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UNDERSTANDING PEDAL POWER

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PREFACE

This paper is one of a series published by Volunteers in Technical Assistance to provide an introduction to specific state-of-the-art technologies of interest to people in developing countries. The papers are intended to be used as guidelines to help people choose technologies that are suitable to their situations. They are not intended to provide construction or implementation details. People are urged to contact VITA or a similar organization for further information and technical assistance if they find that a particular technology seems to meet their needs.

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The author of this paper, VITA Volunteer David Gordon Wilson, is a mechanical engineer at Massachusetts Institute of Technology. The reviewers are also VITA Volunteers. John Furber is a consultant in the fields of renewable energy, computers, and business development. His company, Starlight Energy Technology, is based in California. Lawrence M. Halls is a retired mechanical engineer who designed farm machinery for Sperry-New Holland for 23 years. Lauren Howard is a thinker, inventor, and bicycling advocate. She lives in Charlottesville, Virginia.

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UNDERSTANDING PEDAL POWER

by VITA Volunteer David Gordon Wilson

I. INTRODUCTION

Throughout history human energy has generally been applied through the use of the arms, hands, and back. With minor exceptions, it was only with the invention of the sliding-seat rowing shell, and particularly of the bicycle, that legs also began to be considered as a "normal" means of developing power from human muscles.

A person can generate four times more power (1/4 horsepower (hp)) by pedaling than by hand-cranking. At the rate of 1/4hp, continuous pedaling can be done for only short periods, about 10 minutes. However, pedaling at half this power (1/8 hp) can be sustained for around 60 minutes. Pedal power enables a person to drive devices at the same rate as that achieved by hand-cranking, but with far less effort and fatigue. Pedal power also lets one drive devices at a faster rate than before (e.g. winnower), or operate devices that require too much power for hand-cranking (e.g. thresher).

Over the centuries, the treadle has been the most common method of using the legs to produce power. Treadles are still common in the low-power range, especially for sewing machines. Historically, two treadles were used for some tasks, but even then the maximum output would have been quite small, perhaps only 0-15 percent of what an individual using pedal operated cranks can produce under optimum conditions.

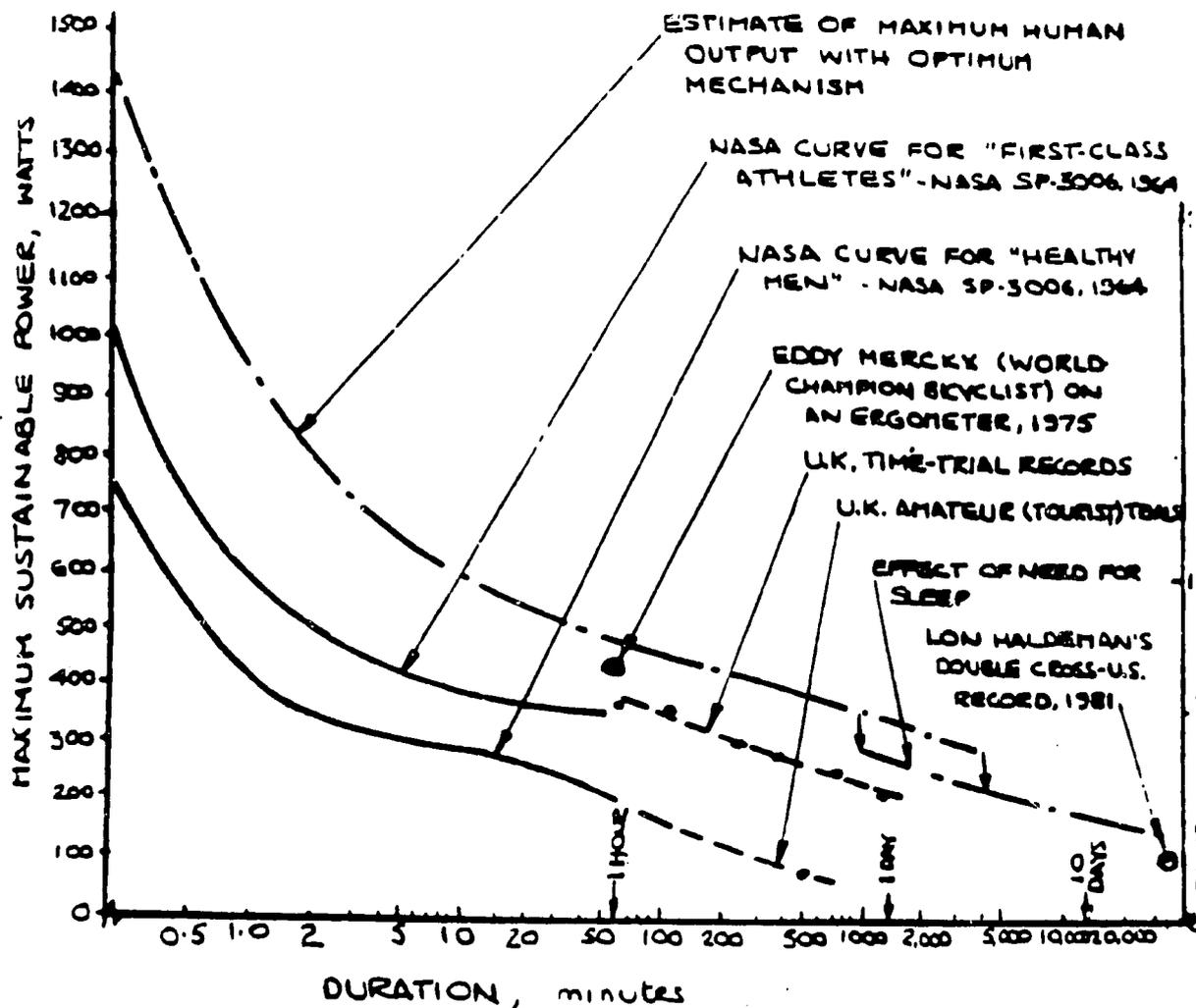
However, the combination of pedals and cranks, which today seems an obvious way to produce power, was not used for that purpose until quite recently. It was almost 50 years after Karl von Kraus invented the steerable foot-propelled bicycle in 1817 that Pierre Michaud added pedals and cranks, and started the enormous wave of enthusiasm for bicycling that has lasted to the present.

