Man Powered Aircraft Group

Man as an Aero Engine

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Introduction

The first basis for the design of any power-driven mechanism is an exact knowledge of the characteristics and capabilities of the power unit available. Without such information no designer is able to start on the initial sketch of the mechanism. The man powered aircraft is no exception and its designers have suffered in the past by insufficient knowledge about man's power. This may seem remarkable because until about two centuries ago almost all the world's work was done by muscle-power, and much of the muscle was human.

This paper sets out to examine the properties of man considered purely as a source of mechanical power. Knowledge of these properties is of interest both in athletics and in the design of man-driven machines. The study was undertaken in order to find out theoretically whether it is possible for man to fly by his own efforts: probably it is[21, 24, 32].

*Based on a lecture given before the Man Powered Aircraft Group on 27th November, 1959. A similar paper based on the lecture is to be published in *Ergonomics*.

We all know that we can work harder for a short period of time than for a long one, but there are few systematic studies (*e.g.* Refs. 17, 20, 27, 28, 30) of the exact way in which power output diminishes as the duration of exercise increases. Extensive physiological studies have been made on running, but in this form of exercise little external work is done, so the results are of only indirect use for the present purpose.

Observations on various types of exercise, from many sources, are plotted in Fig. 2: the best performances at each duration have been extracted and plotted in Fig. 1. Note that, in both cases, the horizontal scale does *not* represent the time from the beginning of exercise, but the duration for which a given constant output can be maintained; a linear scale is used in Fig. 1 and a logarithmic one in Fig. 2. For a short period of time very heavy work can be performed, but the power output diminishes steeply the longer the total duration of exercise. However, when the duration of working is greater than about 5 min., the rate of working diminishes only very slowly with increasing duration of exercise. In order to understand these observations, it is necessary

