International Journal of Aquatic Research and Education

Volume 8 | Number 1 Article 4

2-1-2014

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Recommended Citation

Porter, Ryan; Blackwell, Sarah; Smith, Gerald; Wagner, Dale; Gordin, Richard; and Dolny, Dennis G. (2014) "Metabolic Cost Comparison of Running on an Aquatic Treadmill With Water Jets and Land Treadmill With Incline," *International Journal of Aquatic Research and Education*: Vol. 8 : No. 1 , Article 4.
DOI: 10.25035/ijare.08.01.04
Available at: https://scholarworks.bgsu.edu/ijare/vol8/iss1/4

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International Journal of Aquatic Research and Education, 2014, 8, 20-31
http://dx.doi.org/10.1123/ijare.2013-0023

Metabolic Cost Comparison of Running on an Aquatic Treadmill With Water Jets and Land Treadmill With Incline

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The purpose of this study was to compare the metabolic cost (MC) of running on a land treadmill (TM) at specific inclines with an aquatic treadmill (ATM) at equivalent running speeds with selected jet resistances. Sixteen participants completed two trials on separate days on a TM and ATM. For each trial, subjects either ran against water jet resistances of 0–100% of maximum jet flow capacity in 20% increments (ATM) or inclines of 0–10% in 2% increments (TM). Oxygen consumption (VO2), heart rate (HR), and rating of perceived exertion (RPE) were recorded during each trial. When running at similar speeds with no resistance (jets or incline), ATM yielded lower VO2 than TM ($p < .05$). Adding 40% jets during ATM matched MC during TM at 0% incline. At 60% jets, ATM MC simulated TM MC while running on a 4% incline. Comparable MC was observed during ATM 80% jets and 8% TM incline, while ATM 100% jets yielded greater MC than TM 10% incline. We concluded the differences in MC during TM incline vs. ATM with jet resistances was likely a result of nonlinear application of drag forces on the torso created by the water velocities of the water jets.

Keywords: aquatic exercise, water treadmill

In recent years aquatic exercise has gained interest because it combines the weight-reducing effect of water buoyancy with added drag resistance of moving limbs through water. These features allow individuals who have some orthopedic restriction or limitation to begin retraining before weight-bearing exercise on land is recommended. Individuals with arthritis, musculoskeletal, neurological, and other limitations that could not otherwise maintain cardiovascular health and fitness through regular exercise are provided an environment that may facilitate physical activity. Aquatic training also is recommended for cross training purposes to complement land-based training in athletes prone to overuse injuries. Exercising in an aquatic environment allows the body to undergo less stress and strain normally

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associated with land-based activities (Barela, Stolf, & Duarte, 2006; Harrison, Hillman, & Bulstrode, 1992; Moening, Scheidt, Shepardson, & Davies, 1993).

In an attempt to better mimic land exercise, aquatic treadmill (ATM) exercise was developed to allow individuals to use a more normal ambulatory posture and walking gate compared with other aquatic environments (Pohl, & McNaughton, 2003). Though weight bearing is reduced, aquatic walking training has been shown to yield health benefits similar to other forms of land walking exercise. Such benefits include increased VO_{2max}, and decreased body weight, BMI, fat mass, and body fat percentage (Greene et al., 2009). It should also be noted that a similar VO_{2peak} could be reached using an aquatic treadmill with the body submerged to the xiphoid process, compared with a land treadmill (Silvers, Rutledge, & Dolny, 2007).

