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Modification of a standard bicycle ergometer for underwater use

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Morlock, J. F., and R. H. Dressendorfer. Modification of a standard bicycle ergometer for underwater use. Undersea Biomed. Res. 1(4):335-342.—With a few simple modifications, the standard Quinton-Monark bicycle ergometer can be made suitable for underwater use. Using an ergometer so modified, $\dot{V}_{O_2}$ was measured in 6 young men as a function of pedaling frequency (f, rpm). The resulting data fitted to a third-order polynomial gave the relationship:

$$\dot{V}_{O_2} \text{ (liters/min)} = 0.274 + 0.002025f - 0.000059f^2 + 0.000008f^3$$

with a correlation coefficient (r) of 0.996. The extremely high accuracy of this predictive equation makes this simple ergometer of practical importance to the investigator interested in physiological responses to underwater exercise. A theoretical discussion on the physical meaning of each of the zero-, first-, second-, and third-order terms of pedaling frequency is presented. The discussion and results indicate that it is both theoretically and statistically correct to eliminate the first- and second-order terms of the above third-order polynomial. This results in an equally accurate (r = 0.996) equation of the following form: $\dot{V}_{O_2}$ (liters/min) = $0.274 + 0.000008f^3$.

underwater ergometer
underwater exercise
underwater oxygen consumption

With a few simple modifications, the Quinton-Monark bicycle ergometer (Åstrand 1960) can be converted to a very simple, yet very accurate, underwater ergometer. Its high predictive accuracy and subject nondependency makes this ergometer of practical importance to investigators interested in physiological responses of the working diver. Since the ergometer is both stationary in space and subject nondependent, it is preferable to either a stationary swim ergometer or a free swimming set-up for experimental purposes.

METHODS

Three basic modifications were made. First, two standard automative grease nipples were installed to provide easy regreasing of both the bottom bracket crank bearing and the flywheel bearing. Then a magentic reed switch[1]—to provide continual monitoring of the

[1]Calectro Electronics, Rockford, Illinois

pedaling frequency—was fastened securely to the frame and a small magnet was taped to the inside of the left pedal crank arm. The switch was connected in series with a standard 1.5 volt flashlight battery and the circuit was wired directly to the input terminals of a standard pen-recorder preamplifier. As the crank arm passed adjacent to the reed switch, the circuit was completed and a small pen deflection was produced, resulting in a direct count of pedaling frequency for any given time period. Third, the friction belt was removed and the bicycle ergometer was immersed in a water tank, 152 cm long, 64 cm wide, and 146 cm deep (see Fig. 1).

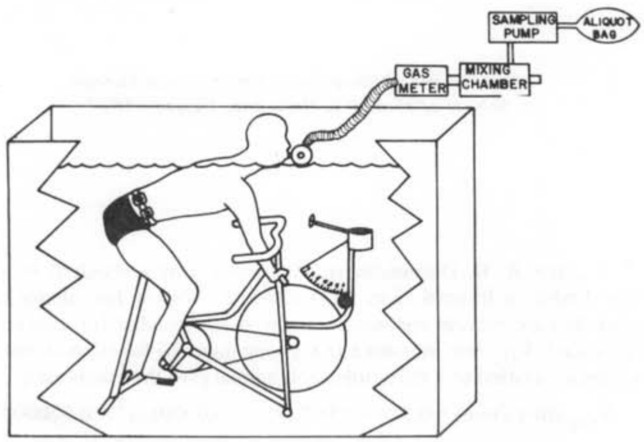

Fig. 1. Diagram of experimental lay-out.

Six male subjects, characterized in Table 1, wearing only swim trunks and a 4-kg weight belt, were immersed to the neck while sitting on the ergometer. The seat height was adjusted so that the legs were fully extended at the bottom-most pedal position. The subject gripped the resting foot pegs rather than the handle bars. This position was chosen to maintain the subject's upper body nearly horizontal, simulating a swimming scuba diver. The position is similar to that used by racing cyclists.

TABLE 1

Subject characteristics

Subjects	Age (years)	Height (cm)	Weight (kg)	% Fat	$\dot{V}O_2$ max (liters/min)	$\dot{V}O_2$ max (ml/kg · min)
DB	24	180	75.5	15	3.35	44
RD	29	178	70.8	9	4.08	58
JM	26	184	69.2	10	3.75	54
BR	29	170	65.4	16	2.06	31
RS	29	172	66.2	12	2.32	35
LW	24	164	58.1	13	2.66	46
						$45 = \bar{x}$

The subjects breathed either room air via a Collins Triple-J (3-J) low resistance mouthpiece or compressed air via a two-stage, double-hose regulator.[2] In the latter system, the compressed air bottle and the attached regulator (to be referred to as scuba) were mounted to the inside wall of the tank.

