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CHANGES IN THE EFFICIENCY OF THE HUMAN BODY ON A BIGYCLE ERGOMETER

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Purpose:

The efficiency of the human body (the ratio between useful work output and the energy consumed in performing it) can be shown to vary as the work load on a bicycle. It has also been shown to vary with cadence, or speed of pedaling. An optimum cadence probably exists for each individual. (1) This optimum may be influenced by factors such as general fitness, cycling experience, lung capacity, sex, etcetera. It may also prove that efficiency does not vary considerably over a broad range of subjects.

Cadence should be measured in revolutions of the pedals per minute (RPM), to avoid confusion. One pedal revolution consists of two leg-strokes. Ballantine (2) describes it in terms of 'strokes per minute' and states that the optimum cadence is from 30 to upwards of 65 (in RPM). Banister and Jackson ran tests (3) through a range from 50 to 120 RPM and, as is later graphically demonstrated, all of these were greater than optimum for their subject, who was "an Olympic Gold Medal oarsman (25 yrs, 196 cm, 85.4 Kg)." (4)

This paper examines efficiency in the light of changes in cadence and suggests means to determine optimum cadence. Results may relate such findings to actual road or track conditions.

Method:

The Fitness Testing Unit, Carleton University, measured the subject's ventilation, heart rate, cadence and the oxygen and carbon dioxide concentrations of his expired gases.

The subject was a male student with some cycling experience, little athletic ability, 25 years of age, 176 cm. height and weighing 755 N. The subject rode a Monark bicycle ergometer (Quinton Instruments, Scarborough, Ontario), adjustable in increments of 0.5 Kp, at four cadences, for five minutes each.

Friction was applied after five minutes of pedaling with no load at the cadences used in the tests, then adjusted to give a power dissipation of approximately 740 Kp per minute for each test. The power dissipated actually varied from 729 to 756 Kp per minute, a difference of about 4.4 W.

Heart activity was monitored with a Cambridge VS4 electrocardiograph, on a single beam Tektronics oscilloscope, and displayed digitally on a Quinton 609 cardiotachometer.

Gases were collected during the fourth and fifth minutes of each test through an Otis-McKerrow open circuit breathing valve, connected by 1¼ inch l. D. plastic tubing (Collins, Braintree, Mass., U.S.A.) and three-way Y-valves to latex-neoprene meteorological balloons. One balloon was filled for each of the last two minutes of each test, for a total of eight gas collections. Samples of the expired gases were analyzed by a Beckman OM-11 electronic oxygen analyzer, and an LB-2 carbon dioxide analyzer, after drying with a granular desiccant.

The total ventilation for each minute was determined by passing the contents of each balloon through a Parkinson-Cowan ventilation meter (Chatham, Ontario) and gas temperature was read from a thermometer at the outlet port of the meter.

A nose clip prevented expired gas from escaping collection, an electronic counter counted pedal revolutions and a metronome was used to help the subject maintain a steady cadence. The valve was suspended in front of the subject by an adjustable spring attachment to the lab ceiling.

TABLE 1

	Minute	Friction setting (Kp)	Cadence (RPM)	Work Rate (Kp m per minute)	Power (Watts)
1	4	2.25	56	756	123
	5	2.25	57	769.5	126
2	4	2	62	744	121.5
	5	2	62	744	121.5
3	4	1.75	71	745.5	122
	5	1.75	71	745.5	122
4	4	1.5	81	729	119
	5	1.5	83	747	122

Table 1, above, gives the settings of the friction device during the fourth and fifth minutes on the bicycle ergometer, the cadences which were achieved at each setting, and the resulting power dissipation by the friction device, or the Work Rate of the subject.

No attempt was made to randomize the order of the tests. They all took place within about an hour's time. The subject's maximal oxygen uptake was found nomographically (5) to be about 2.9 liters per minute. Since the closest recorded uptake (see Table #2) was 70% of the above maximal estimate, it was supposed that the lack of randomization of the four tests did not critically distort the results.

