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# ON THE EXISTENCE OF A MOST EFFICIENT SPEED IN BICYCLE PEDALLING, AND THE PROBLEM OF DETERMINING HUMAN MUSCULAR EFFICIENCY.

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AN optimum rate of work for optimum muscular efficiency has been shown to exist: (1) by the direct measurement of the external work and the oxygen consumption in the human subject; (2) by theoretical application of the findings, derived mainly from experiments on isolated muscle, that, with increasing speed of contraction, the external work obtainable from a muscle diminishes, while the metabolic demands of the muscle also diminish owing to the steadily lessening requirement of energy for maintenance of the progressively briefer contractions. These findings are summarized in Hill's well-known formula:

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

where $E$ = efficiency, $W$ = external work of muscle, $H$ = energy liberated by the muscle in doing work $W$, $W_0$ = maximum theoretical work of the muscle, $t$ = duration of contraction, $k$, $a$, and $b$ are constants.

According to this formula, an optimum efficiency will be obtained at a certain optimum value of $t$. The latter was, in Hill's [1922], and later in Lupton's [1923], experiments on the arm muscles, put at approximately one second. Hill [1922], in comparing this optimum time with the experiments of Benedict and Cathcart [1913] on the professional cyclist, M.A.M., drew attention to the good agreement between the two types of work, since the optimum efficiency in Benedict and Cathcart's experiments was obtained at 70 rev. per min. of the pedals.

This comparison, however, was unjustifiable for two reasons. First, the 70 rev. per min. refers to the pedal sprocket wheel, each revolution of which comprises a contraction of the effector group of muscles first in one and then in the other leg, so that the duration of contraction in the muscles of each effector group cannot exceed half the time of one revolution. Thus, at 70 rev. per min., M.A.M. was actually executing 140 leg movements per min., and the duration of contraction in the muscles of each limb cannot have exceeded, and probably was considerably less than, $\frac{60}{140} = 0{\cdot}43$ sec. Secondly, while M. A. M. showed his highest efficiency at 70 rev. per min., he could seldom be persuaded to pedal at slower rates, and the evidence was insufficient to show that his efficiency might not have been even higher at the lower speeds.

The following experiments were primarily carried out to see how the efficiency would behave at rates slower than 70 rev. per min.

## Experimental.

The authors themselves acted as subjects. The following are their data:

| | G.M.W. | R.C.G. |
|---|---|---|
| Weight (kg.) | 66·5 | 83·8 |
| Height (cm.) | 186 | 183 |
| Surface area (sq. m.) | 1·89 | 2·06 |
| Age | 35 | 30 |
| Post-absorptive basal metabolism (Cals.) | 31·1 | 36·1 |

The work was done on a modified form of Krogh's ergometer [McCall and Smellie, 1931]. This ergometer, like the original Krogh type, may be used to provide a constant load at any speed of the flywheel; the subject's speed is then controlled by metronome.

The ergometer may, however, be used in another way. It is provided with a speed governor, which, when set to a predetermined speed, automatically controls the subject's rate of pedalling by overloading him when he tends to pedal too fast, and releasing some of the load when his rate falls. In this case the load fluctuates and is recorded graphically by the vertical movement of a writing point on a smoked drum. The drum is itself driven from the ergometer flywheel so that the horizontal travel of the writing point is a measure of the flywheel revolutions. The work done is thus readily obtained by measuring with a planimeter the area recorded on the tracing. Two examples of these records are shown in Fig. 1. In most of our experiments this automatically controlled speed method was used. In all cases the speeds were checked by the record of an electrical counter operated from contacts on the ergometer flywheel.

Experiments were always made in the forenoon two hours after a light breakfast. The oxygen intake was determined by the Douglas-Haldane method with all the usual precautions. The two workers shared equally in all details of the routine; when one acted as subject the other performed the analyses and *vice versa*. Both workers were thoroughly accustomed to the Douglas-Haldane technique.

