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THE EFFICIENCY OF BICYCLE PEDALLING IN THE TRAINED SUBJECT.

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IN a previous paper [Garry and Wishart, 1931] an attempt was made to correlate the efficiency of muscular movement at various speeds in bicycle pedalling with Hill's well-known formula:

$$E=\frac{W}{H}=\frac{W_0\left(1-\frac{k}{t}\right)}{aW_0(1+bt)},$$

where E = efficiency,

W = external work of the muscle,

H = energy liberated by the muscle in doing work W,

W_0 = maximum theoretical work of the muscle,

t = duration of the muscular contraction,

and k, a and b are constants.

The observed values were in satisfactory agreement with the numerator of the equation, but attempts to find a relation between the denominator and the metabolic cost of the muscular effort failed signally.

These experiments were carried out on untrained subjects. Recently the opportunity arose to repeat the experiments on a professional racing cyclist. It was hoped that the results obtained would show the differences between the trained and untrained subject, and also, that it might be possible to find more satisfactory agreement in the trained subject between the denominator of Hill's equation and the metabolic energy expended in muscular movement.

The trained subject (C.F.D.) rode as an amateur until 1923, and then as a professional until 1926, when he gave up racing but still kept himself in thorough training. His fitness may be gauged by the fact that, a few days before coming to the laboratory, he rode 209 miles on the road in

12 hours. In 1912 and 1920 he represented England in the Olympic Games. C.F.D.'s age is 48, his height 5 ft. 9½ in., and his nude weight 75 kg.

METHOD.

The technique employed was the same as that for the untrained subjects. A modified Krogh bicycle ergometer was used with a constant speed governor [McCall and Smellie, 1931]. The Douglas-Haldane method was employed to estimate the energy expenditure.

For half an hour the subject pedalled the unloaded ergometer at the speed of the subsequent work experiment. A sample of expired air was then taken; this gave the energy required for the "no-load" movement. The work experiment was then carried out, the subject exerting the maximum effort which he considered he could maintain for 1 hour. Air samples were taken at approximately 30 and 45 min. after the commencement of the work. The data obtained in these two observations showed good agreement in all experiments, and the average values are used in the following calculations. The external work done during the period of collection of the air samples was recorded graphically on a drum driven by the ergometer.

In the untrained subjects it was possible to work at speeds as low as 25 rev. per min. In the case of C.F.D., it was impossible to reach speeds lower than 40 rev. per min. At lower speeds the force exerted by the subject was such that the electrical current necessary to balance this force threatened to burn out the field coils of the ergometer. C.F.D., however, was able to pedal faster than the untrained subjects, and one record was obtained at a speed of 127 rev. per min.

RESULTS.

The results are presented in Table I (corresponding to Table I of the previous paper), both as calories per minute and as calories per leg move-

TABLE I.

Duration of each leg movement t	No load		External work		Total metabolism	
	Cal. per min.	Cal. per leg movement	Cal. per min.	Cal. per leg movement	Cal. per min.	Cal. per leg movement
0·24	8·37	0·0330	2·32	0·0091	15·97	0·0629
0·30	4·72	0·0234	3·00	0·0149	16·22	0·0803
0·38	3·25	0·0208	2·99	0·0192	15·46	0·0991
0·54	2·82	0·0252	2·98	0·0266	15·12	0·1350
0·58	2·84	0·0273	3·16	0·0304	15·65	0·1505
0·70	2·80	0·0326	2·95	0·0343	14·54	0·1691

