

Quantifying Energy Expenditure During Water-Immersion in Non-Trained Cyclists

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ABSTRACT. *This research project was designed to compare energy expenditures during water-immersion and ambient-air states at three external work rates of 50, 100, and 150 W. Eleven participants were tested on two separate occasions on a bicycle ergometer in water-immersion and ambient-air environments for 3 to 4 min at 50 rpm. Oxygen consumptions and heart rates were monitored continuously throughout both sessions. Perceived exertion was assessed at each work rate during the final 30 s of the sampling period. Water-immersion produced higher oxygen consumption values (2.21 ± 0.20 vs. 1.00 ± 0.14 L min⁻¹ at 50 W; 2.64 ± 0.33 vs. 1.45 ± 0.12 L min⁻¹ at 100 W; and 2.86 ± 0.41 vs. 2.00 ± 0.16 L min⁻¹ at 150 W). Heart rates were greater in water (142.70 vs. 97.90 at 50 W; 152.73 vs. 113.14 at 100 W; and 163.82 vs. 135.09 at 150 W). Perceived exertion scores were higher in water (11.7 vs. 8.5 at 50 W; 15.0 vs. 10.6 at 100 W and 17.2 vs. 12.7 at 150 W). Energy expenditure rates were greater in the water-immersion environment (769 vs. 348 W at 50 W; 919 vs. 505 W at 100 W; 995 vs. 696 W at 150 W). It was concluded that at a constant external load, water-immersion produces greater oxygen consumption and heart rate responses compared to values assessed in an ambient-air state. This difference reflects the external load required to move the viscous liquid instead of air.*

Keywords. *Efficiency, Ergometer, Oxygen consumption, Pedaling.*

Mechanical engineering students at the University of Maryland were about to enter a human-powered submarine race. They had questions about power requirements to propel the submarine if the pedaling had to be done underwater. This study grew out of their queries.

With estimates of submarine velocity and drag coefficient, they were capable of estimating power requirements. However, they were not sure whether their calculations gave realistic power and velocity values attainable by working humans. A search of the literature revealed that some relevant measurements had been made, but nothing was found to answer their questions directly.

Submitted for review in March 2007 as manuscript number BEJ 6956; approved for publication by the Biological Engineering Division of ASABE in February 2009.

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Pedaling underwater would be expected to have both physical and physiological consequences. The viscosity of water is about 100 times greater than that of air. Movement of the legs and feet in water would consequently consume more power than the same motions in the air. Rotating surfaces, of wheels for instance, would have greater drag in water compared to air. To the contrary, contacting surfaces rubbing together would be lubricated more in water than in air.

Pedaling in water would have at least two physiological effects. First, water pressure outside the legs would improve venous blood return to the heart, thus improving cardiac efficiency. It would be expected that stroke volume would be somewhat higher and heart rate lower with the legs immersed in water. Water also has a thermal conductivity about 25 times higher than air. Thus, water-immersion promotes heat transfer from the working muscles. Colder muscles generally have lower efficiencies than warmer muscles, so water-immersion could increase oxygen consumption for the same rate of work.

Taking all these effects together, it was not clear how the students' questions should be answered. Thus, this study was undertaken to answer the question about underwater pedaling empirically. The result can then be used for any number of engineering designs with similar circumstances.

Methods

Eleven volunteers agreed to participate in this research project conducted by the Human Performance Laboratory in the Department of Biological Resources Engineering at the University of Maryland at College Park and previously approved by the University's Institutional Review Board. All participants were provided with an informed consent document outlining the procedures and methods applicable to this investigation. Volunteers were asked to read and sign this document before being allowed to take part in this investigation.

Participants were asked to report to the laboratory on two separate occasions to exercise on a bicycle ergometer (Monark AB, Vanberg, Sweden) at 50, 100, and 150 W external work at 50 rpm for approximately 3 to 4 min. This gave time for steady state to be reached. The exercise sessions were conducted in two environments (ambient-air and water-immersion) on separate test days.