On the great majority of days the energy expenditure involved in pedalling the unloaded ergometer (hereafter referred to as "no-load movement") at the speed of the subsequent working experiment was determined. A large number of determinations of the energy cost of

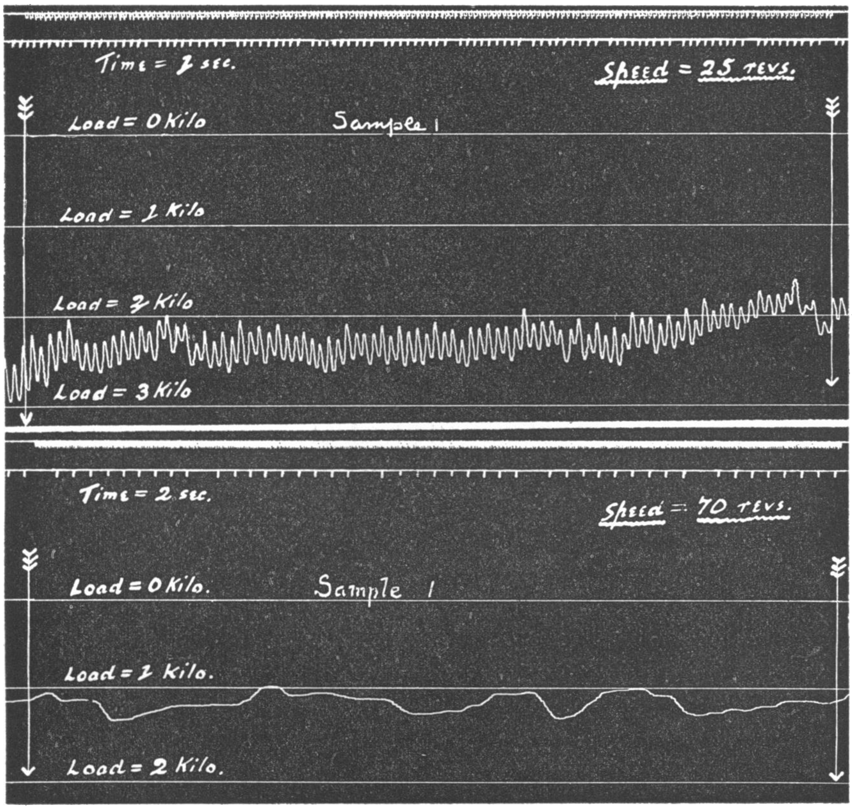



**Fig. 1. Each tracing shows from above downwards: (1) the record of the electrical revolution counter on the ergometer flywheel—used to record beginning and end of air-sampling period; (2) a time trace; (3) various load abscissæ; and (4) the record of the fluctuating load actually applied to the flywheel. The work done is obtained from the area enclosed by the fluctuating load line, the 0 kilo line, and the two vertical arrows. Upper tracing: Maximum effort at 25 revs. per min. of the pedals. Lower tracing: Maximum effort at 70 revs. per min. of the pedals.**

sitting on the bicycle with the feet stationary (hereafter referred to as "work-position basal") were also made. Both in the no-load and in the work experiments, the first collection of expired air was not made until at least 25 min. after the commencement of pedalling. During the work period, the first collection was followed by two further collections at 15 min. intervals. The subject was thus always in the steady state during the taking of the samples.

## RESULTS.

Four series of experiments were done. The first of these was considered as preliminary training and ignored.

The main series (Tables I and II) was one in which the speed governor of the ergometer was used, the subject being required to exert the maximum effort which he considered he could maintain for an hour without showing fatigue. Although this may be criticized on the grounds of demanding subjective evaluation on the part of the subject, it was found in practice that the total energy expenditure per minute was remarkably constant, both in the three collection periods of each experiment, and throughout the whole series of experiments at different speeds. Also, although from the nature of the governing device the speed must fluctuate about the predetermined mean, both the graphic record, and the fact that the predetermined speed was actually registered by the electrical counter even within the comparatively short periods of air collection, show that these fluctuations are brief and small. Owing to the difficulty of precise adjustment of the governor at very rapid speeds, the highest speeds are not identical in the two subjects.