Water depth, running speed, and water jet resistance must be carefully controlled in ATM running because of the influence they have on VO_2. When walking in water shallower than the waist, the metabolic cost is greater due to lower buoyancy (Gleim, & Nicholas, 1989; Pohl, & McNaughton, 2003). Even small adjustments in water depth may have a significant impact on VO_2. At walking speeds of 0.67–1.79 m/s there is a significant difference in VO_2 when comparing a water depth of +10 cm from xiphoid and -10 cm from xiphoid. When comparing VO_2 at walking speeds greater than 1.1 m/s, there is a significant difference when water depth is altered by ± 10 cm (xiphoid and ± 10 cm from xiphoid; Alkurdi, Paul, Sadowski, & Dolny, 2010). ATM running between 2.95–3.8 m/s and submerged to the xiphoid process yields similar VO_2 results as TM at the same running speeds (Rutledge, Silvers, Browder, & Dolny, 2007).

In the aquatic treadmill, drag forces are created by moving limbs through water—a medium much more viscous than air. Additional resistance may be applied using pump-driven water jets. The effect of jet resistances increases drag forces applied to the body and is a product of the magnitude of water flow (usually expressed as a percent of jet capacity) and distance a subject stands from the jet port. Using an ATM with jets, there were no significant differences in metabolic cost while walking comparing 0–25% jet resistances (Greene et al. 2011), while Rutledge et al. (2007) reported a significant increase (14.4%) in metabolic cost comparing 0% vs. 50% jet resistance. When comparing running (2.95–3.8 m/sec) at 50% and 75% jet resistances, Rutledge et al. demonstrated an average increase in VO_2 of 5.4 ml/kg/min while Greene et al. (2011) reported an average increase of 7.4 ml/kg/min at running speeds between 2.68–3.1 m/s and an average increase of 3.5 ml/kg/min VO_2 comparing 75–100% jets when running at 2.68 m/s. Watson et al. (2012) reported an average MC increase of 1.2 ml/kg/min increase per 10% jet resistance increase in walking speeds (0.67–1.34 m/s), and 2.0 ml/kg/min increase per 10% jet resistance increase at running speeds (2.1–3.35 m/s). On average there is about a 2 ml/kg/min VO_2 increase for every 10% increase in jets.

Resistance on a land treadmill is controlled using the slope or incline of the treadmill belt. Though Staab, Agnew, and Siconolfi (1992) reported there was less than 1 ml/kg/min VO_2 increase for each 1% incline, Jones and Doust (1996) and Klein, Potteiger, and Zebas (1997) observed a 2 ml/kg/min and 2.5 ml/kg/min increase, respectively, for every 1% grade adjustment. Bassett, Giese, Nagle, Ward, Raab, & Blake (1985) developed a linear regression prediction equation for TM running at 0% and 5.7% incline. From these equations it is predicted that VO_2 will increase by 11.3 ml/kg/min from 0% to 5.7% grade on a treadmill at any running speed (Bassett et al. 1985). These results are consistent with Jones and Doust (1996) 2 ml/kg/min increase for every 1% increase in treadmill incline. Though the American College of Sports Medicine (ACSM) prediction equation (ACSM, 2010) for treadmill running has been reported to over predict VO_2 (Ruiz & Sherman 1999), its predicted values are close to the above-mentioned values with a 1.7 ml/kg/min for each 1% increase in incline.

As the ATM with jet resistances becomes a more prevalent mode of running exercise, it seems prudent to compare the metabolic cost of ATM running with jet resistances with that of TM running on an incline. This comparison will allow comparable workouts between the modes and facilitate exercise training and rehabilitation efforts.

The primary purpose of this study was to compare the cardiorespiratory and perceived exertion response of running on a land treadmill at selected speeds and grades with that of ATM exercise at selected jet resistances. It was hypothesized that HR and VO_2 will be similar between TM and ATM at identical running speeds and selected inclines and water jet resistances.

