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The Difference in Efficiency and Pulmonary Function While Performing Cycle Ergometry on Land and in Water

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Peer Review

Abstract

The purpose of this study was to quantify the difference in net efficiency and pulmonary function while performing cycle ergometry on land in water. Thirty healthy adults (mean ± SD, age, 20 ± 2 y; stature, 165 ± 10 cm; mass, 70 ± 5 kg) participated in one day of testing consisting of both land and water conditions. Heart rate, O_2 consumption, CO_2 production, rated perceived exertion, and minute ventilation were measured for both conditions at rest, pedaling at no resistance, 50, and 100 W for two minutes. A repeated measures two-way ANOVA with post hoc tests was used to analyzed the data. The magnitude of physiological functions (rated perceived exertion, minute ventilation, energy expenditure, & heart rate) increased at higher resistance levels (50 and 100W) in water as compared to land. Efficiency decreased at 50 and 100W in water. Energy expenditure and minute ventilation both increase while cycling in water, resulting in a decrease of efficiency by 4.61%. This is due to the drag forces associated with fluid dynamics. This study and its results add to the understanding of water exercise and are beneficial to the rehabilitation and the general well-being and health of the population.

Keywords

aquatic exercise, physiological responses, stationary biking, energy expenditure

BACKGROUND

Water exercise is an increasingly popular workout for elderly people, injured athletes, joint replacement patients, overweight individuals, and pregnant women (Benelli, Ditroilo, & De Vito, 2004; Cassady & Nielsen, 1992; Finkelstein et al., 2012; Greene, Greene, Carbuhn, Green, & Crouse, 2013). It creates a buoyant condition that decreases stress on joints and skeletal structures as compared to land exercise (McGinnis, 2013). As water-based exercise is utilized more frequently in the fitness world, it is important to quantify the different physiological reactions water elicits in terms of work rate and efficiency. Quantifying these reactions is important in keeping the general public and these specific populations safe from overexertion and/or injury (Benelli et al., 2004; Cassady & Nielsen, 1992; Finkelstein et al., 2012; Greene et al., 2013). Physical therapists, personal trainers, and aquatic center staff can use this knowledge to strategically incorporate water-based exercise, improving the quality of exercise prescription for their clientele. However, few if any existing studies have provided information about efficiency and pulmonary function in water versus land at a measured workload. The quantification of workload in our study is significant and novel.

Pulmonary function, in its simplest form, is the exchange of gas between a human's body and the ambient air. One test that quantifies the effectiveness of an individual's pulmonary function is minute ventilation (V_E), the volume of air inspired or expired per unit of time. This test can provide insight into the mechanisms of pulmonary function in different exercise environments at different work rates (Beam & Adams, 2014).

Although there have been several studies exploring various land versus water exercises associated with fluid dynamics, it is still yet to be quantified in terms of work rate (Barbosa, Garrido, & Bragada, 2007; Giacomini et al., 2009; Silvers, Rutledge, & Dolny, 2007). Many of these studies focus on modes of exercise that are difficult to measure in terms of work rate. Thus, there has been relatively little research systematically comparing the physiological responses when completing identical exercise workloads (e.g. watts) in water versus on land. Cycle ergometry, better known as stationary biking, can provide a precise, accurate, and reliable measurement of work rate. Using this mode of exercise, work rate in water can be quantified, allowing for a comparison to the same work rate performed on land.

By accurately measuring the work rate of cycling, a reliable quantification of efficiency is achievable. The first law of thermodynamics, energy cannot be created or destroyed, only transformed (Ettema & Lorås, 2009), explains how efficiency of a system can be achieved. The thermodynamic potential, enthalpy, is the sum of the internal energy of a system as well as the product of pressure and volume. While considering energy change of muscle contraction it can be simplified that enthalpy change is equal to internal energy change since muscle volume is essential constant. Enthalpy consists of free energy and entropy. The change in free energy is what drives reactions because when work is performed ATP hydrolysis liberates energy and therefore drives another reaction leading to more work production.

However, not all the free energy can be utilized to produce work, instead a small amount is released as heat, increasing entropy. The efficiency of the human body is dependent on the ratio of work output divided by energy expended above rest (Ettema & Lorås, 2009). Energy expended above rest in relation to human movement is

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determined by measuring resting energy expenditure or basal metabolic rate (BMR) followed by energy expenditure during activity.