With a view to obtaining efficiencies from the ratio

$$\frac{\text{external work increment}}{\text{metabolism increment}},$$

two other series were undertaken, in which light and moderate amounts of work were done on the same day, at each of the various speeds. The light always preceded the heavier effort. In all series no particular sequence of loads was followed from day to day.

The results are tabulated below.

(*a*) *Work-position basal.* The following averages were obtained in the two subjects:

| | G.M.W. | R.C.G. |
|---|---|---|
| No. of observations | 8 | 10 |
| Cal. per min. (average) | 1·46 | 1·54 |

(*b*) *No-load movement.* In all, 33 experiments were made on R.C.G., and 22 on G.M.W. The values, given in Table I, are taken from a smooth curve drawn through the actual experimental points.

(*c*) *Maximal effort series.* Data for the external work and metabolism are given in Table I, and the efficiencies calculated from three different base lines in Table II.

TABLE I.

G.M.W.

| Speed Rev. per min. | No load: Cal. per min. | No load: Cal. per leg movement | External work Cal. per min. | Total energy output: Cal. per min. | Total energy output: Cal. per leg movement |
|---|---|---|---|---|---|
| 25 | 2·26 | 0·0452 | 1·01 | 7·56 | 0·1512 |
| 28 | 2·36 | 0·0421 | 0·93 | 6·89 | 0·1230 |
| 35 | 2·62 | 0·0374 | 1·03 | 7·59 | 0·1084 |
| 45 | 2·71 | 0·0301 | 1·23 | 7·82 | 0·0869 |
| 52 | 2·79 | 0·0268 | 1·30 | 7·97 | 0·0766 |
| 70 | 3·53 | 0·0252 | 1·18 | 7·93 | 0·0566 |
| 86 | 4·90 | 0·0285 | 1·18 | 9·17 | 0·0533 |
| 95 | 5·61 | 0·0295 | 1·03 | 9·02 | 0·0475 |
| 98 | — | — | — | — | — |

R.C.G.

| Speed Rev. per min. | No load: Cal. per min. | No load: Cal. per leg movement | External work Cal. per min. | Total energy output: Cal. per min. | Total energy output: Cal. per leg movement |
|---|---|---|---|---|---|
| 25 | 2·48 | 0·0496 | 1·30 | 10·01 | 0·2001 |
| 28 | 2·66 | 0·0475 | 1·55 | 10·75 | 0·1920 |
| 35 | 2·71 | 0·0387 | 1·48 | 9·45 | 0·1350 |
| 45 | 2·77 | 0·0308 | 1·63 | 9·82 | 0·1091 |
| 52 | 3·03 | 0·0291 | 1·88 | 10·45 | 0·1005 |
| 70 | 4·16 | 0·0297 | 1·55 | 9·86 | 0·0704 |
| 86 | 5·54 | 0·0322 | 1·64 | 11·54 | 0·0671 |
| 95 | — | — | — | — | — |
| 98 | 6·66 | 0·0340 | 1·52 | 10·80 | 0·0551 |

TABLE II.

| | Gross efficiency | | Efficiency after deducting work-position basal | | Efficiency after deducting no-load | |
|---|---|---|---|---|---|---|
| | G.M.W. | R.C.G. | G.M.W. | R.C.G. | G.M.W. | R.C.G. |
| Speed | p.c. | p.c. | p.c. | p.c. | p.c. | p.c. |
| 25 | 13·4 | 13·0 | 16·6 | 15·4 | 19·1 | 17·3 |
| 28 | 13·5 | 14·4 | 17·1 | 16·8 | 20·5 | 19·2 |
| 35 | 13·6 | 15·7 | 16·8 | 18·7 | 20·7 | 21·9 |
| 45 | 15·7 | 16·6 | 19·4 | 19·7 | 24·1 | 23·1 |
| 52 | 16·3 | 18·0 | 20·0 | 21·1 | 25·1 | 25·4 |
| 70 | 14·9 | 15·7 | 18·2 | 18·7 | 26·8 | 27·3 |
| 86 | 12·9 | 14·2 | 15·4 | 16·4 | 27·6 | 27·2 |
| 95/98 | 11·4 | 14·1 | 13·6 | 16·3 | 30·2 | 36·5 |

(*d*) *Moderate and light effort series.* Table III gives the external work and metabolic data, and Table IV shows the efficiency calculated (1) as a gross efficiency, and (2) from the ratio $\frac{\text{external work increment}}{\text{metabolism increment}}$.