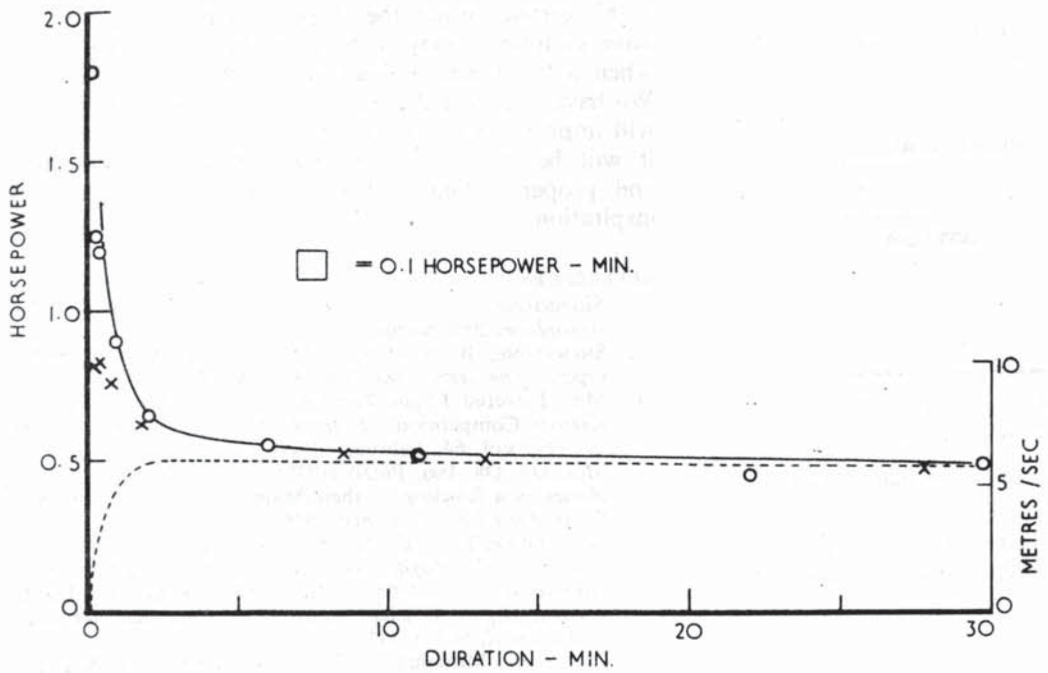

FIGURE 1. Left-hand ordinate; circles, maximal external mechanical power produced by champion athletes, data extracted from Fig. 2. Right-hand ordinate; crosses, running speed, world records[12]. Abscissa; total duration of exercise (*not* time elapsed since the beginning of exercise). The broken line shows the energy available from oxidative processes. To this is added 0·58 h.p. minutes of work from anaerobic (hydrolytic) sources, to give the theoretical curve, full line.
N.B. 1 h.p. = 0·746 kilowatts = 76 Kg.-wt. metre, sec.$^{-1}$.

to know something of the physiology of muscular exercise.

The Physiology of Muscular Exercise

The function of muscles is to transform chemical into mechanical energy. All the chemical processes take place at constant temperature, that is, their energy does not appear at an intermediate stage as heat. For this reason muscle is quite unlike a heat engine. Though the chemical processes involved are very complicated, muscle achieves an efficiency (= work output/chemical energy used) of 20 to 25 per cent under favourable conditions: the chemical energy comes ultimately from the oxidation of foodstuffs, most probably of the carbohydrate glycogen and fats, to carbon dioxide and water.

From the long-term point of view, energy production by muscle thus depends on an adequate supply of oxygen, which must be absorbed at the lungs and transported by the blood-stream to the active muscles. Both lungs and blood-stream have a limited capacity, which in turn sets a limit to the steady-state energy production. Fit young men can absorb up to 4 litres of oxygen per minute[3, 25], the maximum absorption that has been recorded is 5·4 litres/min., by an Olympic athlete. Since 1 litre of oxygen yields about 0·1 h.p. minutes of mechanical work under optimal conditions, the steady-state power output must be limited to 0·4 – 0·54 horse power, depending on whether we are considering fit ordinary men or champion athletes. This prediction correlates well with direct measurements of mechanical power output (*see* Figs. 1 and 2).

Chemical Considerations

Although the ultimate source of muscular energy is oxidation, the immediate source of energy is the hydrolysis of various compounds, such as adenosine triphosphate, creatine phosphate and, when oxygen is lacking, most important of all, the hydrolysis of glycogen to lactic acid (*see e.g.* Ref. 18). The *rate* of these hydrolytic reactions is not limited by the supply of reactants from outside the muscle, and it may therefore be very high, though the *total amount* of energy available is limited by the amounts of such chemicals stored in the muscle. As shown in Fig. 1 the experimental measurements of maximal work-production (circles) satisfactorily fit a theoretical curve (full line) constructed on the assumptions:— (*i*) that there is a steady oxidative energy production of 0·5 h.p. falling to 0·475 h.p. after 25 min. as a result of long-term fatigue (broken line); (*ii*) that to this is added a "lump-sum" of mechanical work derived from hydrolytic reactions. This amounts in practice to about 0·6 h.p. minutes, which can be released over a long or short period, according to need.

The theoretical calculation is made slightly more complex by the fact that the oxygen consumption provoked by exercise does not rise instantly to its full value as soon as exercise begins. It rises instead with a roughly exponential time-course (half-time approximately 30–40 sec.)[14]. Thus during a short bout of maximal exercise a disproportionate amount of energy has to come from anaerobic processes[23]. Since the resulting metabolites are initially responsible for stimulating the increase in oxygen intake, this increase does not occur until the metabolites have accumulated to some degree.

The experimental points in Figs. 1 and 2 both refer to a steady rate of power production, maintained for the duration indicated. A theoretical analysis into oxidative and hydrolytic components makes it possible to forecast the limits of performance if the task set involves non-uniform power production; in this case, the hydrolytic "lump-sum" must be distributed in an appropriate way as a function of time.