The main use of pedal power today is still for bicycling, at least in the high-power range (75 watts and above of mechanical power). In the lower-power range there are a number of uses of pedal power—for agriculture, construction, water pumping, and electrical generation—that seem to be potentially advantageous, at least when electrical or internal-combustion engine power is unavailable or very expensive.

II. OPERATING PRINCIPLES

POWER LEVELS

The power levels that a human being can produce through pedaling depend on how strong the pedaler is and on how long he or she needs to pedal. If the task to be powered will continue for hours at a time, 75 watts mechanical power is generally considered the limit for a large, healthy non-athlete. A healthy athletic person of the same build might produce up to twice this amount. A person who is smaller and less well nourished, but not ill, would produce less; the estimate for such a person should probably be 50 watts for the same kind of power production over an extended period. The graph in Figure 1 shows various record



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FIGURE 1: Human Power Output Pedaling

limits for pedaling under optimum conditions. The meaning of these curves is that any point on a curve indicates the maximum time that the appropriate class of person could maintain the given average power level.

Power levels are also directly related to the environment of the person doing the pedaling. To be able to continue pedaling over an extended period, a person must be able to keep cool--whether because the ambient temperature is low enough, or because there is adequate breeze.

There is a vital difference between pedaling a stationary device and pedaling a bicycle at the same power output. On a bicycle, much of the pedaling energy goes into overcoming wind resistance; this wind resistance, however, provides an important benefit: cooling. Because of the wind, even in hot, humid climates, so long as the bicyclist drinks enough liquids, dehydration and heat stroke are unlikely to occur.

On the other hand, when pedaling a stationary device on a hot or humid day at more than about half the maximum possible power output, there is a considerable danger of the pedaler's collapsing because of an excessive rise in body temperature. Therefore, it is essential that an individual pedaling such a stationary device in hot or humid conditions be provided with shade from the sun, plenty of water, and preferably some sort of fan. A portion of the power that the pedaler is producing can be used to drive this fan; this is an efficient use for the power, since it will help prevent damage to the pedaler's health.

PEDALING RATE

How fast should a person pedal? Human beings are very adaptable and can produce power over a wide range of pedaling speeds. However, people can produce more power--or the same amount of power for a longer time--if they pedal at a certain rate. This rate varies from person to person depending on their physical condition, but for each individual there is a pedaling speed somewhere between straining and flailing that is the most comfortable, and the most efficient in terms of power production. (For centuries, this fact was apparently not recognized. The predominant method of human power production was to strain with maximum strength against a slowly yielding resistance. This is neither comfortable nor efficient. Neither is the opposite extreme of flailing at full speed against a very small resistance.)