Because of their submaximal nature, the results given in Tables III and IV are open to criticism, and little stress is laid on them. Nevertheless, with both light and moderate efforts, the gross efficiencies show an optimum in the same region as with the maximal efforts. The low values

TABLE III.

| | G.M.W. | | | | R.C.G. | | | |
|---|---|---|---|---|---|---|---|---|
| | External work | | Total energy output | | External work | | Total energy output | |
| | Light | Moderate | Light | Moderate | Light | Moderate | Light | Moderate |
| Speed | Cal. per min. | | | | Cal. per min. | | | |
| 25 | 0·29 | 0·61 | 3·10 | 4·81 | 0·39 | 0·83 | 4·21 | 6·59 |
| 45 | 0·60 | 1·23 | 4·31 | 7·71 | 0·58 | 1·17 | 4·92 | 7·53 |
| 70 | 0·34 | 0·89 | 4·38 | 6·58 | 0·69 | 1·39 | 6·15 | 9·25 |
| 86 | 0·49 | 0·94 | 6·00 | 7·54 | 0·54 | 1·15 | 6·64 | 9·00 |
| 95/98 | 0·49 | 0·70 | 7·40 | 8·18 | 0·61 | 1·08 | 8·36 | 9·78 |

TABLE IV.

| | Gross efficiency | | | | Efficiency from:— $\frac{\text{work increment}}{\text{metabolic increment}}$ | |
|---|---|---|---|---|---|---|
| | Light load | | Moderate load | | | |
| Speed | G.M.W. | R.C.G. | G.M.W. | R.C.G. | G.M.W. | R.C.G. |
| 25 | 9·4 | 9·3 | 12·7 | 12·6 | 18·7 | 18·5 |
| 45 | 13·9 | 11·8 | 16·0 | 15·5 | 18·5 | 22·6 |
| 70 | 7·8 | 11·2 | 13·5 | 15·0 | 25·0 | 22·6 |
| 86 | 8·2 | 8·1 | 12·5 | 12·8 | 29·2 | 25·8 |
| 95/98 | 6·6 | 7·3 | 8·6 | 11·0 | 26·9 | 33·1 |

are, of course, due to the relatively large part that the work-position metabolism plays in the total metabolism. The values obtained from the $\frac{\text{work increment}}{\text{metabolism increment}}$ ratio are equally open to criticism [Hill, 1922]. It is, however, interesting that the results are similar to those obtained in maximal efforts when the cost of the no-load movement is deducted. Calculation of the efficiency after deduction of the no-load metabolism may, of course, be regarded as similar to its calculation on a work-increment basis.

## DISCUSSION.

Benedict and Cathcart's [1913] investigations of the gross efficiency at various speeds from 70 to 130 pedal rev. per min. (140 to 260 leg movements per min.) gave a maximum of 20·6 p.c. at 70 rev. per min.

TABLE V.

| | Base line | Average efficiencies (all speeds and loads) p.c. | Average efficiencies (heaviest load only) p.c. |
|---|---|---|---|
| 1. | ............................................ (gross) | 17·0 | 19·9 |
| 2. | Post-absorptive metabolism, lying | 19·1 | 21·4 |
| 3. | Work-position metabolism | 19·7 | — |
| 4. | Metabolism of subject on motor-driven ergometer | 27·0 | — |
| 5. | Metabolism of subject driving unloaded ergometer | 30·0 | — |
| 6. | $\frac{\text{Work increment}}{\text{Metabolic increment}}$ Moderate—light load | 30·0 | — |
| | Heavy—moderate load | 33·0 | — |

In their comprehensive experiments they discuss the difficulty of obtaining a suitable base line from which to measure the excess metabolism actually devoted to the external work, and state the efficiencies of M. A. M. as calculated from various base lines. Table V summarizes their results. It is apparent from these figures how much the efficiency may vary with the base line selected, a difficulty commented on by various other workers, *e.g.* Lindhard [1915] and Dickinson [1929].