Of course, the stores of hydrolysable chemicals must be replenished after the exercise is over, the energy

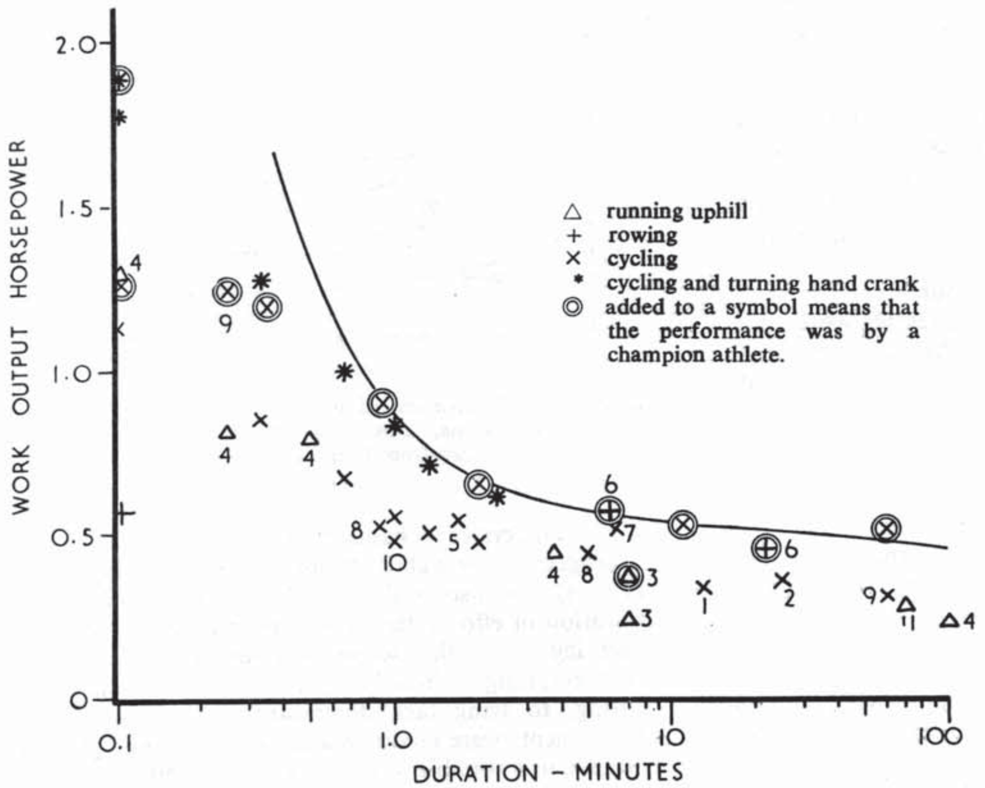

FIGURE 2. Maximal output of external mechanical power (h.p. linear scale) plotted against total duration of exercise (min. logarithmic scale). The logarithmic scale has been used to display the experimental points clearly. Full line is the theoretical curve shown in Fig. 1. The numeral indicates the source from which the experimental point was derived. Points without numerals: champion cyclists, ⊗ Ref. 21; ordinary cyclists, ×, also ordinary cyclist performing hand-cranking in addition, * Ref. 29.
1, Abbott *et al*; 2, Asmussen; 3, Bannister; 4, Benedict *et al*; 5, Bonjor; 6, Henderson *et al*; 7, Karpovich *et al*; 8, Nielsen *et al*; 9, Raleigh; 10, Tuttle; 11. Unna.

needed being obtained from additional oxidation. Thus the "oxygen debt" accumulated during exercise is paid off during recovery. The maximum oxygen debt that can be accumulated is about 20 litres. This might be expected to yield about 2 h.p. minutes, but we have seen that in practice only a third of this (0·6 h.p. minutes) is actually obtained as external mechanical work. The reason for the inefficient utilisation of the oxygen debt is not altogether clear.

Mechanical Considerations

The speed with which a muscle shortens depends on the force to be overcome: the larger the force, the slower the shortening, and vice versa. No work is done if the force is zero, or if the force is so great that the speed is zero; though chemical energy will be consumed almost as usual[31]. In order to achieve an optimal conversion efficiency of 20 to 25 per cent, force and speed of movement must be suitably matched to one another. It so happens that the optimum occurs when the force has about one-half, and the speed of movement has about one-quarter, of their respective maximum values[15]. For the greatest power output, regardless of economy, the force should be somewhat less and the speed somewhat greater. When using a machine, such as a bicycle, it is usually possible to adjust the gearing so that the load is matched to the muscles; but in many athletic pursuits this is not the case. Some examples will be discussed later.

