Peak Cardiorespiratory Responses during Aquatic and Land Treadmill Exercise

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ABSTRACT

SILVERS, W. M., E. R. RUTLEDGE, and D. G. DOLNY. Peak Cardiorespiratory Responses during Aquatic and Land Treadmill Exercise. *Med. Sci. Sports Exerc.*, Vol. 39, No. 6, pp. 969–975, 2007. **Purpose:** Aquatic treadmill exercise has traditionally been used for aerobic training during rehabilitation; however, its ability to elicit comparable cardiorespiratory stress compared with land exercise is unclear. The purpose of this study was to investigate the cardiorespiratory (CR) responses elicited during maximal-effort protocols using an aquatic treadmill (ATM) and a land treadmill (TM). **Methods:** Twenty-three college runners participated in two continuous, incremental peak oxygen consumption protocols (ATM and TM) until volitional exhaustion. For the ATM protocol, subjects were submerged in 28°C water to the xiphoid process. ATM speed was increased incrementally to 206.8 ± 23.1 $\mathrm{m \cdot min^{-1}}$, and water jet resistance was increased 10% every minute thereafter. For the TM protocol, speed was increased to 205.3 ± 22.3 $\mathrm{m \cdot min^{-1}}$, and grade was increased 2% every minute thereafter. Rest between sessions was at least 48 h. Oxygen consumption ($\dot{V}O_2$), heart rate (HR), minute ventilation ($\dot{V}_E$), tidal volume (V_T), breathing frequency (f), and respiratory exchange ratio (RER) were measured continuously, with peak values used for analysis. Rating of perceived exertion (RPE) was recorded immediately after each test, and blood lactate (LA) was measured 3 min afterward. **Results:** $\dot{V}_E$ and f were significantly greater in ATM versus TM; however, $\dot{V}O_2$, HR, V_T, RER, LA, RPE, speed, and exercise times were similar for both protocols. **Conclusions:** Despite differences in $\dot{V}_E$ and f, it seems that the fluid resistance created by water and jets in an ATM elicits peak CR responses comparable with those seen with inclined TM. These findings suggest that ATM running may be as effective as TM running for aerobic conditioning in fit individuals. **Key Words:** WATER, HYDROSTATIC, CROSS-TRAINING, AEROBIC, ENDURANCE

Aquatic running is well accepted as a form of conditioning for athletes recovering from injury and for those seeking an effective mode of cross-training (27). Its popularity stems from its ability to reduce repetitive strain and stress to the lower extremity from musculoskeletal loading that is normally associated with land-based activities (22). Therefore, substituting aquatic exercise for land running could be potentially beneficial for individuals susceptible to overuse injuries (i.e., tendonitis, plantar fascitis, stress fractures).

The most common form of aquatic running is deep-water running (DWR), where participants run in place with a tethered pulley system and a buoyant belt/vest or across the deep end of a pool (12). However, DWR has been shown to be quite different from land running in terms of lower-extremity muscle recruitment and kinematics (22) because of the absence of a ground-support phase and the additional resistance of moving through water. Additionally, most studies have demonstrated that DWR produces lower peak oxygen consumption ($\dot{V}O_2$) and heart rate (HR) compared with treadmill exercise on land (6,10,12–14,23,30), with DWR averaging 87 and 90% of land exercise for peak $\dot{V}O_2$ and HR, respectively (27). Several factors may account for this difference, including water's hydrostatic effect of increasing thoracic pressure, resulting in a lower HR during DWR (2,5,8); the above-mentioned lack of a ground-support phase (22); water temperature (9,22); self-selected stride rate and/or exercise intensity (30); and unfamiliarity with DWR technique (13).

Shallow-water running (SWR) has become popular as an alternative form of aquatic running because of a closer resemblance to land locomotion (12,27). Participants typically run in the shallow end of an indoor pool immersed to a water level typically about waist deep. SWR combines the added resistance of lower-limb movements in water (19) with a reduced ground reaction force relative to the depth of submersion (24). Several earlier studies have compared SWR with land running (10,15,26,30) and have noted mixed cardiorespiratory responses. For example, SWR in waist-level water produced peak $\dot{V}O_2$ and HR responses that were respectively 84 and 94% those of land treadmill running (10).

