THE HUMAN POWER PLANT

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Members of this audience will be familiar with previous papers on human power generation given by Wilkie and Davies (5, 7, 23). Since then there have been advances in the knowledge of physiology concerned with muscle metabolism and its limitations, but the ability of Man (or Woman) to perform physical work has changed little. Unfortunately, evolution of the human species does not advance as rapidly as the evolution of composites and computers!

The way in which Man breaks down complex, high energy compounds into simpler substances with the release of stored energy has been well described (14, 16). For the first few seconds of exercise, the metabolism of high energy phosphates, adenosine triphosphate (ATP) and creatinine phosphate (CrP) provide a diminishing amount of energy (Figure 1) A large amount of power is available from this source and has been shown to provide (in different types of exercise) up to 4 kW for 0.2 s, 1.2 kW for 5 s and 800 W for 10 s (1, 6, 22). However, even while phosphate breakdown is proceeding, the metabolism of carbohydrate, mainly muscle stores of glycogen has already commenced and rapidly becomes the most important energy source (Figure 2).

Initially, oxygen supply to the working muscle is poor, and although there are same limited muscle stores, the majority of early glycogen breakdown (glycogenolysis) occurs anaerobically (without oxygen). Pyruvic and lactic acid, are formed and accumulation of the latter is important in the fatigue of anaerobically exercising muscle. Anaerobic glycogenolysis has a limited capacity, and in order to sustain a high power output, oxygen must be supplied to the muscles to allow oxidation of pyruvic acid, preventing the excess accumulation of lactic acid. As the cardiorespiratory system responds to an increased oxygen demand, aerobic energy production accelerates and for study state exercise lasting over a few minutes, the maximum amount of oxygen an individual can extract from the atmosphere per minute (VO_2max) correlates well with his maximal continuous power output. This means that it is reasonable to select a human powered aircraft (HPA) pilot on the basis of his VO_2max, a test which takes perhaps twelve minutes, even though the length of a flight may be an hour or more. During exercise of a lower intensity, and longer duration, fat metabolism becomes a significant energy source as it delays the depletion of glycogen stores, which is an important limiting factor in exercise longer than one hour (17). However, with the power output necessary for HPA flights of under an hour, fat metabolism is probably relatively unimportant, and I will not discuss it further here.

To summarise the important limiting factors, in short term exercise where the energy released exceeds the capacity of the cardiorespiratory system to supply oxygen to the working muscles, fatigue is probably caused by accumulation of lactic acid which alters muscle pH, slowing released is dependant upon aerobic processes and fatigue occurs with vital biochemical reactions. In longer duration exercise, the energy exhaustion of the carbohydrate fuel supply (1).

Figure 3 schematicaly represents the relative contributions of aerobic and anaerobic processes to the total energy yield in a maximal effort lasting 60 minutes, at constant power output. It can be seen that, initially, the anaerobic component (corresponding to phosphate metabolism and anaerobic glycogenolysis) is of greater importance, but at two minutes, the contributions from anaerobic and aerobic mechanisms are equal. Thereafter oxidative metabolism provides most of the energy. Equality of aerobic and anaerobically obtained energy occurs earlier or later in exercise depending on whether the effort is more or less intense, and maximal anaerobic effort produces more power than maximal aerobic effort, but the former is comparatively short-lived. Early in exercise a comparatively high power output is available, but for longer durations a lower value must be accepted (Figure 4). Note that in this figure oxygen uptake is presented on the right hand vertical axis and the value initially exceeds recorded (7.41 min^{-1}) (1) illustrating that anaerobic processes must be contributing to the total energy yield at this stage.

Figure 5 demonstrates how exercise at an increasing percentage of VO_2max reduces time to exhaustion. A pilot with a high VO_2max when given a set power output to maintain will therefore exercise longer as he is working at a lower relative work intensity: e.g. if two pilots have a VO_2max of 3 liters and 5 liters, this might sustain 225 W and 375 W respectively.

If a HPA requires 200 W for cruise, this represents 89% and 53% of individual could maintain this for several hours whereas the untrained maximum for each pilot, and, from Figure 5, the better trained pilot could manage only minutes.

Leaving aside the question of genetic endowment, an individual's ability to produce power depends mainly upon training and the duration for which a given power output is required: Figure 4 shows that a trained individual is more effective than one untrained. The two most successful HPA pilots to date, Bryan Allen and Kanellos Kanellopoulos would be expected to fall somewhere along the upper curve in this figure. They were both slim, so their power to weight ratio was high, something which is probably more important than power output alone. The Daedalus pilots team produced an average of 5.25 W kg^{-1} when working at maximum oxygen uptake, a value which could be sustained for the few minutes necessary for the seaplane competition, and exceeded for a short period at take-off if necessary. However, for the marathon competition a value of 80% of this is more feasible. This yields 4.2 W kg^{-1}, or 294 W total power output assuming a pilot mass of 70 kg However, efforts requiring a power output greater than this, or even above 5.25 W kg^{-1} (equivalent to VOmax) may be sustained for short periods if required, utilising anaerobic processes. It must be remembered that, as stated in Lilley and Fielding's paper (13), concentration on the task of flying may reduce expected power output somewhat: they suggest by 10%. Further, flying whilst producing an intense physical effort is likely to produce a decrement in flying skill (8).

On average, in longer duration aerobic exercise, it may be expected that 1 l of oxygen consumed in one minute will provide 75 W of power for this period. In fact, about 300 W of energy are produced, but three quarters of this performs no useful work and is dissipated as heat: the average mechanical efficiency of muscular exercise is therefore 25%. This Figure 6 shows two subjects, both of whom have a similar VO_2max (about varies between individuals and Nadel found a range of 18% to 33.7% (15). 70 ml kg^{-1} min^{-1}), but one can produce 3.31 W kg^{-1} and the other 4.21 W kg^{-1} when working at 70% of VO_2max, a difference of 27%. The reason for this variation in apparently equally well trained athletes lies partly in the recruitment of muscles not directly involved in producing power, some using the upper body to a greater extent, but more importantly in the differences in efficiency between the enzymatic processes involved, which are related to muscle fibre type (1, 14). The less efficient subject requires more oxygen for a given power output and is therefore working closer to his maximum aerobic capacity: he could be expected to fatigue earlier than the more efficient of the two. The conclusion from this is that whilst maximal oxygen uptake can be used to separate the trained from the untrained, it is not adequate, by itself, to predict who is likely to make a good human power plant.

