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# Metabolic-Cost Comparison of Submaximal Land and Aquatic Treadmill Exercise

**Erin Rutledge, W. Matthew Silvers, Kathy Browder, and Dennis Dolny**

***Purpose:*** To evaluate the metabolic cost of varying aquatic treadmill (ATM) exercise speed and water-jet resistance and compare with land treadmill (TM) conditions at similar running speeds. ***Methods:*** Fifteen participants (7 men, 8 women, age 22 ± 4 years, height 173 ± 8 cm, weight 66.9 ± 9 kg) submerged to the xiphoid process completed nine 5-min submaximal ATM trials at 174-, 201-, and 228-m/min treadmill speeds with water-jet resistances set at 0%, 50%, and 75% of capacity. Oxygen consumption ($VO_2$), expired ventilation ($V_{E[BTPS]}$), tidal volume ($V_T$), breath frequency (*f*), heart rate (HR), oxygen ($O_2$) pulse, and ratings of perceived exertion (RPE) were recorded during each trial. The corresponding TM speeds that yielded $VO_2$ costs similar to ATM conditions were determined. Repeated-measures ANOVA and paired *t* tests were employed to determine significance ($p < .05$). ***Results:*** Increasing running speed and water-jet resistance both significantly increased $VO_2$, HR, $V_{E(BTPS)}$, $O_2$ pulse, and RPE. Women were lower ($p < .05$) than men in $VO_2$, $V_{E(BTPS)}$, $O_2$ pulse, and $V_T$ and higher in HR and *f* in all ATM trials. Comparable ($p > .05$) metabolic costs ($VO_2$) were observed when TM speeds were similar to ATM speeds without jet resistance. The addition of jet resistance increased ($p < .01$) the land TM required to elicit a similar metabolic cost by 27.8 and 54.6 m/min, respectively. ***Conclusions:*** These results suggest that ATM yields similar metabolic costs to land TM in running speeds of 174–228 m/min.

***Key Words:*** running, water, $VO_2$, cardiorespiratory

Aquatic running is well accepted as a form of conditioning for athletes recovering from injury and by those seeking an effective mode of cross-training (Reilly, Dowzer, & Cable, 2003). Its popularity stems from its ability to reduce repetitive strain and stress to the lower extremity from musculoskeletal loading normally associated with land-based activities (Moening, Scheidt, Shepardson, & Davies,

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1993). Therefore, substituting aquatic exercise for land running could be potentially beneficial for individuals susceptible to overuse injuries (i.e., tendonitis, plantar fasciitis, stress fractures).

Aquatic running is typically performed in deep water, with runners suspended in the water with a buoyant vest or belt and the feet not touching the bottom (Reilly et al., 2003). Deep-water running (DWR) has been demonstrated to be effective in maintaining or improving cardiorespiratory fitness, although the kinematic data suggest that the lower extremity running stride mimics a piston-like action (Mercer, Groh, Black, Gruenenfelder, & Hines, 2005; Moening et al., 1993) more similar to stair stepping (Mercer et al.) than to running. The other common training mode is shallow-water running (SWR). SWR might have more in common with land-based running because it is a closed-chain movement with a support phase in the stride cycle. Previous SWR studies either had participants run in a shallow pool with the water level set at approximately waist level, depending on the pool and the participant's height (Napoletan & Hicks, 1995; Pohl & McNaughton, 2003; Town & Bradley, 1991), or used an aquatic treadmill (ATM; Gleim & Nicholas, 1989). With higher water levels buoyancy increases, resulting in lower ground-reaction forces (GRFs; Harrison, Hillman, & Bulstrode, 1992; Miyoshi, Shirota, Yamamoto, Nakazawa, & Akai, 2004), yet a greater frontal area is created to magnify drag forces (Pöyhönen et al., 2001). For example, Gleim and Nicholas found that running on an ATM at submaximal speeds in ankle, patellar, and midthigh water levels required significantly greater $VO_2$ than running in waist-deep water and land running. SWR metabolic cost appears to be inversely related to water depth.

Added resistance during SWR can be achieved through the use of water jets. The use of these jets directed at an individual's torso is expected to increase the metabolic cost of running at a given speed, similar to, but likely less in magnitude than, that observed with the use of a water current in a swimming flume. Currently there are no quantitative findings demonstrating the physiological comparison of running on an ATM with and without jet resistances or determining the equivalent land-running speed during land-treadmill (TM) exercise to elicit comparable metabolic costs. The value of these findings might allow athletic trainers, coaches, and strength and conditioning specialists to develop training protocols in ATM to maintain or improve cardiorespiratory function while significantly reducing repetitive stress of GRFs incurred during land-based training.

## Purpose

The primary purpose of this study was to determine the effect of varying ATM speeds and jet resistances on selected metabolic and cardiorespiratory variables. A secondary purpose was to determine the running speed on TM that elicited comparable metabolic costs. We hypothesized that (a) the added resistance of treadmill running in water without jet resistance would be counteracted by the effect of buoyancy and yield metabolic costs comparable to equivalent TM speeds, (b) the additional resistance of water jets would cause a significant increase in the metabolic cost of ATM, and (c) the added jets in ATM conditions would require TM speed to significantly increase to obtain comparable metabolic costs.