Raising the water level during SWR increases the magnitude of water resistance, thereby increasing metabolic demand for a given workload. Presumably, this added cost of energy expenditure is not compensated for by the hydrostatic

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TABLE 1. Physical characteristics of the participants.

	Female (*N* = 11)		Male (*N* = 12)	
	Mean (SD)	Range	Mean (SD)	Range
Age (yr)	22.1 (2.3)	19.0–26.0	24.8 (3.8)	19.0–33.0
Height (cm)	167.1 (13.9)	158.0–182.0	178.9 (5.4)	173.0–191.0
Weight (kg)	60.9 (7.9)	50.9–77.3	73.0 (5.4)	67.5–82.7

force of buoyancy until the water level approaches and/or exceeds waist level (15,26). Unfortunately, greater depths of water submersion during SWR increase the frontal resistance encountered by forward locomotion through water, which may degrade running mechanics (19,22).

Aquatic treadmills present an SWR solution that mitigates the increased frontal resistance by eliminating forward locomotion through the water. Consequently, a more natural gait pattern is possible, which may enhance the specificity of SWR training. Recent advances in technology have improved the functionality of aquatic treadmills, offering broader flexibility in treadmill speeds, water-submersion level, and external fluid resistance via water jets. Combined, these benefits may be used to augment the metabolic response of exercise. For instance, Gleim and Nicholas (15) found that running on an underwater treadmill at submaximal speeds in ankle, patellar, and midthigh water levels required significantly greater oxygen consumption than waist-deep water and land running. These observations suggest that aquatic treadmill running has the capacity to invoke cardiorespiratory responses similar to those of land running, and that the level of water submersion influences this response.

Perhaps an ideal SWR training condition would use aquatic treadmill running at a water level that would provide a significant reduction in lower-body loading to reduce joint and limb stress, plus a fast exercise pace to maximize drag forces established by limb movement through the water, without a degradation in running mechanics (19,26).

Therefore, the purpose of this study was to evaluate the peak cardiorespiratory responses to maximal-effort exercise during land treadmill running and SWR on an aquatic treadmill. We hypothesized that the increased drag forces in water would be countered by the effects of buoyancy, resulting in similar peak cardiorespiratory responses between the testing modalities.

METHODS

Participants. Twenty-three recreationally competitive male (*N* = 12) and female (*N* = 11) runners participated in this investigation (Table 1). Criteria for participation included at least 6 months of consistent aerobic training (at least three sessions per week, ≥ 30 min per session). All participants completed informed consent waivers consistent with the policy statement regarding the use of human subjects and written informed consent as published by *Medicine & Science in Sports & Exercise*® and approved by the University of Idaho human assurance committee.

Experimental design. A 2 × 2 mixed-model approach was employed to investigate the effects of the running protocol on cardiorespiratory, rating of perceived exertion (RPE), and blood lactate (LA) measures. Each participant completed two maximal-exertion running protocols; one on a land treadmill (TM), and the other on an aquatic treadmill (ATM). Protocol order was randomized to minimize investigator and testing bias. Rest between testing sessions was at least 48 h, to maximize performance on each protocol.

Equipment. ATM protocols were performed on a HydroWorx 2000 (HydroWorx, Middletown, PA) that consisted of a small 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. Running was untethered, and buoyancy devices were not used. 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. The metabolic cart's reliability and validity have been reported elsewhere (3). Water-resistant chest-strap transmitters (Polar T31, Polar, Lake Success, NY), which had been validated previously (16), were worn by participants to monitor HR Perceived exertion was assessed immediately after each test using the Borg 15-point RPE scale. To measure postexercise LA, a handheld lactate analyzer (Lactate Pro, ARKRAY, Inc., Minami-Mu, Kyoto, Japan), which had been validated previously against the LDH enzyme method (21), was used.

