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BICYCLE CRANK LENGTH AND LOAD --- EFFECT
UPON OPERATOR ENERGY EXPENDITURE

by

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Approved by:


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INTRODUCTION

Few roles remain in our technological society where man still functions as a source of mechanical power. One machine which has survived and which depends upon man as a controlled power source is the bicycle. Not only has the bicycle survived, but it has also increased in importance as a practical mode of personal transportation. This is exemplified by the increased world production of bicycles. Between 35 and 40 million bicycles are currently manufactured each year, with the United States and China accounting for about six and five million each, respectively (Wilson, 1973). Of this total world production, approximately 16 million bicycles were sold in the United States in 1973. This is about five million more than the number of motor vehicles sold (Fee, 1974). In most of the world, the bicycle plays a far more significant role in the field of transportation than does the automobile.

The reasons for this continued interest in the bicycle lie in the fact that it possesses many advantages over other forms of transportation. These advantages include its small demand for energy and material resources, its almost negligible pollution effects, its reliability, its small space requirements, and its positive contribution to health.

As with other man-machine relationships, the bicycle should be designed to fit the characteristics and capabilities of the operator. Only when the bicycle is designed and adjusted to fit the individual operator can maximum comfort, efficiency, and performance be achieved.

Design and Adjustment

The bicycle is designed both structurally and mechanically to take

advantage of the characteristics and capabilities of the human operator. Power is transmitted effectively by the bicycle's simple mechanical system. The gearing system permits rapid shifting so that maximum benefit can be derived from the kinetic energy of the rotating legs. The rolling resistance is minimized by the use of large diameter, narrow wheels and high pressure pneumatic tires. A reduced weight is achieved through the use of wire-spoke wheels and tubular frame construction.

These design features are such that they are effective for all bicycles irrespective of the physical characteristics of the individual operator. It is at the points where the operator makes contact with the bicycle that allowances for individual differences must be considered. These three points are the handlebars, saddle, and pedals.

Handlebar adjustment. Because the most significant source of energy loss on a bicycle is due to the wind resistance offered by the operator, DeLong (1965) recommends a more efficient posture where the rider leans forward with the back at a 45 degree angle. In this position, the back muscles receive assistance from the arm and hand muscles in supporting the trunk of the body. He also advises that the hand grips should be angled up at about ten degrees. Sloane (1970) and Baranet (1973) recommend that the top bar of the handlebars be level with the nose of the saddle.

It should be pointed out that all of the above handlebar adjustment recommendations are based on the authors' personal opinions and not from empirical studies.

Saddle adjustment. The saddle allows the operator to sit on the

bicycle, relieving the leg muscles of their supporting function and resulting energy consumption. In adjusting the saddle, Baranet (1973) suggests that the saddle should be horizontal or with a slight upward tilt at the nose to prevent the body weight from sliding forward.

There have been various studies to determine the optimal seat height, and most of them conclude with similar recommendations. Hertzberg (1972) says that the line from the pedal crank axis to the center of the saddle should be inclined 20 to 30 degrees behind vertical. He also recommends that the distance between the saddle and pedals should be such that the operator must fully extend his legs in order to touch his heels on the pedals in their furthest positions.

An experiment by Thomas (1967) showed that the most efficient saddle height is 109% of the inside leg length (from the pubic symphysis palpation bone in the crotch to the bottom of the heel). He also found that changes in saddle height of 4% of inside leg length affected power output by approximately 5%. His experimental design was one of a short duration, maximal power test with all variables, except the saddle height, standardized or accounted for in the statistical analysis. The subjects were timed in performing a heavy work load of 500 kg/min on a bicycle ergometer at four different saddle heights. These saddle heights were 105%, 109%, 113%, and 117% of the subjects' crotch height.

Both of the above saddle height adjustment criteria allow the leg to approach the fully extended position during the pedaling cycle. It is known that as leg muscles approach their fully extended position, they are capable of exerting more power. However, any complete straightening of the leg would interfere with the smooth, continuous rotary motion of

the leg.