Were any of the tests done at maximal levels, the increasing order of difficulty of the work might have contributed to the deterioration of efficiency due to the onset of fatigue.

Results:

Table #2, below, shows the measurements taken and the results of calculations and nomographic determinations of the measurements.

TABLE 2

	Minute			VE (uncorr) ATPS (1)	VE (corr) STPD	STPD (corr)	O2 %	CO2 %	true O2 %	VO2 (l per miin)	EO2 (Kcal per l)	Heart Rate (bpm)	Power used (Kcal per min)	Power required (Watts)	R
1	4			37.1	33.8	0.91	16	4.74	5.07	1.71	4.93	132	8.43	588	0.93
	5			40.6	36.9	"	16	4.5	4.56	1.68	4.98	136	8.37	584	0.98
2	4			40.4	36.8	"	16	4.37	4.72	1.74	4.92	139	8.56	597	0.92
	5			42.6	38.7	"	16	4.37	4.6	1.78	4.94	142	8.79	613	0.94
3	4			46.5	42.3	"	17	4.08	4.53	1.92	4.89	148	9.39	655	0.89
	5			47	42.8	"	17	4.03	4.29	1.83	4.93	148	9.02	629	0.93
4	4			43.4	39.5	"	16	4.27	4.8	1.9	4.88	154	9.27	646	0.88
	5			50.5	45.9	"	17	4.08	4.41	2.02	4.92	154	9.94	693	0.92

data from this experiment		Efficiency (%)	Cadence (RPM)	Heart Rate (BPM)
	1	21.22	56.5	134
	2	20.1	62	141
	3	19.02	71	148
	4	18	62	154
data from Banister and Jackson		19.2	50	
		18.45	70	
		18.1	80	
		16	100	
		11.77	120	

