³ but none have provided details on their jet intensities in terms of drag force. Quantification of drag forces will provide an objective basis for interpreting VO2.
responses with incrementally greater water-jet intensities. Accordingly, the purpose of this study was to quantify the effect of water-jet intensity on jet velocity, drag force, and VO$_2$ during aquatic-treadmill walking.

**Methods**

There were 3 independent experiments in this study: flow-velocity assessment, drag-force assessment, and VO$_2$ assessment. All 3 utilized an aquatic treadmill (HydroWorx™ 2000, Middletown, PA; water and air temperatures 30° and 24° C, respectively) that allowed pressure-driven water jets to be adjusted in 1% increments to a maximal 100% intensity. Participants read and signed an informed-consent form approved by the institution’s ethics committee.

Flow velocities were measured using an electromagnetic flow meter (Marsh-McBirney Flo-Mate™, Frederick, MD) attached to an open-channel velocity sensor (Flo-Mate™ 2000, Frederick, MD). The velocity sensor was positioned in maximal current flow 1 m perpendicular to the jet nozzles. This is the position where participants were located for experiments 2 and 3 (Figures 1 and 2). The velocities were averaged over 15 seconds at 9 different jet intensities at 0% to 80% (Figure 3). Velocity measurements were repeated 2 times at each jet intensity.

Drag forces were measured on 3 male volunteers with considerably different body masses (64, 77, and 120 kg) and frontal areas measured between the xiphoid and iliac crest (600, 880, and 1250 cm$^2$). Drag-force measurements were made directly with a force transducer attached to a floor-mounted anchor and a line attached to the subject, who was suspended at the xiphoid water depth (Figure 2). Water-jet intensities of 0% to 80% were tested. The force data were sampled at 100 Hz and averaged over 30 s at each intensity. Force measurements were repeated 2 times.

VO$_2$ was measured on 3 male and 2 female volunteers (age 37.2 ± 11.3 y, height 172 ± 3.4 cm, body weight 611 ± 96 N) who were physically active university students or staff with previous aquatic-treadmill experience. VO$_2$ measurements derived from expired-air analyses were collected while participants walked on the aquatic treadmill at the 9 different jet intensities (0–80%; Figure 1). Participants self-selected a walking speed (1.03 ± 0.03 m/s, or 2.3 miles/h) that was then maintained for each jet intensity with a water depth set to the xiphoid process (~72% of body-weight support). Participants walked for 2 minutes at each jet intensity, which was randomly assigned after 0%.

Throughout the entire 18-minute walking protocol, VO$_2$ was recorded using a calibrated computerized online metabolic measurement system (Parvomedics True One 2400, Sandy UT). Calculations of VO$_2$ (mL · kg$^{-1}$ · min$^{-1}$) were averaged over the last minute of each jet intensity. Test–retest reliability of average flow velocities and drag forces between assessments was examined with an intraclass correlation coefficient (ICC). Flow-velocity and drag-force values were analyzed descriptively (mean, SD) and expressed as a best-fit regression equation. Finally, VO$_2$ scores were compared between jet intensities using a repeated-measures ANOVA with follow-up multiple comparisons (Tukey); alpha = .05.

![Figure 1](https://example.com/image1.jpg) — Aquatic-treadmill setup illustrating water-jet direction and participant position relative to jets and water level. The jets were directed horizontally to the abdominal region. Real-time frontal- and sagittal-plane video images were provided as feedback to ensure that participants walked centered and 1 m from the jets.

![Figure 2](https://example.com/image2.jpg) — Illustration of the apparatus for measuring drag forces. Drag forces were measured with a force sensor attached to a line fixed at one end and attached to the harness on the other end. Measurements were made on a person suspended with a pulley system to avoid ground-reaction forces.
A Method to Quantify Drag Forces in a Pool

Results
Reliability was high for test–retest flow-velocity and drag-force data (ICCs = .99). Water-jet velocities (range 0–1.2 m/s), drag forces (range 0–47 N), and VO₂ values (range 11.4 ± 1.0 to 22.2 ± 3.8 mL · kg⁻¹ · min⁻¹) increased with jet intensities of 0% to 80% of maximum (Figure 3). Regression equations revealed that flow velocity was linear with jet percent, and drag force was proportional to jet percent squared (Figure 3). A main effect for the ANOVA was observed (P = .001), and follow-up comparisons revealed that VO₂ values increased significantly after the 20% jet intensity (Figure 4).