Method

Participants

Seventeen subjects (9 men, 8 women) were recruited via word of mouth and flyer distribution. Mean (standard deviation) statistics for participants were: age (years): 26 (7); height (cm): 173.0 (8.8); weight (kg): 65.9 (10.0); body fat (%): 13.6 (6.3); VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$): 53.53 (8.33). Participants came from the surrounding community and included members of the Utah State University (USU) track team, local running clubs, and other well-trained volunteers from the Cache Valley area. Participants read and signed a release form that describes all study procedures before participation. All participants were well-trained runners that had been participating in at least four aerobic training sessions/week, and at least 30 min/session (or an average of 25–30 miles/week) for at least six months. Participants were also free of acute illnesses, injuries, orthopedic conditions, or disabling injuries that would have prevented them from running. They also were free of pain or any restrictions that would interfere with normal running form. The purpose for these criteria was to anticipate that the subjects could complete all the trials of this study. Details of this study and all procedures involved were reviewed and approved by the university institutional review board (IRB) for research using human subjects.

Equipment

All ATM trials were completed on a HydroWorx 2000 (HydroWorx, Middletown, PA). Water temperature was maintained at 30 °C. TM trials were done on a FreeMotion Incline Trainer Basic (FreeMotion Fitness, Colorado Springs, CO, USA). Metabolic measurements were obtained using a True One 2400 automated metabolic system (Parvo Medics, Sandy, UT, USA). HR was monitored using a Polar T31 water-resistant chest-strap transmitter (Polar, Lake Success, NY, USA). Skinfolds were measured using a Lange Skinfold Caliper (Beta Technology, Santa Cruz, CA, USA). Ratings of perceived exertion were assessed using the Borg's 15-point scale (Borg, 1982).

Procedures

There were a total of three sessions. Each session was separated by at least 48 hr. All participants had a familiarization session in which they used both the land and underwater treadmills before testing began. The familiarization session consisted of the following:

1. Recording subject's age, height, and weight;
2. Taking skinfold measurements at the chest, abdomen, and thigh locations for men (Jackson & Pollock, 1978), and at the triceps, suprailiac, and thigh locations on women (Jackson, Pollock, & Ward, 1980). These measurements were used to estimate each participant's body density (Db). Db was converted to body fat percentage (BF%) using the Siri equation (Siri, 1961);
3. A VO_{2peak} test conducted on the aquatic treadmill consisting of running beginning at a self-selected pace and increasing 0.22 m/s for each minute until the subjects reached their fastest comfortable running speed. Each minute thereafter the percent water jet was increased 10% until VO_{2peak} criteria were met, or until the subjects indicated they were unable to continue at that pace and water jet resistance. At that point, the treadmill was immediately stopped and the test ended. After the pulmonary valve and headgear were removed, the subject walked slowly while cooling down from the test. The test was only considered a VO_{2peak} if at least one of the following criteria was met: a respiratory exchange ratio (RER) greater than 1.15, a plateau of VO_2, and a HR within 10 beats of the age predicted max (220—age).

Sessions two and three were randomized by either running on land or on the aquatic treadmill. Each session began with a five minute warm up at a self-selected pace. Each participant completed 18 trials (they will be referred to as stages from here on) within each session. Stages within each session were randomized for each participant by drawing each of the 18 conditions out of a box. The aquatic treadmill stages consisted of six jet resistances (0, 20, 40, 60, 80, and 100% of jets flow capacity) at each of three different self-selected walking/running speeds (slow, medium, and fast). Stages lasted a minimum of three minutes or until steady state was reached. Steady state was defined by two 60-s averages of VO_2 within 2 ml/kg/min. Each 60-s average was calculated using four consecutive readings taken in 15-s increments. Participants mean (*SD*) average speeds (m/s) were: slow—2.32 (0.27), medium—2.68 (0.32), fast—3.04 (0.36). The water jet resistances were two adjustable jets aimed to cover the participant's umbilicus one meter from the heads of the jets. All subjects were submerged to the level of the xiphoid process.

The land treadmill stages were conducted at the same three self-selected speeds as the aquatic treadmill stages. Land stages were performed at 0, 2, 4, 6, 8, and 10% grades. During all stages, oxygen consumption (VO_2) and heart rate (HR) were monitored continuously and averaged for each minute. Rating of perceived exertion (RPE) was recorded immediately following each stage.