Individuals were positioned on the bicycle ergometer with the seat height adjusted to produce a partial bend in the knee in the extended position. Next, the participant was instructed to pedal at 50 rpm while the ergometer work setting was gradually adjusted by the investigator to the desired work rate. A speedometer was used to maintain the appropriate 50 rpm pedal cadence. A 10 to 15 min recovery period was allowed before imposing the next work rate, to allow heart rate and oxygen consumption values to return to baseline. Physiological variables were monitored during the recovery phase to ensure return to baseline. The participant was repositioned on the ergometer for the next assessment and instructed to begin pedaling at the required cadence while the ergometer setting was adjusted to the new work rate to perform for another 3 to 4 min. Another 10 to 15 min recovery period followed this assessment phase prior to executing the final work rate. The order of the mechanical loads was not completely randomized; the 150 W load in water was often performed first in water because it was such a heavy burden.

The water-immersion session was conducted in an industrial-sized tank modified with a false floor to provide a support base for the ergometer. A pulley system was employed to lower the ergometer inside the tank, which was previously filled with tap water. The temperature inside this tank was maintained at approximately 23°C to 25°C. Participants were allowed to warm up and stretch for approximately 5 to 10 min prior to entering the tank. A ladder was positioned inside the tank, permitting volunteers with access to enter and leave the tank. Subjects were immersed only to their waists; their upper bodies were not immersed. Test procedures were identical in water and air, although water pedaling required longer recovery times between work rates. Foot clips were not used for either condition.

The Monark bicycle ergometer has a disk wheel in the front encircled by a flexible band. As the band is tightened, friction between the band and the disk causes a greater force to be applied. This force is measured by a lever arrangement. Mechanical power load can be determined from the force, the disk radius, and the speed at which the disk is rotated by pedaling. Thus, identical external loads could be imposed on the subject in water or in air, although the belt had to be tightened considerably more in water to give the same force because of the lubrication properties of water.

A Hans Rudolph (Kansas City, Mo.) two-way breathing valve was used to collect expired air from participants in both sessions. A portable mixing chamber was used with a Fleisch (Phipps and Bird, Richmond, Va.) pneumotach to assess expiratory air flow, and a Perkin Elmer (Pomona, Cal.) model 1100 mass spectrometer was used to determine gas composition of the expired air. A custom computer software program was used to calculate oxygen consumption by integrating expiratory airflow and gas data. Oxygen consumption data were collected throughout the session as 30 s averages and monitored graphically on a computer monitor screen. Steady-state oxygen consumption was recorded as the final 30 s reading.

Heart rates were determined using either a Hewlett Packard (Siemens, Andover, Mass.) monitoring system or a Polar (Kempele, Finland) heart monitor. In the ambient-air session, skin surface electrodes were used with cables connected to the monitoring system. The Polar heart rate monitor was used to assess heart rates in the water-immersion session. This procedure required attaching a transmitter strap along the participant's lower sternum to interface with a receiver worn on the participant's wrist. Heart rate data were collected throughout the assessment periods, with average reported values determined in the final 30 s at each work rate.

The Borg scale (6 to 20) was used to assess perceived exertion. This measurement was taken in the final 30 s at each work rate.