Each subject was asked to sit quietly on the ergometer for 10 min before a 2-min expired gas collection was taken. The subject then proceeded to pedal consecutively at 20, 40, 50, 60, and maximum rpm for 5 min. The desired pedaling frequency was obtained by having the subject keep time with a metronome. A continual check on the pedaling rate was given by the magnetic reed switch discussed earlier. Sometimes the subject was asked to repeat a given load if he was not pedaling at the correct rpm in order to make the 3J vs scuba comparison easier. Two 1-min expired gas collections were obtained at each frequency from minutes 3 to 4 and 4 to 5 in order to verify that a steady state of oxygen consumption had been reached. The protocal above was followed for each of the six subjects breathing either room air or compressed air while immersed in 30°C water.

Oxygen consumption was measured by one of two standard open-circuit methods by collection of expired gas. The first method, which was later replaced, consisted of passing the expired gas through a high speed Parkinson-Cowan flowmeter to measure $\dot{V}_E$ and then into a 4-liter baffled mixing chamber. An aliquot sample of 1-liter was continuously withdrawn from the mixing chamber over the entire collection period via a Beckman microcatheter sample pump. This was then analyzed for O_2 and C_{O_2} content by either a Beckman E-2 or OM-11 oxygen analyzer and a Beckman LB-1 C_{O_2} analyzer. The second method consisted of collecting the entire gas volume in meterological balloons, as described by Daniels (1971), and analyzing for O_2 and C_{O_2} content as described above. Expired gas volume was measured in a 350-liter Tissot spirometer. $\dot{V}_{O_2}$ (STPD) was then calculated according to the principles outlined by Consolazio, Johnson, and Pecora (1963).

RESULTS AND DISCUSSION

The results for each subject can be found in Table 2. By Student's paired t test, no significant difference in $\dot{V}_{O_2}$ was found between breathing room air or compressed air in 30° water. Therefore, all of the data were pooled and the relationship between $\dot{V}_{O_2}$ and pedaling is illustrated in Figure 2.

For reasons discussed later, polynomial regression analysis of the following form was applied:

$$\dot{V}_{O_2} = C_0 f^0 + C_1 f^1 + C_2 f^2 \cdots C_n f^n . \qquad (1)$$

Results of this analysis gave the best fit (r) = 0.996 when n = 3. The coefficients (± SE [Dixon 1968]) are as follows:

$$C_0 = +0.274$$
$$C_1 = +0.00202 \pm 0.00360$$
$$C_2 = -0.000059 \pm 0.000110$$
$$C_3 = +0.000008 \pm 0.000000$$

[2] U.S. Divers, Santa Ana, Calif.

TABLE 2
Individual data relating pedaling frequency and oxygen uptake (liters/min) during scuba and 3J (Collins Triple-J valve) breathing.

	RD				JM				DB			
	Scuba		3J		Scuba		3J		Scuba		3J	
	rpm	VO_2	rpm	VO_2	rpm	VO_2	rpm	VO_2	rpm	VO_2	rpm	VO_2
rest	0	.30	0	.24	0	.22	0	.29	0	.30	0	.29
"20"	20.0	.44	20.0	.37	20.0	.42	20.0	.35	22.0	.33	20.0	.44
"40"	39.5	.77	39.0	.62	41.0	.67	38.0	.86	36.0	.57	38.5	.66
"50"	52.0	1.26	52.0	1.25	48.5 49.5	1.12 1.21	50.0	1.23	48.0	1.10	51.0	1.14
"60"	59.5 62.5	1.86 2.08	59.5	1.84	61.0	2.00	58.0	1.74	60.0	1.71	59.0	1.83
"70"	68.0 78.0	2.57 3.63	72.5	3.06	71.5 76.0	3.00 3.67	69.0	2.66	74.0	3.24	70.0 74.0	3.11 3.29
max	79.0	4.08	80.0	3.90	78.0* 80.0	3.78* 3.75	76.0* 79.0	3.69* 3.75	76.0* 76.0	3.31* 3.33	74.0	3.35

	LW				RS				BR			
	Scuba		3J		Scuba		3J		Scuba		3J	
	rpm	VO_2	rpm	VO_2	rpm	VO_2	rpm	VO_2	rpm	VO_2	rpm	VO_2
rest	0	.22	0	.23	0	.34	0	.30	0	.23	0	.25
"20"	23.0	.44	23.0	1.47					20.0	.37	20.0	.32
"40"	40.0	.65	40.0	.72	44.5	.94	45.0	1.10	36.0	.47	39.5	.69
"50"	50.5 56.0	1.18 1.62	50.5	1.28	49.5	1.20	49.0	1.20	50.0	1.16	52.0	1.15
"60"	61.0 62.0	1.83 1.98	59.5	1.77	58.0 62.0	1.69 1.94	58.5	1.69	58.0	1.80	57.0	1.82
"70"												
max	69.0	2.67	69.0	2.66	68.0	2.29	68.0	2.32	62.0	2.01	63.5	2.06