Testing protocols. Table 2 displays the testing protocols for each condition. For the ATM protocol, male subjects wore spandex shorts, and female subjects wore spandex shorts and a sports bra. No buoyant devices, such as flotation belts or vests, were used during the ATM protocol. Initial and final treadmill speeds were established on the basis of information solicited from participants relative to typical daily workout running pace and, if available, best performance times covering 5- to 10-km road races in the

TABLE 2. Testing protocols for land and aquatic treadmills.

	Mean (SD) Initial Workloads	Progression	Mean (SD) Final Workloads	Mean (SD) Test Times
Land treadmill	170.2 (33.7) m·min^{-1} 0% grade	Increased speed 13.4 m·min^{-1} every minute for 4–5 min, then increased grade 2% every minute to fatigue	205.3 (22.3) m·min^{-1} 9.5% (2.2) grade	8.7 (1.2) min
Aquatic treadmill	162.8 (27.2) m·min^{-1}	Increased speed 13.4 m·min^{-1} every minute for 4–5 min, then increased jets 10% every minute to fatigue	206.8 (23.0) m·min^{-1}	8.8 (1.5) min

3 months before testing. Water jets were directed at the torso of each subject to provide an additional adjustable resistance during testing. Participants were submerged to the xiphoid process and positioned approximately 1 m away from the water jets to standardize the amount of fluid resistance. Underwater sagittal- and frontal-plane camcorders connected to video screens in front of the pool provided the investigators and participants real-time feedback about 1) position in relation to the water jets, and 2) running gait, to ensure that the ATM protocol did not degrade participants' running form near exhaustion. On the basis of pilot testing sessions, 40% water jet resistance was chosen as the beginning resistance for the first ATM speed to promote normal running gait and to minimize "float time" over the treadmill belt. After a 4- to 6-min warm-up, participants began the test, running at their predetermined initial speed, with 40% water jet resistance for 1 min. Thereafter, speed was increased 13.4 $m{\cdot}min^{-1}$ every minute for 4 min, to a maximum of 206.8 ± 23.0 $m{\cdot}min^{-1}$, with water jet resistance remaining constant at 40%. Once maximum speed was reached, water jet resistance was incrementally increased 10% every minute until volitional exhaustion. Air temperature in the room was maintained at 24 ± 1.0°C, 43 ± 2% relative humidity.

For the TM protocol, subjects wore the same clothing as ATM, with the addition of running shoes. The treadmill speeds were chosen as described by the ATM protocol. Grade was initially set at 0%. After a 4- to 6-min warm-up, participants began the test, running at their predetermined initial speed, with speed incrementally increased 13.4 $m{\cdot}min^{-1}$ every minute to a maximum of 205.3 ± 22.3 $m{\cdot}min^{-1}$. Thereafter, grade was increased by 2% every minute until volitional exhaustion. Similar protocols have proven to be very reliable ($r = 0.90–0.96$), with a coefficient of variance (CV) of 2.3–5.6% (29). Air temperature was 21.1 ± 1.0°C. Data for $\dot{V}O_2$, HR, tidal volume (V_T), ventilation ($\dot{V}_E$), breathing frequency (f), and respiratory exchange ratio (RER) were sampled continuously during testing. Four 15-s samples around the highest 15-s $\dot{V}O_2$ sample were averaged to express peak 1-min values for each variable. Three minutes after completion of both ATM and TM protocols, 5 μL of whole blood from participants' fingertips was obtained and placed on an analyzer testing strip. Lactate values were reported in millimoles per liter.

Statistical analysis. TA double MANOVA was employed to test for the effects of modality (TM and ATM), gender, and gender–modality interactions for the set of dependent variables ($\dot{V}O_2$, HR, LA, $\dot{V}_E$, V_T, f, RER, RPE, test time and final speed).

RESULTS

Mean, standard deviation, and univariate test results for each of the measured variables are presented in Table 3 for the entire group. No data were missing, nor were there any univariate or multivariate outliers at $\alpha = 0.05$. Results of the evaluation of assumptions for double MANOVA were satisfactory.

TABLE 3. Comparison of peak cardiorespiratory responses during land treadmill and aquatic treadmill protocols.