The amount of angular movement made by the thigh is a closely related factor which is also affected by the saddle height. Because muscles have optimum strength ranges for particular movements, a change in saddle height would cause a change in the angular movement of the thigh which would affect the operating efficiency. This angular movement of the thigh will also be a consideration in the adjustment of pedal crank length which is presented in the next section.

Pedal Cranks. The angular movement of the operator's foot and leg is determined in part by the length of the bicycle pedal cranks. That is, the angular distance moved by the foot and leg is less for a shorter crank than for a longer crank for each revolution of the crankshaft. However, because of the smaller distance moved with the shorter lever arm (crank), the operator has to exert more force on the pedal to produce the same amount of work (assuming a constant load). Consequently, the energy expenditure of the operator is dependent upon the pedal crank length under constant cadence and load conditions.

The optimum crank length, therefore, is the length at which the combination of angular leg movement and applied force minimizes the energy expenditure of the operator. For this reason, the length of the bicycle pedal crank is a critical factor in designing and adjusting the bicycle for maximum efficiency.

A standard crank length found on bicycles is about 17.1 centimeters. In studies where bicycle ergometers are used, the length of the cranks is typically held constant from one subject to another. This means that a small subject has to work through a different range of motion than a

large subject. For this reason, it is difficult to make between - subject comparisons.

Hertzberg (1972) indicates that one standard crank length is not acceptable by recommending crank lengths ranging from 17.8 to 22.9 centimeters, depending on the body dimensions of the operator. Using the anthropometric data provided by Woodson and Conover (1960), these crank lengths correspond to percentages of crotch height of 23.4% to 25.0% for 5th percentile to 95th percentile males. Unfortunately, Hertzberg did not specify which body dimensions were relevant or how to determine what crank length to use.

Ellis (1968) recognized this problem when he emphasized that by standardizing the crank length and having different subjects with varying physical characteristics using it, the efficiency of the system is changed. This occurs because the leverage systems of the responding parts and those supporting them are varied. Morehouse and Miller (1948) concur with this conclusion when they state that the mechanical efficiency of muscular movements is affected by the length of the power arm, the length of the weight arm, the angle of the pull by the muscle as affected by the attachment to the lever, and the action of synergic and antagonistic muscles. For these reasons, subjects of different physical dimensions will work through different ranges of motion and may be forced to use different musculature. A study by Rasch and Pierson (1960) also demonstrated that the force developed in any segment of the body is a function of the segment's position relative to those to which it is connected.

There have been no studies conducted to determine what the optimum crank length should be in relation to the physical characteristics of the

individual. There have been, however, various experiments to determine the effect of variations in knee angle upon static leg strength. Two of the earlier studies (Carpenter, 1938; Clarke, Elkins, Martin, and Wakin, 1950) found that the greatest strength occurs within the range of knee angles from 105 to 124 degrees. The measurements were made from the trochanter (connection between femur and hip) to the point on the outside of the middle of the knee opposite the head of the tibia, and from that point to the outer malleolus (connection between tibia and foot at the ankle).

Woodson (1960) recommends that for an action which requires maximum strength, the angle at the knee would be about 120 degrees. A more recent study by Linford and Rarick (1968) found that static leg strength is the greatest and remains about the same when the knee is bent at an angle between 130 and 164 degrees, but as the angle decreases beyond 130 degrees, strength decreases. They measured the angular position of the knee with a goniometer at the moment of the maximum recorded score.

None of the above studies, however, were conducted on a bicycle ergometer using rotary, continuous motions. All of these studies were conducted under static conditions. They were also tested at short duration, maximal loads rather than at sustained, submaximal loads. The body position was also much different than that of a bicycle operator. In these studies, the subject was tested either doing an inverted leg press or pushing against a load with his feet while sitting on a chair (back supported). It is probable that any one or a combination of these variables could change the efficiency of the various knee angles found in these studies.

Load and Cadence

There have been several studies conducted to determine the loads, cadences, and power outputs that man can perform under various conditions. The power which a muscle system delivers to an external load is dependent upon the speed at which the load is moved and on its size. With a high velocity of muscle shortening the available force is small, although the maintenance heat of contraction is also small. When a muscle moves slowly, the force is large but the maintenance heat of contraction is also large. Intermediate velocities of contraction will give maximum efficiency (Falls, 1968).