A further interesting observation from Nadel was that cycling in a semirecumbent position did not affect either mechanical efficiency or VO_2max when compared to upright cycling. It is well known that VO_2max in a supine position is less than when upright, (2). The assumption has been that the semirecumbent position would give values somewhere in between the two (5), but Nadel did not find this to be the case. There are as you know, advantages in having the pilot adopt a degree of recumbency as this will enable a reduced frontal area to be incorporated in the design with concomitant savings in drag.

One aspect of power generation which, in my opinion, has not been adequately investigated, is whether or not the use of hand cranking, in addition to leg work, can appreciably improve power output. Czerwinski (4) published data on the combined use of arms and legs based on previous work by Ursinus in the 1930's (21). He found that arm and leg work produced more power than leg work alone (Figure 7). Further, Astrand and Saltin found that the time to exhaustion was doubled to six minutes when the same workload was shared by both arms and legs (Figure 8). They did not, however, find a higher VO_2max in arm and leg cranking when compared to leg cranking alone. Other workers have found a higher VO_2max in combined exercise, although nothing like the increase one might expect from the greater muscle mass involved (11, 18). Bergh (3) investigated oxygen uptake in various types of exercise, these being uphill treadmill running; arm cranking, cycling, and arm cranking plus cycling. For the arm and leg exercise a special ergometer was built (Figure 9). Average VO_2max in treadmill running was 4.44 $l.min^{-1}$, compared with 4.12 $l.min^{-1}$ in cycling, a difference which has been observed previously (11). VO_2max for arm work alone was 3.01 $l.min^{-1}$ corresponding to 73% of the value for cycling. For combined arm and leg exercise VO_2max was increased by 6.8% when the load on the arms was 10-30% of the total, but for an athlete specifically trained in arm work (a canoeist) VO_2max was reached when 40% of the total load was taken by the arms. Bergh states one reason for some other workers not demonstrating

an increase in VO_2max with combined arm and leg work may be that the relative workload on the arms was net optimised. In his study the average VO_2max for cycling alone was 4.12 $l.min^{-1}$ and it could be in power output of 21 W (assuming 1 l of oxygen can be utilised to produce increased by 0.28 l when arm work was added giving a potential increase 75 W power).

It was also found that, for these subjects, an average power output of 375 W proved supramaximal, and adequate to elicit VO_2max both for legwork alone and for arm plus legwork. VO_2max and duration of exercise also measured with leg work producing 375 W, and with arm cranking providing an additional 180 W and 75 W, giving a total power output of 555 W and 450 W respectively. It was found that VO_2max was not increased over the value obtained when the total power output was 375 W, but the time to exhaustion was reduced from just over 6 minutes to 1 min. 30 s at 555 W and to 2 min 40 s at 450 W

It would therefore appear that the addition of hand cranking to leg cranking could benefit the power available in prolonged human powered flights by about 7%, this being the increase in VO_2max which may be expected in the combined exercise. Further, in short duration flights, approximately 20% more power than that available for cruise may be utilised for over 2 1/2 minutes, 50% for 1 1/2 minutes and, presumably, an even greater percentage for a shorter time.

It seems that any increase in VO_2max from the use of extra muscles can be attributed to a greater oxygen extraction from the blood. Any increase is therefore modest, since large increases in oxygen uptake are dependent mainly upon an increased cardiac output, and the maximal value for this can virtually be achieved with legwork alone (1, 3). The much greater additional power available from the arms for short duration exercise therefore depends upon anaerobic processes. What is unknown is the power which can be obtained when both arm and leg cranking are combined and are working at maximum intensity for short periods such as those a seaplane may require for its take-off run, and when a reduced (but still high) power output is required thereafter for climb or cruise.

Problems arising from the use of arms to supplement leg cranking are aircraft control, extra weight, and the complexity of the machinery involved. Also, if arm work is necessary for only a short period at the beginning of flight, once this requirement is completed the mechanisms incorporated in the design become dead weight, since they are not allowed to be jettisoned according to the Kremer rules.

To overcome the control problem a multicrew/engine aircraft could be considered. In the two crew situation, the pilot would provide leg power alone, and fly the aircraft, with the "stoker" concentrating on producing power with legs and arms as appropriate. Using two crew members, the "Toucan" improved the power to weight ratio when compared to contemporary single pilot aircraft. However, only leg cranking was utilised (by both crew) and it suffered from the same design problems as other early HPAs in that it was cumbersome, fragile and difficult to repair (Pressnell, M., personal communication). I think it would be worthwhile for consideration to be given to the concept of multi-crew aircraft using modern materials and construction techniques (it would certainly make the sport more social!).

I would now like to consider some of the different mechanical devices which have been used to assist the HPA pilot in harnessing in the most efficient manner his physical effort.

It is well known that mechanical efficiency in cycling varies with the pedalling rate. When cruising, a comfortable pedalling rate (for a well trained cyclist) is about 70 rpm. For maximum power output over a short period of time e.g. 20 s? Higher rate is necessary, and in 200 m bicycle sprints pedalling rates of 150 rpm or more are not uncommon (Thompson, G., personal communication). This would suggest the use of a variable pitch propeller (as in the Daedalus aircraft) or a gearing arrangement, when there is a large variation between minimum and maximum power output. Efficiency at varying rpm is shown graphically in Figure 10.

Another variable which has been shown to influence maximum power output in cycling is the position of the seat (9). Less attention has been directed to crank length, and the standard crank is 17.5 cm. In a study which investigated five different crank lengths from 12.5 to 22.5 Inbar (12) found that for maximal exercise lasting 30 s a 5 cm deviation from 17.5 cm produced a deterioration in mean power output of only 0.77% with a shorter crank, and 1.23% with a longer one (Figure 11). For very short or very long legged individual's an adjustment in crank length should be made, but for the average HPA pilot the standard of 17.5 cm is satisfactory, so long as the seat position is correct.