Statistical Analysis

Descriptive statistics were calculated for all variables. In addition, three (one for each speed) 2 × 6 repeated-measures ANOVA were used to determine any significant difference between land and water conditions and between resistance levels for

VO_2, HR, and RPE. When necessary, an LSD analysis was used to determine the location of significance. The confidence level was $p < .05$ for all analyses.

Results

One participant was not able to complete the study due to illness. One participant was unable to complete the ATM 100% jets at the medium and fast speeds. A number of subjects also struggled to complete several conditions and these stages were reviewed. If a subject's VO_2 did not increase on that stage compared with the immediately lower intensity stage, then the data for that stage were excluded. There were 8 stages excluded from ATM fast speed with 100% jets, 2 from ATM fast speed with 80% jets, 4 from TM fast speed at 10% incline, and 3 from TM fast speed with 8% incline.

When running speeds were combined, metabolic cost (MC), as determined by oxygen consumption, was greater ($p < .05$) for TM stages 1, 2, and 3 (0, 2, & 4%) inclines compared with the ATM at 0, 20, & 40% jet resistances. TM stages 4 and 5 (6 and 8%) inclines were comparable to ATM at 60 and 80% while ATM stage 6 (100%) jets were greater than TM at 10% incline (Table 1). When the three running speed conditions were analyzed separately, significant differences ($p < .05$) occurred for a different number of stages: stages 1, 2, 3, 4 (TM > ATM) and 6 (ATM > TM) in the slow speed, stages 1, 2, 3 (TM > ATM) and 6 (ATM > TM) in the medium speed, and stages 2 and 3 (TM > ATM) in the fast speed (Table 1).

For VO_2 (Figure 1), HR (Figure 2), and RPE (Figure 3), all three speeds follow the same regression trend per condition. Independent of speed, ATM has a cubic regression ($R^2 = .99$) while TM has a linear regression (HR and RPE $R^2 = .99$; VO_2 $R^2 = .95$).

Table 1 Oxygen Consumption (ml/kg/min) M+(*SD*) Across All Running Speeds and Conditions for ATM and TM

ATM	Slow	Medium	Fast	All Speeds Combined
1–0%	25.3 (4.9)	28.7 (5.7)	32.5 (7.4)	28.8 (6.7)
2–20%	26.0 (4.5)	29.6 (5.7)	34.0 (8.2)	29.9 (7.0)
3–40%	28.9 (5.7)	31.7 (6.0)	35.6 (6.5)	32.1 (6.6)
4–60%	33.1 (5.0)	38.5 (6.7)	41.5 (7.5)	37.7 (7.2)
5–80%	41.6 (5.3)	45.4 (6.4)	49.4 (5.8)	45.3 (6.5)
6–100%	49.9 (6.1)$^@$	50.8 (6.6)$^@$	53.5 (5.2)	51.1 (6.1)
TM				
1–0%	28.7 (4.1)$^\#$	32.3 (5.0) $^\#$	35.0 (4.5)	32.0 (5.1)
2–2%	30.9 (3.7) $^\#$	34.6 (4.8) $^\#$	38.4 (4.9) $^\#$	34.6 (5.4)
3–4%	33.5 (4.1) $^\#$	36.7 (4.8) $^\#$	41.2 (5.2) $^\#$	37.2 (5.6)
4–6%	36.9 (4.6) $^\#$	41.1 (5.2)	44.8 (5.5)	40.9 (5.9)
5–8%	40.0 (5.2)	43.2 (4.8)	47.9 (5.4)	43.4 (5.9)
6–10%	42.8 (4.7)	47.0 (5.5)	50.2 (5.8)	46.4 (6.0)

= TM > ATM ($p < 0.05$); @ = ATM > TM ($p < 0.05$); ATM = aquatic treadmill; TM = land treadmill.