	Land Treadmill	Aquatic Treadmill	
	Mean (SD)	Mean (SD)	P Value
$\dot{V}O_2$ ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	52.5 (8.4)	52.8 (7.7)	0.46
HR (bpm)	190.0 (11.4)	188.8 (10.4)	0.30
LA (mM)	12.1 (2.5)	12.2 (2.6)	0.91
$\dot{V}_E$ ($L{\cdot}min^{-1}$)	124.4 (29.9)	135.2 (30.0)	0.00*
V_T ($L{\cdot}min^{-1}$)	2.48 (0.60)	2.46 (0.55)	0.72
Breaths per minute	50.0 (6.7)	55.3 (6.2)	0.00*
RER	1.17 (0.05)	1.15 (0.04)	0.11
RPE	18.7 (1.3)	18.4 (1.4)	0.29
Test time (min)	8.7 (1.2)	8.8 (1.5)	0.84
Final speed ($m{\cdot}min^{-1}$)	205.3 (22.3)	206.8 (23.0)	0.63

* $P \leq 0.05$.

Significant differences ($P < 0.001$) were identified in $\dot{V}_E$ and f between the TM and ATM protocols for the group. No differences ($P > 0.05$) were observed for $\dot{V}O_2$, HR, LA, V_T, RER, RPE, test time, and final speed between testing protocols. There was no gender × modality interaction (multivariate $F_{8,14} = 1.66$, $P > 0.05$, $\eta^2 = 0.54$), and univariate tests showed no significant differences by gender between the two running protocols.

DISCUSSION

Results of the present study suggest that SWR on an aquatic treadmill can elicit similar peak cardiorespiratory responses compared with land treadmill running during maximal-exertion testing. This is not surprising; we had hypothesized that the drag forces imposed by the adjustable fluid resistance (e.g., water jets) would oppose the effects of buoyancy when submerged to the xiphoid process during the ATM protocol. We attempted to keep the testing protocols as similar as possible, including factors such as speed and test time. Each protocol successfully invoked peak cardiorespiratory responses to a comparable degree.

Previous SWR research has produced mixed results regarding cardiorespiratory responses (10,15,26,30). The differences may reside in the use of different testing protocols and in the use of an aquatic treadmill versus a static pool surface for SWR.

In a comparison of maximal-effort land and SWR, Town and Bradley (30) have observed reduced peak $\dot{V}O_2$ and HR responses during SWR (90 and 89%, respectively) compared with land. However, their SWR protocol was based on self-selected intensities and a fixed timeline (≤ 4 min), which may have limited the participants' ability to reach maximal cardiorespiratory values. Also, SWR was performed in 1.3 m of water, untethered, on a static pool surface, which reduced stride rate to 108 strides per minute and possibly altered running mechanics because of the substantial frontal resistance of forward locomotion in the water. These factors may have contributed to the reduced cardiorespiratory response.

Dowzer et al. (10) also have demonstrated reduced peak $\dot{V}O_2$ and HR (84 and 94%, respectively) when SWR was compared with land treadmill running. Their SWR protocol employed the use of a Wet Vest in 1.2 m of water. Descriptive data of the participants reported their mean height to be 1.72 ± 0.07 m, suggesting that water height may not have been set at waist level as reported but, rather, closer to the xiphoid process level. Immersion to the xiphoid process has been shown to decrease limb loading by 72% (17), and 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 the water.

Our SWR peak cardiorespiratory responses were similar to those seen on land; this conflicts with the aforementioned observations. Several explanations lend support to these findings. First, SWR was performed on an aquatic treadmill, which decreased the frontal resistance of forward locomotion (e.g., participants ran in place while the treadmill belt moved below) and may have helped to elicit a gait- and muscle-recruitment pattern comparable with that seen over land (19). Second, the aquatic treadmill allowed us to administer workloads during the ATM protocol via manipulation of treadmill speed and adjustable fluid resistance (e. g., water jets), as well as customize the water height to ensure that each participant was submerged to the xiphoid level. At this water level, the forearm and a portion of the arm were submerged throughout arm swing. Moving the arms through water likely required more energy expenditure than in the air on land. Combined with an open-ended testing timeline, we feel that the aquatic treadmill afforded each participant an opportunity to exercise to his or her maximal potential.