The use of constant torque mechanisms (19) and elliptical chain wheels (10) have been suggested, and the "Muscalair" team claim a 5% improvement in power output using the latter (20). One difficulty in evaluating such devices is that training in their use can affect performance. It can take a month of regular riding before a cyclist becomes efficient with a new bicycle and it is only when he has been studies have not taken this into account. Harrison (10), performed a detailed study of various types of ergometer and found that, in fit men, the best power output for a period of five minutes was obtained from adequately trained that a true comparison can be wade some “forced rowing” whereby the subject rowed an ergometer whose seat was fixed and which conserved the kinetic energy at the end of each stroke, thereby overcoming the major problem in this type of exercise of accelerating and decelerating the body parts (Figure 12). Harrison obtained 12.5% more power with this method than with normal pedalling, although this advantage diminished with time. However, I suspect that this improvement in power output could be achieved using arm cranking in addition to leg cranking (a technique not studied by Harrison), and with a simpler mechanical system.

In conclusion, leg cranking in the upright or semirecumbent position has proved to be a reliable and efficient method for providing thrust in human powered aircraft, and this is likely to remain the favoured method for the next generation of aircraft. However, useful improvements in power to weight ratio may be obtained by the addition of arm work, especially for short periods, or by using a multi crew aircraft mechanical systems can be justified requires further study.

Acknowledgements

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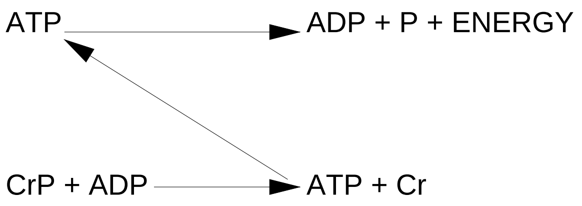

Figure 1. Breakdown of high energy phosphates adenosine triphosphate and creatinine phosphate with release of energy for muscle contraction.

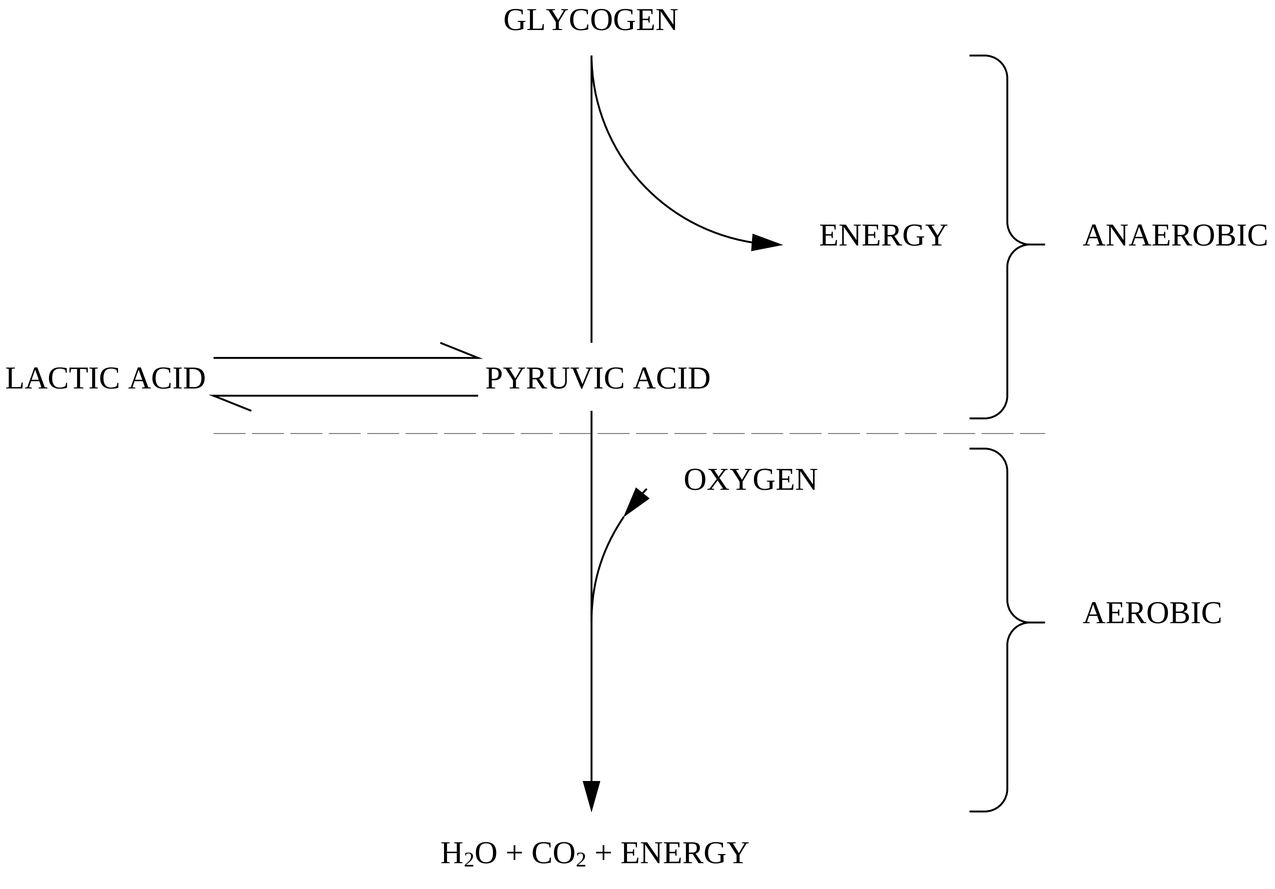

Figure 2. Simplified representation of the anaerobic and aerobic breakdown of glycogen. The metabolism of pyruvic acid to release energy depends upon an adequate supply of oxygen. Early in exercise (or at high exercise intensities) the supply is Inadequate and lactic acid is formed.