In order to achieve an optimal chemical to mechanical energy conversion efficiency which Hill (1939) found to be from 20% to 25%, the force and speed of movement must be appropriately matched to one another. Therefore, because there is an optimal speed of execution for which the energy expenditure is minimum, the cadence at which the subject operates clearly influences the muscle efficiency.

Load. Astrand, Hallback, Hedman, and Saltin (1963) found that an untrained subject cannot perform at more than about 50% of his maximal oxygen uptake during one hour of continuous work. In a later study, Astrand and Rodahl (1970) found that loads of 1.43 kcal/min (100 watts) for female subjects and 2.15 kcal/min (150 watts) for male subjects were suitable for short duration work tests. Mueller (1939) found that healthy men using rotary pedals can easily achieve approximately .86 kcal/min (60 watts) over many hours, or 1.43 kcal/min (100 watts) for about half an hour.

Cadence. Sloane (1970) and Henkel (1972) found that a cadence of 65 to 85 crank revolutions per minute was a pace that could be maintained comfortably over a long time period. These were personal opinions rather than the results of empirical studies. A lower cadence of 60 crank revolutions per minute was found by Astrand and Rodahl (1970) to be suitable for long pedaling periods.

Hill (1922) found that the time occupied in the most efficient muscle contraction is about one second. This would correspond to a pedaling cadence of 60 revolutions per minute.

PROBLEM

As was indicated in the introduction, there has been little research done concerning the relationship between the pedal crank length and the anthropometric characteristics of the operator. Because this is a crucial consideration in designing and adjusting the bicycle for the most efficient operation in terms of energy expenditure, it was felt that a study in this area would be beneficial.

Specifically, the hypotheses were:

1. There is a crank length which is a direct proportion of the operator's crotch height which causes the least energy to be expended by the operator.
2. The crank length which causes the least energy to be expended by the operator is dependent on the load.

METHODS

Equipment and Measurement Techniques

Ergometer. A bicycle ergometer (Monark, Sweden) was used to simulate a bicycle in this study (Figure 1). The resistive load was adjustable by turning a handwheel which increased or decreased the tension in the friction belt. The load was read from a pendulum scale which the wheel was controlling. The gearing and circumference of the wheel were so dimensioned that one revolution of the pedals moved a point on the rim of the wheel six meters. By recording the distance pedaled per minute, the mechanical energy produced could be calculated. A metronome was used to allow the subject to pedal at the correct cadence.

A new crankshaft and variable length cranks were fabricated and installed on the ergometer (Figure 2). These cranks could be adjusted from 11.5 to 24.0 centimeters in length. They consisted of threaded metal rods attached to the crankshaft. Onto each of these rods could be threaded two different length tapped pipes equipped with pedals.

Spirometer. A Collins respirometer (spirometer) was used to measure the oxygen consumption of the subjects. This is a device in which the quantity of oxygen consumed from a tank of oxygen is directly recorded. When using a spirometer to measure energy expenditure, it is usually assumed (Grollman, 1969) that 4.825 kcal are liberated for each liter of oxygen consumed.

Heart Rate Monitors. Heart rate sensors were taped to the subjects' chests and then monitored by a Beckman Dynograph direct writing recorder.

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Figure 1. Photograph of the bicycle ergometer.