Efficiency can be measured in multiple way, however, the most relevant is net efficiency. Net efficiency is calculated by subtracting out all energy expended that is not directly related to the work being produced, called a baseline subtraction (Ettema & Lorås, 2009). Calculating efficiency requires the measurement of energy expenditure at a given work rate utilizing a metabolic cart, Douglas bag, or other breath-by-breath analysis methods. Energy expenditure is calculated by measuring the O_2 consumed and CO_2 produced at a given work rate (energy expenditure ($J\ s^{-1}$)= [(3.869 x VO_2) + (1.195 x VCO_2) x (4.186/60) x 1000)]) (Weir, 1949). By taking into account the substrate utilization the O_2 and CO_2 measurements allow the quantification of energy expenditure to be more accurate (i.e. lipids vs. carbohydrates). Factors that affect efficiency of human movement consist of cadence (Ettema & Lorås, 2009), resistance (Ettema & Lorås, 2009), muscle fiber type, movement type, fitness level/experience, and possibly the environment (water, air, etc.). Very little research has explored the link between a water environment and efficiency in cycling.

Therefore, the purpose of our study was to quantify the difference in efficiency and pulmonary function during leg-only cycle ergometry in water and on land.

METHODS

Thirty healthy adult volunteers participated in this study (20 ± 2 years old, 165 ± 10 cm in stature, and 70 ± 5 kg in mass). The institutional review board reviewed and approved the study and all the participants completed an informed consent. Participants completed the physical activity readiness questionnaire (PAR-Q) (Beam & Adams, 2014), were familiarized with the procedures and assigned an initial condition of either cycling in water or on land. Half the participants began in the water and half began on land, counterbalancing the order of the conditions.

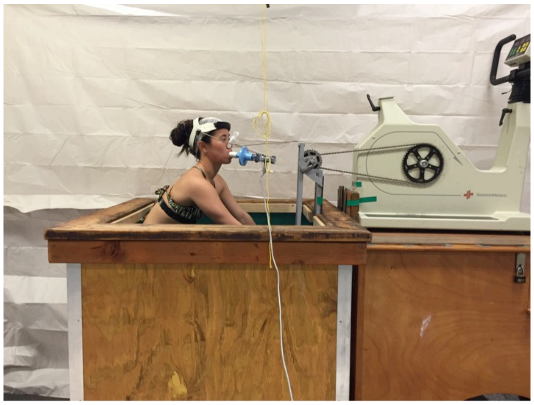

Figure 1. Bike setup with dunk tank.

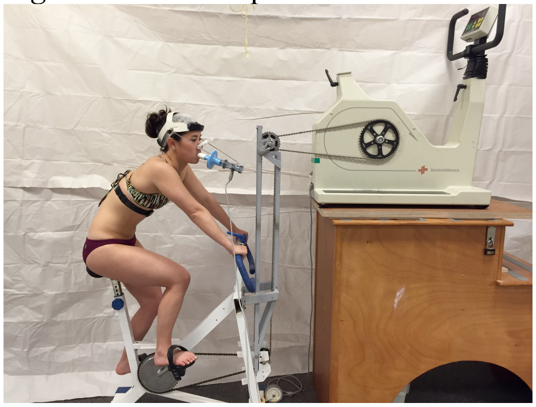

Figure 2. Bike setup without dunk tank.

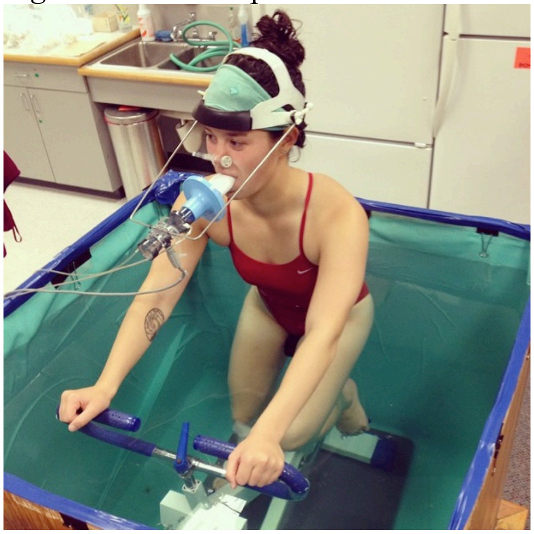

*Figure 3***.** Participant cycling in water.

Testing Specifications

A Monark ergometric 824e cycle ergometer was modified in order to transfer the power out of the water tank to an external electromagnetically braked SensorMedics cycle ergometer, which provided the resistance (Figures 1 & 2). The bike was uniform for all participants by ensuring the seat height produced a slight knee bend at full leg extension. Participants were required to sit upright with their hands on the handlebars and feet on the pedals at all times during testing. In both conditions participants did not wear shoes. The water height was at or above the level of the iliac crest with the knees never breaking the surface of the water while pedaling. The water temperature was maintained at 32±2° C (89° F) which is considered the thermoneutral temperature (Yazigi et al., 2013) in water, meaning the body does not have to heat up or cool down. The air temperature was maintained at 21±2° C (70° F).