# Methods

## Participants

Sixteen participants (8 men, 8 women; see Table 1) were recruited from undergraduate exercise classes and the University of Idaho varsity track and field team. Any participant who had previous or current physical conditions that would limit their participation in the study were released from participating. Criteria for participation included having undergone consistent aerobic training (≥3 sessions/week, ≥30 min/session) for at least the preceding 6 months. All participants completed informed-consent waivers consistent with the policies regarding the use of human participants and written informed consent as approved by the University of Idaho Human Assurance Committee.

## Equipment

ATM protocols were performed in a HydroWorx 2000 (HydroWorx, Middletown, PA) that consisted of a 2.6 × 3.9-m pool kept at 28 °C with a treadmill built into an adjustable-height floor. Water jets inset at the front of the pool provide an adjustable water-flow resistance. TM protocols were performed on a standard adjustable-incline treadmill (Woodway Desmo S, Woodway, Waukesha, WI). Expired air was analyzed using an automated metabolic system (True One 2400, Parvo Medics, Sandy, UT) that was calibrated immediately before each testing session. Water-resistant chest-strap transmitters (Polar T31, Polar, Lake Success, NY) were worn by participants to monitor heart rate (HR). Ratings of perceived exertion (RPE) were assessed immediately after each test using Borg's 15-point scale (Borg, 1982).

## Protocol

All participants completed one session of exercise in the HydroWorx 2000. The session began with a 5-min warm-up at a self-selected pace, followed by stretching in the pool. During the session the participants completed nine trials. All trials were conducted with the participants submerged to the level of the xiphoid. During pilot testing it had been determined that this level promotes a normal running gait for ground contact and reduces the degree of "float" during the noncontact phase of the stride cycle, even though this buoyant condition unloads approximately 70%

**Table 1 Descriptive Statistics of Participants, *M* (*SD*)**

| | Age, years | Weight, kg | Height, cm | Body fat, % | $VO_{2peak}$, ml · kg$^{-1}$ · min$^{-1}$ |
|---|---|---|---|---|---|
| Women, $n = 8$ | 19.38 (1.19) | 60.86 (6.21) | 167.01 (4.45) | 14.5[a] (6.36) | 44.17 (5.59) |
| Men, $n = 7$ | 24.63[b] (4.57) | 72.95[b] (7.00) | 178.28[b] (5.83) | 10.1 (1.47) | 59.08[b] (1.32) |
| Total, $N = 15$ | 22 (4.2) | 66.91 (8.94) | 172.64 (7.68) | 12.7 (6.28) | 53.24 (8.53) |

[a]Women > men ($p < .05$). [b]Men > women ($p < .05$).

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of body weight based on GRFs (Harrison et al., 1992). Three ATM speeds were selected (174, 201, and 228 m/min) to represent a range commonly chosen by athletes at the university during workouts on the ATM. Each ATM speed was tested with the jet resistance set at 0%, 50%, and 75% capacity (Table 2). The water-jet settings were chosen based on feedback during pilot testing from athletes during training and rehabilitation sessions. For a typical ATM speed, jets set at 50% flow was considered a "medium," and 75% flow, a "hard," resistance to run against. The location at which the jets hit the participants was standardized by targeting the jets toward the torso, immediately above the umbilicus. There were visual markers on the front and side of the pool to help the participants stay directly in front of and at a 1-m distance from the water jets. In addition, underwater video cameras recorded each participant's lower extremity running motion from frontal and sagittal views, and these were displayed on monitors directly in front of the participant during testing. This provided the participants with immediate visual feedback to help them maintain proper orientation with the water jets. All male participants wore snug-fitting spandex shorts, and the women wore similar shorts over a one-piece swimsuit in order to minimize variation in drag forces caused by clothing.

Expired air and HR were sampled continuously during testing. During each trial $VO_2$ was monitored, and once it appeared that the participant was reaching steady state (plateau of $VO_2$ during Minutes 2–3), data were collected for three consecutive minutes. The variables measured each minute were $VO_2$, HR, $V_{E(BTPS)}$, $V_T$, and *f*. Respiratory-exchange ratio, $O_2$ pulse, and $V_E/VO_2$ were calculated, and RPEs were solicited from participants at the end of each trial. Participants were given 3 min of rest between trials. Protocol order was randomized to minimize investigator and testing bias.

After at least 48 hr recovery from ATM, participants reported to complete the TM protocol. The initial TM speeds (0% incline) to elicit metabolic costs comparable to those observed during ATM trials were calculated from ACSM metabolic

**Table 2 Aquatic Treadmill Protocol**

| Trial | Jet resistance (%) | Speed (m/min) |
|---|---|---|
| 1 | 0 | 174 |
| 2 | 50 | 174 |
| 3 | 75 | 174 |
| 4 | 0 | 201 |
| 5 | 50 | 201 |
| 6 | 75 | 201 |
| 7 | 0 | 228 |
| 8 | 50 | 228 |
| 9 | 75 | 228 |

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equations (American College of Sports Medicine, 2006). Participants began each trial running at the preselected speed, and cardiorespiratory measures were collected beginning with the third minute. If after 2 min of data collection the average $VO_2$ value differed by ±2.0 ml · $kg^{-1}$ · $min^{-1}$, the treadmill speed was adjusted in 6.7-m/min increments accordingly and data collection continued. Once the $VO_2$ was within the accepted range, data were collected for 3 min at the new speed. The same variables were recorded for TM as described for ATM.