A simple rule is that most people engaged in delivering power continuously for an hour or more will be most efficient when pedaling in the range of 50 to 70 revolutions per minute (rpm). See Figure 2. For simplicity's sake, we will use 60 rpm, or one revolution of the pedal cranks per second, as an easy reference value for estimates of the gear ratios required to drive a given load.

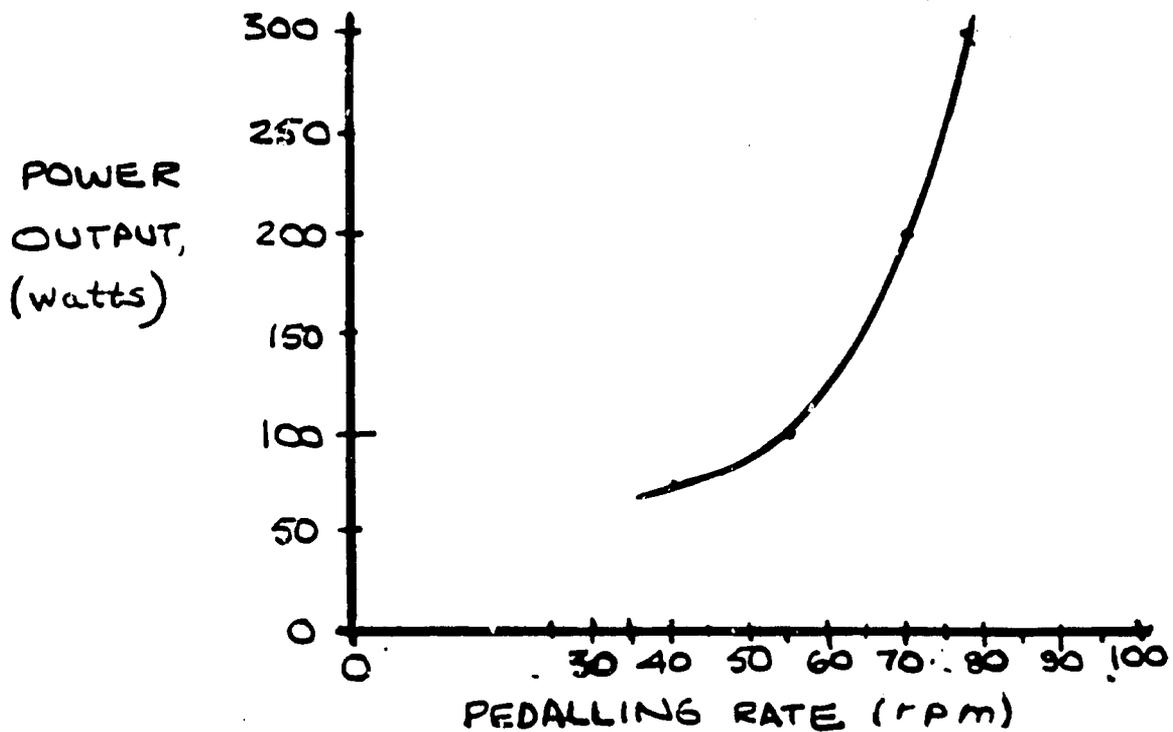


FIGURE 2: How Optimum Pedaling Rate Varies with Desired Power Output

GEAR RATIOS

The relationship between the rotating speed of whatever is being driven and the pedaling rate (both expressed in revolutions per minute) is called the gear ratio. Most practical applications of pedal power will use bicycle-chain drives, which on bicycles range from 1:1 (the rear wheel turns at the same speed as the cranks) to 5:1 (the rear wheel turns at five times the speed of the cranks) for high gears.

Very-Low-Power Applications

There are some very-low-power applications of pedal power, in which the required power output is so far below that of which human beings are capable that maximum efficiency is not a concern. For example, sewing machines are generally limited to a less than optimum value to allow the sewing table to be placed at a convenient height. The pedaler provides a range of sewing speeds without gear-change mechanisms. A large step-up ratio is usually given by a round belt made of leather. It cannot transmit large torques; this inability serves a purpose, because when the sewing needle jams, the belt slips, preventing the needle from breaking.