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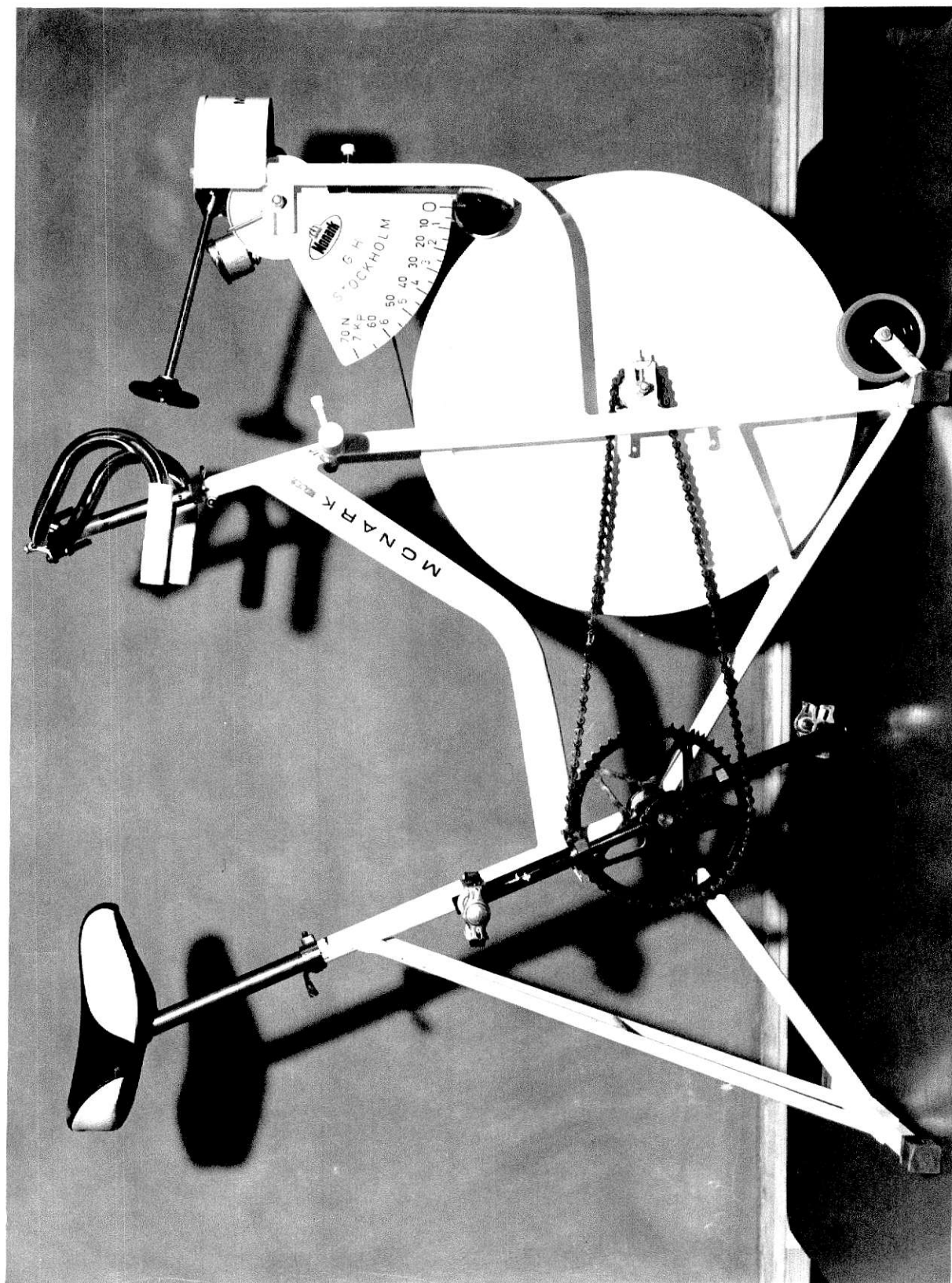
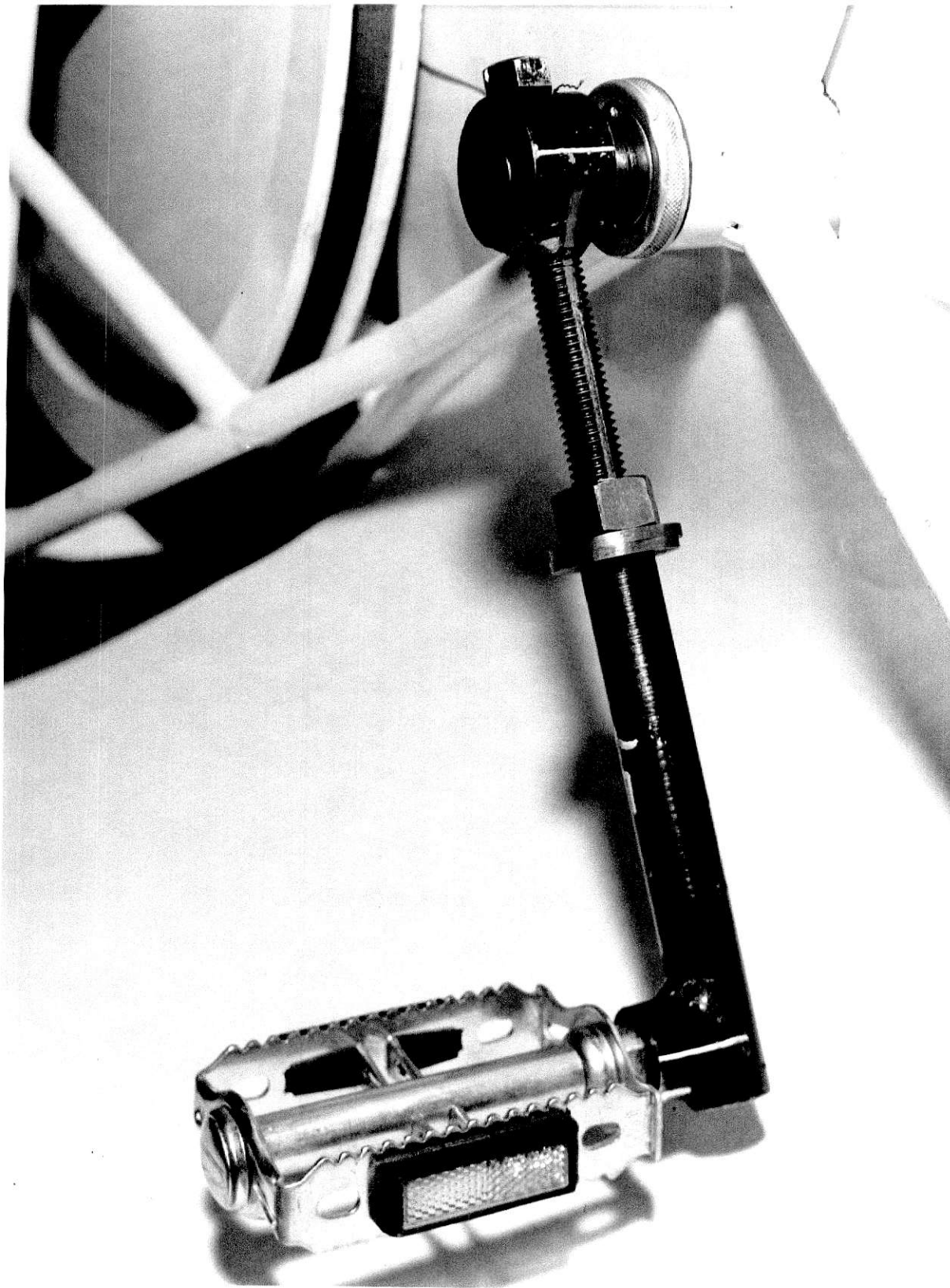