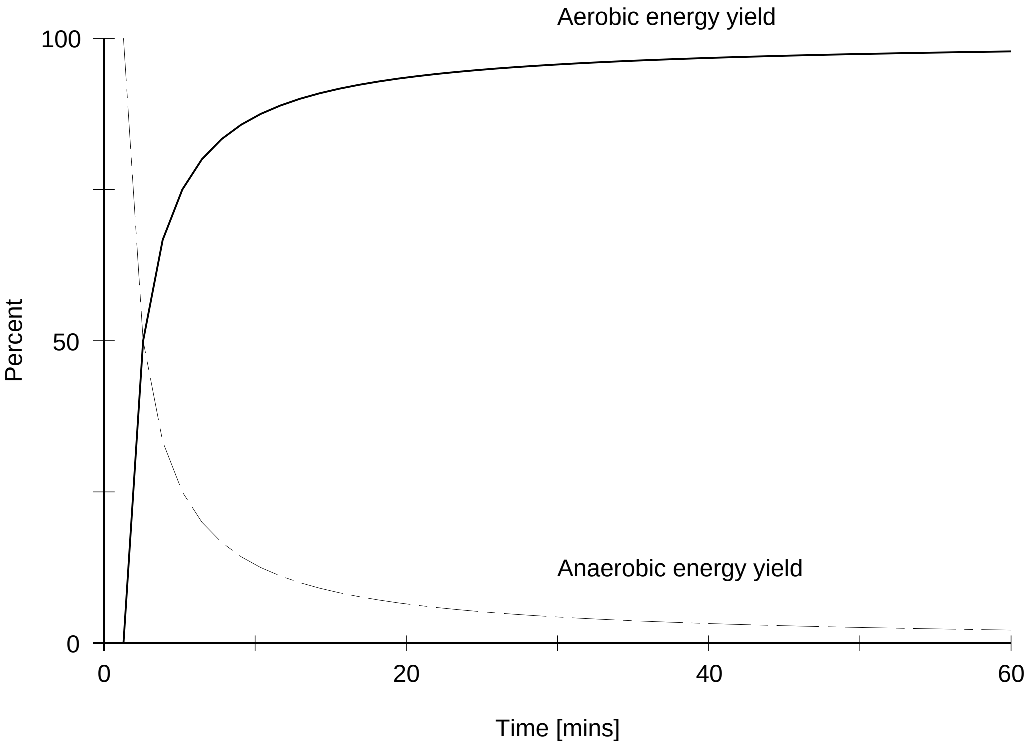

Figure 3. Relative contributions of aerobic and anaerobic processes to total energy yield in a maximal effort lasting 60 minutes at constant power output. (From Astrand and Rodahl, 1986.)

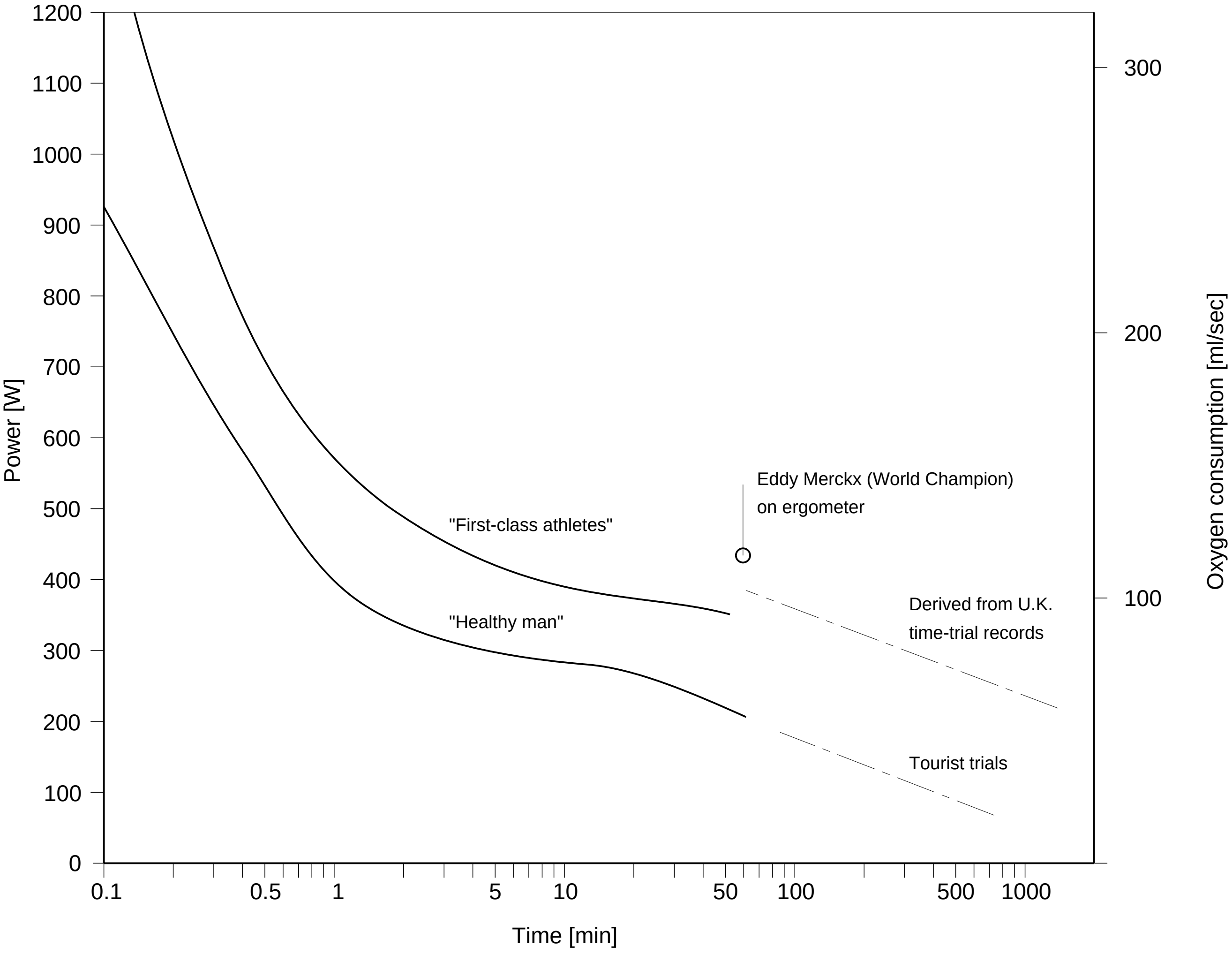

Figure 4. Available steady state power output in cycling for varying duration. (From Whitt and Wilson, 1982.)