Discussion
This study presented methodology for quantifying water-jet flow velocities and drag forces with aquatic-treadmill use and examined how different jet intensities influenced VO₂ during gait. The use of a flow meter and a force transducer provided repeatable flow-velocity and drag-force data, respectively. Increasing jet intensities produced linear increases in fluid velocity and nonlinear increases in drag force and VO₂ (Figures 3 and 4). A main effect for the ANOVA was observed (P = .001), and follow-up comparisons revealed that VO₂ values increased significantly after the 20% jet intensity (Figure 4).

Figure 3 — (A) Flow-rate and (B) drag-force values (mean, SD error bars) at jet intensities of 0–80% of maximum. Water-jet velocity increased linearly, while drag forces rose nonlinearly because of the second-degree effect of relative velocity on drag forces. Please note that most SD bars were smaller than the data marker.

Figure 4 — Oxygen uptake values (mean, SD error bars) at jet intensities of 0–80% of maximum. Oxygen uptake was significantly different at most jet intensities above 20%. *Different from all other conditions (P < .05). †Different from all other conditions except 30% (P < .05). ‡Different from all other conditions except 50% or 60% (P < .05).

VO₂ values for the 0% jet intensity (11.4 mL · kg⁻¹ · min⁻¹) were comparable to values reported in previous aquatic-treadmill studies (10–13 mL · kg⁻¹ · min⁻¹). VO₂ values tend to be similar between aquatic-treadmill walking at the xiphoid water depth and land-treadmill walking when speeds are matched and greater than 0.97 m/s. Results of the current study follow the logic presented in Eq. 1, where drag forces are proportional to the square of the fluid velocity (Figure 3). Accordingly, as drag forces increase, for a given treadmill speed, a proportional increase in VO₂ would be expected prior to lactate thresholds.

Drag-force data reported in Figure 3 provide a basis for understanding how jet intensities influence energy expenditure during aquatic-treadmill gait. For example, a drag force of 3.6 N was required to produce a significant rise in VO₂ during aquatic-treadmill walking. The jet intensity that corresponds with this rise in VO₂ was 30% (Figure 4). Greene et al did not observe a significant rise in VO₂ until the 50% jet intensity. However, they did not make assessments at 30% or 40%, suggesting that the percentage threshold may have been missed in their study. Results of the current study indicate that VO₂ may be substantially increased on an aquatic treadmill while maintaining a relatively slow walking speed (ie, 2.3 miles/h). For instance, energy expended was essentially doubled at a jet intensity of 80% compared with 0% with no increase in walking speed. This effect of aquatic jets is perhaps a desirable feature for populations that have limited walking-speed capabilities (eg, postinjury athletes or the elderly) and the desire to maintain or improve aerobic fitness.

Regarding limitations, flow velocities were specific to the aquatic treadmill tested. Our drag-force measures may have been overestimated since jet-flow velocities were measured in 1 location and flow velocities may not be uniform on all aspects of contact with the torso. Finally, the angle of the line to the harness shown in Figure 2 (~10–20°) likely increased the measured forces slightly compared with the horizontally directed drag forces. Likewise, the friction of the line running over the edge of the pool likely decreased the measured forces slightly. We ignored both effects, as we assumed them to be relatively small compared with the drag-force magnitudes. In addition, we cross-checked our values by computing drag forces with Eq. 1, where v² = data from Figure 3(A), A = 0.091 m² (mean from our participants),
\(C_d = 0.70\), and \(\rho = 1000 \text{ kg/m}^3\). For example, predicted drag forces at 80% jets (46 N) were comparable to measured drag forces reported in Figure 3(B) (47 N).

Considering these limitations, the methods of this study allowed for a reliable assessment of hydrodynamic flow velocities and drag forces using relatively inexpensive tools common to civil engineering and biomechanics. Quantification of these variables provides a fundamental understanding of aquatic-jet use and its effect on VO\(_2\) during aquatic-treadmill walking.

**Acknowledgments**

This study was supported by grants from the National Swimming Pool Foundation. The authors declare that they have no conflict of interest.

**References**