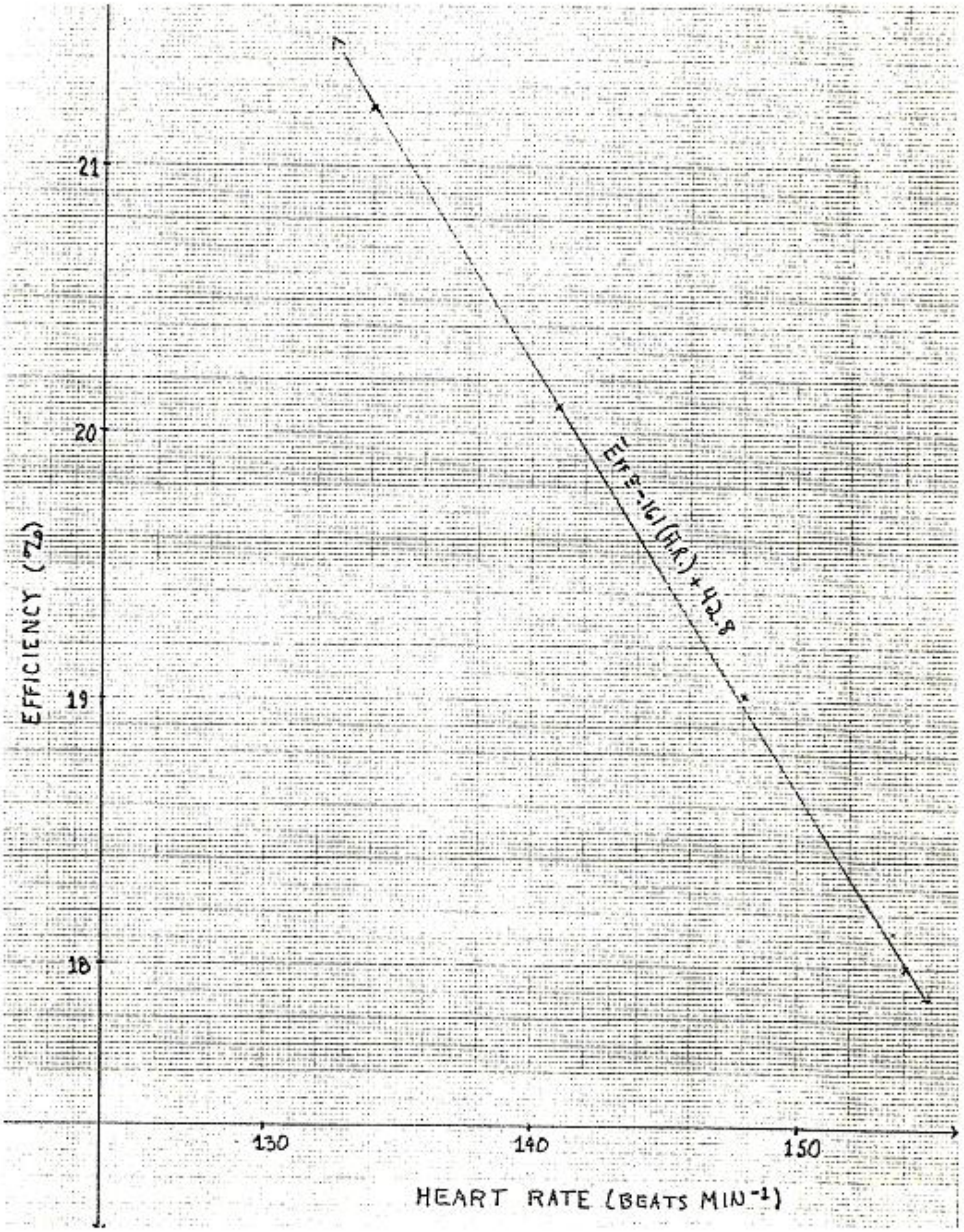
TABLE 3

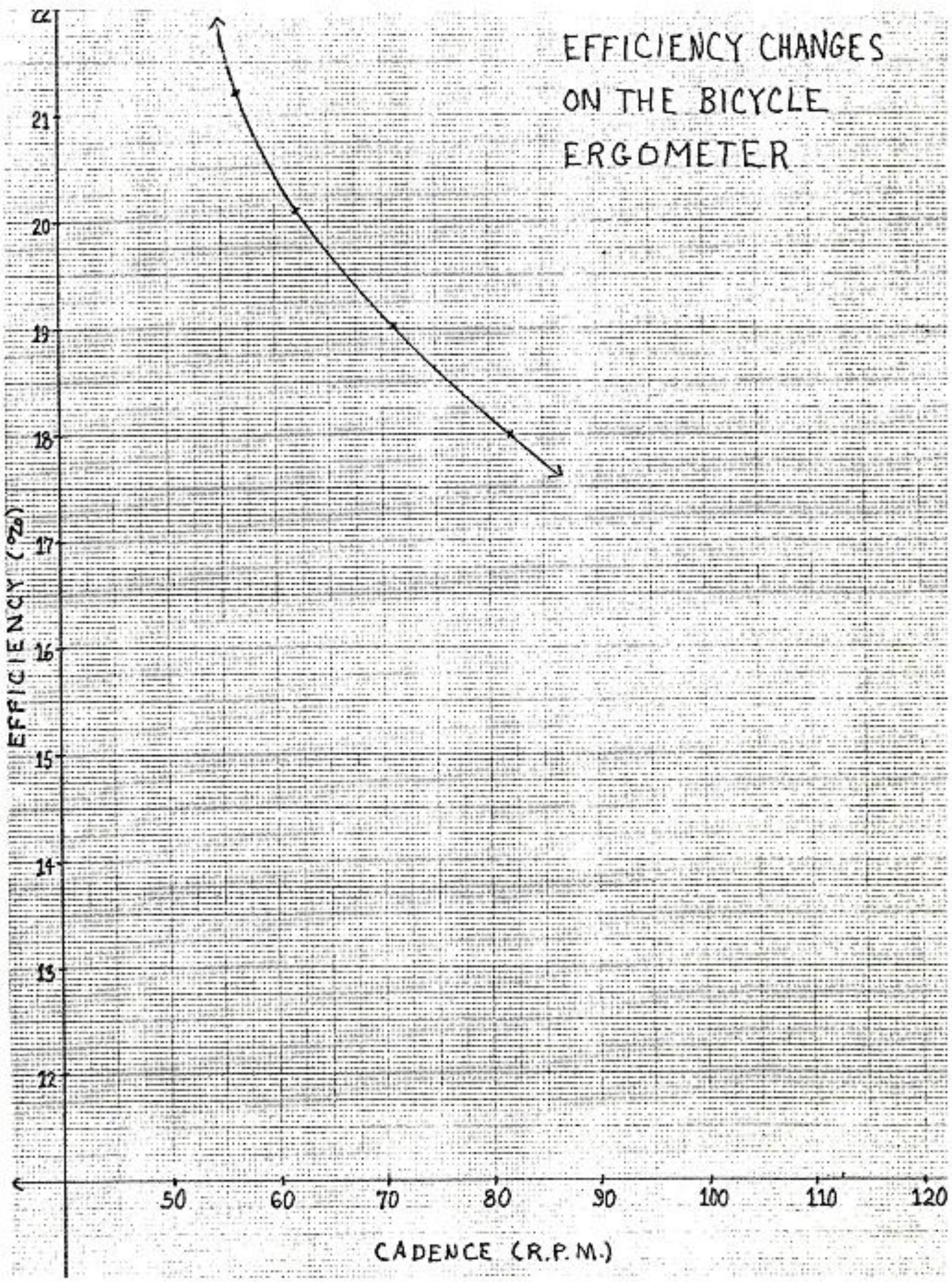
Table #3 gives the calculated average values used in the graphs.