It should also be noted that the conversion from chemical to mechanical energy in muscle is a one-way process. Animals are obliged to employ reciprocating movements, not rotations, so the kinetic energy of their limbs is continually altering. Energy given to accelerate a limb will inevitably be wasted unless there is a mechanism to decelerate the limb again and store the energy. If the movement has to be checked by the contraction of antagonistic muscles, these will use up yet more energy, not gain it[1].

Experimental Data

In presenting the data collected from many sources an attempt has been made to distinguish between the results obtained from different types of exercise, and also to distinguish champion athletes from healthy non-athletes. This last distinction may seem somewhat arbitrary, but when it is made, the experimental points fall into two fairly well-defined sets. The champion athletes (double circles in Fig. 2) can develop 20 to 30 per cent more power than healthy normal men can, for a given type of exercise.

RUNNING (Fig. 2; triangles)

Running is not a good way of producing external mechanical work. Sprinting at 7 m./sec.—a speed which can be kept up for perhaps 30 sec.—only 0·16 h.p. appears as external work, in overcoming air resistance. At the same time an estimated 2·4 h.p. is dissipated internally; 0·6–0·7 h.p. in raising and lowering the centre of gravity, and 1·7 h.p. in changing the kinetic energy of the limbs[9]. Sprinting against an artificial resistance has yielded 0·31 h.p. of external power[7], but this must also be only a small fraction of the actual mechanical power developed. However, the metabolic changes resulting from running have been extensively studied (*e.g.* Refs. 4, 14, 23). Fast running has been shown to be very uneconomical; a large increase in energy expended leads to only a small increase in speed.

The same effect can be seen in Fig. 1 (crosses). At speeds less than about 6 m./sec., running speed decreases in exactly the same way with increasing duration of exercise as does the working ability of the body. But in short bouts of exercise (duration less than 1 min.), running speed falls off compared with the ability to perform external work (compare crosses and circles in Fig. 1). The chief importance of the crosses in Fig. 1, is that they support the conclusion that a rate of working that can be kept up for 10 mins. can almost be kept up for 30 mins. or even an hour.

The triangles in Fig 2 all represent work done while running uphill. Normally this activity merely leads to an increase in the potential energy of the body, but it could, in theory at least, be made available by using a treadmill.

ROWING

Rowing, using a sliding seat (Fig. 2; upright crosses) is an effective method of producing external mechanical work so long as the duration is more than two or three minutes. For shorter bouts it is very uneconomical because of the disproportionate wastage of energy from acceleration and deceleration of the whole body that results when this type of movement is made at high frequency[28]. The advantage that might have been expected theoretically from the use of a larger muscle-mass is thus not obtained in practice.

PEDAL-CYCLING (Fig. 2; diagonal crosses)

Cycling can be adapted to various durations of maximal effort. The mechanical system involved is simple and lends itself to the free use of the power obtained; gearing can be readily adjusted; maximum use can be made of the kinetic energy of the moving limbs. In cycling the full steady-state power production of the body can be developed. Thus the muscle-mass of the legs is evidently more than large enough to utilise all the oxygen that can be absorbed. The maximum rate of pedalling, under no-load conditions, *e.g.* in roller-racing, is about 180 r.p.m., the optimum for greatest efficiency is about 60 r.p.m., and the speed used in cycling contests (where economy may have to be sacrificed to output) varies from 60–120 r.p.m.