Now, according to Hill's formula

$$E = \frac{W_0(1-k/t)}{aW_0(1+bt)},$$

with increasing $t$, the efficiency must rise to an optimum and again fall. This is true whatever value be given to $b$, the "maintenance" constant. In Hill's original inertia flywheel experiments, in which the formula was first developed, $b$ was given a value such that the maximum efficiency calculated from the formula would be 26 p.c. This figure was assumed to represent the actual maximum efficiency of human muscle, and an important factor in Hill's selection of this figure was the average efficiency of 27 p.c. recorded by Benedict and Cathcart for M. A. M., when the motor-driven ergometer base line was used. This particular base line was considered by Hill to be the most valid. In Hill's formula the optimum duration of contraction corresponding to an efficiency of 26 p.c. is practically 1 second.

Later, Lupton [1923] determined by actual metabolic measurement the energy cost both of setting up and maintaining contraction in the arm muscles used in the inertia flywheel experiments. He obtained values for $b$ essentially in accord with the value adopted by Hill; his observations gave a mean value for the optimum efficiency of 26·7 p.c. and an optimum duration of contraction of 1·36 sec. In the same paper, Lupton records observations on the efficiency of stair climbing as determined by oxygen consumption methods; he found a maximum efficiency of 24·4 p.c. with an optimum step duration of 1·3 sec. In these stair-climbing experiments the efficiencies were calculated after deducting a work-position basal.

Cathcart, Richardson and Campbell [1924], in experiments on a hand ergometer, found a maximum efficiency of 24·7 p.c. (calculated after deducting the metabolism in the lying position, but not post-absorptive), and an optimum duration of contraction of $\frac{60}{80}$ or 0·75 sec. Campbell, Douglas and Hobson [1920], in bicycle pedalling, found efficiencies of 24 to 25 p.c. (deducting work-position basal). Only one speed, 50 pedal rev. per min., was investigated, but it is noteworthy that this speed was chosen because the subjects found it to be the most comfortable. Atzler, Herbst, Lehmann and Müller [1925] found, for hand-crank turning, an optimum duration of 0·7 sec.