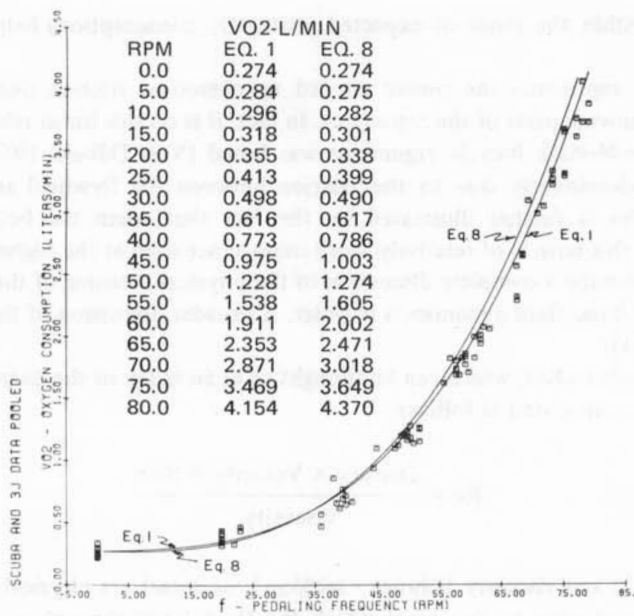

Fig. 2. Energy costs as a function of increasing workload.

Table 3 illustrates both the absolute value and the percentage of total (in parenthesis) of each of the terms in Equation 1 as pedaling frequency varies from 10 to 80 rpm. One sees that the f^0 term remains constant but becomes relatively less important as frequency increases. Both the f^1 and f^2 terms are of relatively little importance when expressed as a percentage of total $\dot{V}_{O_2}$ and, because they are opposite in sign and of approximately equal magnitude, they tend to cancel each other out. Finally, Table 3 illustrates that the f^3 term becomes progressively more important as frequency increases until, at 80 rpm, it represents almost the entire energy expenditure.

TABLE 3

Partitioned estimated oxygen consumption. ( )% contribution of total at each level of f.

VO_2 (liters/min) =		0.274	+ 0.002025f	– 0.000059f^2	+ 0.000008f^3
10	0.29635	0.274 (92.45)	0.02025 (6.83)	0.005900 (1.99)	0.008000 (2.69)
20	0.35490	0.274 (77.20)	0.04050 (11.41)	0.023600 (6.64)	0.064000 (18.03)
30	0.49765	0.274 (55.05)	0.06075 (12.20)	0.053100 (10.67)	0.216000 (43.40)
40	0.77260	0.274 (35.46)	0.08100 (10.48)	0.094400 (12.21)	0.512000 (66.26)
50	1.22775	0.274 (22.31)	0.10125 (8.24)	0.147500 (12.01)	1.0000000 (81.44)
60	1.91110	0.274 (14.33)	0.12150 (6.35)	0.212400 (11.11)	1.7280000 (90.41)
70	2.87065	0.274 (9.54)	0.14175 (4.93)	0.289100 (10.07)	2.7440000 (95.58)
80	4.15440	0.274 (6.59)	0.16200 (3.89)	0.37760 (9.08)	4.0960000 (98.59)

An f^0 term was expected since, even if the subject performs no external work, he would still have a resting $\dot{V}_{O_2}$. The fact that the C_0 coefficient turned out to be 0.274 liters

O_2/min (well within the range of expected resting O_2 consumption) helps to substantiate this point.

The f^1 term represents the power needed to overcome friction due to solid-to-solid contact of the moving parts of the ergometer. In fact, it is on this linear relationship that the original Quinton-Monark bicycle ergometer was based (Von Döbeln 1954), the frictional work being predominantly due to the friction between the flywheel and the adjustable tension belt. This is further illustrated by the fact that when the belt is removed for underwater use, this term is of relatively small importance even at the higher frequencies.

In order to provide a complete discussion of the physical meaning of the f^2 and f^3 terms, a brief review of basic fluid dynamics is in order. A broader discussion of this subject is given by Shapiro (1961).