Procedures

Each participant was fitted with a heart rate monitor (Polar WearLink + Coded Transmitter W.I.N.D.). After participants were positioned in water tank, baseline O_2 consumption and CO_2 production were measured via Cardinal Healthcare Viasys SensorMedics Vmax 229 metabolic cart for two minutes. Cycling commenced and was continuous, consisting of three intensity levels; 0, 50, and 100 watts. At each level the participants cycled for two to three minutes in order to reach and maintain a steady state. O_2 consumption and CO_2 production were collected along with V_E and heart rate (HR). Rate of perceived exertion (RPE) was assessed 30 seconds before the end of each resistance level. The procedure was identical for the water and land conditions, with a mandatory resting period between the two conditions.

Data Analysis

Data was collected during the last minute of each intensity level for O_2 consumption, CO_2 production, HR, RPE and V_E and was averaged and analyzed. Principles of indirect calorimetry were utilized to quantify energy expenditure at each level (resting, 0, 50, and 100 watts) by using the average O_2 consumption and CO_2 production. The equation for energy expenditure utilized was $(J\bullet s^{-1}) = [(3.869 \text{ x } VO_2) + (1.195 \text{ x } VCO_2) \text{ x } (4.186/60) \text{ x } 1000)]$ (Weir, 1949). At both 50 W and 100 W conditions, net efficiency was calculated. To analyze each variable of interest (RPE, HR, V_E, energy expenditure, efficiency), repeated measures two-way ANOVA and appropriate post hoc tests compared land/water (two levels) and power (rest, 0 W, 50 W, 100 W) with alpha = 0.05. Observed statistical power was also computed using alpha = 0.05.

RESULTS

With regard to RPE, repeated measures 2x4 ANOVA was utilized to investigate the effect of land/water condition (two levels) at four power levels (rest, 0 W, 50 W, 100W). Main effects were revealed for land/water condition (F_{29}=19.843, p<.001, observed statistical power = 0.981) and for power condition (F_{27}=85.591, p<.001, observed power = 1.00). Furthermore, an land/water x power interaction was observed (F_{27}=12.309, p<.001, observed power = 0.997). Subsequent post hoc tests showed no difference in RPE between water and land conditions at rest (t_{29}=0.57, p=0.573) and while pedaling at no resistance (t_{29}=1.41, p=0.169). However, RPE increased while pedaling in water at 50W (t_{29}=3.40, p=0.002) and 100W (t_{29}=6.50, p<0.001). (Figure 4)

With regard to HR, repeated measures two-way ANOVA revealed no main effect for land/water condition

(F_{29}=.078, p=.782, observed power = 0.058); however, a main effect of power (F_{27}=252.723, p<.001, observed power = 1.00) and land/water x power interaction was revealed (F_{27}=11.690, p<.001, observed power = 0.998). Post hoc tests showed no difference between water and land conditions while pedaling at no resistance (t_{29}=0.59, p=0.563) and 50W (t_{29}=1.80, p=0.082). Interestingly, during rest HR was 10.18 BPM lower in water (t_{29}=4.80, p<0.001). Conversely, while pedaling in water at 100W, HR was 3.13 BPM higher (t_{29}=2.10, p=0.045). (Figure 5)

With regard to V_E, repeated measures two-way ANOVA revealed main effect for land/water (F_{29}=15.856, p<.001, observed power = 0.97) and for power (F_{27}=339.720, p<.001, observed power = 1.00). Additionally, a land/water x power interaction was observed (F_{27}=32.083, p<.001, observed power = 1.00). Post hoc tests indicated no difference in V_E between water and land conditions at rest (t_{29}=1.52, p=0.139) and while pedaling at no resistance (t_{29}=0.72, p=0.476). However, V_E was higher in water at 50W (t_{29}=4.37, p<0.001) by 4.12 L/min and at 100 W (t_{29}=8.41, p<0.001) by 8.39 L/min. (Figure 6)

With regard to energy expenditure, ANOVA revealed main effects for land/water condition (F_{29}=28.863, p<.001, observed power = 0.999) and power (F_{27}=1240.628, p<.001, observed power = 1.00), in addition to a land/water x power interaction (F_{27}=53.837, p<.001, observed power = 1.00). Post hoc tests, comparing land to water, found no difference in energy expenditure at 0 W (t_{29}=1.84, t=0.0758). At rest, energy expenditure was lower in water (t_{29}=2.21, p=0.035) by 12.94 J/s. However, while pedaling in water, energy expenditure was higher at 50W (t_{29}=7.15, p<0.001) by 82.23 J/s and at 100W (t_{29}=10.40, p<0.001) by 99.86 J/s. (Figure 7)