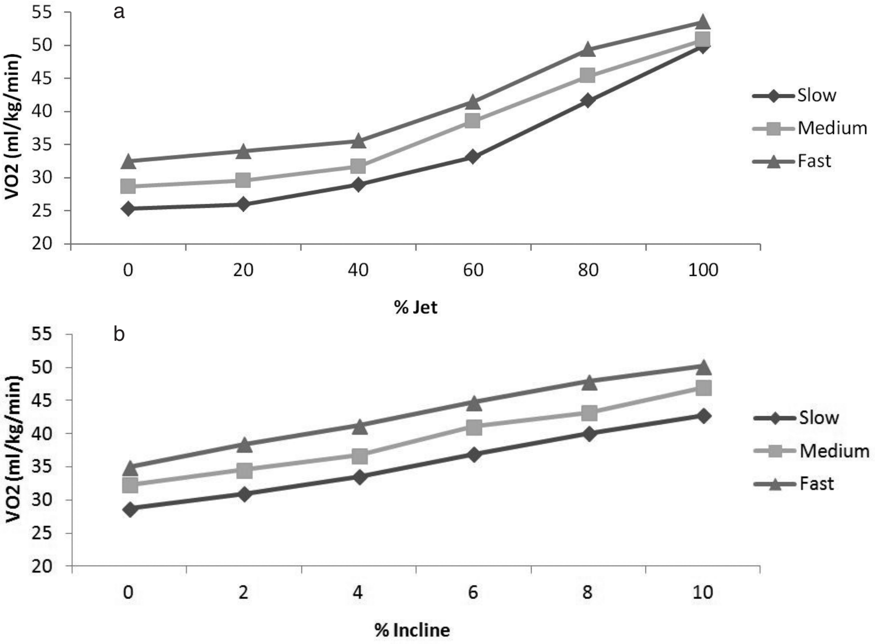

Figure 1 – a) VO_2 ATM. b) VO_2 TM.

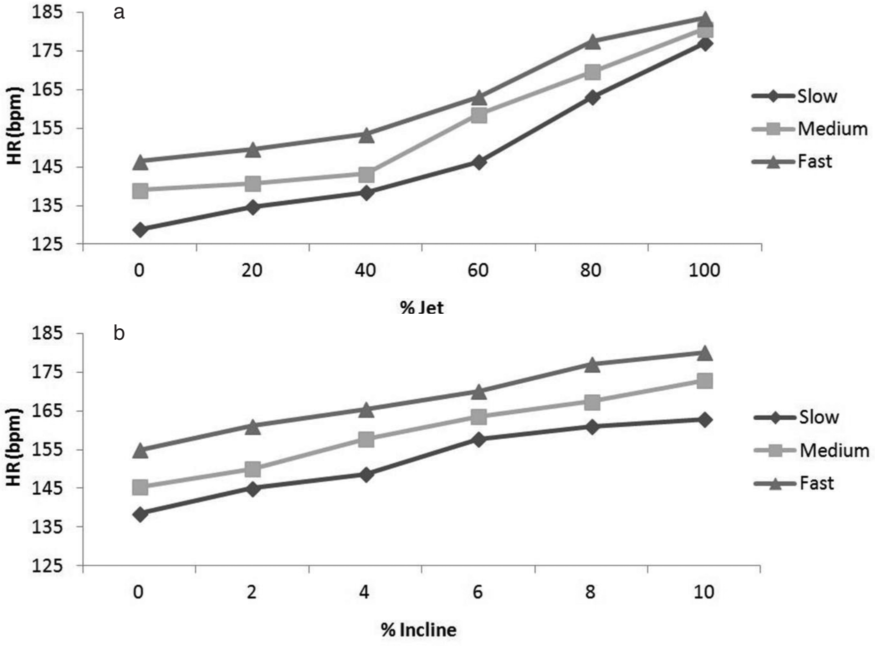

Figure 2 – a) Heart rate ATM. b) Heart rate TM.