Figure 2. Photograph of the modified crank system.



Dependent Variables

Since the work levels used in this study were submaximal, the work time needed to be about six minutes in length so that respiration and circulation would have time to adapt. That is, after about five minutes, a steady state occurs in the heart rate and pulmonary ventilation functions.

Oxygen consumption. In a study by Consolazio, Johnson, and Pecora (1963), the quantity and rate of chemical energy utilized in the body was related reliably to the quantities and rates of oxygen consumed. Therefore, the quantity of oxygen consumed can be used to express the total chemical energy converted over a period of time. Astrand, et al. (1963) found that for every liter of oxygen consumed in combustion, 4.7 to 5.05 kcal are liberated.

The use of oxygen consumption as a criterion for measuring energy expenditure was judged to be readily applicable to this experiment. The reason for this is that large muscle groups must be employed if a work test is centered on an analysis of the oxygen consumption, and, in this case, the muscle mass of the legs is more than enough to utilize all of the oxygen that can be absorbed by the blood stream.

Furthermore, since the subject must be physically attached to the equipment by an oxygen hose and mouthpiece, his movement is necessarily restricted. The subject in this experiment would not normally move his head to any great extent, and, for this reason, this restriction was not a disadvantage here.

Gross heart rate. As mentioned earlier, forces produced in the muscles during exertion can be either transferred to the surroundings by the

skeletal system or they can be reacted against within the body, as in an isometric contraction or static effort (maintenance of tension). In both situations, force is produced when chemical energy is expended, but in the latter case no work is done on either the surroundings or the body because a displacement is not produced by the force. In bicycle riding there is probably a considerable amount of static effort.

Static muscular loading affects the oxygen consumption of an individual to a much lesser degree than it affects the heart rate of an individual. For this reason, it was thought that oxygen consumption and gross heart rate measurements taken at the same time during the work task could give a good insight into the influence of the static loading on the subject.

Incremental heart rate. Because the maximal heart rate not only varies with age but also within the same age group, incremental measurements of heart rate should be taken. Incremental heart rate is the heart rate above the basal or resting heart rate, that is, gross heart rate minus basal heart rate. This heart rate is a direct result of the physical activity of the person and, therefore, is a measure which filters out most of the effects due to the different characteristics of the subjects. In one study (Andrews, 1967) it was found that the large variations in the magnitude of error due to individual differences found in heart rate data could be reduced to statistical insignificance by using incremental measures of heart rate.

Rating of perceived exertion. At the completion of each experimental

condition, the subject was asked to rate his perceived exertion according to the following RPE Scale (rating of perceived exertion) which was developed by Borg (1962):

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

The instructions used by the subject for this rating are shown in Table 1. The values of the RPE Scale were selected to be as close as possible to one-tenth of the corresponding heart rate. Several studies (Borg, 1962; Borg and Linderholm, 1967; Skinner, Borg, and Buskirk, 1970) have obtained high correlations between ratings and heart rate. There appears to be a fairly linear relation between RPE and heart rate. The purpose of this investigation is to study the relation between perceived

TABLE 1

Instructions for Rating Perceived Exertion

At the end of each six minute pedaling task, you are to rate your perceived exertion on the basis of how hard the work "felt". Do not pay attention to any particular or local feeling of exertion. Make the rating by quoting a number from the following RPE Scale.

- 6
- 7 Very, very light
- 8
- 9 Very light
- 10
- 11 Fairly light
- 12
- 13 Somewhat hard
- 14
- 15 Hard
- 16
- 17 Very hard
- 18
- 19 Very, very hard
- 20

Record this number below:

Subject Number _____

Task One _____

Task Two _____

Task Three _____

Task Four _____

Task Five _____

Task Six _____

exertion and heart rate in physical work where the same muscle groups in different motions are involved.

Independent Variables

Load. Two work loads which would simulate actual conditions encountered in bicycle riding were used for this study. The lighter load represented a condition found when riding a bicycle on level ground with no head wind. The heavier load represented a condition found when riding a bicycle up a hill or against a head wind.

For the purposes of this study, it was also desirable to select two loads which would cause the heart rate to be at least 100 and not more than 150 beats per minute. This requirement was necessary because a work load that was too light would have allowed extraneous factors to influence the pulse reaction. A work load that was too heavy would have implied a certain risk to the subject. A study by Simonson (1971) concluded that under carefully standardized conditions, the relationship between heart rate and oxygen uptake in normally active young men is linear up to about 70% of maximal oxygen uptake for most individuals.

In a study by Gamberale (1972) using a bicycle ergometer, work loads of .72 kcal/min (50 watts) and 1.43 kcal/min (100 watts) produced heart rates of 104 and 130 heart beats per minute, respectively. A pilot study by Gross (1974) found that a load of 1.72 kcal/min (120 watts) was sufficient to produce a heart rate in the upper region of the desired range. The cadence used was 60 crank revolutions per minute.