PEDAL-CYCLING WITH HAND-CRANKING (Fig. 2; stars)

The total amount of energy immediately available from hydrolytic reactions is limited by the initial size of the chemical stores in the *active* muscles. Therefore, maximal use of hydrolytic energy sources can be made only by employing and exhausting as large a mass of muscle as possible. So for short bouts of exercise, the more muscle employed, the greater the power developed. Accordingly, it has been found[28,29] that simultaneous cycling and hand-cranking yields about 50 per cent more power than cycling alone, but only for a short time; Ursinus[28,29] found that the advantage is rather small after 5 to 10 min., when the power output becomes limited by oxygen supply rather than by muscle-mass. Four different types of machine for combined arm and leg movement were thoroughly investigated by Ursinus, who concluded that simple rotation of a 17·5 cm. crank by hand and foot was the most effective arrangement, as well as being mechanically the simplest (Fig. 3). He also established the optimal speed for each duration of effort; the best phase relation between arm and leg; and the scope and limitations of various postures, ranging from lying on the back, through normal sitting, to lying face downwards. Most of Ursinus' experiments were made on a subject who, though not an athlete, was yet able to produce for two minutes a power output equal to that of the best athletic cyclists using the legs only. If cycling athletes were to benefit to a similar degree from the use of their arms as well as their legs, this would substantially raise the experimental points at the extreme left-hand side of Figs. 1 and 2, so that they fell closer to the theoretical curve.

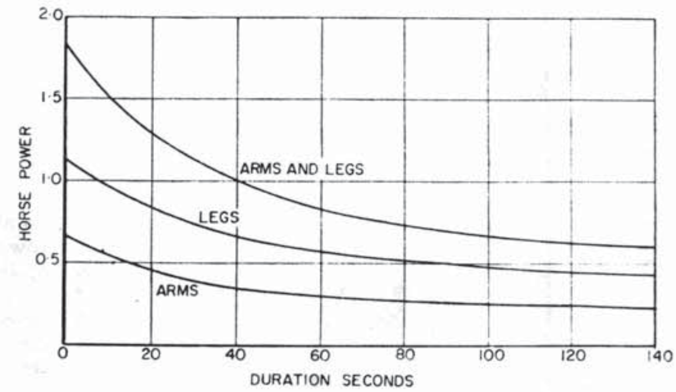

FIGURE 3. Comparison of horse power produced from work done by legs alone, arms alone and arms and legs combined. Redrawn from Ursinus. Ordinary subject.

Efforts of Short Duration

The points plotted at 0·1 min. in Fig. 2 are not strictly comparable with one another. They represent maximum peak outputs whose short but uncertain durations depended on many factors, for example, on the inertia of the apparatus. The bout of exercise will in each case have consisted of a number of repeated movements. It is of interest to consider what may be the power output of the body during a *single* movement, occupying a second or less. In this case the power is limited only by the mass of muscle that can be brought to bear effectively, for fatigue can hardly arise within such a short time. A theoretical upper limit of about 11 h.p. is set by two facts: that the body is about 45 per cent muscle; and that human muscle can develop about 0·3 h.p. per kilogram when it is shortening against a matched load[31]. The full amount of power could only be extracted, of course, if it were possible to connect every muscle in the body to a suitable load, then to throw them all into contraction at once. The mere fact that muscles are almost all arranged in the body in antagonistic pairs may be expected to reduce the theoretical limit for any practical movement to perhaps 5 or 6 h.p.

In order to investigate the peak power output of the body in more detail, it would be necessary to construct a machine for the specific purpose of absorbing the work from arms, torso and legs at optimal speed; it seems that no existing athletic task is suitable.

Conclusion

It is deduced from the published literature that the usable external power output of the body is limited in the following manner for the reasons stated :

(1) In single movements (duration less than 1 sec.) to less than 6 h.p.; by the intrinsic power production of muscle, and by the difficulty of coupling a large mass of muscle to a suitably matched load.

(2) In brief bouts of exercise (0·1 – 5 min.) to 2 – 0·5 h.p.; by the availability in the muscles of stores of chemical substances that can yield energy by hydrolysis.

(3) In steady-state work (5 min. to 150 min. or more) to 0·5 – 0·4 h.p.; by the ability of the body to absorb and transport oxygen.

(4) In long-term work, lasting all day, to perhaps 0·2 h.p.; by wear and tear of muscles, the need to eat and so on.

All these figures refer to champion athletes; ordinary healthy individuals can produce less than 70 – 80 per cent as much power.

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