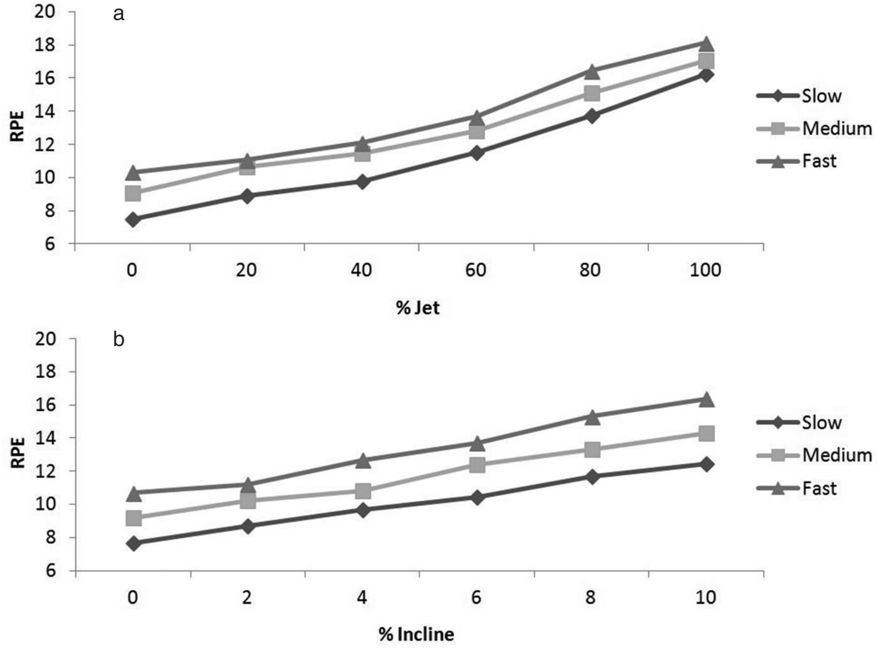

Figure 3 – a) Rating of perceived exertion ATM. b) Rating of perceived exertion TM.

HR followed a similar trend as VO_2 for all speeds (Table 2). TM was significantly greater ($p < .05$) than ATM for stages 1, 2, 3, 4, and 6 in the slow speed, 1, 2, and 3 in the medium speed, and 1, 2, 3, and 4 in the fast speed, respectively.

RPE did not mimic the VO_2 and HR trend. The faster the speed, the more similar the RPE became across conditions (Table 3). In the slow speed, ATM was greater ($p < .05$) than TM in stages 4, 5, and 6. For the medium speed ATM was greater than TM in stages 5 and 6. In the fastest speed, ATM was greater than TM in stage 5 (Table 3).

Discussion

There are few studies that have compared the MC of TM running and ATM running. This comparison is important for both therapists and conditioning specialists for two reasons. First, weight bearing is reduced due to buoyancy in the aquatic environment (Harrison et al. 1992). This allows postsurgery patients, arthritis patients, patients with limited mobility due to obesity, and other populations with mobility restrictions to become more mobile with less pain involved. Second, most therapists and conditioning specialists use land-based exercise for their prescription. To allow a clinician to prescribe aquatic treadmill exercise as training or rehabilitation supplement, there must be an understanding of how a land treadmill compares to an aquatic treadmill in terms of VO_2, HR, and RPE.