In this study, loads of .86 kcal/min (60 watts) and 1.50 kcal/min

(105 watts) were used. These loads not only produced heart rates in the desired range, but also represented the loads that would be encountered during actual bicycle pedaling. The cadence was 60 crank revolutions per minute.

Crank length. The crank lengths used in the study were predetermined proportions of the crotch heights of the subjects. The range of crank length adjustments available limited these proportions to an approximate range of .15 to .26. These proportions are based on the 5th percentile to the 95th percentile of crotch heights (Woodson and Conover, 1960).

Gross (1974) found that the optimal proportion lies between .17 and .23 for a load of 1.72 kcal/min.

The three proportions investigated in the present study were .17, .20, and .23.

Subjects

An incidental sample of ten male subjects, age 21 to 31, was selected from graduate and undergraduate students at Kansas State University. The subject data can be seen in Table 2. Each subject was tested individually, and each received \$3.00 for his participation of about one and one-half hour.

Astrand and Rodahl (1970) found that, at a given submaximal load, bicycling demands about the same energy output regardless of the subject's age, training, or physical condition. No special precautions were taken, therefore, to select any particular type of subject.

TABLE 2

Subject Data

Subject	Age (yrs)	Weight (kg)	Height (cm)	Crotch Height (cm)	Knee Height (cm)
1	25	102	185	87	53
2	26	101	193	93	58
3	22	68	178	87	51
4	31	59	170	81	49
5	25	59	168	79	49
6	23	77	183	90	51
7	28	87	179	89	54
8	23	78	183	87	46
9	22	79	183	88	52
10	21	60	168	78	45
Mean	24.6	77.0	179.0	85.9	50.8

Procedure

The study consisted of ten experimental sessions each of which was 90 minutes in length. The sessions were composed of six rest periods and six experimental trials. Each of the experimental sessions was the same for each subject, except that the experimental treatments were presented to each subject in a different random order.

The subjects were instructed not to engage in energetic bodily activity during the hours preceding the test, not to eat for at least one hour before the test, and not to smoke for at least 30 minutes prior to the test. The purpose of these instructions was to reduce the influence these factors would have on the subjects' heart rates. A sample pretest instruction sheet is shown in Table 3. The subjects were also required to read and sign the Written Informed Consent form shown in Table 4.

Upon the subject's arrival in the laboratory, several anthropometric measures were taken. These included the subject's height, weight, crotch height (measured from the pubic symphysis palpation bone in the crotch to the bottom of the foot), and crotch to knee distance (measured to the head of the tibia on the knee). His age and bicycling experience were also recorded. A sample subject information sheet is shown in Table 5.

The subject was then seated and connected to the heart rate sensors. At this time, his basal heart rate was taken. It was taken at that time to avoid the effect of the subjects' anticipatory heart rate increase. He was then instructed to read the task instructions (Table 6) and to ask any questions he may have concerning the experiment. While the subject was reading the instructions, the first experimental condition was prepared.

TABLE 3

Preliminary Instruction Sheet

Your heart rate is influenced by many factors. Bodily activity, food ingestion, and smoking are three of the most significant. Because heart rate is one of the dependent variables in this experiment, these factors must be controlled as much as possible.

Therefore, please observe the following instructions:

1. Do not engage in energetic bodily activity during the hours preceding the test.
2. Do not eat for at least one hour before the test.
3. Do not smoke for at least 30 minutes prior to the test.

Also, please read and sign the Written Informed Consent form accompanying this preliminary instruction sheet. Have it with you when you arrive for the experiment.

TABLE 4

Written Informed Consent

The experiment involves pedaling a bicycle ergometer at light to moderate work loads for six minute intervals which are followed by five minute rest periods. The experiment will last approximately 1.50 hours. You may become tired during the experiment but you should not become fatigued or exhausted.

You will be connected to heart rate monitoring equipment by means of sensors taped to your chest. You will also breathe oxygen through a metabolic tube for the last two minutes of each pedaling interval. There will be no new experimental procedures used in this study.

If at any time during the research you feel that you cannot go on, you are free to quit. Naturally, I hope you will feel that you can continue to completion. Feel free to ask any questions you may have concerning the procedures of the experiment.