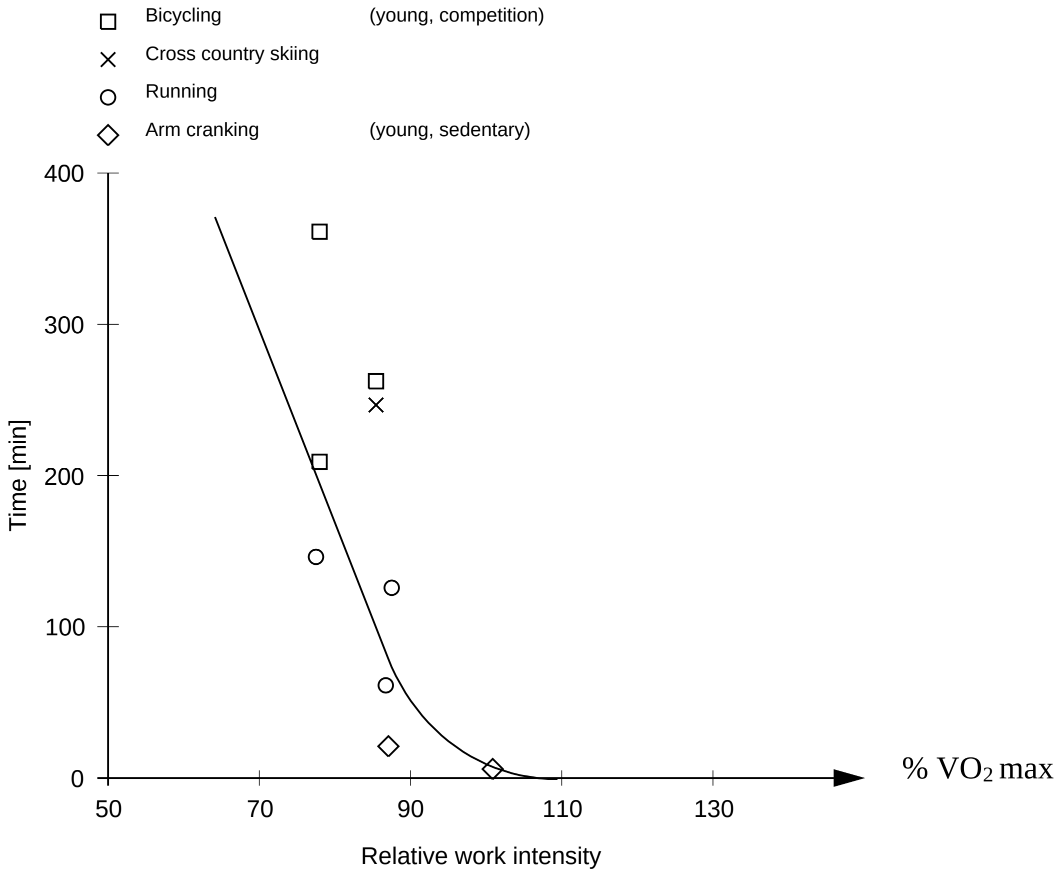

Figure 5. Time to exhaustion when exercising at various relative work intensities. (From Savard, 1987.)

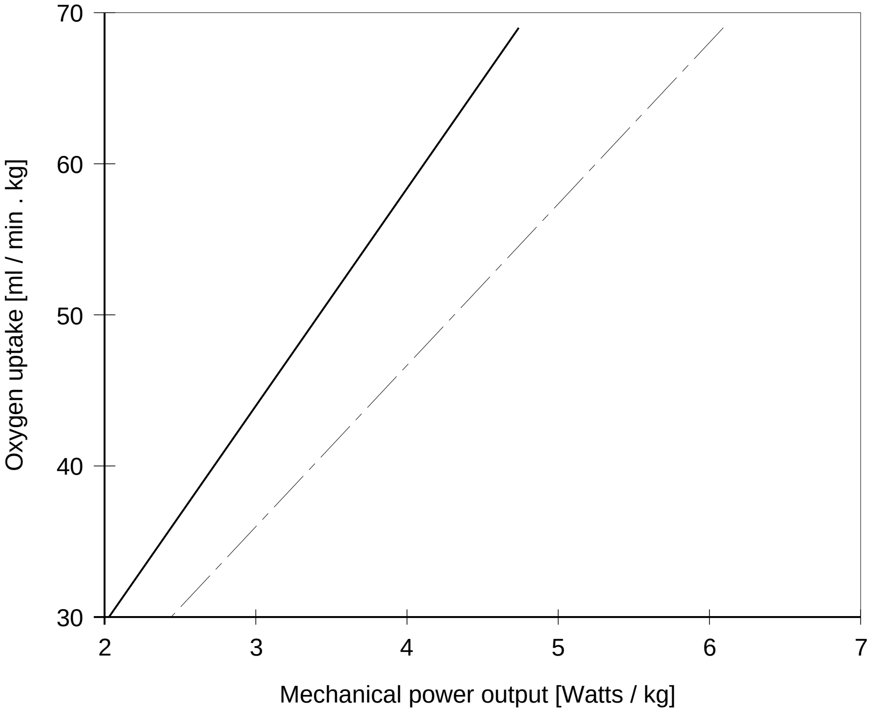

Figure 6. Variation in power output with oxygen uptake in two subjects with similar VO_2 max. (From Nadel, 1988.)