Graph #1, below, shows Efficiency versus Heart Rate and an equation derived from the line.

Graph #2, below, shows efficiency versus cadence.

Graph #3 shows a curve on the same scale, drawn from data published by Banister and Jackson.


21
20
19
18
EFFICIENCY (%)
Eff = -.161(H.R.) + 42.8
130
140
150
HEART RATE (BEATS MIN^{-1})


EFFICIENCY CHANGES ON THE BICYCLE ERGOMETER
EFFICIENCY (%)
22
21
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12
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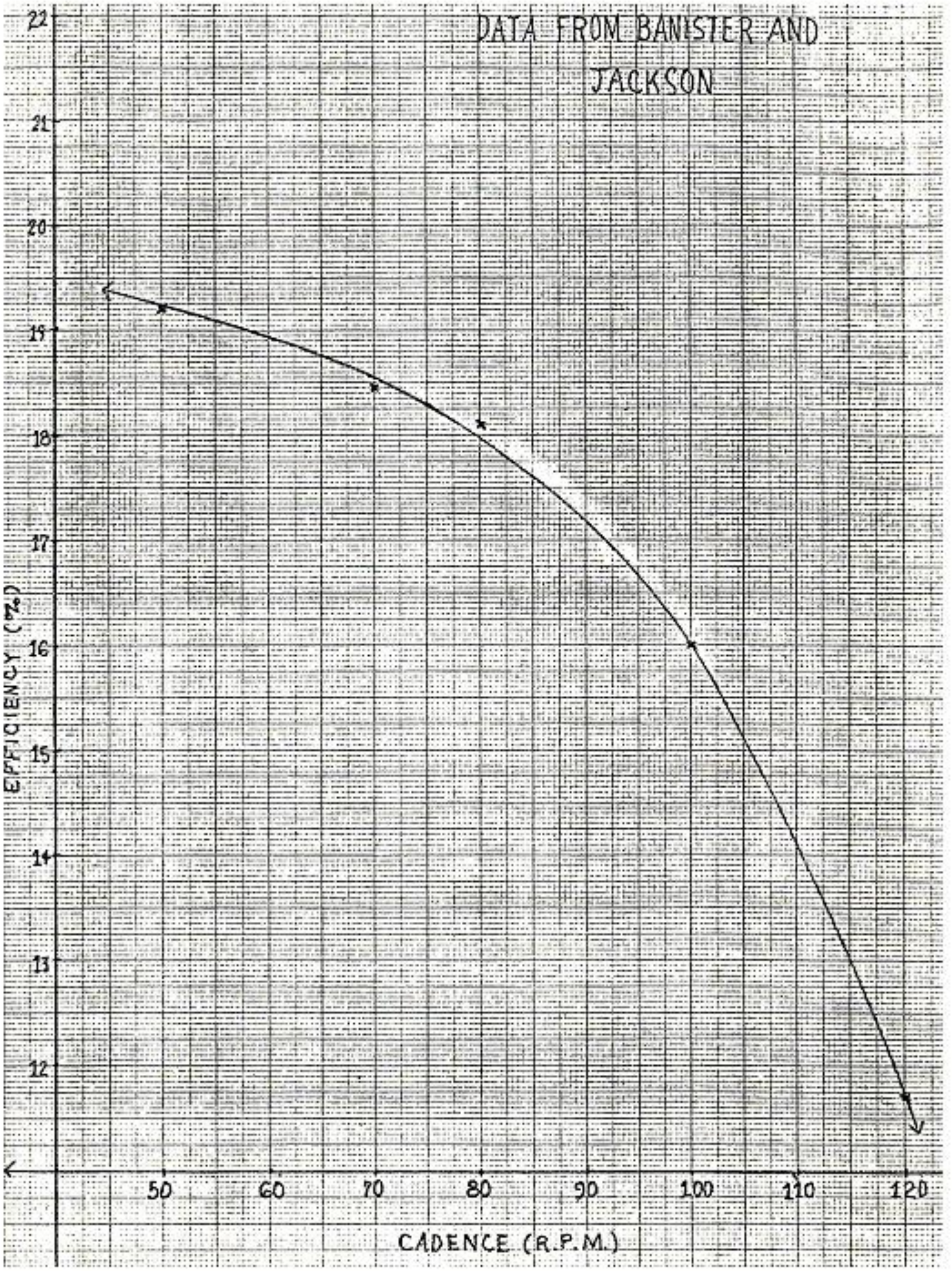
60
70
80
90
100
110
120
CADENCE (R.P.M.)


DATA FROM BANISTER AND JACKSON
EFFICIENCY (%)
22
21
20
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17
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15
14
13
12
50
60
70
80
90
100
110
120
CADENCE (R.P.M.)

Discussion:

The graph of efficiency versus heart rate suggests two things:

1. A test of optimum cadence might be carried out using only heart-monitoring equipment (the minimum heart-rate recorded being that occurring at the subject's optimum cadence).

2. Exercise tests on cardiac patients should be carried out at or close to the optimum cadence for these patients. Programs could be developed to gradually decrease the efficiency at which these exercises are done, by decreasing and/or increasing their cadences, to help the heart become gradually accustomed to more and more strenuous activity.

The second graph, with its overlay indicates that the attempt to find the subject’s **optimum** Cadence failed. The graph shows *decreasing* Efficiency with **higher** Cadences. In order to accurately estimate the **optimum** Cadence by graphical means, a similar number of points should show a corresponding *decrease* of Efficiency at Cadences **lower** than he subject’s **optimum**.

Further experimentation to document this could also corroborate the statement that the lowest heart rate recorded reflects the subject's optimum cadence.

The differences between the two curves of efficiency versus cadence show that the relationship between the variables is not constant among different individuals, and support the statement by Ballantine that optimum does vary noticeably between subjects.

It should be noted that the overlay graph (from Bannister and Jackson) is not as accurate as the graph of the results of the current paper because

a) a rough figure of 5 Kcal^{-1} for thermal equivalent of oxygen was used, since that paper did not give sufficient information to calculate it, and

b) minute volumes of oxygen were obtained using measurements in which unknown amounts of uncertainty were inherent.

The idea for this experiment came from a similar one done in the first semester of the Physics course at Algonquin College, Ottawa, Ontario, wherein the purpose was to find the efficiency of a car engine. The experiment makes use of the equation:

$F = ma$, where

- m - represents the mass of the moving car and driver (or bike and rider)

- a - represents the acceleration caused by the force F.