Descriptive statistics were calculated for all variables on all ATM trials. A multivariate general linear model using a split-split plot design and missing subclasses was used to analyze for significant differences across all ATM trials for HR, $VO_2$, $V_{E(BTPS)}$, $V_E/VO_2$, $O_2$ pulse, $V_T$, *f*, RER, and RPE for all speeds. The resistance main effect and the Resistance × Speed interaction were tested by an overall residual error. A Tukey's post hoc analysis was used to identify significant differences as necessary. ATM versus TM comparisons for each variable were assessed by paired-sample *t* tests. The level of confidence for all analyses was set at $p < .05$.

# Results

## ATM Trials

One male participant was unable to complete the TM trial because of injury. One female participant was unable to complete the three ATM trials with 75% jet capacity, and one female participant was unable to complete the trials at 75% jet capacity at 201 and 228 m/min.

There was a significant ($p < .01$) main effect for ATM speed and jet resistance. Regardless of gender, $VO_2$ (Figure 1), RPE (Table 3), and $O_2$ pulse (Table 4) significantly ($p < .01$) increased as ATM speed (228 > 201 > 174 m/min) and jet resistance within a given speed increased (75% > 50% > 0%). HR (Figure 2), $V_{E(BTPS)}$ (Figure 3), and RER (Figure 4) were significantly ($p < .01$) greater at 228 than at 201 and 174 m/min and within each ATM speed as jet resistance increased (75% > 50% > 0%).

Ventilatory equivalent (Table 5) was significantly ($p < .05$) greater during 75% than 0% jet-resistance trials for all speeds and for 228 than 174 m/min for all jet

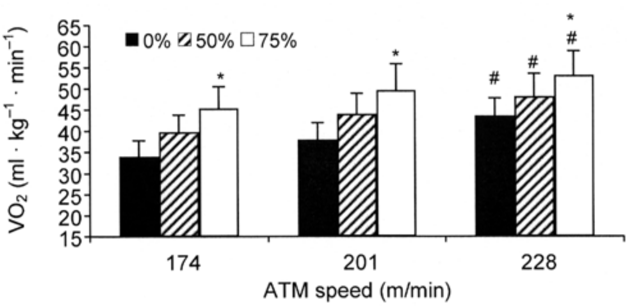


**Figure 1** — Oxygen uptake ($VO_2$) during aquatic treadmill (ATM) trials. #75 > 50 > 0% ($p < .01$) at each speed. *228 > 201 > 174 m/min ($p < .01$).

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**Table 3 Ratings of Perceived Exertion (Borg Units) for Aquatic Treadmill Trials, *M* (*SD*)**

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Women | 10.1 (2.2) | 11.0 (1.1) | 13.8 (2.7) | 10.8 (4.1) | 13.0 (1.6) | 15.9 (2.7) | 13.3 (1.9) | 14.9 (2.9) | 17.1 (2.7) |
| Men | 8.9 (1.5) | 11.0 (1.4) | 11.6 (2.4) | 9.5 (1.0) | 11.5 (1.6) | 14.6 (3.3) | 11.5 (0.9) | 13.3 (2.1) | 16.5 (2.6) |
| Total | 9.5[a] (1.9) | 11.0 (1.2) | 12.7 (2.7) | 10.1 (2.9) | 12.3 (1.7) | 15.2 (2.9) | 12.4 (1.7) | 14.0 (2.6) | 16.8[b] (2.5) |

*Note*. Men < women ($p < .05$) for Trials 1, 3, and 5–8.

[a]228 > 201 > 174 m/min ($p < .05$) for all jet resistances. [b]75 > 50 > 0 ($p < .05$) for all speeds.

**Table 4 Oxygen Pulse (ml $O_2$/beat) for Aquatic Treadmill Trials, *M* (*SD*)**

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Women | 12.94 (2.5) | 14.1 (2.3) | 15.6 (1.9) | 13.61 (1.9) | 15.05 (1.83) | 16.32 (2.7) | 14.75 (2.43) | 15.51 (2.13) | 16.93 (2.69) |
| Men | 17.35[a] (3.33) | 18.68 (2.65) | 21.53 (2.62) | 20.29 (2.45) | 22.32 (2.5) | 23.4 (2.92) | 21.48 (3.10) | 23.06 (2.51) | 23.43 (2.48) |
| Total | 15.14[b] (2.93) | 16.32 (3.36) | 18.61 (3.52) | 16.74 (4.10) | 18.42 (4.40) | 19.54 (3.81) | 17.89 (4.30) | 19.29 (4.50) | 20.43[c] (4.30) |

[a]Men > women ($p < .05$) for all trials. [b]228 > 201 > 174 m/min ($p < .05$) for all jet resistances. [c]75 > 50 > 0% ($p < .05$) for all speeds.