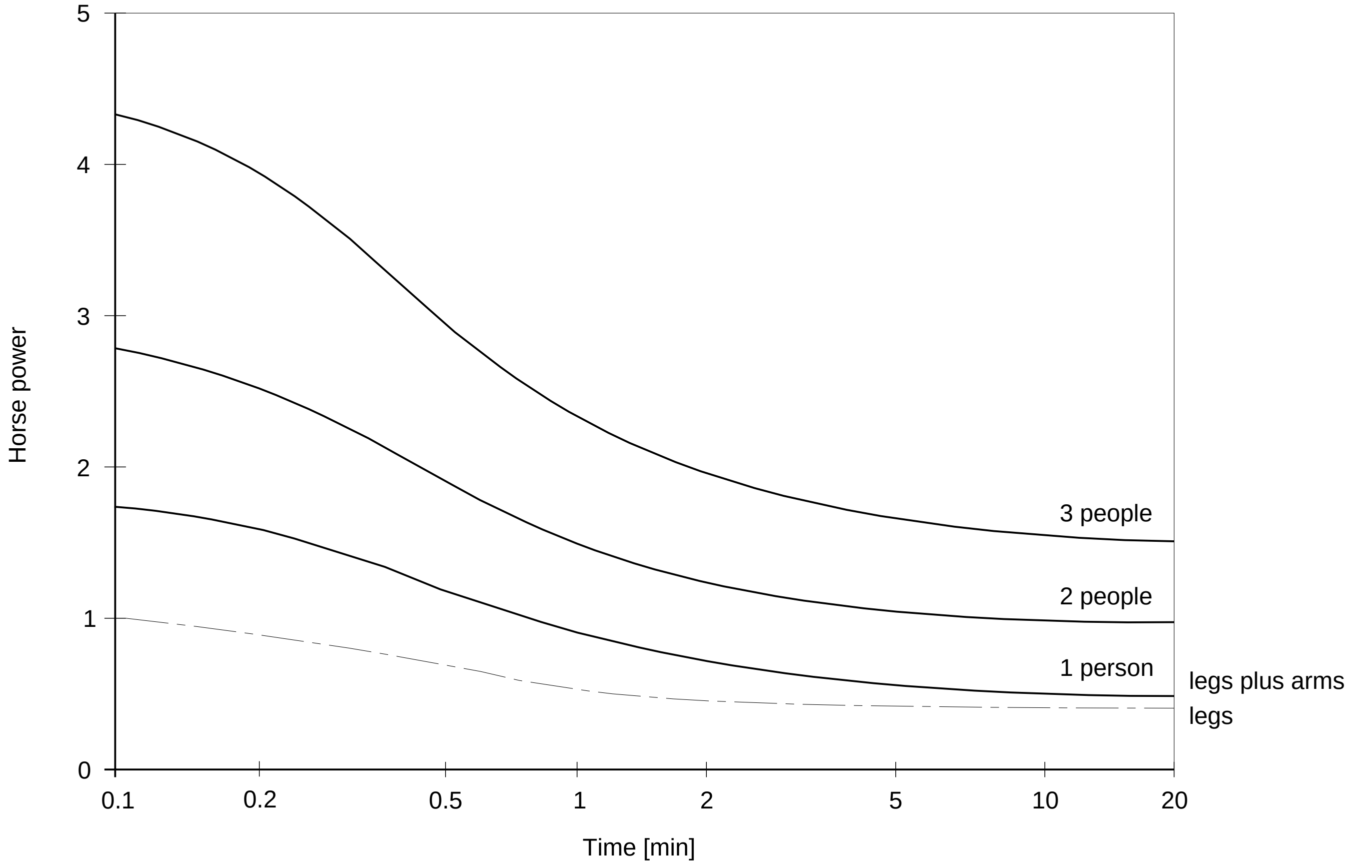

Figure 7. Power output using both arms and legs.
(From Czerwinski, 1961.)