High-Power Applications

An example of an application at the higher-power end of the scale is a hypothetical maximum-power drive for an irrigation pump. Let us suppose that the pump has the speed-versus-power characteristics shown in Figure 3, and that the pedalers will be paid to produce as much power as they comfortably can for periods of two hours at a time.

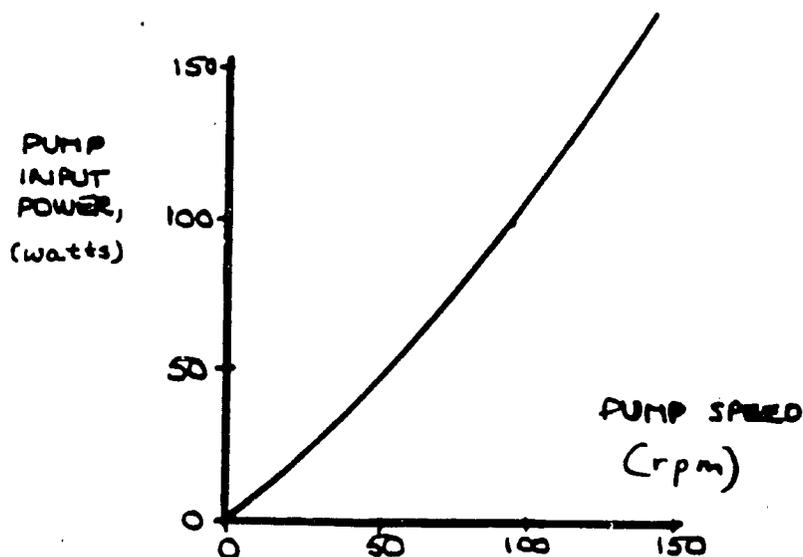


FIGURE 3: Hypothetical Pump Characteristics

Choosing a conservative value from Figure 1, we estimate that a mechanical output of 100 watts seems reasonable for this length of time. Furthermore, we estimate from Figure 2 that the optimum pedaling speed to give this power output is 55 rpm. We can then see from Figure 3 that when the pump absorbs 100 watts, its speed of revolution should be 95 rpm. We need, therefore, a step-up gear of 95:55. We have available a set of bicycle cranks and pedals with a chainwheel having 48 teeth. To achieve our ratio of 95:55, we then need

$$48 \times 55/95 = 27.8 \text{ teeth on the cog (the smaller sprocket attached to the pump shaft).}$$

Ideally then, we should use a sprocket of 28 teeth. However, sprockets of 27, 28, or 29 teeth would be acceptable.

No allowance has been made in this calculation for energy losses in the chain transmission. This is because a single chain going over two sprockets is very efficient--over 95 percent, even for unlubricated, worn, or dirty chains.

However, some applications require two stages of step-up transmission, and in these cases, power losses are greater. For instance, suppose that a ventilation fan must be driven for a long period at 900 rpm, and the optimum pedaling speed is

estimated to be 60 rpm. The step-up ratio is then $900:60 = 15:1$. The smallest sprockets generally available for bicycles have 12 teeth. The chainwheel for a single step-up stage would need:

$$12 \times 15 = 180 \text{ teeth.}$$

Such a chainwheel is not available, but even if one were specially made, it would have a diameter far too large to pedal around. Moreover, using a very large chainwheel with a very small cog produces a small angle of contact (or wrap) around the cog; this causes high tooth wear on the cog.

Therefore, a step-up ratio of 15:1 is better produced by a two-stage step-up gear. For example, a standard high-gear arrangement from a bicycle could be used. It has a chainwheel of 48 teeth driving a cog of 13 teeth, fixed to a second shaft on its own bearings* (for instance, another bicycle crankset with another chainwheel of 48 teeth on the countershaft, driving a cog of 12 teeth on the shaft to be driven. The combination would then be

$$(48/13) \times (48/12) = 14.8.$$

this is close enough to 15:1 to be useful.

In this case, it would be best to assume that there would be a 10 percent loss of power. For example, if the pedaler can produce an output of 50 watts for the desired period, the driven device will receive 45 watts input.