Table 2 Heart Rate (bpm) M+(*SD*) Across All Running Speeds and Conditions for ATM and TM

ATM	Slow	Medium	Fast	All Speeds Combined
1–0%	129 (16)	139 (14)	147 (16)	138 (17)
2–20%	135 (11)	141 (14)	150 (18)	142 (16)
3–40%	138 (12)	143 (12)	154 (14)	145 (14)
4–60%	146 (13)	159 (13)	163 (12)	156 (14)
5–80%	163 (11)	170 (7)	178 (8)	170 (11)
6–100%	177 (9)$^{@}$	181 (25)	183 (9)	176 (18)
TM				
1–0%	139 (15)$^{\#}$	145 (15) $^{\#}$	155 (17) $^{\#}$	146 (17)
2–2%	145 (15) $^{\#}$	150 (21) $^{\#}$	161 (16) $^{\#}$	152 (18)
3–4%	149 (14) $^{\#}$	158 (14) $^{\#}$	165 (14) $^{\#}$	157 (15)
4–6%	158 (17) $^{\#}$	164 (14)	170 (13) $^{\#}$	164 (15)
5–8%	161 (15)	167 (13)	177 (11)	168 (14)
6–10%	163 (14)	173 (14)	180 (10)	172 (14)

= TM > ATM ($p < 0.05$), @- ATM > TM ($p < 0.05$); ATM = aquatic treadmill, TM = land treadmill.

Table 3 Rating of Perceived Exertion (6–20 Borg Units) M+(*SD*) Across All Running Speeds and Conditions for ATM and TM

ATM	Slow	Medium	Fast	All Speeds Combined
1–0%	7.5 (1.5)	9.1 (1.8)	10.3 (1.7)	9.0 (2.0)
2–20%	8.9 (1.7)	10.7 (1.9)	11.1 (1.4)	10.3 (1.9)
3–40%	9.8 (1.8)	11.5 (1.2)	12.1 (1.6)	11.1 (1.8)
4–60%	11.5 (1.7)$^{@}$	12.8 (1.6)	13.7 (1.2)	12.7 (1.7)
5–80%	13.8 (2.1) $^{@}$	15.1 (1.6) $^{@}$	16.5 (0.9) $^{@}$	15.0 (2.0)
6–100%	16.2 (1.5) $^{@}$	17.1 (1.6) $^{@}$	18.1 (1.1) $^{@}$	17.0 (1.6)
TM				
1–0%	7.7 (2.0)	9.2 (1.6)	10.7 (1.4)	9.2 (2.1)
2–2%	8.7 (1.6)	10.2 (1.9)	11.2 (1.6)	10.1 (1.9)
3–4%	9.7 (1.6)	10.8 (1.9)	12.7 (1.1)	11.1 (2.0)
4–6%	10.4 (2.1)	12.4 (1.7)	13.7 (1.6)	12.2 (2.2)
5–8%	11.7 (2.1)	13.3 (2.0)	15.3 (1.9)	13.3 (2.5)
6–10%	12.5 (2.5)	14.3 (1.9)	16.4 (1.5)	14.2 (2.5)

@ = ATM > TM ($p < 0.05$); ATM = aquatic treadmill, TM = land treadmill.

Results of the current study show that the MC of the TM and ATM were significantly different across most comparable conditions. As was expected, the TM condition had a linear relationship as incline increased (Jones & Doust, 1996; Klein et al. 1997). On average, VO_2 increased ~3 ml/kg/min for every 2% increase in TM incline. This is consistent with previous research that reports anywhere from less than 2 ml/kg/min increase with 2% incline increase (Staab et al. 1992), up to 5 ml/kg/min increase with a 2% incline increase (Klein et al. 1997). Jones and Doust (1996) reported a 4 ml/kg/min increase with a 2% increase in incline.

In contrast, the ATM condition displayed a cubic relationship. This relationship may be due to the application of the drag force of water flow acting on the body. When the drag force of jet settings ranging from 0–80% was directly measured using a force transducer (Bressel, Smith, Miller, & Dolny, 2012) it was determined that the drag force was proportional to the jet% resistance squared. Relatively little change in drag force was observed until the jet resistance settings reached ~30%. The present study supports this by demonstrating little increase in VO_2 until reaching 40% water jet resistance. With the subjects placed one meter from the jet nozzle (identical to the current study) at these low jet flow rates it appears the jet flow pattern may essentially dissipate as it reaches the subject. At 40% jet resistance setting, the flow velocity was great enough to produce a drag force that was very reproducible. This would account for the relatively small change in MC during ATM trials when the jet resistance settings were set at 0 and 20%. Under these conditions, the effect of buoyancy (reducing MC) was not balanced by the cumulative drag forces of the limbs moving in water and a lower MC compared with land was observed. Beyond 40% jet settings the added drag forces combined with buoyancy raised the MC of ATM until the 80% jet resistance setting exceeded the MC observed at 8% TM incline.