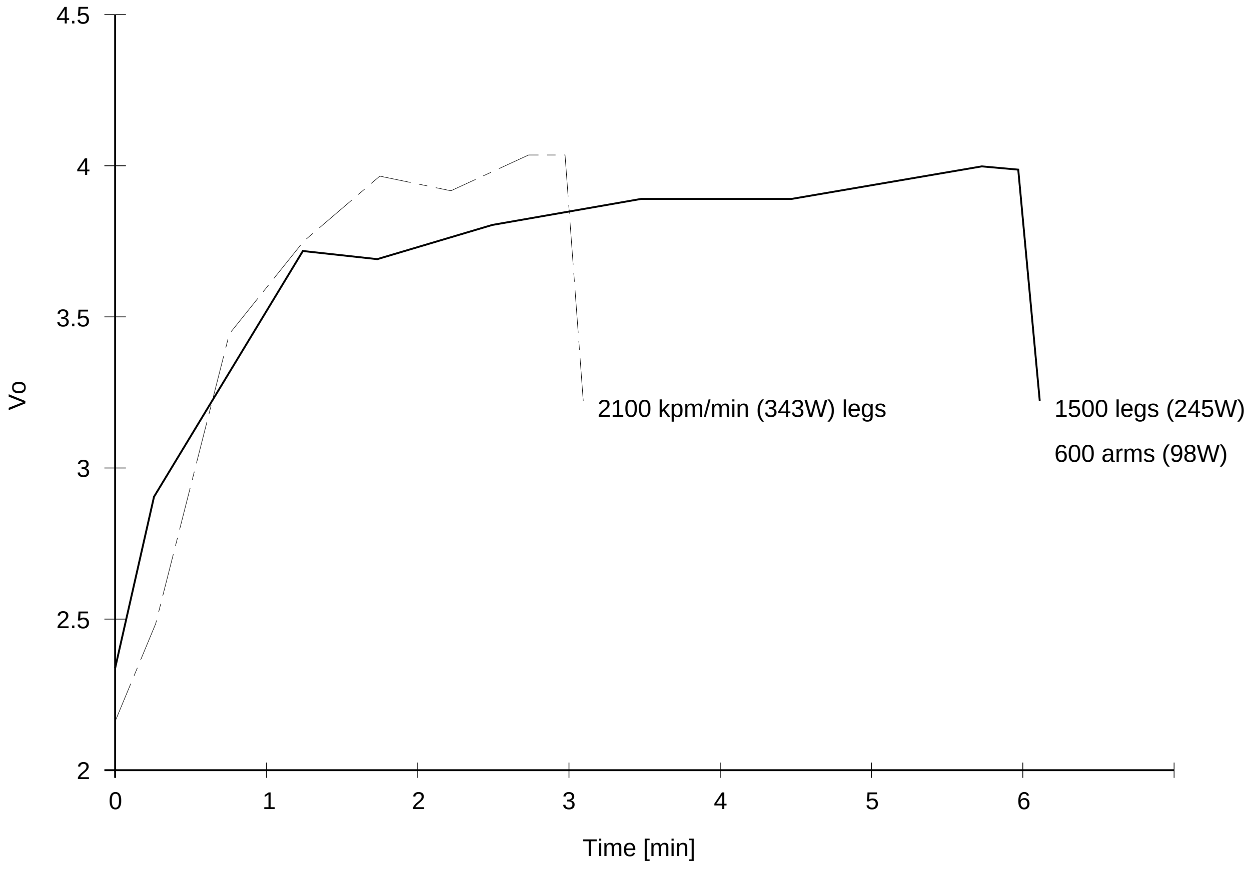

Figure 8. Increase in oxygen uptake and time to exhaustion when legs alone and legs plus arms are involved in generating power. (From Astrand and Saltin, 1961.)

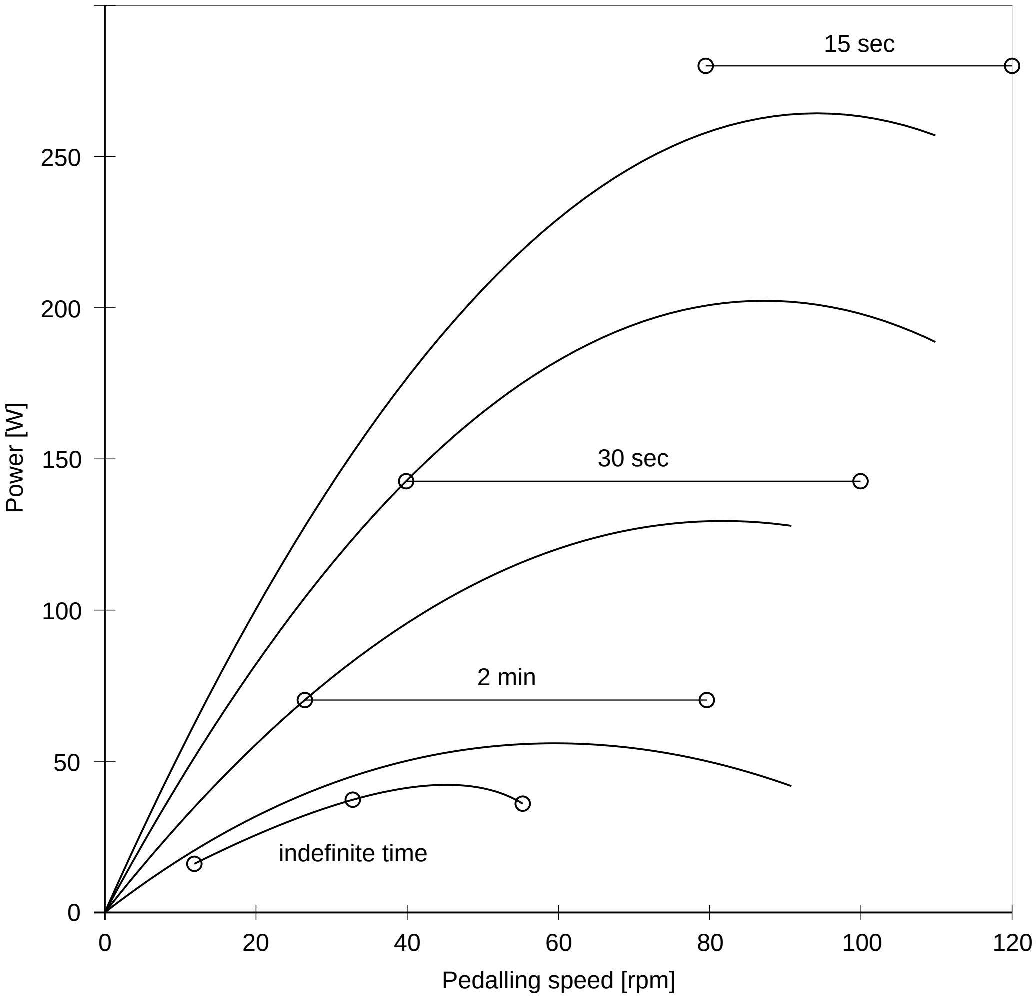

Figure 10. Variation in maximum power output at different pedalling speeds (From Whitt and Wilson, 1982.)