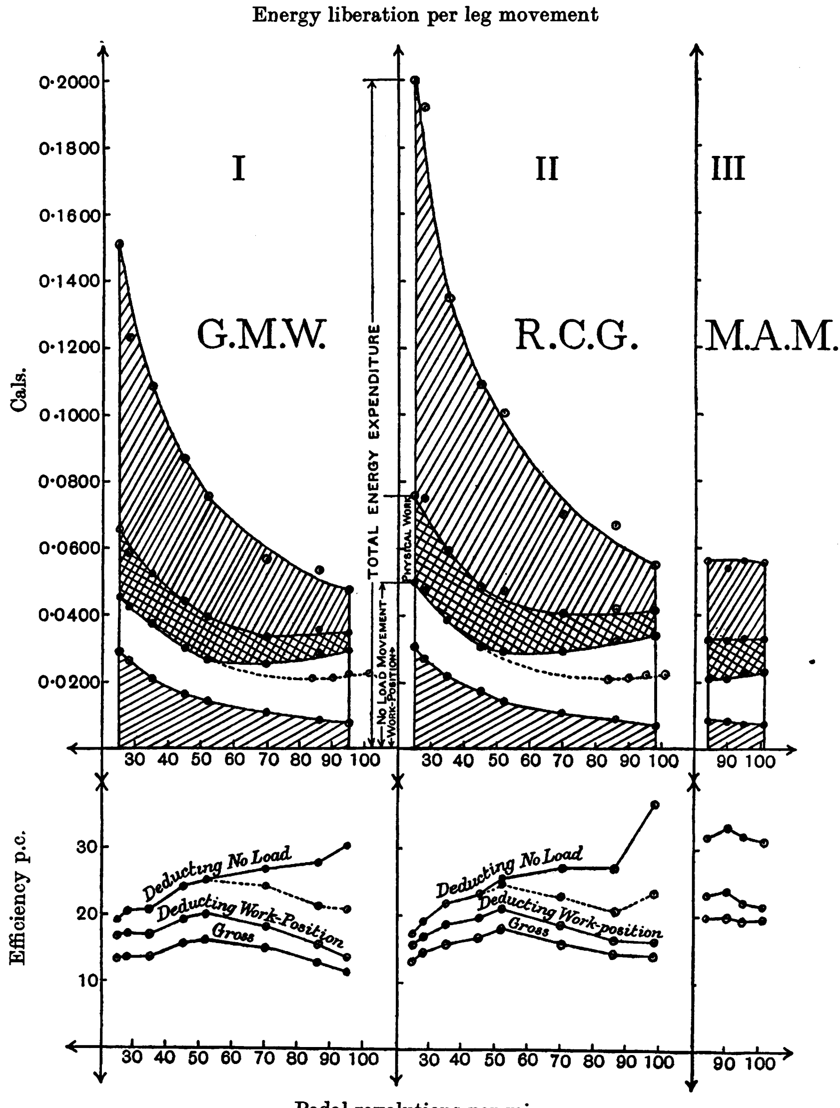
Recently, Dickinson [1929] has carried out a series of experiments on the efficiency of bicycle pedalling at various speeds. The load was kept approximately constant and the speed alone was varied. The duration of the working period was relatively short (from approximately 1 to 10 min.) and the metabolism was estimated by the excess oxygen method. In these experiments Dickinson found a maximum efficiency of 21·8 p.c. at an optimum duration per leg movement of 0·9 sec. (work-position basal deducted). Her results showed good agreement with the predictions from Hill's formula, but she notes and discusses various complicating factors which prevent unqualified acceptance of the values experimentally obtained for the constants.

The concept aroused by Hill's efficiency formula is one of a muscle or simple muscle group exerting the maximum effort of which it is capable, and of the energy expended by that muscle or muscle group alone. The formula takes no account of the energy cost of maintaining the body in the working position, a cost comprised within the work-position basal, nor does it take account of the energy expenditure of all those muscles which serve to provide a fixed point from which the effectors of the external work may act. Further, the excess respiratory and cardiac work demands an energy expenditure which does not appear in the formula, and the energy cost of moving the limbs themselves, though perhaps in some cases negligible, in others may be quite the reverse.

Theoretically the determination of the metabolic requirement of driving the unloaded ergometer should take account of all these accessory sources of energy expenditure, with the exception of the excess respiratory and cardiac work. There is, however, no guarantee that the movements of the subject driving the unloaded ergometer are reproduced exactly during the performance of the work; in fact, the operators' subjective impression is that they are often quite different. In the same way it is doubtful if even the cost of sitting on the bicycle with the pedals stationary is of the same magnitude during movement, loaded or unloaded, at the various speeds.

In experiments of the present type the relation of the results to Hill's formula is best brought out by their expression as physical work and energy cost per leg movement. The results expressed in this way are included in Table I, and set out graphically for G. M. W. in Graph I, and for R. C. G. in Graph II. For the sake of comparison the few data for

M.A.M., in which no-load metabolisms were available, have been taken from Benedict and Cathcart's paper and treated similarly (Graph III).




In these graphs the uppermost curve represents the total energy output; the lowest the work-position metabolism; and the curve immediately above this the metabolism of driving the machine unloaded. On this last curve as abscissa a fourth curve of the physical work has been drawn; the physical work is thus represented by the distances between this curve and the no-load curve. While open to criticism, the external work has been depicted in this way in order to provide a better visual representation of its magnitude relative to that of the excess energy output (total energy less no load energy).

The points illustrated by the tables and the graphs may be summarized as follows:

(1) The efficiency, as calculated on a gross basis and also after the deduction of the work-position metabolism, shows a definite optimum at 104 leg movements per min.