The data gives much insight because no other studies have investigated such small increments of increase in jet percentage. A similar trend was noticed by Watson et al. (2012) when increasing jet resistance by 33% between stages, and when increasing jet resistance by 25% between stages (Greene et al. 2011). In that study, Greene et al. developed regression equations for the prediction of VO_2 when running on an aquatic treadmill. One equation was for use of the aquatic treadmill between 0–25% jet resistance settings. The second equation was for use of the aquatic treadmill when > 25% jet resistance settings were used. According to Porter, Alkurdi, and Dolny (2011), body mass index scores could account for greater buoyancy and therefore a lower VO_2. Perhaps some measure of body adiposity should be taken into consideration when attempting to predict MC during ATM.

As noted by Rutledge et al. (2007), comparison of studies at different water depths should be avoided because of the great impact water depth has on MC. In their study, they found that participants submerged to the xiphoid process, with no jet resistance, exerted similar amounts of MC as land running. The same depth was used in the current study, yet the MC on land was greater than in water with no added resistance. Because the populations in these two studies were nearly identical, further research is needed to understand why difference existed between the results of these studies.

In the current study, it was noted that VO_2 at the fast speed 100% jets, and HR at the medium and fast speed 100% jets were not statistically different from their opposing TM condition. In about half the stages that were excluded from statistical analysis, the participant's VO_2 could not go any higher because it had already reached its peak at the 80% jet resistance setting. A greater increase in VO_2 and HR may have been noticed during these stages had participants not been so close to their peak performance. In the other half of the excluded stages, participants had not yet reached their peak VO_2. A lack of VO_2 increase in those participants may be due to an alteration in running form to accommodate the magnitude of the jet resistances.

At all speeds, RPE was not significantly different ($p < .05$) in the first three stages (0, 2, and 4% incline and 0, 20, and 40% jets). In the last three stages (6, 8, and 10% incline and 60, 80, and 100% jets), TM RPE continued to increase linearly while ATM PRE increased cubically with increased resistance. This trend follows that observed changes for VO_2 and HR and demonstrates the efficacy of RPE to reflect change in exercise intensity, especially when reflected in metabolic rate or heart rate (Borg, 1982). Though no other studies have involved as many stages for each mode, this supports the trends reported in previous research (Brubaker, Ozemek, Gonzalez, Wiley, & Collins, 2011; Rutledge et al. 2007). This could be due to the resistance (drag force) that existed in the water but not on the land.

It is recognized that there were limitations to this study. Most participants did not have an extended degree of experience on the aquatic treadmill. This may have been a factor when participants self-selected their running speeds. Some participants may have underestimated the difficulty of the ATM jets that made it quite difficult to complete these stages. Therefore we recognize the 100% jet resistance stages may not reflect steady state exercise conditions. We recommend future research select a more conservative set of running speeds and/or recruit a more fit subject population to successfully complete the running stages at 100% jet settings, therefore causing fewer unusable results at the fast speed and 100% jets.

In conclusion, the relationship between MC and jet resistance settings in ATM is quite different than TM incline. The TM incline provided a linear increase in MC while the ATM jet resistance settings provided a cubic rise in MC. The ATM response may be a result of nonlinear application of drag forces on the torso created by the water velocities of the water jets when subjects are positioned one meter from the jet nozzles. Regardless of the inability to directly compare MC of these two methods, this data now gives researchers and clinicians a greater understanding of the relationship.

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