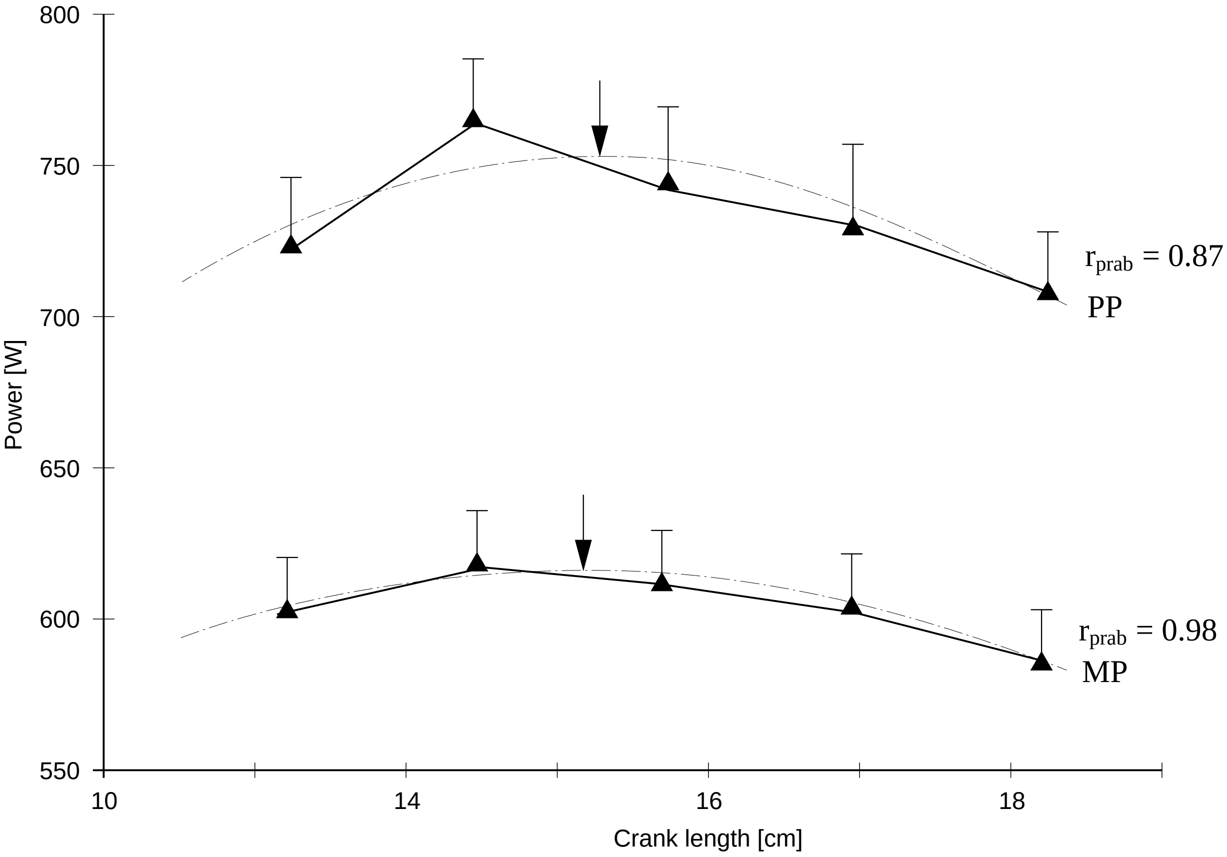

Figure 11. Variation in mean power (MP) and peak power (PP) with different crank lengths in exercise of 30s. duration. (From Inbar, 1983.)

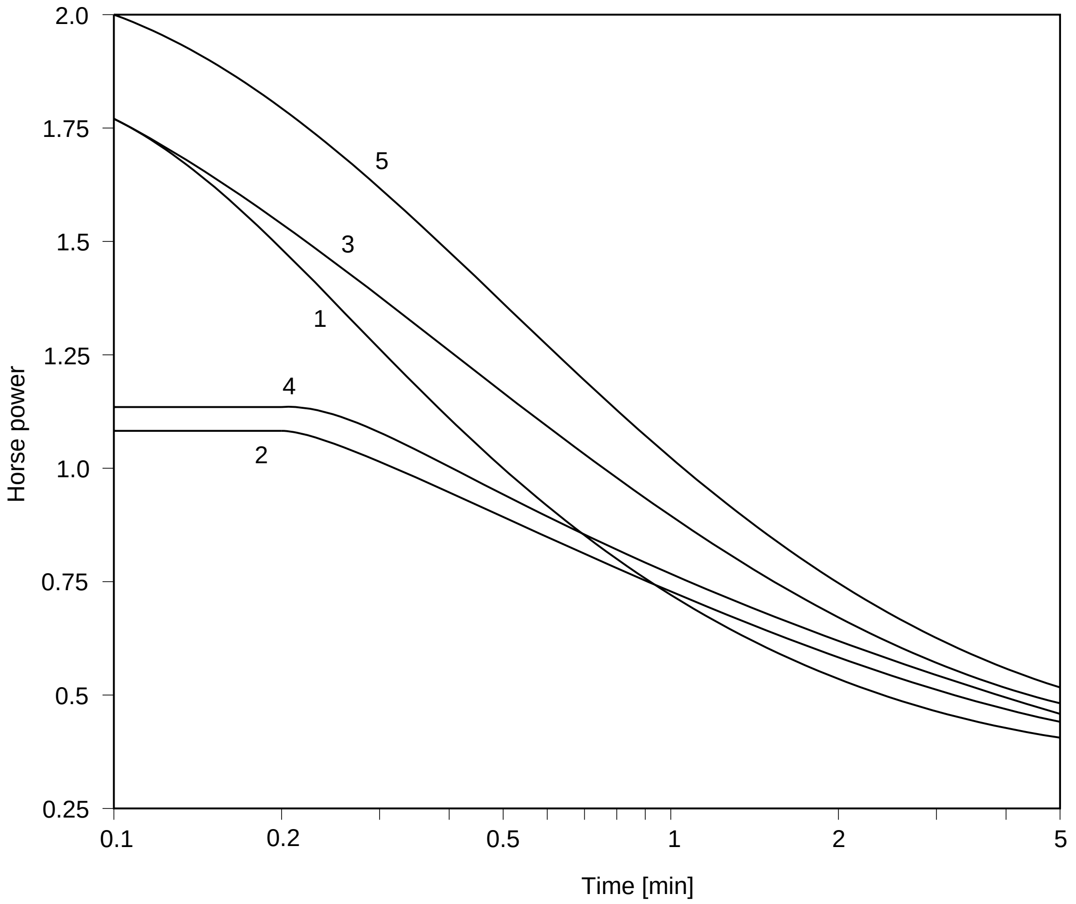

Figure 12. Human power from various actions. (From Harrison, 1970.)
curve 1. cycling
curve 2. free rowing feet fixed
curve 3. forced rowing, seat fixed
curve 4. free rowing, seat fixed
curve 5. forced rowing, seat fixed