Reynolds number (Re), which can be thought of as an index of the degree of laminar and turbulent flow, is calculated as follows:

$$\text{Re} = \frac{\text{Density} \times \text{Velocity} \times \text{Size}}{\text{Viscosity}} \tag{2}$$

Density (gm/cm^3) and viscosity [(dynes $\cdot$ sec)/cm^2, or poise] are physical characteristics of the fluid moving relative to an object which the fluid flows through or around. Velocity (cm/sec) is the velocity of the fluid relative to the object, whereas size, expressed in units of length (cm), represents a linear dimension perpendicular to the direction of fluid flow. For simple cases, such as fluid flowing in a rigid tube or around a sphere, the size term is represented by the diameter of the tube or sphere. For more complex shapes, a concept known as hydraulic radius is often introduced. Hydraulic radius is the quotient of the cross sectional area perpendicular to the flow path and the perimeter of this area. The complex mechanisms and shapes of the subject-ergometer system immersed in water make it virtually impossible to estimate either size or velocity in order to calculate Re.

Nevertheless, it seems safe to assume that size, density, and viscosity remain constant at the various pedaling frequencies, and that the relative speed between the various moving components and the enveloping fluid increases as pedaling frequency increases and therefore, so does Re.

In addition, Re is the ratio if inertial drag forces to the viscous drage forces of the system. Viscous drag is due to the deformation of the fluid by an object moving, in this case, through it. Inertial drag forces are due to the acceleration of the fluid particles caused by continual impact between object and fluid particles. Thus, at very low Re, the inertial drag forces can be ignored as compared to the viscous drag forces. At high Re, the viscous drag forces become less important and the inertial forces dominate.

Drag forces for low Re numbers are described by Stokes Law of Drag which states:

$$\text{Viscous drag force } \alpha \text{ (Velocity)} \times \text{(Viscosity)} \times \text{(Size)}. \tag{3}$$

The fact that power is porportional to the drag force velocity product (Eq. 4) indicates that the power needed to overcome viscous drag is proportional to velocity squared (Eq. 5), i.e.

$$\text{Power } \alpha \text{ (Drag force)} \times \text{(Velocity)}; \tag{4}$$

and a combination of Equations (3) and (4) results in:

$$\text{Power} \propto (\text{Viscosity}) \times (\text{Size}) \times (\text{Velocity})^2. \quad (5)$$

At high Re the inertial drag force dominates. There is no exact law of drag for high Re systems but empirical results for geometrically simple systems indicate that inertial drag forces are related in the following manner to velocity, density, and size (Shapiro 1961):

$$\text{Inertial drag} \propto (\text{Velocity})^2 \times (\text{Density}) \times (\text{Size})^2. \quad (6)$$

Combining Equations (6) and (4) results in a proportional relationship between the power to overcome inertial drag and velocity cubed:

$$\text{Power} \propto (\text{Density}) \times (\text{Size})^2 \times (\text{Velocity})^3. \quad (7)$$

As pedaling frequency increases, the energy expenditure becomes extremely dependent on the f^3 term (as seen in Table 2) and indicates that the majority of the O_2 consumed is used to overcome inertial drag which dominates at high Re. This hypothesis was further substantiated when the data were analyzed by a BMD02R stepwise regression analysis (Dixon 1968). As a result, when one only entered the C_0 and C_3f^3 terms, a r^2 value of 0.9928 was obtained. This may be interpreted to mean that 99.28% of the O_2 consumption can be explained by the resting and f^3 term. This results in a much simpler, highly significant (F ratio 11668.2 $P < 0.01$) equation of the following form.

$$\dot{V}_{O_2} = .274 + .000008f^3. \quad (8)$$

Due to the 52:14 gear ratio between the crank sprocket and the flywheel sprocket, the flywheel is spinning almost four times as fast as the subject is pedaling. This makes the flywheel by far the fastest moving of all the moving parts in the water and the most likely candidate for the cause of most of the inertial drag. This allows one to postulate that the inertial drag on the flywheel and possibly the chain and crank mechanisms is the cause of most of the energy expenditure. This hypothesis is also consistent with the small amount of subject variability found in the oxygen consumption measurement.

The simple modifications described enable one to convert a standard Quinton-Monark bicycle ergometer found in most human performance laboratories for underwater use. Even though the actual workload imposed on the subject is not known in conventional units of power, it can be indexed by pedaling frequency. In the practical sense, this allows the workload to be varied and under the control of the investigator over the entire physiological range of the subjects tested. Additionally, this ergometer enables the investigator to predict accurately the energy expenditure of subjects in terms of $\dot{V}_{O_2}$ prior to the actual exercise test. This is of practical importance in allowing the investigator to hold $\dot{V}_{O_2}$ constant for any given series of experiments or to hold percent $\dot{V}_{O_2}$ max constant if one previously determines the given individual's $\dot{V}_{O_2}$ max for this particular type of exercise.

Finally, the high correlation coefficient between energy expenditure and workload, indexed by pedaling frequency, indicates that the ergometer is extremely subject independent.

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