(2) The efficiency, calculated after deduction of the no-load metabolism, shows a progressive rise with increasing speed. The validity of efficiencies, calculated on this basis, entirely depends, of course, on the assumption that the no-load as determined experimentally exists unaltered in amount during the performance of the external work. The doubtful nature of this assumption we have already commented on.

(3) The cost of the no-load movement shows a minimum about 120 leg movements per min. Deducting the work-position basal, the cost of moving the legs alone has a minimum at 104 leg movements per min. (G.M. W.), and 90 leg movements per min. (R.C. G.). Thus, it would appear that, in the present subjects at least, the cost of doing internal work in moving the limbs themselves, and the gross cost of doing external work, are equally at a minimum in the region of 104 leg movements per min. The criticism might be advanced that, in the no-load movement, the subject is doing some external work in overcoming the frictional resistance of the ergometer, but the magnitude of this work is relatively very small.

(4) The graphs bring out the point that, at the higher speeds, a very large proportion of the total energy expenditure is absorbed in the no-load movement. At the highest speeds the ratio $\frac{\text{cost of no-load movement}}{\text{total metabolism}}$ is, for G.M.W. 62·1 p.c., for R.C.G. 61·7 p.c. and for M.A.M. 40·7 p.c. In fact, by prolonging the curves for the total energy expenditure and for the cost of the no-load movement, they would be found to meet, in both of the present subjects, at a speed of approximately 120 rev., *i.e.* a duration of leg movement of 0·25 sec. At this speed all the energy liberated would be absorbed by the no-load movement (cf. with *k* below).

(5) In comparing the present untrained subjects with the professional cyclist, M.A.M., we find the following (at 95–98 rev. per min.):

| | Energy expenditure per leg movement (Cal.) | | |
|---|---|---|---|
| | G.M.W. | R.C.G. | M.A.M. |
| Total... ... ... ... | 0·0475 | 0·0551 | 0·0561 |
| No load ... ... ... | 0·0295 | 0·0340 | 0·0228 |
| Excess of total over no load | 0·0180 | 0·0211 | 0·0333 |

Thus it appears that the fundamental difference between the trained and untrained subject is the cost of the no-load movement. No doubt the trained subject, by his more perfect coordination, is able to stabilize his body in the working position by the use of fewer accessory muscles. In this connection it is interesting to note that the present subjects observed a tendency of their no-load metabolism to fall at the higher speeds as the experiments progressed. If we assume that this fall would, through training, have gone on until their no-load metabolism diminished to that of M.A.M., then the efficiencies (calculated after deducting the no-load metabolism) would run somewhat as the dotted lines in the efficiency graphs. This calculation is introduced merely to show how greatly the actual metabolic cost of the external work may be influenced by the magnitude of the no-load metabolism.

(6) An attempt was made to compare our results, expressed per leg movement, with Hill's efficiency formula.

The numerator of this formula shows that the external work derivable from a muscle diminishes with increasing speed. In an infinitely slow contraction the external work $W$ would be equal to $W_0$, the potential energy of the tense muscle; with increasing speed, $W$ becomes a smaller and smaller fraction of $W_0$ until, when the contraction is so brief that $t = k$, no external work is done at all. Apart from any strict interpretation of $k$ as a constant indicative of the viscous resistance of the muscle, the relation $W = W_0(1 - k/t)$ has been shown to hold in many types of muscular effort. Most of these have been really maximal efforts, efforts which have rapidly produced a considerable oxygen debt. There seems, however, no theoretical reason why it should not hold in subjects working, as in the present experiments, in the steady state; though the fact that the subject has to gauge his effort as one which he can maintain for an hour or so will make the results more liable to variation.

While we do not wish to stress the following calculations, more particularly the value of $W_0$ as being the *maximum theoretical work* of the limb muscles, it seems worth recording that the variation of external work with speed in the present subjects (especially in G.M.W.) can be brought more or less into line with the formula by deriving a value for $k$ from two extreme speeds and applying this value to the calculation of the external work which should be done at the intermediate speeds (Table VI).