III. DESIGN VARIATIONS

CRANK LENGTH

The crank length is the distance between the center of the pedal-spindle and the crank axis; that is, it is the radius of the circle defined by each pedal as it turns. The normal crank on an adult's bicycle is 165 to 170 millimeters (mm) long. However, people remain able to produce near maximum power output at any crank length from between 165 and 180 mm, so long as they have a period to practice pedalling at the new length.

SHAPE OF CHAINWHEEL

Evidence from tests suggests that elliptical chainwheels with a relatively small degree of elongation--that is, with a ratio of major to minor axis of the chainwheel ellipse of no more than 1.1:1--do allow most pedalers to produce a little more power. No subject tested showed a reduction in power. It is therefore recommended that, when elliptical chainwheels are available at a reasonable price, they be used. However, the gain in power output is small, and this must be considered when comparing costs and benefits.

PEDALING POSITIONS

There are three common pedaling positions:

o The first is the upright position used by the majority of cyclists around the world. In this position, the seat, or saddle, is located slightly behind where it would be if it were a seat, or vertically above the crank axis; the hand grips are placed so that the rider leans forward just slightly when pedaling. Tests have shown that subjects using this position are able to produce the most pedalling power when the top of the saddle is fixed at a distance 1.1 times the leg length to the pedal spindle at the pedal's lowest point.

o The second position is the position used by riders of racing bicycles with dropped handlebars, when they are holding the upper parts of the bars. Their back is then at a forward lean of about 40 degrees from the vertical. Their saddle height requirements are similar to those of cyclists in the first position. (The position of the racing bicyclist who is trying to achieve maximum speed is not suitable for power production on a stationary device. Even racing bicyclists sometimes experience great pain after a long time in this position, and the position is unnecessary on a stationary device because there is no wind resistance to overcome.)

o The third position is the position used in modern semi-recumbent bicycles. The placement of the center of the pedaling circle relative to the seat is shown in Figure 4. In this seating position, the pedaling forces are countered by the lower back

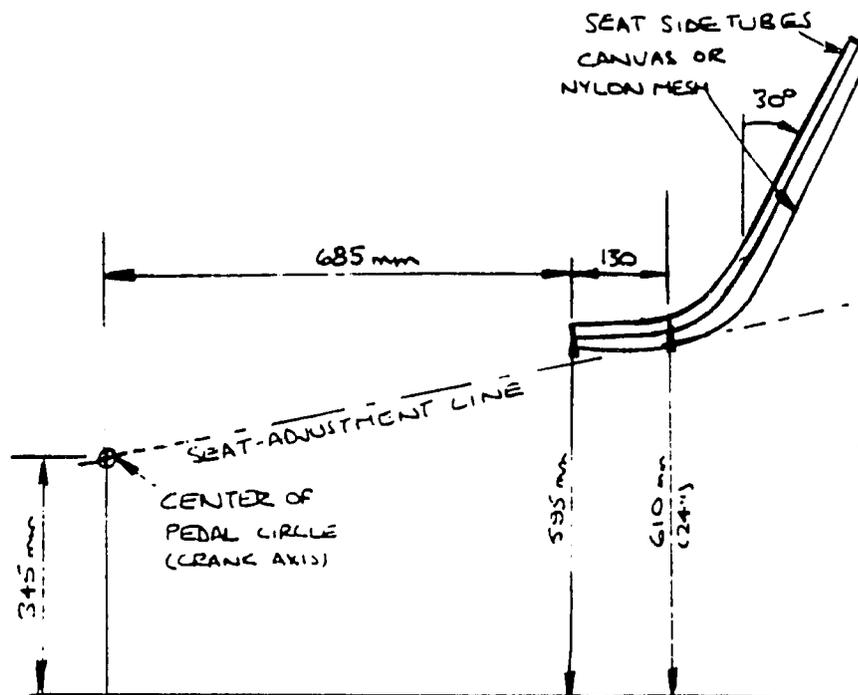


FIGURE 4: Semi-Recumbent Pedaling Position

pushing into the seat (which is similar in construction to a lawn chair made of tubes and canvas). The arms and hands do not need to remain on the handlebars to perform this function, the way they usually do in the first two positions. They can remain relaxed, and free to guide the work that the pedaler is powering. The upper body too can remain relaxed, and the chest is in a position that makes breathing easier than when the pedaler bends forward. The major disadvantage of this position is that, since the pedaler's legs move forward from the body, it may be hard to position large, deep equipment like a lathe or saw so that it is in reach without being in the way. In almost all other respects, the semi-recumbent position is highly desirable, though not essential.