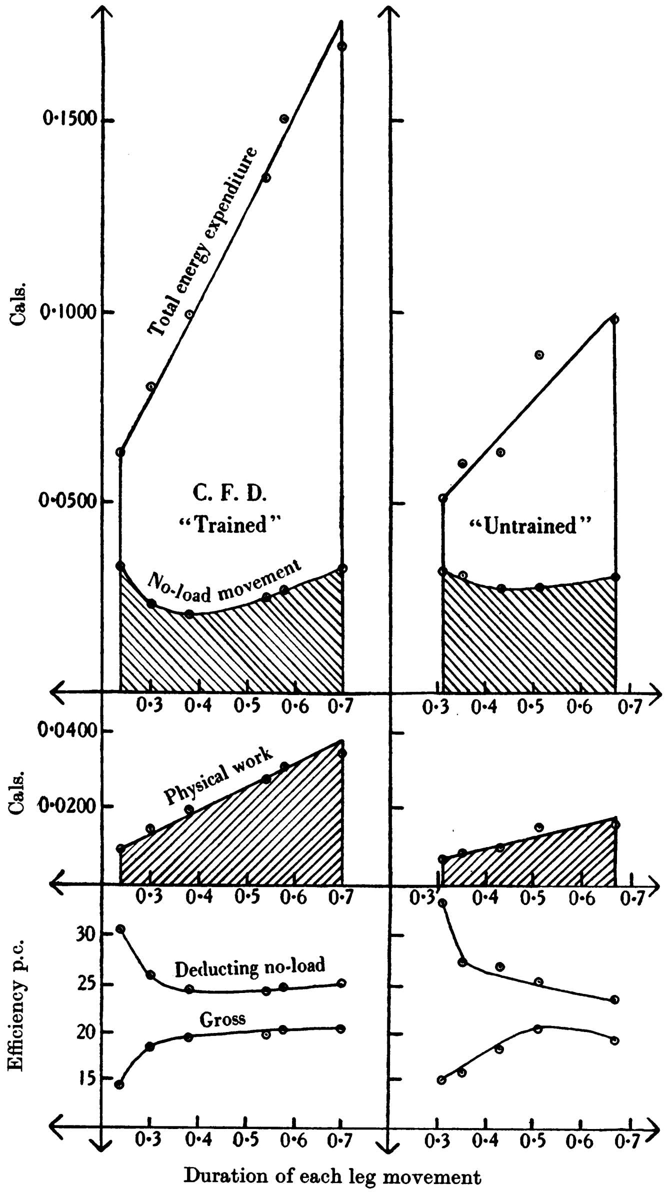
Cals.
0·1500
0·1000
0·0500
Total energy expenditure
C. F. D.
"Trained"
"Untrained"
No-load movement
0·3 0·4 0·5 0·6 0·7
0·3 0·4 0·5 0·6 0·7
0·0400
0·0200
Physical work
0·3 0·4 0·5 0·6 0·7
0·3 0·4 0·5 0·6 0·7
Efficiency p.c.
30
25
20
15
Deducting no-load
Gross
0·3 0·4 0·5 0·6 0·7
0·3 0·4 0·5 0·6 0·7
Duration of each leg movement

Fig. 1.

ment. The gross efficiencies and the efficiencies obtained after deducting the energy involved in the "no-load" movement (nett efficiency) are shown in Table II.

TABLE II.

Duration of each leg movement t	Gross efficiency	Nett efficiency
0·24	14·5	30·6
0·30	18·5	26·1
0·38	19·4	24·6
0·54	19·7	24·2
0·58	20·2	24·8
0·70	20·3	25·1

Fig. 1 presents the results graphically. For comparison, averages of the results obtained from the two untrained subjects [Garry and Wishart, 1931] over the same range of speeds are treated in similar fashion. The abscissa records the duration of each leg movement, *i.e.* half the time of each revolution of the pedal sprocket wheel. The ordinate shows, in calories per leg movement, (1) the total energy expenditure—top curve of upper graph; (2) the cost of "no-load" movement—lower curve of upper graph; and (3) the external work—lower graph.

This graph shows that, in the trained subject as compared with the untrained:

(1) The total metabolism is greater at all speeds.

(2) The external work is greater at all speeds.

(3) The cost of the "no-load" movement is not only relatively but also absolutely less.

(4) The gross efficiency is very constant except at very high speeds.

(5) The nett efficiency is actually lower due to the low cost of the "no-load" movement.

DISCUSSION.

(1) Within the range of speeds covered by C.F.D., there is no evidence for an optimum rate in bicycle pedalling. It is extremely unfortunate that the design of the ergometer prevented speeds lower than 40 rev. per min. being investigated.

(2) The nett efficiency rises, as it did in the untrained subjects, with shortening of the duration of the muscular movement. There is also a tendency for the nett efficiency to rise as the muscular contraction is prolonged. This appears to emphasize once more that no satisfactory base line for metabolic experiments of this type has yet been obtained.

(3) There is, nevertheless, a speed at which the energy expended in the "no-load" movement is at a minimum. In the trained subject this minimum occurs at a higher speed than in the untrained subjects.

(4) The fraction of the total metabolic energy expended in the "no-load" movement is probably an expression of the fitness of the subject, and of his better muscular coordination for a definite type of movement. In this respect, C.F.D., our subject, compares very favourably with M.A.M., the professional cyclist studied by Benedict and Cathcart [1913]. At speeds in the neighbourhood of 100 rev. per min., the ratio $\frac{\text{cost of "no-load" movement}}{\text{total metabolism}}$ is: for the untrained subjects, 62 p.c.; for M.A.M., 41 p.c.; and for C.F.D., 29 p.c.

(5) In this paper, as in the last, the results have been expressed as energy output per leg movement, so that an attempt may be made to fit our results to Hill's efficiency formula. Using a k and a W_0 derived from the data obtained at the two extreme speeds, the theoretical external work was calculated for the intermediate speeds. The results are shown in Table III. The agreement is quite fair. The value of 0·194 so obtained for k shows that W will be zero at a speed of 154·6 rev. per min. The same value for k is obtained by extrapolation of the total metabolism and "no-load" curves to their meeting point.