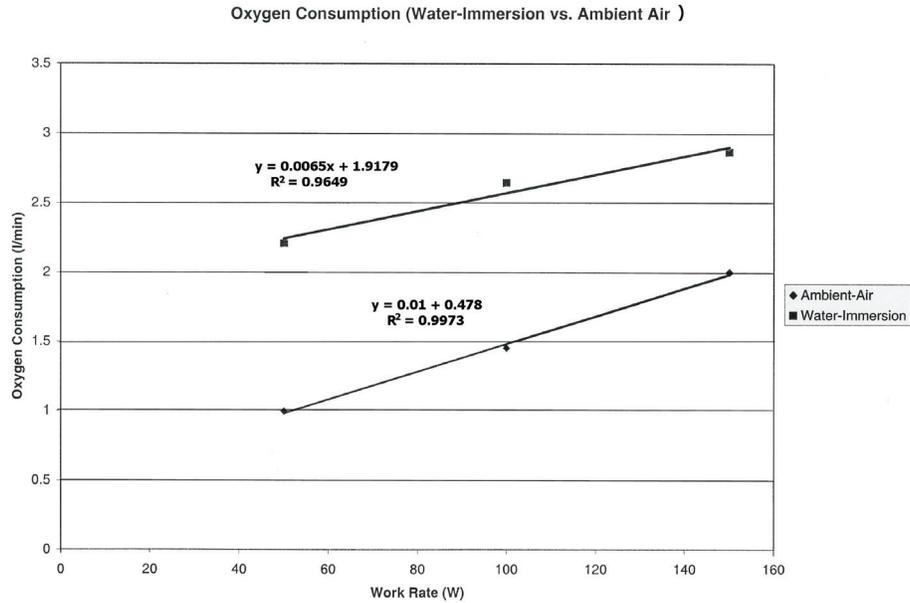
Means and standard deviations were determined for all variables. T-tests were conducted to determine if means differed between work rates (50, 100, and 150 W) and conditions (ambient-air and water-immersion).

Results

Subject demographics are presented in table 1. Linear relationships were observed between work rate and the dependent variables examined in this investigation (figs. 1 through 4). Table 2 shows the means and standard deviations for oxygen consumption at constant external loads (50, 100, and 150 W) in the ambient-air and water-immersion states. Oxygen consumption was statistically significantly different

Table 1. Subject demographics.

Subject	Age (years)	Height (cm)	Mass (kg)	Gender
1	41	173	93.2	m
145	33	177	93.0	m
289	22	183	81.8	f
290	27	178	68.2	m
305	23	190	90.9	m
306	22	183	79.5	m
307	22	168	61.4	f
308	23	185	78.2	m
310	36	170	70.9	f
313	21	183	88.6	m
314	19	190	84.1	m
Average	26.4	180	80.9	
SD	7.1	7.7	10.6	

**Figure 1. Average oxygen consumption variation with external work rate for air and water pedaling. Oxygen consumptions were about twice as large for water pedaling.**

between work rates in both environments ($p \leq 0.05$). At constant external loads, the water-immersion environment produced greater oxygen consumption values compared to observations taken in the ambient-air state.

Heart rates were statistically significantly different between work rates in both ambient-air and water-immersion environments. At similar mechanical loads, the water-immersion state produced significantly higher heart rate responses compared to measurements determined in ambient air.

Perceived exertion values were statistically significantly different between work rates in all ambient-air states. At similar external loads, the water-immersion state

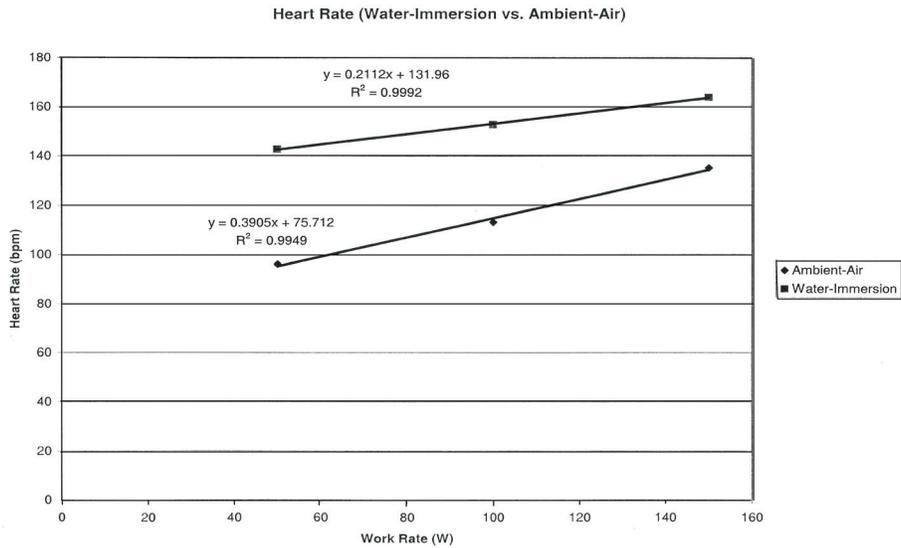


Figure 2. Average heart rates with external work rate for air and water pedaling. Heart rates were higher for water pedaling.