One can find this force by measuring mass and acceleration. The car and driver are weighed and then, on the road, the car is taken out of gear and allowed to coast. The car is timed as it slows down from one velocity to another. The acceleration is defined as the change in velocity per unit of time.

The calculated value thus obtained of force is then multiplied with the velocity, midway between the two velocities chosen for the acceleration measurement, to obtain the amount of power the car

<u>required</u> (Pr) to move the car at that velocity. *(P = Fv).* The rest is wasted (not used for moving). This corresponds to power dissipated, or <u>required</u> (Pr) by the bicycle ergometer. The rest is wasted (not used to overcome the friction device).

If it is known how many miles per gallon the car gets at the same velocity used in the above power calculation, and that one gallon of gas contains approximately 165 MJ of energy, one can calculate the amount of energy <u>used</u> (Pu) per second at that same velocity. This is power <u>used</u> (Pu), or the rate of energy consumption.

If the car or bicycle only used what was required, it would be 100% efficient. The ratio of what was actually required (Pr) to what was used (Pu) in achieving the requirement is the efficiency. If it were 100%, only what was required would be used. If only a tenth of what was used were required, the efficiency would be 1/10.

Dividing the power <u>required</u> (Pr) by the figure for power <u>used</u> (<u>Pu)</u> to cover the distance with the same friction, gives the Efficiency (Eff) of the engine. Eff = Pr/Pu; what used is always more than required, except in perpetual motion machines.

Measuring the power <u>required</u> (Pr) to move a bicycle and rider on the road or track can be done in a manner similar to that described above for the car, instead of using the ergometer.

The bike and rider would be weighed, and using a fairly accurate speedometer one would measure the acceleration. Most speedometers add a noticeable amount of friction to the machine, so for these purposes a frictionless electronic speedometer such as the one described in the March 1977 issue of Popular Electronics (6) is preferable. When the calculation of power <u>required</u> (Pr) to move the bike and rider has been made, the work load can be adjusted accordingly on the bicycle ergometer.

For example, if the power required (Pr) to move the bike and rider at 12 mph, at a cadence of 50 RPM, is found to be about 130 W, and a point on the friction wheel of a bicycle ergometer moves 6 meters per revolution of the pedals, the friction setting should be about 2.56 Kp, or 26 N. Then the gas collection can be done.

Only by using the gas analysis methods of this experiment can the measurement of power used (Pu) by the cyclist be made.

Once it has been universally established that optimum cadence corresponds to minimum heart rate, it will be possible to find an individual’s optimum by simply monitoring his or her heart rate.

Optimum cadence can easily be maintained on the road or track using a small portable electronic metronome.

SAMPLE CALCULATIONS:

Power Required (Pr):
Pr = Friction x Cadence (RPM) x 6 m/rev
Pr = 2.25 Kpm/minute x 56 RPM x 6 m/rev = 756 Kpm/min = 123 Watts

STPD correction: from table similar to one found in (9)

True Oxygen Percentage and Respiratory Exchange Ratio:
from nomogram of Dill and Fölling (7).

Minute volumes of oxygen:
VO2 = VE(corr)STPD (l per minute) x True O2 %.
VO2 = .0507 x 33.8 l per minute = 1.71 l /minute

Thermal Equivalent of oxygen: Respiratory exchange ratio (R) is the ratio of CO2 produced to O2 consumed. (8) Thermal equivalent of O2 when burning carbohydrates is 5.0 Kcal per liter. When burning fats it is 4.7 Kcal per liter. When burning only fats R = .7, and when burning only CHO R = 1.0. Therefore R plus 4 is equal to the thermal equivalent of O2 for individual values of R. R = .9 therefore EO2 = 4.93 Kcal per liter.

Power Used (Pu):
Pu (Kcal/min) = E02 (Kcal / liter) x V02 (liters per min)
Pu = 4.93 Kcal/l x 1.71 l per min = 8.43 Kcal / min.