IV. APPLICATIONS OF PEDAL POWER

PEDAL POWER FOR TRANSPORTATION

The principal use of pedal power around the world is for the transportation of people and goods. A bicycle used by itself can carry a rider, plus 50 to 100 kilograms of goods in a front and/or rear carrier, on the cross-bar, or on the rider's head. The carrying capacity of a bicycle can be greatly increased by attaching a trailer to it. One model of trailer has seats for two adults, and allows the bicycle to be easily converted into a rickshaw.

A rickshaw is usually made from the front or rear portion of a standard bicycle, connected to a load-carrying platform over a two-wheel axle. Rickshaws can carry an extraordinary quantity of people and goods. In Bangladesh, they are responsible for transporting several times the total freight and passengers carried by all railroads, trucks, and buses combined.

However, the potential productivity of these rickshaws is greatly reduced by the fact that virtually every one of them has only a single-speed gear. Sometimes the gear mechanism is even deliberately converted to single speed. When the author lived in Nigeria, the most common bicycle was a Raleigh Roadster, which came equipped with a three-speed gear, but the retailers normally wired the gear-change lever in the low-gear position. A driver who has only one gear available must exert much more effort to pedal the rickshaw. The strain is severe and unnecessary, and productivity is greatly reduced.

OXFAM, an international development and relief organization, has done considerable work on a three-wheeled pedal operated vehicle capable of carrying payloads of over 150 kilograms. Called an "Oxtrike," the vehicle uses a three-speed gearbox in its transmission and a mild steel sheet frame. The frame can be manufactured on a small scale, using foot-powered cutters, hand operated folding machines, and welding or riveting. It can be fitted with passenger seats or a cargo box.

It should be noted that an ordinary bicycle frame is not sturdy enough for payloads of this size. The weight also requires particularly good brakes. The Oxtrike's mild steel construction addresses the first problem. The braking system includes both the standard lever brakes on the front and a foot pedal on the rear. Each wheel has its own brake drum, with a balance bar to distribute the force equally.

OTHER USES OF PEDAL POWER

General Considerations

Broadly speaking, applications of pedal power are possible when the power level required is below a quarter of a horsepower (that is, below about 200 watts). Common applications of stationary pedal power include pumping water, grinding grains or metals, shredding, or threshing.

Pedal power can also be used to generate electricity for individual uses--to operate room lights, a television set, or a projector, for example. Surplus power could be diverted to a battery-charging circuit. The easiest way to do this is simply to drive either a DC generator or an AC alternator through a circuit feeding a battery in parallel with the load. The same circuit could be used for an alternator of higher power, chain-driven from the cranks, through an appropriate gear ratio.

Other pedal power applications include:

- o Cassava graters
- o Coffee pulpers
- o Coffee/grain hullers
- o Cracking of oil palm nuts
- o Fiber decorticaters--sisal, manila, hemp, etc.
- o Winches or hoists
- o Balers
- o Potter's wheels
- o Flexible shaft drive for portable grinders, saws, etc.
- o Tire pumps
- o Sewing machines

The use of pedal power for agricultural implements that have to move across soft or uneven ground is not recommended. A mower described and illustrated in Bicycling Science (see Bibliography) required so much energy to move the mower across the ground that a small proportion of the rider's total energy went into mowing. This loss of energy would occur for any use--like plowing, cultivating, or harrowing--in which the vehicle had to move across the ground. McCullagh's Pedal Power describes some designs in which the pedaling unit is stationary at one edge of the plot, while the plow or other implement, guided by a second worker, is pulled by a rope or chain. This principle should be tried out further.

The Dynapod

Bicycles can sometimes be adapted to drive the devices mentioned above, but the result is often inefficient. It is frequently cheaper in initial and maintenance costs to use a properly designed and constructed dynapod.

A dynapod is a portable pedaling device that consists of a stand, saddle, handlebar, pedals, and sprocket wheel. The name comes from the Greek words for "power" and "foot." Dynapod power varies according to the size and fitness of the operator and the length of time spent pedaling.

There are three kinds of dynapods: 1) A one-person dynapod that utilizes belt drive. It can be built either with or without chaindrive. 2) A two-person dynapod that can be pedaled either by one person at a time, or by two people together. It is also possible to fit a special adaptor so that a direct shaft drive leads off the unit and powers a flour mill or other machine. (When this is done, only one person can pedal at a time.) 3) A one-person dynapod that has belt drive, chain drive, and direct drive. It is very similar to the two-person dynapod.