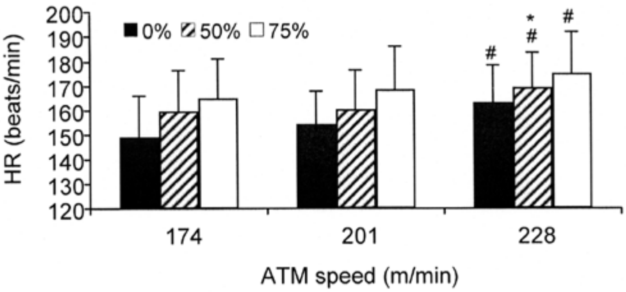


**Figure 2** — Heart rate (HR) during aquatic treadmill (ATM) trials. #75 > 50 > 0% ($p < .01$) at each speed. *228 > 201 & 174 m/min ($p < .01$).

resistances. Tidal volume was significantly ($p < .05$) greater for Trial 9 than for Trials 1, 2, and 4 (Table 6). Breathing frequency (Table 7) was significantly ($p < .05$) greater during Trial 6 than during Trials 1, 4, and 5, and during Trial 9 it was significantly ($p < .05$) greater than during all other trials except Trial 6.

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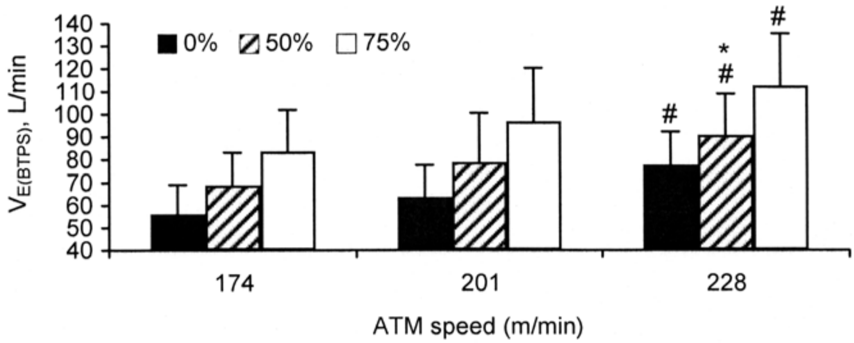


**Figure 3** — $VE_{(BTPS)}$ during aquatic treadmill (ATM) trials. #75 > 50 > 0% ($p < .01$) at each speed. *228 > 201 & 174 m/min ($p < .01$).

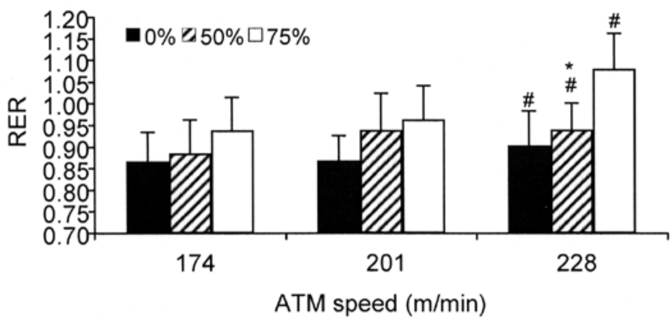


**Figure 4** — RER ($VCO_2/VO_2$) during aquatic treadmill (ATM) trials. #75 > 50 > 0% ($p < .01$) at each speed. *228 > 201 & 174 m/min ($p < .01$).

**Table 5 Ventilatory Equivalent ($VE/VO_2$) for Aquatic Treadmill Trials, *M* (*SD*)**

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Women | 26.22 (3.7) | 27.01 (3.6) | 28.27 (4.7) | 26.75 (5.4) | 27.84 (4.3) | 29.37 (3.2) | 30.07 (5.6) | 31.08 (5.1) | 33.44 (4.4) |
| Men | 24.75 (2.7) | 26.96 (4.0) | 26.75 (3.9) | 23.72 (3.3) | 26.13 (5.3) | 29.91 (5.9) | 24.52 (2.9) | 27.74 (4.3) | 30.98 (5.8) |
| Total | 25.53[a] (3.3) | 26.99 (3.6) | 27.51 (4.0) | 25.33 (4.6) | 27.04 (4.5) | 29.65 (4.5) | 27.48 (4.6) | 28.39 (4.8) | 32.19[a,b] (4.9) |

*Note*. Women > men ($p < .05$) for Trials 4, 7, and 9.

[a]75% > 0% ($p < .05$) jet resistance for all speeds. [b]228 > 201 m/min for all jet resistances.

**Table 6 Tidal Volume (L) for Aquatic Treadmill Trials, *M* (*SD*)**

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Women | 1.82 (0.29) | 1.97 (0.31) | 2.11 (0.33) | 1.87 (0.36) | 2.15 (0.32) | 2.1 (0.30) | 2.04 (0.31) | 2.03 (0.26) | 2.19 (0.22) |
| Men | 2.34[a] (0.30) | 2.32 (0.45) | 2.91 (0.31) | 2.62 (0.48) | 2.91 (0.48) | 2.77 (0.31) | 2.94 (0.45) | 2.98 (0.32) | 3.04 (0.42) |
| Total | 2.06 (0.39) | 2.13 (0.46) | 2.48 (0.51) | 2.21 (0.56) | 2.52 (0.55) | 2.46 (0.46) | 2.49 (0.59) | 2.47 (0.57) | 2.65[b] (0.55) |

[a]Men > women ($p < .05$) for all trials. [b]Trial 9 > 1, 2, and 4 ($p < .05$).