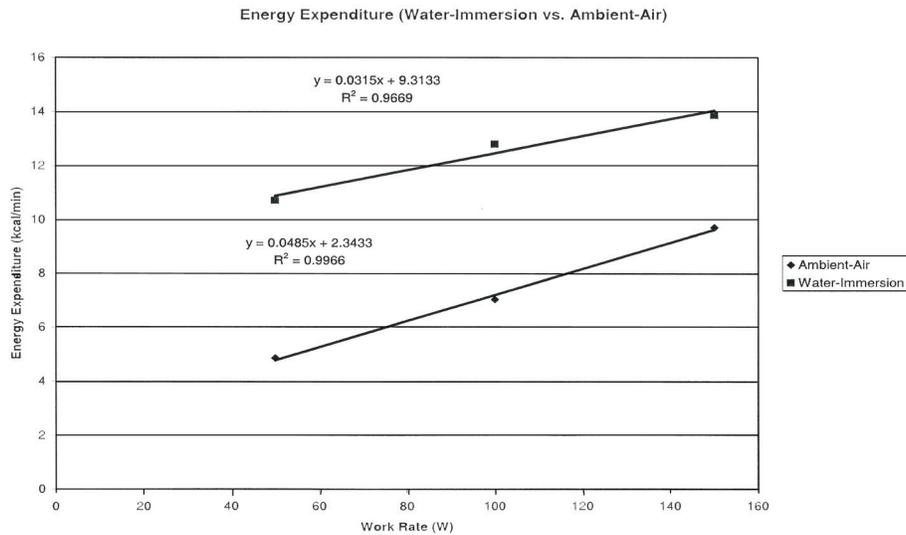


Figure 3. Physiological work rates with external work for air and water pedaling. Physiological work rates were nearly twice as large for water pedaling.

produced higher perception responses compared to values assessed in the ambient-air environment.

Physiological work rate data are also presented in table 2. This information was calculated by multiplying oxygen consumption ($L \text{ min}^{-1}$) by 348 to convert to watts. Physiological work rates in water were about double those in air. Gross mechanical

Rating of Perceived Exertion (Water-Immersion vs. Ambient-Air)

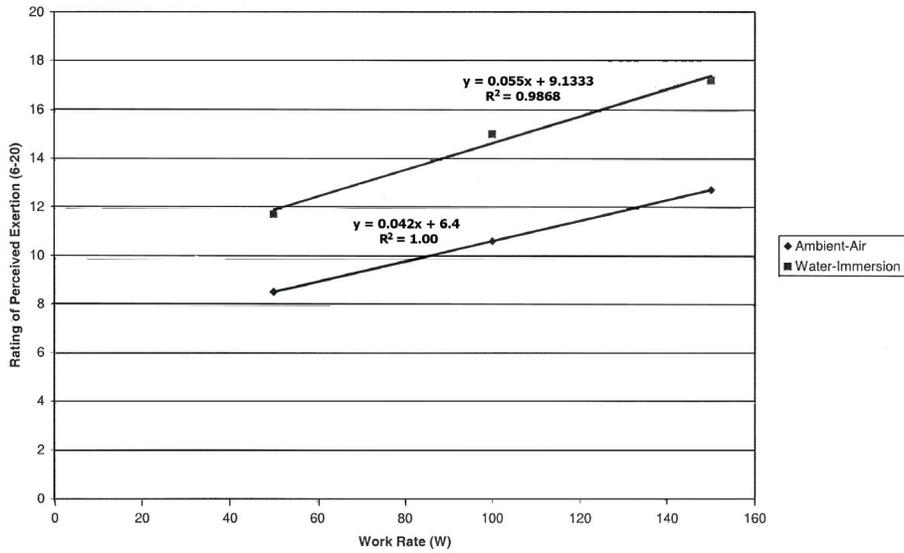


Figure 4. Ratings of perceived exertion with external work rate for air and water pedaling. Water pedaling was perceived as much more difficult than air pedaling.