The two-person dynapod illustrated below (Figure 5) has been attached to a grain mill, but the unit can be adapted to a wide

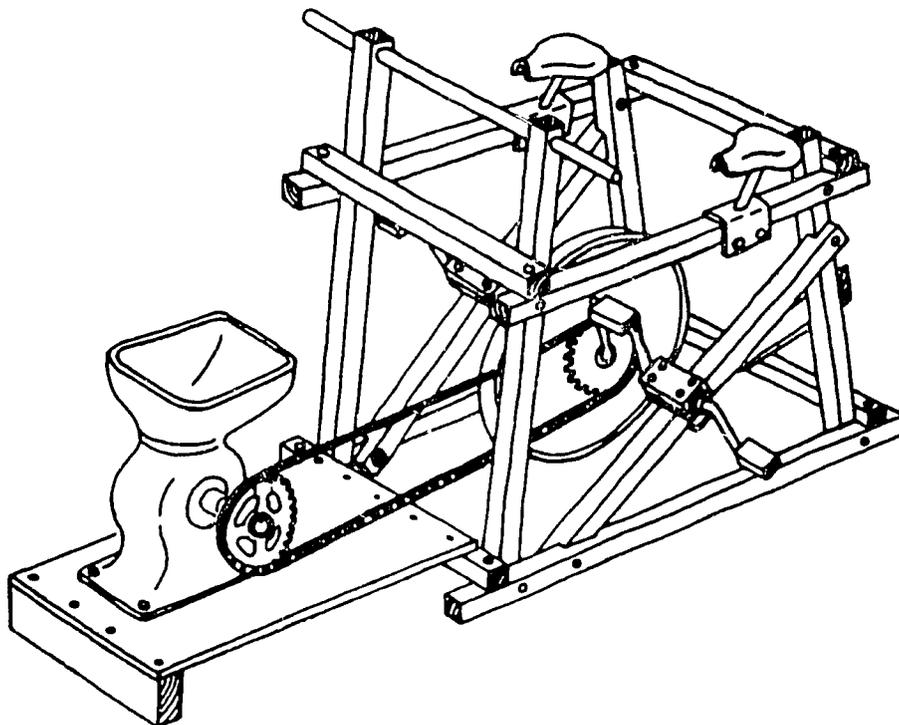


FIGURE 5: Two-person Dynapod with Chaindrive Operating a Grain Mill. Chainwheel is shown on left-hand side for illustration only.

variety of uses. The dynapod frame can be made of wood or welded steel, depending on cost and availability of materials. A heavily weighted flywheel provides extra power and smoothes out the pedal stroke, reducing operator fatigue.

A similar device, designed to draw irrigation water from shallow wells in Bangladesh, consists of a welded steel frame with a drive wheel attached to the plunger of a handpump (Figure 6).