**Table 7 Breathing Frequency (breaths/min) for Aquatic Treadmill Trials, *M* (*SD*)**

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Women | 28.7 (6.7) | 31.7 (5.1) | 37.5 (6.4) | 31.6 (6.8) | 32.5 (4.7) | 41 (6.7) | 35.2 (3.6) | 37.1 (7.4) | 47.3 (8.1) |
| Men | 26.8 (6.3) | 30.8 (9.4) | 31.7 (7.4) | 27.5 (6.2) | 31.5 (10.2) | 39.2 (9.6) | 27.7 (5.5) | 34.6 (7.2) | 40.7 (10.1) |
| Total | 27.6 (6.4) | 30.1 (8.1) | 30.8 (7.4) | 28.8 (6.6) | 29.7 (8.1) | 32.6 (8.7) | 30.1 (4.6) | 31.2 (7.4) | 34.6 (9.8) |

*Note*. Men < women ($p < .05$) for Trials 1, 3, 4, 7, and 9. Trial 9 > all trials except 6 ($p < .05$). Trial 6 > 1, 4, and 5 ($p < .05$).

There was a significant ($p < .001$) gender effect during ATM trials. Men had significantly ($p < .001$) greater $VO_2$ (Figure 5), $V_{E(BTPS)}$ (Figure 6), $V_T$ (Table 6), and $O_2$ pulse and lower HR (Figure 7) than women for all ATM trials. Women had a greater ($p < .05$) $V_E/VO_2$ than men for Trials 4, 7, and 9 and a greater ($p < .05$) *f* for Trials 1, 3, 4, 7, and 9. Women exercised at a greater ($p < .05$) percentage of $VO_{2peak}$ than men (85.5% ± 9% vs. 77.4% ± 11%). Women reported RPE to be greater ($p < .05$) than men did during Trials 1, 3, and 5–8 (Table 3).

## ATM Versus TM Trials

There were no significant differences between the $VO_2$ measured in the ATM trials and the comparable TM conditions (Table 8). TM speed required to elicit comparable metabolic costs to that of ATM was significantly ($p < .01$) greater than all ATM trials except 1, 4, and 7. These were the ATM trials without water-jet resistance. As in ATM, TM $VO_2$ was significantly ($p < .05$) greater for men than for women ($p < .001$). HR was significantly ($p < .05$) greater during TM than during ATM for all trials except 1, 4, and 7 (Table 8). Women's HRs were significantly ($p < .001$) greater than men's. RPE was significantly ($p < .05$) greater during TM than ATM for Trials 3 and 5. TM *f* was significantly ($p < .05$) greater than ATM for Trials

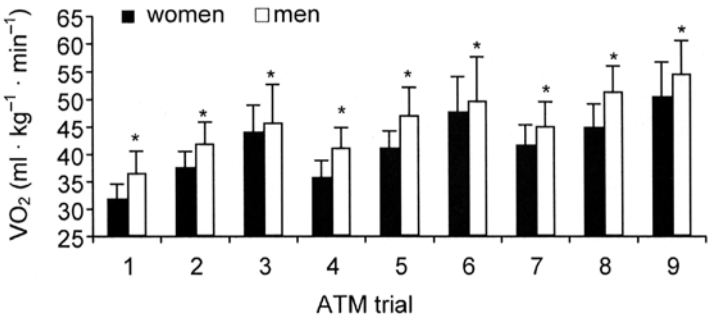


**Figure 5** — $VO_2$ for men versus women during aquatic treadmill (ATM) trials. *Men > women ($p < .001$) for all trials.

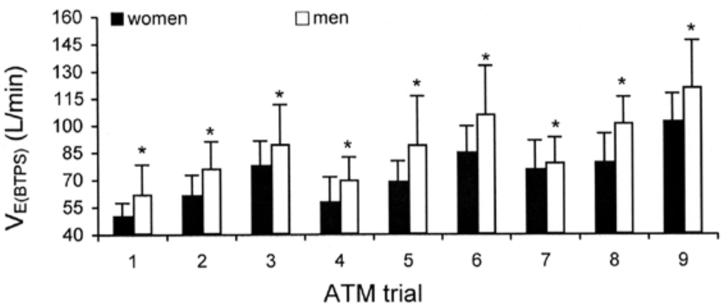


**Figure 6** — $VE_{(BTPS)}$ for men versus women during aquatic treadmill (ATM) trials. *Men > women ($p < .001$) for all trials.

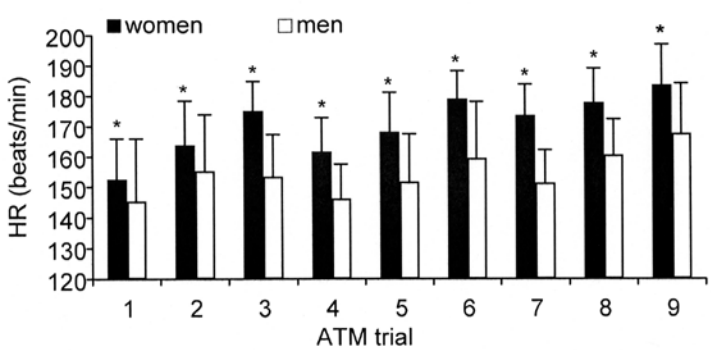


**Figure 7** — HR for men versus women during aquatic treadmill (ATM) trials. *Women > men ($p < .001$) for all trials.

**Table 8 Oxygen Uptake ($VO_2$, ml · kg$^{-1}$ · min$^{-1}$) and Heart Rate (HR, beats/min) During Aquatic Treadmill (ATM) and Comparable Land Treadmill (TM) Speeds (m/min), *M* (*SD*)**