Additional support for our findings can be found in SWR studies that have compared cardiorespiratory responses at varying water-submersion levels during submaximal testing on aquatic treadmills (Table 4). Pohl and McNaughton (26) have observed that running in thigh-level water on an underwater treadmill at 116.7 m·min^{-1} yielded significantly higher $\dot{V}O_2$ (39 mL·kg^{-1}·min^{-1}) than in waist-deep water (30 mL·kg^{-1}·min^{-1}). In a similar study, Gleim and Nicholas (15) have demonstrated that while running at 134.1, 147.5, and 160.9 m·min^{-1} on an underwater treadmill, $\dot{V}O_2$ and HR were higher as water levels rose from ankle to patella to midthigh when compared with land running. They also reported that running in waist-deep water produced $\dot{V}O_2$ values comparable with those seen during land treadmill running at speeds of 134.1 m·min^{-1} and faster. Napoletan and Hicks (25) have noted a significant reduction in $\dot{V}O_2$ (13.6 mL·kg^{-1}·min^{-1}) when participants performed SWR on an underwater treadmill at 91.7 m·min^{-1} while submerged in chest-deep water compared with thigh-deep water.

These SWR comparisons reaffirm that water-submersion level has considerable influence on peak cardiorespiratory responses during aquatic treadmill exercise. We hypothesize that ATM resulted in a lower stride cadence than did TM. Pohl and McNaughton (26) report significantly greater stride rates on land (149 strides per minute) than in waist-deep water (122 strides per minute) for subjects running 116.7 m·min^{-1}. Despite the reductions in stride rate, $\dot{V}O_2$ cost/stride increases as a function of the buoyancy/fluid-resistance relationship (19). When buoyancy is inadequate to provide substantial limb unloading, as is typically seen in water levels below the waist, drag forces imposed by fluid resistance substantially elevate the metabolic cost, as evidenced by increased $\dot{V}O_2$, $\dot{V}O_2$ cost/stride, and HR (15,26). Conversely, when water-submersion levels meet or exceed waist height, increases in buoyancy counteract concomitant increases in workload imposed by fluid resistance, resulting in similar or reduced $\dot{V}O_2$ and HR (15,25,26).

As illustrated in Table 5, most DWR research has shown lower peak cardiorespiratory responses in comparison with land treadmill running by an average of 87 and 90% for peak HR and $\dot{V}O_2$, respectively (12,27). To explain the diversity of observations, several factors must be taken into account; each of these factors is discussed below.

TABLE 4. Comparison of results from SWR studies.

				Peak Mean Values				
Author	**Mode**	**Protocol**	**Depth**	**$\dot{V}O_2$**	**HR**	**$\dot{V}_E$**	**RER**	**LA**
Dowzer et al. (10)[a]	Land	Treadmill	—	55.4	176	137.1	1.11	—
	SWR	Aquatic treadmill	Waist	45.9	165	124.9	1.07	—
	DWR	Flotation vest, tethered	Neck	41.3	153	110.9	1.08	—
Gleim and Nicholas (15)[b]	Land	Treadmill	—	34.4	142	—	—	—
	SWR	Aquatic treadmill	Patella	47.2	179	—	—	—
			Midthigh	50.0	187			
			Waist	33.4	156			
Pohl and McNaughton (26)[c]	Land	Treadmill	—	23.6	124	—	0.88	—
	SWR	Aquatic treadmill	Thigh	39.4	162	—	0.85	—
			Waist	30.5	30		0.85	
Town and Bradley (30)[a]	Land	Treadmill	—	67.0	183	—	1.14	7.9
	SWR	Pool surface	Waist	60.3	162	—	1.02	6.4
	DWR	No flotation, no tether	Neck	49.0	157	—	1.05	6.4

SWR, shallow-water running; DWR, deep-water running.

[a] Values reported are maximal data.