TABLE III.

t	W calculated from $W_0 = 0{\cdot}0474$ and $k = 0{\cdot}194$	W found
0·24	—	0·0091
0·30	0·0167	0·0149
0·38	0·0232	0·0192
0·54	0·0304	0·0266
0·58	0·0315	0·0304
0·70	—	0·0343

(6) In our previous paper we found it impossible to make the results from untrained subjects fit the denominator of Hill's equation. We found it equally impossible with the present results obtained from the trained subject. This is best shown by using the device of Dickinson [1929] in which $(1-k/t)/E$ is graphed against t. Theoretically the points should fall on a straight line, and from it a may be read off as the coordinate corresponding to zero time, and $b\ (=-1/t)$ as the coordinate corresponding to $(1-k/t)/E=0$.

In the graph of Fig. 2, k is taken as 0·194, the value derived above. This value cannot be grossly in error. In Dickinson's graph the experimental values of E used were obtained by dividing the observed external work by the total metabolic cost less the resting work-position basal metabolism. As determination of the metabolic cost for the movement of the effector muscles is the stumbling block in finding the efficiency, we give three curves, E_1, E_2, and E_3. In E_1 the gross efficiency is used, in E_2 the efficiency calculated in the manner employed by Dickinson, and in E_3 the nett efficiency (total metabolism less "no-load").

It is obvious that all three curves have the same general form, and all give values for a and b which are mathematically negative and

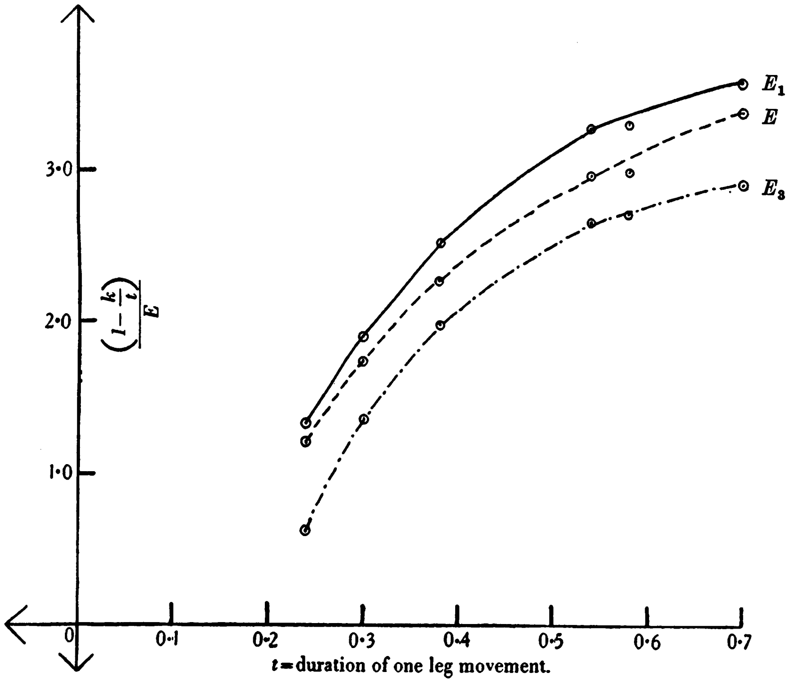

Fig. 2.

physiologically meaningless. While it is probable that the true cost of the "no-load" movement differs very materially from our determined values, yet Fig. 2 brings out the point that no series of "no-load" values would at once give a straight line and acceptable values of a and b. One cannot escape the conclusion that Hill's formula, in its metabolic aspect, is inapplicable to muscular tissue working in the "steady state."

It seems that in all experiments on the efficiency of muscular movement in the intact animal, it is impossible to assess accurately the quota of energy devoted solely to the muscular movements from which the external work is derived. Thus, the "nett efficiency," however interesting academically, is no evaluation of the true efficiency of the working muscle groups. In actual practice, the only result of importance is the total energy cost to the body, viz. the gross efficiency. This point demands emphasis, since the experimental differences between gross and nett efficiencies may be very considerable. Furthermore, as in the present determinations, increased rate of movement diminishes gross efficiency while increasing nett efficiency.

A point of some practical importance emerges from the fact that the maximum gross efficiency is attained at the slower speeds of pedalling. C.F.D.'s racing speed is in the neighbourhood of 100 rev. per min., which seems to show that racing technique is open to question. By increasing the gearing of the bicycle, it should be possible to use the slower more efficient speed of muscle movement. Of course, this in practice applies only to track racing, because, on the road, hills prevent the use of very high gearing. Nevertheless, Japanese cyclists racing on the road over long distances use a speed of about 70 rev. per min. [Furusawa, personal communication].

SUMMARY.

Observations on the efficiency of bicycle pedalling have been made on a professional cyclist. These observations were made in the "steady state," using a modified Krogh bicycle ergometer and the Douglas-Haldane technique.

Certain differences between the trained and untrained subject are recorded.

As with our previous observations on two untrained subjects, we found it impossible to correlate the results satisfactorily with the efficiency formula of A. V. Hill.

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