Table VI.

| | G.M.W. $W_0$ = 0·0213 Cal., $k$ = 0·236 | | R.C.G. $W_0$ = 0·0323 Cal., $k$ = 0·232 | |
|---|---|---|---|---|
| | $W$ calculated from $W_0$ | Actual $W$ | $W$ calculated from $W_0$ | Actual $W$ |
| Speed | Cal. per leg movement | | | |
| 25 | 0·0171 | 0·0202 | 0·0261 | 0·0261 |
| 28 | 0·0166 | 0·0166 | 0·0253 | 0·0277 |
| 35 | 0·0154 | 0·0147 | 0·0231 | 0·0211 |
| 45 | 0·0138 | 0·0137 | 0·0211 | 0·0181 |
| 52 | 0·0126 | 0·0125 | 0·0193 | 0·0181 |
| 70 | 0·0096 | 0·0084 | 0·0148 | 0·0111 |
| 86 | 0·0069 | 0·0069 | 0·0108 | 0·0095 |
| 95/98 | 0·0054 | 0·0054 | 0·0078 | 0·0078 |

(In G.M.W. $k$ was calculated from the speeds of 28 and 95 revs. as the work for 25 revs. was obviously out of line.)

Further, according to theory, $k$ is also the limiting duration of leg movement at which the external work would become zero. With the above values of $k$, external work would become impossible in G.M.W. at a speed of 254 leg movements (127 pedal rev.) per min., and, in R.C.G. at a speed of 259 leg movements (129 pedal rev.) per min. As noted above, extrapolation from the graphs indicates a total absorption of the energy expenditure in the no-load movement at very similar speeds.

(7) The denominator of Hill's formula expresses the finding that the energy used by muscles in doing work is made up of a constant factor necessary to set up contraction and a factor for maintaining the contraction, the latter increasing in magnitude as the speed falls. We have been quite unable to make our results for the excess metabolism (total metabolism less no-load metabolism) conform to a formula of this type. This is but a further indication of how difficult it is to obtain, in ordinary metabolic experiments, a true value for the metabolism actually devoted to the work. It is solely with this energy quota that the denominator in Hill's formula is concerned. The formula takes no account of the energy for ordinary maintenance of the body, of the considerable and speed-varying fraction of energy utilized in stabilizing the body during the work, nor of the demands of the cardiac and respiratory muscles. Unless means of eliminating these accessory but essential modes of energy expenditure by satisfactory no-load experiments can be devised, anything but the most general application of Hill's formula to experiments of the present type seems impossible.

## SUMMARY.

Experiments on the efficiency of bicycle pedalling in two subjects, using a Krogh ergometer with a special speed governor, have been carried out over a wide range of speeds.

The optimum gross efficiencies obtained were 16·3 p.c. in one subject and 18 p.c. in the other.

These optima were obtained at about 52 pedal rev. per min., *i.e.* when the duration of contraction of the effector muscles could not have exceeded 0·6 sec.

The metabolic cost of driving the unloaded ergometer also showed a minimum in the neighbourhood of the same speed.

The efficiencies calculated after deducting the metabolic cost of the work position were, on the whole, 2 to 3 p.c. higher, and showed an optimum at the same speed.

The efficiencies obtained after deducting the metabolic cost of the no-load movement showed a progressive rise with increasing speed. The validity of the efficiencies calculated on this basis is discussed.

The presence of an optimum efficiency at a certain speed is in accord with the general deduction from A. V. Hill's efficiency formula, but the impossibility of isolating the fraction of the total metabolic energy devoted to the actual effector muscles makes the rigid application of Hill's formula to metabolic experiments on the human subject in the steady state impossible.

It is impossible to obtain experimentally the real efficiency of the effector muscles in any human effort, owing to the difficulty of getting an accurate no-load base line. In fact the only efficiencies obtainable from metabolic experiments on the human subject, that are of any practical value, are gross efficiencies.

The authors would like to express their indebtedness for valuable criticism to Prof. E. P. Cathcart, at whose suggestion this research was begun.

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