Table 2. Comparison of results between air and water pedaling oxygen consumption ($L \cdot min^{-1}$).^[a]

	External Work Rate (W)	Air Pedaling	Water Pedaling
Oxygen consumption ($L \cdot min^{-1}$)	50	1.00 ± 0.14	2.21 ± 0.20
	100	1.45 ± 0.12	2.64 ± 0.33
	150	2.00 ± 0.16	2.86 ± 0.41
Heart rate (beats min^{-1})	50	96.05 ± 10.43	142.70 ± 16.72
	100	113.14 ± 13.61	152.73 ± 20.65
	150	135.09 ± 18.20	163.82 ± 16.17
Physiological work rate (W)	50	348	769
	100	505	919
	150	696	995
Gross efficiency (%)	50	14	6.5
	100	20	11
	150	22	15
Perceived exertion	50	8.5	11.7
	100	10.6	15.0
	150	12.7	17.2

^[a] Values given are means ±SD. Physiological work rates were converted from oxygen consumption rates with $348 W = 1 L \cdot min^{-1}$.

efficiencies were determined by dividing external work rate by calculated physiological work rate. Efficiencies were about half as much in water compared to air.

Discussion

This project was designed to quantify oxygen consumption, heart rate, and energy expenditure responses on a leg ergometer during water-immersion at three constant

external loads (50, 100, and 150 W). Our findings indicate that water-immersion cycling produces higher oxygen consumptions, heart rates, rates of energy expenditure, and perceived exertion values compared to observations taken in the air at similar external loads.

These results differ somewhat from previous water-immersion investigations showing no difference or lower cardiorespiratory responses in the water-immersion state compared to ambient-air environments (Christie et al., 1990; Dressendorfer et al., 1976; Sheldahl et al., 1984; Wells et al., 1986). Methodological differences may explain why the present research findings differ from previously published reports. Christie et al. (1990) examined oxygen consumption and heart rate responses in healthy males cycling in ambient-air and water-immersion states at 40%, 60%, 80%, and 100% of $\dot{V}O_2$ max and reported similar oxygen consumption values between environments. Their work loads were relative rather than absolute as the work loads were here. Dressendorfer et al. (1976) assessed maximal oxygen consumption and heart rate responses in seven participants in water-immersion and ambient-air states and reported similar maximal oxygen consumption values between environments, with lower heart rate values (10 beats min^{-1}) occurring in the water-immersion condition. Maximal oxygen consumption values might not be expected to change for similar muscle groups used. Sheldahl et al. (1984) reported no difference in heart rates at work loads corresponding to 1.2, 1.5, and 1.8 L O_2 min^{-1} . For the same type of work, the relationship between oxygen consumption and heart rate would be expected to remain the same, although the relationship of heart rate and oxygen consumption changes as the type of work changes (Johnson, 2007). Bréchat et al. (1999) examined ventilatory responses in water-immersion and ambient-air environments using work loads corresponding to 60% maximal oxygen consumption. Their ergometer work rate was set at 69 and 121 W in the water-immersion and ambient-air states, respectively, to produce similar constant physiological loads between environments. The same authors also evaluated oxygen consumption responses in the water-immersion and ambient-air environments using a constant mechanical load (122 W) that elicited greater oxygen in the water-immersion state.

The present study imposed constant external load in both air and water. For this condition, it would be expected that the additional burden of moving water instead of air would require higher oxygen consumption rates, and that was what has been observed. Hence, differences between results from the present study and reviewed published reports are probably due to methodological differences.

Gross mechanical efficiencies were obtained by dividing mechanical work rates by physiological work rates. No account was taken for basal metabolic processes. Values obtained were in expected ranges, and, again, efficiencies were lower for water-immersion.