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| ATM $VO_2$ | 33.97 | 39.81 | 45.28 | 37.96 | 43.94 | 49.63 | 43.60 | 48.07 | 53.18 |
| | (4.0) | (4.1) | (5.3) | (4.0) | (5.0) | (6.1) | (4.0) | (5.5) | (5.8) |
| TM $VO_2$ | 33.53 | 38.98 | 44.06 | 37.25 | 42.39 | 48.64 | 42.40 | 47.40 | 51.53 |
| | (4.0) | (4.7) | (5.4) | (3.8) | (5.1) | (6.0) | (4.0) | (5.7) | (5.7) |
| ATM HR | 149 | 160 | 165 | 155 | 160 | 169 | 163 | 169 | 175 |
| | (16) | (16) | (15) | (13) | (16) | (17) | (15) | (14) | (17) |
| TM HR | 144 | 161 | 170 | 159 | 168 | 176 | 169 | 175 | 185 |
| | (9) | (13) | (18) | (11) | (16) | (19) | (17) | (13) | (16)[a] |
| TM speed | 179 | 212 | 238 | 204 | 228 | 262 | 228 | 254 | 276 |
| | (2.3) | (3.5)[b] | (3.2)[b] | (2.9) | (3.2)[b] | (4.3)[b] | (2.9) | (3.7)[b] | (4.0)[b] |

[a]TM > ATM ($p < .05$). [b]TM speed > ATM speed ($p < .05$).

6–9. $V_T$s were similar between TM and ATM. $O_2$ pulse, $V_{E(BTPS)}$, and $V_E/VO_2$ were generally lower for TM than ATM and approached ($p = .08$) but failed to reach significance.

## Discussion

The results of the present study demonstrate that increasing ATM speed and adding water-jet resistance both significantly increase the metabolic cost of ATM exercise. These results support and extend earlier research by Gleim and Nicholas (1989). In their study, running in waist-deep water produced comparable $VO_2$ values to those seen during TM running at speeds of 134.1–160.9 m/min. We found similar results with faster treadmill speeds, but our water depth was greater (xiphoid level). The differences in water levels between these studies make it difficult to make direct comparisons. Kato, Onishi, and Kitagawa (2001), however, reported that SWR at 200 m/min in water depth set at the umbilicus yielded a greater $VO_2$ cost than TM at the same speed· This contradicts the results of Gleim and Nicholas and the present study and might reflect differences in water depth, participant population, familiarity with SWR, and training state (Frangolias, Rhodes, & Taunton, 1996).

Water depth has a profound effect on the magnitude of buoyancy. Immersion to the anterior superior iliac spine, xiphoid process, and seventh cervical vertebra reduces limb loading by 57%, 71%, and 85%, respectively (Harrison et al., 1992). In participants walking in shallow water, Miyoshi et al. (2004) have also demonstrated proportional decreases in GRFs with increasing water depth. The water depth chosen in the present study (to the xiphoid) was based on the highest possible water depth during pilot work at which participants could maintain what we thought was a reasonably normal running gait with limited “float” during the nonsupport phase of the stride cycle.

When buoyancy is reduced, as seen in water levels below the waist, drag forces imposed by fluid resistance substantially elevate the metabolic cost as evidenced by increased $VO_2$, $VO_2$ cost/stride, and HR (Gleim & Nicholas, 1989; Napoletan & Hicks, 1995; Pohl & McNaughton, 2003). Pohl and McNaughton observed that running in thigh-deep water at 116.7 m/min yielded significantly higher $VO_2$ (39 ml · kg$^{-1}$ · min$^{-1}$) than waist-deep water (30 ml · kg$^{-1}$ · min$^{-1}$). Gleim and Nicholas demonstrated that running at 134.1, 147.5, and 160.9 m/min resulted in higher $VO_2$ and HR as water levels rose from ankle to patella to midthigh than land running. Napoletan and Hicks noted a significant reduction in $VO_2$ (13.6 ml · kg$^{-1}$ · min$^{-1}$) when participants performed SWR at 91.7 m/min while submerged in chest- versus thigh-deep water.

At the water level in the present study, the forearm and a portion of the upper arm were submerged throughout arm swing. Moving the arms through water likely required more energy expenditure than in the air on land (Hall, MacDonald, Madison, & O’Hare, 1998). Because water depth appears to profoundly influence energy expenditure during water exercise, the results of the present study should not be inferred to apply to other water depths.