[b] Values were obtained while running at 160.9 m·min^{-1}.

[c] Values for running at 187.6 m·min^{-1}.

TABLE 5. Comparison of results from DWR studies.

				Peak Mean Values				
Author	**Mode**	**Protocol**	**Depth**	**$\dot{V}O_2$**	**HR**	**$\dot{V}_E$**	**RER**	**LA**
Brown et al. (4)[a]	Land	Treadmill	—	45.2 (m) 40.1 (f)	196 195	—	—	—
	DWR	Flotation belt, tethered	Neck	39.1 (m) 30.1 (f)	184 174	—	—	—
Chu et al. (6)[a]	Land	Treadmill	—	47.1	192	82.9	1.18	9.0
	DWR	Flotation belt, tethered	Neck	43.2	182	82.0	1.11	8.6
Dowzer et al. (10)[a]	Land	Treadmill	—	55.39	176	137.1	1.11	—
	SWR	Aquatic treadmill	Waist	45.94	165	124.9	1.07	—
	DWR	Flotation vest, tethered	Neck	41.27	153	110.9	1.08	—
Frangolias and Rhodes (11)[a]	Land	Treadmill	—	59.7	190	109.0	1.2	10.4
	DWR	Flotation belt, tethered	Neck	54.6	175	105.9	1.1	9.8
Frangolias and Rhodes (12)[a]	Land	Treadmill	—	59.7	189	109.0	1.22	10.7
	DWR	Flotation belt, tethered	Neck	54.2	174	104.8	1.10	9.7
Frangolias and Rhodes (13)[a]	Land	Treadmill	—	58.8	188	106.6	1.19	—
	DWR	Flotation belt, tethered	Neck	53.8	173	104.4	1.12	—
Glass et al. (14)[a]	Land	Treadmill	—	53.1	189	—	0.94	11.2
	DWR	Flotation vest, tethered	Neck	47.1	174	—	0.98	14.9
Nakanishi et al. (23)[a]	Land	Treadmill	—	49.5	194	107.0	1.07	13.8
	DWR	Flotation vest, no tether	Neck	39.0	169	89.4	1.03	9.2
Town and Bradley (30)[a]	Land	Treadmill	—	67.0	183	—	1.14	7.9
	SWR	Pool surface	Waist	60.3	162	—	1.02	6.4
	DWR	No flotation, no tether	Neck	49.0	157	—	1.05	6.4

SWR, shallow-water running; DWR, deep-water running.

[a] Values reported are maximal data.

The blunting effect of $\dot{V}O_2$ and HR is commonly attributed to a central shift in blood volume, resulting from the hydrostatic pressure of water on the thoracic cavity, which increases central venous return, preload, and stroke volume while simultaneously decreasing HR (2,5). A reduction in HR at given workloads in the water may also be a function of decreased sympathetic activity, which is normally elevated during land exercise to control HR (8). A substantial reduction in peak HR may ultimately limit peak $\dot{V}O_2$ and other cardiorespiratory measures. Our results, however, show no disparities between peak $\dot{V}O_2$ and HR during TM and ATM, suggesting that other factors (added form and wave-drag resistances) may have offset the expected declines in these variables.

Water temperature and its effect on cardiorespiratory responses is another factor to consider. Craig and Dvorak (9) 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 may lower HR. Although our water temperature was set at 28°C, Craig and Dvorak (9) also point out that exercise intensity can lower the acceptable level of thermoneutrality when performing moderate- to high-intensity exercise. Similarly, McArdle et al. (20) found that fairly low exercise intensities ($\geq$ 1.25 $L{\cdot}min^{-1}$) were enough to maintain rectal temperatures near land-based values for subjects submerged in 20°C and 28°C water. With the exercise intensity performed in this study, we feel that water temperature was not a limiting factor for peak cardiorespiratory responses during ATM.