Regarding efficiency, repeated measures AVOVA revealed main effects for land/water condition (F_{29}=149.985, p<.001, observed power = 1.00) and power (F_{29}=200.547, p<.001, observed power = 1.00), with a land/water x power interaction (F_{29}=10.976, p=.002, observed power = 0.61). Post hoc tests showed lower net efficiency pedaling in water, as compared to land, at both 50W (t_{29}=8.89, p<0.001) and 100W (t_{29}=12.29, p<0.001). (Figure 8)

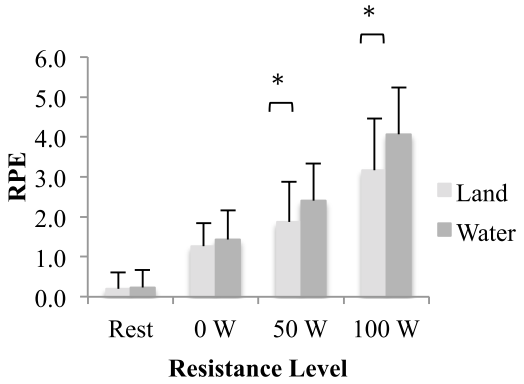

Figure 4. The difference in RPE while performing cycle ergometry at 4 different resistance levels on land and in water. Asterisks indicate a significant difference between the land and water conditions.

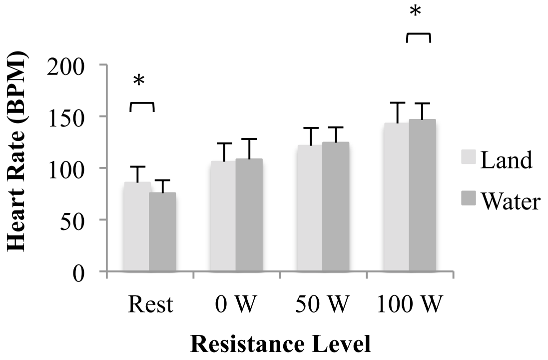

Figure 5. The difference in heart rate while performing cycle ergometry at 4 different resistance levels on land and in water. Asterisks indicate a significant difference between the land and water conditions.

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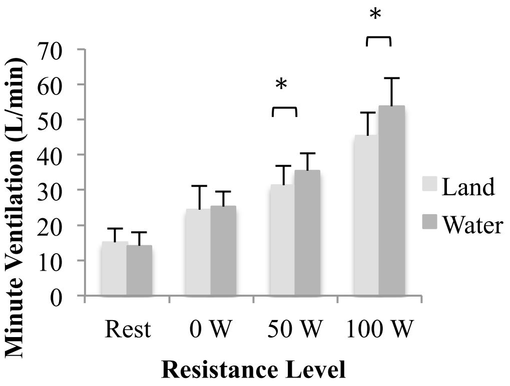

Figure 6. The difference in minute ventilation while performing cycle ergometry at 4 different resistance levels on land and in water. Asterisks indicate a significant difference between the land and water conditions.

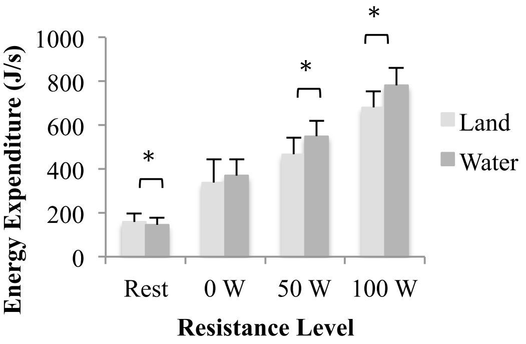

Figure 7. The difference in energy expenditure while performing cycle ergometry at 4 different resistance levels on land and in water. Asterisks indicate a significant difference between the land and water conditions.

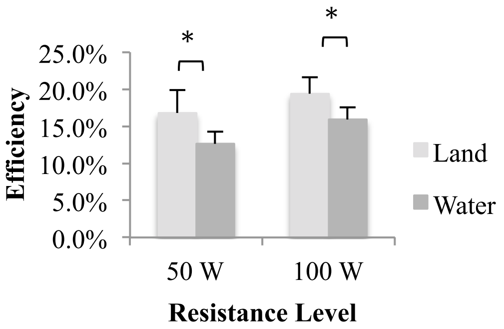

Figure 8. The difference in net efficiency at 50 and 100 W while performing cycle ergometry on land and in water. Asterisks indicate a significant difference between the land and water conditions.