These SWR comparisons confirm that water-submersion level has considerable influence on cardiorespiratory responses during ATM exercise. We hypothesized that ATM would result in a lower stride cadence than TM. Pohl and McNaughton (2003) reported significantly greater (22%) stride rates on land (149 strides/min) than in waist-deep water (122 strides/min) during running at 116.7 m/min. Kato, Onishi, and Kitagawa (2001) reported significantly lower stride rates during running at 200 m/min in waist-deep water than on land. Gleim and Nicholas (1989) proposed that running in thigh-deep or shallower water provides little buoyancy, and thus the added drag forces in water magnify the overall metabolic cost. At waist-deep water level, participants tend to float during the nonsupport phase of the gait cycle, allowing for fewer strides to be taken at a given running speed. We have yet to systematically evaluate stride rate in ATM, but in reviewing videotape recorded during the ATM and TM trials stride rate appears to be approximately 30% lower in ATM than in TM. This difference is somewhat greater than that reported by Pohl and MacNaughton (2003) but less than the 52% difference in stride rate for SWR versus TM reported by Town and Bradley (1991). Differences in running pace and water depth might account for the variability reported.

Despite the reductions in stride rate, the metabolic cost of water running is not significantly lower because of the increased $VO_2$ cost per stride. The energy expenditure per stride ranges from 30% to 56% greater during water running than land running (Brown, Chitwood, Beason, & McLemore, 1997; Frangolias & Rhodes, 1996; Kato, Onishi, & Kitagawa, 2001; Pohl & MacNaughton, 2003), decreasing as a function of the buoyancy–fluid resistance relationship. Muscle recruitment might also differ. Miyoshi et al. (2004) reported that biceps femoris and soleus EMG were greater and less, respectively, when walking in water than those observed during TM. Masumoto, Takasugi, Hotta, Fujishima, and Iwamoto (2004) and Pöyhönen, Keskinen, Hautala, Savolainen, and Mälkiä (1999) reported lower EMG patterns for several lower extremity muscles during walking in water versus on dry land. Whether this difference remains at running speeds requires further investigation.

SWR protocols have also employed a Wet Vest in 1.2 m of water (Dowzer, Reilly, Cable, & Nevill, 1999), resulting in significantly lower $VO_{2max}$ values for SWR than TM exercise. Participants' reported mean height in that study was 1.72 ± 0.07 m, suggesting that water height might not have been set at waist level as reported but, rather, closer to the xiphoid process. The added buoyancy of the Wet Vest presumably magnified lower body unloading, which might have decreased the workload to a point that reduced maximal cardiorespiratory responses in SWR. The fact that we were able to produce comparable metabolic costs in ATM and TM suggests that excessive water buoyancy would limit a person's ability to maximize metabolic rate, which is commonly observed when maximal testing in TM is compared with DWR (Reilly et al., 2003).

Throughout all trials men tended to demonstrate higher $VO_2$ levels than women in both conditions, which has been reported in previous studies (Cassady & Nielsen, 1992; Mercer & Jensen, 1997). This might be attributed to the fact that female participants in the present study had a greater average body-fat percentage (14.5% ± 6.4% vs. 10.0% ± 1.5%) than the men. The lower body density in women would increase buoyancy in this group, which should decrease the metabolic cost. It has been reported that an increase in buoyancy reduces the muscle-mass requirement for movement, at least in DWR (Mercer & Jensen). In addition, the men were taller and heavier than the women. This difference likely resulted in a larger frontal area for the men, which increased the drag force, especially when the legs were swung forward during the stride cycle. In a previous study (Pöyhönen et al., 2001) men and women of similar stature and slightly greater average weight than those in the present study were evaluated for frontal area of the lower lag and measured drag forces during leg-extension movement in water. On average, the men's leg-drag force was 95% greater than that of women (89 vs. 45 N), even though the projected frontal area differed by 16% (0.0862 vs. 0.0742 $m^2$).

For all participants the need to move and accelerate water surrounding all limbs has been identified as an "added-mass" condition, which depends on the size, shape, and flow pattern of water surrounding a moving extremity (Nilsson, Thorstensson, & Halbertsma, 1985). Water turbulence magnifies the frictional resistance of water and increases with speed of movement. Further study is needed to evaluate the relationship of body density and buoyancy and the effect of weight distribution on metabolic cost at varying water depths.

The higher HR demonstrated by women in the presence of the lower $VO_2$ has also been previously reported (Cassady & Nielsen, 1992; Mercer & Jensen, 1997) and likely reflects lower stroke volumes as a result of smaller heart volumes in women, although this was not determined in the present study. The HR–$VO_2$ relationship still appears to be linear in ATM, as was that previously observed in TM (Astrand & Rodahl, 1986).

RPE also increased with increases in exercise intensity, which supports findings of previous research (Brown et al., 1997; Dowzer et al., 1999; Reilly et al., 2003). In all nine trials women reported a higher RPE despite their lower $VO_2$ than in men. This was not surprising. Although women might benefit more from buoyancy, the women were also exercising at a higher percentage of $VO_{2max}$ (84% ± 9% vs. 77% ± 11%). This might have influenced their perception of effort more than the difference in body composition.

No previous study had used an ATM with adjustable jet resistance. We assumed that the addition of water-jet resistance would increase the metabolic cost of exercise at each speed. This would allow a participant to increase metabolic cost without having to increase running speed. For example, the average metabolic cost of running at 174 m/min with 75% jet resistance for all participants (Trial 3) yielded a metabolic cost slightly greater (45.28 vs. 43.58 ml · $kg^{-1}$ · $min^{-1}$) than running at 228 m/min with no jets (Trial 7). This demonstrates the benefit of water-jet resistance in ATM. Athletes who might be restricted from performing running workouts at normal training paces might use the added jet resistance to increase the metabolic demand of their workout while reducing orthopedic risk.