Comparing oxygen consumption values between water and air at the same work rates shows a nearly constant difference at the two lower work rates, but a markedly smaller difference at 150 W. It is unclear why this should be so, but there are clues. The one inconsistent tabled value is the oxygen consumption at 150 W in water. Is it possible that pedaling in water at this high work rate disrupted the smooth cadence present at lower work rates? It was noticed that pedaling became choppy with more rocking motion for this one condition. One would expect, however, that such a motion might cause higher, not lower, oxygen consumption rates. At an average of 2.85 L

min^{-1} , some subjects may have reached their maximum oxygen consumption values (typically about 3.2 L min^{-1}). From the water-air differences at lower work rates, an oxygen consumption value of 3.2 L min^{-1} might be expected at 150 W. This value would be close to, if not above, the maximum oxygen consumption values for some of our subjects. If this is true, then some oxygen consumption values would be capped at the maximums.

There might be some concern that the front disk wheel rotating in water compared to air would impose an additional external load on the subject not accounted for by the force on the band. Although not measured, this additional load would have been the same at all mechanical loads as long as the rotation rate of the wheel remained the same, and it was not likely to be significant compared to the results of moving legs, feet, and pedals in the water.

There is one additional factor that could bear on the differences between oxygen consumption values for the two different environments. Although the air and water temperatures were about the same, water might be expected to remove more heat than air from moving legs and feet. It is possible, therefore, that leg muscles were cooler in the water than in the air. Efficiencies of cooler muscles are likely lower than those of warmer muscles. Thus, oxygen consumption values might be influenced by more than just the more dense and viscous surrounding fluid. When subjects first entered the water, they complained about the cold. After a very short amount of time pedaling, however, the water did not seem too cold.

In the present study, a linear relationship was exhibited between work rate and perceived exertion in both environments, with the water-immersion state producing greater exertion values at each mechanical load. This observation is similar to findings reported in a project by Brown et al., (1996) examining perceived exertion responses during deep-water and land-based treadmill runs. These authors reported that perceived exertion was dependent on leg speed and that the water-immersion state produced greater perceived exertion values at constant leg speeds. Hall et al. (1998) showed similar elevated responses for perceived exertion in immersed treadmill walking. Frangolias et al. (2000) examined water-immersion and land-based running at ventilation thresholds determined during the maximal oxygen consumption tests in both environments. Their findings showed that the rating of perceived exertion (RPE) did not differ between environments when assessing exertion using the water-immersion ventilatory threshold exercise intensity. In contrast, perceived exertion was significantly greater in the water-immersion state when the land-based ventilatory threshold work rate was used to assess perceived exertion responses. These authors reported lower maximal oxygen consumption and ventilatory threshold responses in the water-immersion state. These findings indicate that water-immersion produces elevated perceived exertion responses and that this response is intensity dependent.

The elevated physiological work rate expenditure responses displayed in the present water-immersion state agree with previous findings reported by Darby and Yaeckle (2000) showing higher caloric cost (70 to 140 W) in the water-immersion environment. The present investigation produced greater caloric values in the water-immersion state, with values ranging from 300 to 400 W. The greatest water vs. air difference for physiological work rate occurred at the lowest mechanical work rate.

Water-immersion is also used for athletic training and rehabilitation. Water-immersion activities are an alternative training modality used by individuals attempting to reduce stress from acute or chronic skeletal muscle injuries. Water-based activi-

ties take place in a buoyant environment that attenuates impulse loads applied to the skeletal muscular system. This effect creates an ideal exercise environment for elderly, obese, and injured individuals attempting to maintain fitness capacity without incurring the stress associated with high-impact activities. Results from this study could help in designing this type of training environment.

What this experiment showed quite clearly is that the movement of the legs, feet, and pedals in water at 50 rpm imposes an additional oxygen consumption penalty of about 1.2 L min^{-1} and a heart rate increase of about 30 to 50 beats min^{-1} . At different pedaling rates, these differences would be expected to change. If someone now comes to us to ask about the increased physiological burden of pedaling an underwater vessel, we will be able to answer with data instead of speculation.

Conclusions

Oxygen consumption, heart rate, physiological work rate, and perceived exertion were all higher in water than in air. Physiological work rates in water were found to be nearly double those in air. Gross mechanical efficiencies of the movements were about one-half those in air.

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