DISCUSSION

The effect of exercise intensity on RPE, HR, and V_E is well established in literature; thus, it was not surprising that ANOVA revealed main effects of power (exercise intensity) for RPE, HR, and V_E in our study. However, we were most interested in the comparison of land versus water at various quantified power levels, which was accomplished via post hoc tests.

Post hoc tests showed energy expenditure was higher when cycling in the water conditions at 50W and 100 W, while efficiency was lower. Efficiency was determined to be 4.51% lower in the water. This is due to the fluid mechanics of the water condition. There are two main components that constitute fluid mechanics, drag force and buoyant force (McGinnis, 2013). The drag force may have caused lower efficiency and higher energy expenditure. Drag force is the component that acts in opposition to the motion of an object, slowing down the relative velocity through fluid. Therefore, in order to maintain the same rate of pedaling against the same resistance as on land, the body must utilize more energy to overcome the added drag force. This in turn could be an indirect measure of the added work that water imposes on the body in order to pedal at the same rate as compared to on land.

At rest, the heart rate and energy expenditure were lower in water than on land. This is consistent with previous findings suggesting a decrease in physiological response that occurs when the human body is submerged in water (Alberton et al., 2014; Barbosa et al., 2007; Benelli et al., 2004; Cassady and Nielsen, 1992; DeMaere and Ruby, 1997; Silvers et al., 2007). By this mechanism, heart rate is lowered by the increase in venous return due to the hydrostatic pressure on the lower torso and legs (Silvers et al., 2007). In theory, this may slightly decrease energy expenditure at rest. In contrast, there was no difference in heart rate and energy expenditure while pedaling at no resistance and 50W. This could be a result of the HR (initially lower in the water) increasing at a faster rate than the HR on land. Once pedaling began in the water condition at a low work rate, HR equaled that on land. However, at a higher work rate, the water HR eventually surpassed the land HR at the same high work rate. This phenomenon was also reflected in the energy expenditure results.

Minute ventilation and RPE were also found to be higher while cycling in water as compared to cycling on land at 50W and 100W. The extra force needed to overcome the drag from the water likely required additional muscular effort and the requisite increase in energy expenditure. Increasing energy expenditure, in most cases, leads to an increase in minute ventilation and RPE. This was probably the case in our study, as shown by the increase of minute ventilation and RPE while exercising in water, as compared to land, at the higher power levels.

More information is needed to fully understand how water can be used for exercise in meaningful ways. There is extensive research supporting the best way to perform each of the swimming strokes as well as research concerning deep water running. However, studies focusing on different forms of exercise in the water, such as cycling, are still very limited. Further investigation into the difference in efficiency and pulmonary function while performing tasks in the water may provide insights for exercise prescription, including the effects of rpm, water temperature, power settings, etc. on the physiological responses of the exerciser.

Due to the configuration of our study, the number of power levels that we could investigate was relatively limited. Further investigation of higher intensity levels, including maximal, would be beneficial. Additionally, it would be beneficial to investigate other modes of exercise, RPM, temperatures, and depths of water submersion when exercising. The composition of the sample population was also a limiting factor, as our sample was a college-age group available through convenience sampling. This makes it difficult to apply the findings to a broader population, such as individuals with health limitations. By quantifying efficiency of the body while performing cycle ergometry, the effect water exercise has on the physiological functions is now better understood and can be utilized as reference for further investigations.

CONCLUSION

Our findings support previously established knowledge of resting heart rate values in water. Our results demonstrate that physiological functions increase while exercising at higher resistance levels in the water, as compared to exercising on land. These findings are likely due to the additional drag force added by the water condition. To the best of our knowledge, we are the first study to quantify the difference in efficiency in water as compared to land. The 4.61% decrease in efficiency provides unique information about the effect of water on the human body while exercising. This may be beneficial to the rehabilitation and the general well being of certain populations, such as joint replacement patients, injured athletes, pregnant women, and individuals suffering from muscular weakness and other forms of weight bearing limitations. Water exercise offers an attractive alternative to land based exercise; therefore it is becoming increasingly popular within the therapeutic and exercise communities. Although this research set up may not be practical for the general population, it is still important for scientists to quantify the physiological effects elicited by different work rates in water. The new understanding of water exercise found in this study may allow people such as physical therapists, athletic trainers, and personal trainers to better prescribe exercise to their patients and clients. Land exercises are well established and easily recommended to people. However, water exercises are not as well understood. As this form of exercise becomes more and more popular the need to fully understand it becomes more important.

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