The second purpose of this study was to determine whether the metabolic and cardiorespiratory costs reached in ATM could be matched on a TM at similar speeds. Results of the present study suggest that SWR on an ATM can elicit metabolic expenditures similar to those in TM running during submaximal exercise at the running paces and water depth studied. We hypothesized that the drag forces imposed by running in water would be countered by the beneficial effects of buoyancy, resulting in one force essentially canceling out the other in terms of their influence on metabolic cost. Based on $VO_2$ measurements in the present study it appears that our hypothesis is valid. We were able to produce comparable $VO_2$ values on land during TM exercise at essentially the same TM speeds as those in ATM with no jet resistance. ATM Trials 1, 4, and 7 used no jet resistance, and the average differences between ATM and TM speeds were only 6.1, 2.5, and 1.0 m/min, respectively, while the differences in $VO_2$ values were 1.4%, 1.9%, and 2.8%, respectively. Therefore, within the range of running speeds and water depth used in this study it appears that the metabolic costs of ATM and TM are quite similar. Based on the results of Gleim and Nicholas (1989), at least at 174 m/min, this result was expected.

Although the differences approached, but did not reach, statistical significance, the trend for reduced $V_{E(BTPS)}$ and $V_E/VO_2$ in ATM might be attributed to the hydrostatic pressure of water on the thoracic cavity, which reduces lung compliance, resulting in lower lung volumes (Agostini, Gurtner, Torri, & Rahn, 1966; Hong, Cerretelli, Cruz, & Rahn, 1969). Similar values for $V_{E(BTPS)}$ during TM and DWR have been reported previously (Svendenhag & Seger, 1992).

It is notable that HR was lower in most ATM trials than in TM trials. A lower HR has been observed when participants exercised at the same $VO_2$ in DWR than in TM (Svedenhag & Seger, 1992; Yamaji, Greenley, Northey, & Hughson, 1990). The lower HR observed in water than in land exercise is commonly attributed to a central shift in blood volume, a result of the hydrostatic pressure from water on the thoracic cavity, which increases central venous return, preload, and stroke volume while simultaneously decreasing HR (Arborelius, Balldin, Lilja, & Lindgren, 1972; Christie et al., 1990). A reduction in HR at given workloads in the water might also be a function of decreased sympathetic activity, which is normally elevated during land exercise to control HR (Connelly et al., 1990).

Water temperature and its effect on cardiorespiratory responses is another factor to consider. Craig and Dvorak (1966) suggest that water temperatures greater than or equal to 30 °C elicit HR responses similar to those seen in air, whereas temperatures below 30 °C might lower HR. Although our water temperature was set at 28 °C, Craig and Dvorak also point out that exercise intensity can lower the acceptable level of thermoneutrality during moderate- to high-intensity exercise. Similarly, McArdle, Toner, Magel, Spinal, and Pandolf (1992) found that fairly low exercise intensities (≥1.25 L/min) were enough to maintain rectal temperatures near land-based values during submersion in 20 and 28 °C water. With the exercise intensity used in this study, we think that water temperature was not a limiting factor for cardiorespiratory responses during ATM.

We acknowledge several limitations of our study. First, we have not quantified the magnitude of the water jets' resistance. The percentage scale provided by the manufacturer reflects the capacity of the jets relative to peak operation. It would be beneficial to establish water-jet resistance, say, for each 10% increase in jet use. This would allow ATM trials to mimic treadmill tests on land that incorporate increases in speed and incline to manipulate work rate. Second, for several participants, especially during Trials 5, 6, 8, and 9, RER exceeded 1.0, bringing into question the presence of a true steady state for $VO_2$. Participants who were having difficulty maintaining running form or unable to complete the required time at these trials were not included in the analysis. Third, although the intra- and intervariability in metabolic cost during TM is well known (Morgan, Martin, Krahenbuhl, & Baldini, 1991), research is lacking for ATM. For example, the coefficient of variation (CV) for $VO_2$ during submaximal TM ranges from 1.32% to 6.4% in men (Daniels, Scardina, Hayes, & Foley, 1984; Morgan et al.,1991) and 5.8% to 8.0% in women (Allor, Pivarnik, Sam, & Perkins, 2000; Hall, Figueroa, Fernhall, & Kanaley, 2004). When variation in submaximal $VO_2$ between runners is expressed as a percentage of the range of $VO_2$ scores/mean $VO_2$ scores, the variation is 20–30% (Daniels, 1985). Using the results of the present study, the CV was 11.5% for men and 9.6% for women, with variations of 26.1% and 27.5%, respectively. Our results appear to have a bit more variability than TM. To address this issue, however, requires a greater number of participants tested at two separate sessions for each ATM trial.

In light of our findings and the current literature, perhaps an ideal SWR training condition should incorporate ATM running at a water level that provides a significant reduction in lower body loading to reduce joint and limb stress, plus a fast exercise pace that maximizes drag forces established by limb movement through the water without a degradation in running mechanics (Kato et al., 2001; Pohl & McNaughton, 2003). Further testing with an ATM should investigate cardiorespiratory responses using different combinations of water submersion and fluid resistance at maximal exercise intensities. It appears that ATM training might be a viable exercise alternative to TM running to maintain or improve fitness for injured and healthy individuals alike.

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