Efficiency:
Eff (%)= Pr / Pu x 100
Pr = 756 Kpm/min = 125 w
Pu = 8.43 Kcal/min = 588 w
123 / 588 x 100 = 20.92 %

Cadence: Cadences were averaged as above.
Heart Rates shown are also the averages between the two minutes measured in each test.

Graphs:

For values of Efficiency, Cadence and Heart Rate used in the graphs the Cadences in the fourth and fifth minutes of each test were averaged to give average Work Rate for each test. R and V02 were similarly averaged for the two tests to give average Power Input for each test.

Efficiencies used in the graph of data from Jackson and Banister:

At 70 RPM VO2 (l/min) = 0.517 + .00184W (Kpm/min). (9).
At 740 Kpm/min, VO2 = .517 + .00184(740) = 1.88 l/min.
Pin (Kcal/min) = 5 Kcal/l x 1.88 l/min = 9.4 Kcal/min.
9.4 Kcal/min = 655 W.
Pout = 740 Kpm/min = 120.9 W.
Efficiency = 18.45 %

Abbreviations:

VB - Volume of expired gas.
ATPS - Ambient temperature and pressure, saturated.
STPD - Standard temperature and pressure, dry.
V_{O2} - Minute volume of oxygen.
E_{O2} - Combustion energy of oxygen.
H.R. - Heart rate.
R - Respiratory Exchange Ratio.

References:

1 Richard Ballantine, *Richard's Bicycle Book*, (New York, 1974), p. 60.
2 Ballantine, p. 60.
3 E. W. Banister and R. C. Jackson, *The Effect of Speed and Load Changes on Oxygen Intake for Equivalent Power OutputsDuring Bicycle Ergometry*, Int. Z. angew. Physiol. Einschl. Arbeitsphysiol, 24 (1967) p. 285.
4 Banister and Jackson, p. 285.
5 Per Olof Åstrand, and Kaare Rodahl, *Textbook of Work Physiology*, (New York, 1970), pp. 356-7.
6 George W. Handig, *Build a Digital Bicycle Speedometer*, Popular Electronics, vol. 11, no. 5 (March, 1977), pp. 39-41.
7 D. B. Dill and A. Fölling, *Studies in muscular activity II. A nomographic description of expired air*, J. Physiol., 66 (1928), pp. 155-5.
8 Benjamin Ricci, *Physiological Basis of Human Performance* (Philadelphia, 1967), p. 175.
9 Banister and Jackson, p. 287.

APPENDIX:

PERSONAL TRANSPORTATION: CAR OR BICYCLE?

Car engine efficiencies are generally in the same ballpark as those found in this paper to be common to the human body when cycling. One car was measured as having gone from 65 to 55 MPH (a range of .5 m/s) in an average of 11.8 seconds. This gave it an acceleration of .381 m/s/s. The car massed 1593.2 Kg., so the friction it overcame at 60 MPH (27 m/s) was 607 N. Thls force multiplied by the velocity gave it a power output of 16589 watts. The car consumed 1 gallon of gas (165 MJ) every 28 miles at this speed, so its energy consumption rate was 97 KW. Therefore its efficiency was about 17%.

If the human body could use a source of energy as cheap as gasoline it would be much more economical as a means of transportation. At an energy consumption rate of 700 watts (greater than any of the rates recorded in the foregoing experiment) and an average speed of 12 MPH a cyclist would get about 776 miles per gallon of gas.

163 MJ of energy at today's prices will cost a fair amount, certainly more than a gallon of gas does. For city driving (when mileage per gallon is lowest) 12 MPH is acceptable. A bicycle can usually outrace most other forms of urban transportation in peak traffic hours. It is easier to park, lasts longer, and costs less than a car to buy and maintain.

A bike cannot be used under snowy winter conditions without major modifications. For long distance travel the bicycle is not fast enough for most purposes, but because it is slower it is much more enjoyable than the automobile in all but worst weather and as long as there is no snow or ice on the road.

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