Despite the multitude of aquatic running studies observing blunted cardiorespiratory responses, some studies have reported LA to be significantly higher during maximal DWR exercise than on land (14). It is thought that anaerobic metabolism may be elevated during DWR as a result of lower perfusion pressure and total muscle blood flow in the legs from the hydrostatic forces of water (10). It is also possible that short exercise protocols or unfamiliarity with DWR technique could have contributed to elevated concentrations of LA, which ultimately capped peak $\dot{V}O_2$ responses (12,13). We did not observe this effect in the present study.

Running technique may be partially responsible for the blunted $\dot{V}O_2$ and HR responses seen in DWR studies. Drag forces imposed by water can limit stride rate, contributing to a reduction in the overall workload (10). In a comparison between treadmill running and DWR, Frangolias and Rhodes (11) have shown mean stride rates of 176 and 108 strides per minute during TM and DWR maximal-effort testing. Town and Bradley (30) have shown DWR stride rates of 84 strides per minute compared with reported observations of 160–210 strides per minute during land treadmill running. Stride rate aside, motor unit recruitment is potentially altered and reduced because of the absence of ground contact and changes observed in running kinematics (13,19,22). Furthermore, the magnified effects of buoyancy during DWR may reduce the workload to a point that peak cardiorespiratory responses similar to those seen on land are not possible. Our study did not use DWR running techniques, but we believe these factors may help explain the reduced cardiorespiratory responses seen in the literature.

Several researchers have observed similar or lower maximal $\dot{V}_E$ responses during DWR comparisons with land running (4,11,23). Reductions in $\dot{V}_E$ may be attributed to the hydrostatic pressure of water on the thoracic cavity, which reduces lung volumes and compliance (1,18). Our observations, however, show $\dot{V}_E$ and f to be significantly higher in ATM than in TM. In support of our findings, Brown et al. (4) have observed a 48% higher $\dot{V}_E$ during

DWR than on land. It has been noted by other researchers that maximal-intensity exercise in the water increases f while bringing about a concomitant decrease in V_T (28). The work of breathing is increased under these conditions to produce equivalent $\dot{V}_E$, implying that the respiratory muscles consume a larger portion of the $\dot{V}O_2$, which limits available oxygen to the legs and, consequently, reduces the peak $\dot{V}O_2$ response during DWR (7). Therefore, to achieve levels of $\dot{V}O_2$ similar to those seen on land, Hong et al. (18) suggest that an increase in $\dot{V}_E$ is necessary, spurred by an increase in f. This rationale seems to be the most likely explanation for our findings.

Whereas TM testing protocols have demonstrated their reliability for replicating peak $\dot{V}O_2$ (29), we acknowledge that less is known regarding the reliability of water exercise testing. There is limited information specific to SWR test reliability. Only one study (13) has examined the relative familiarity of DWR in trained runners. That study found that subjects with prior experience with DWR (especially with intense DWR training) were able to attain a $\dot{V}O_{2max}$ closer to that observed on land than were subjects who did not use DWR in their training. The actual $\dot{V}O_{2max}$ value in DWR was not significantly different on the basis of familiarity with DWR. Rather, the calculated difference score (TM $\dot{V}O_{2max}$ − DWR $\dot{V}O_{2max}$) between land and water testing was significantly different on the basis of DWR familiarity.

With ATM, the incremental increase in treadmill speed and water jet resistances most likely correspond, to some degree, with the increases in treadmill speed and incline (slope) experienced with land protocols. Also, both of our conditions contain a phase of ground support, which is absent in DWR. ATM conditions may be easier to adjust to than DWR. However, at present, we do not have test–retest reliability data for ATM. Therefore, our results should be considered preliminary until complete test–retest data are available.

The results of the present study demonstrate that SWR on an underwater treadmill can elicit peak cardiorespiratory responses similar to those seen during land-based treadmill running, provided that an appropriate balance is struck between buoyancy and fluid resistance (as dictated by water-submersion level and/or adjustable fluid-resistance levels). Further testing with an aquatic treadmill should investigate cardiorespiratory responses using different combinations of water submersion and fluid resistance at maximal exercise intensities. In light of our findings, ATM training may be a viable training alternative to maintain and/or improve fitness levels for injured and healthy athletes alike.

The results of the present study do not constitute endorsement of the product by the authors or ACSM.

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