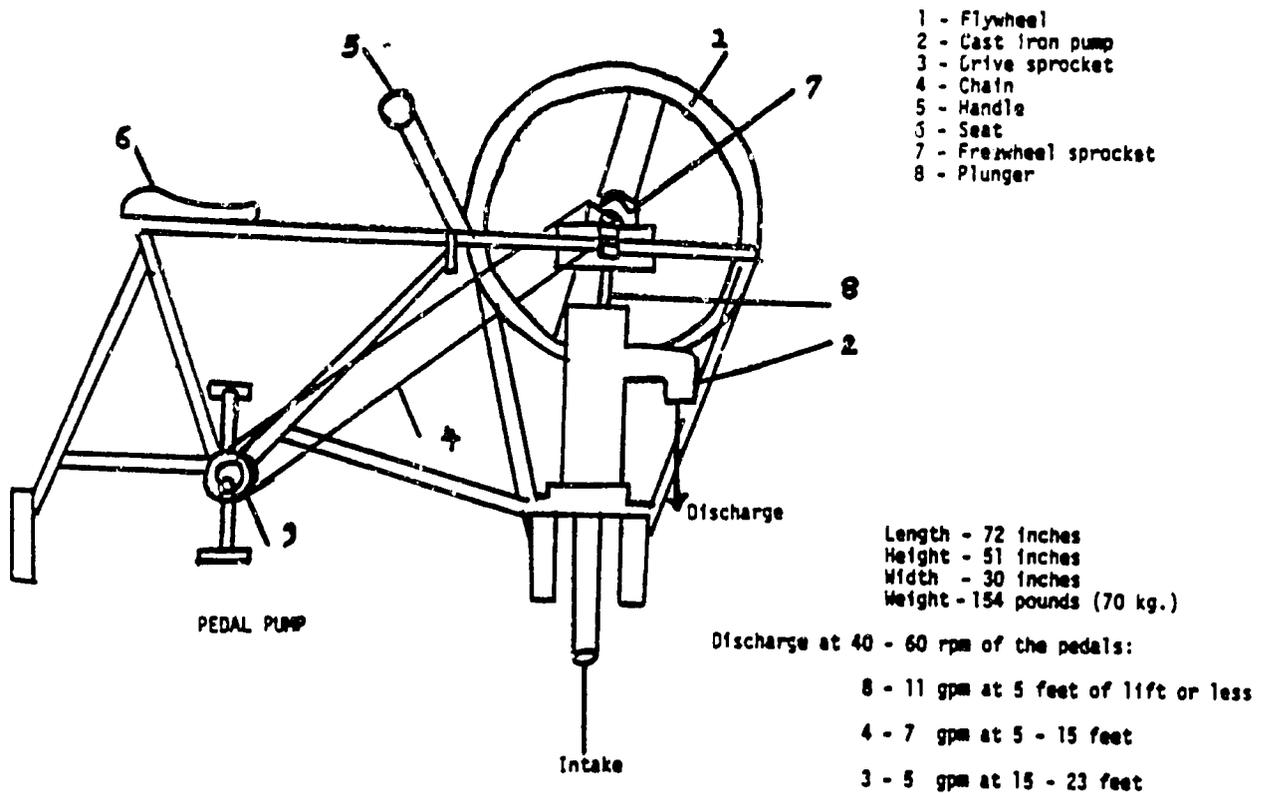


FIGURE 6: Pedal Powered Irrigation Pump

V. COMPARING THE ALTERNATIVES AND CHOOSING THE APPROPRIATE TECHNOLOGY

Whether or not pedal power is advantageous for an application depends absolutely on local conditions. In many countries, gasoline (petrol) is highly subsidized; one consequence is that pedaled rickshaws, for example, are giving way to ones run by small internal combustion engines. However, in locations far from reliable fuel supplies and maintenance shops, internal combustion engines are not so attractive an alternative, and pedal-powered devices may be much more suitable.

Pedal power is often a comfortable choice because it is a familiar technology--even though it may be used in unfamiliar

ways. Construction and maintenance skills are generally available among village artisans, as are spare parts from used bicycles.

Depending on the application, pedal power can be extremely versatile. A dynapod can operate a pump during the growing season, run a thresher at harvest time, and power a grain mill throughout the year. Its portability allows it to be moved from site to site to go where the work is.

Choice of pedal power--or any technology--must be made by carefully comparing the alternatives for the application desired and the availability of resources--construction and maintenance skills, financing, raw materials, labor. Whether machines are made locally or purchased from nearby factories or even importers, they should be within the capability of local people to maintain and repair in order to avoid so far as possible lengthy periods when they are out of service.

At this level especially, pedal power often compares favorably with wind or water power. A windmill, for example, often requires considerably more resources in funds and construction time and skill than does a pedal-power unit based on a bicycle. Windmills within the capability of a local village builder will generally be limited to a size giving an average output of 50 to 100 watts (though the maximum output may be 1 kilowatt). Windmills are more subject to the vagaries of the weather. While energy storage can help minimize the effect of variations in the wind, high winds and other kinds of severe weather often cause minor damage, and occasionally cause major damage.

Windmills in this range are probably best suited to charging batteries and to pumping water for irrigation, stock watering, or potable water supply. But even for these purposes, a pedaled pump might be preferable. It was found by the author's VITA group, for instance, that the output of a Savonius-rotor windmill in average Boston area winds was so small--even when the windmill was mounted on a headland overlooking the sea--that the windmill's output could be exceeded by a pedal-power unit operated for only two to four hours per week.

A pedaled pump may have several advantages if a farmer wishes to irrigate field crops: it is often less expensive to build; it can supply water at the most suitable times of the day and of the crop growth cycle; and it can be used at more than one location and possibly for more than one purpose.

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