The purpose of this experiment is to determine the effect of changing the crank lengths on the performance and comfort of the individual rider. At your request, I will provide you with feedback on the nature of the research results if you desire.

I have read and understand the above information. I agree to voluntarily participate as a subject in the experiment.

signature

TABLE 5

Information Sheet

Subject Name (Print) _____

Age _____

Weight _____

Height _____

Crotch Height _____

Crotch to Knee Distance _____

Bicycling Experience:

- 1) Do you own a bicycle now? _____
 - a) If yes, how long have you owned it? _____
 - b) If yes, how many hours per month do you ride it? _____
- 2) If you do not own a bicycle now, have you ever owned a bicycle? _____
 - a) If yes, how long has it been since you owned it? _____
 - b) If yes, how many hours per month did you ride it? _____

TABLE 6

Task Instructions

This experiment will last approximately 90 minutes. You will perform six pedaling tasks under various conditions of crank length. At the end of each of these six minute tasks, you will be allowed to rest while the ergometer is readied for the next condition.

You will be required to pedal the ergometer at a cadence of 60 crank revolutions per minute throughout all six conditions. A metronome will provide this cadence for you. You will be given a two minute orientation to timed cycling before the experiment begins.

At a point four minutes through each task, the oxygen tube mouthpiece will be placed in your mouth in order to record the amount of oxygen you consume during the task. The mouthpiece fits inside your mouth between your lips and your teeth. You will be given the opportunity to practice putting it in your mouth before the experiment begins. It is also necessary that you wear a nose clamp during the task.

You will be wearing the heart rate sensors throughout the experiment. Be careful not to pull them loose. If you think that one has come loose, let the experimenter know immediately.

At the end of each six minute task, the experimenter will signal you to stop pedaling. You will now be asked to rate the task according to your perceived exertion. Separate instructions will be provided before you make this rating.

If you have any questions concerning the experiment, please ask them at this time.

Using the crotch height measurement, the three crank lengths and saddle height to be used were calculated. The crank lengths were specified proportions of the crotch height, and the saddle height was 109% of the crotch height. The top of the handlebars were set at the same height as the top of the saddle. This information was recorded on a subject data form (Table 7).

After this, the subject was instructed to sit on the ergometer while his knee angle was measured when the pedal was in the top position, crank in line with the seat tube. The angle was measured with a protractor between the malleolus bone on the ankle, the head of the tibia on the knee, and the middle of the thigh. This is the same method used by Lindeburg (1964) in his study of leg angles and leg strength. These angles were then recorded on the subject's data sheet. These angles were measured for each of the three crank lengths used for each subject. In order to give the subject an orientation to timed cycling, he was instructed to pedal in time with the metronome for two minutes. He was also instructed to place the mouthpiece in his mouth to give him practice in this. After resting for two minutes, the subject was ready to begin the first task condition. He was fitted with a nose clamp and told to begin.

After four minutes of pedaling, the mouthpiece from the spirometer was placed in the subject's mouth and his oxygen consumption was measured and recorded for two minutes. His heart rate was monitored during the last minute of the task with the strip recorder. Figure 3 shows the subject on the ergometer during an experimental task.

The subject was then allowed to rest for five minutes while the apparatus was made ready for the next condition.

TABLE 7

Subject Data Form

Subject Number _____

Crotch Height _____ cm.

Proportions used _____

Crank Lengths _____

Saddle Height _____ cm.

Basal Heart Rate _____ beats/minute

Loads _____

Knee Angles (for shortest to longest crank lengths, respectively)

Pedal in top Position _____

Sequence of Treatments

	<u>Proportion</u>	<u>Crank Length</u>	<u>Load</u>
1)	_____	_____	_____
2)	_____	_____	_____
3)	_____	_____	_____
4)	_____	_____	_____
5)	_____	_____	_____
6)	_____	_____	_____

Barometric Pressure _____

Temperature _____

Figure 3. Photograph of a subject performing the experimental task.



Statistical Design

A completely randomized, 3 (Crank lengths) by 2 (Loads) by 10 (Subjects) factorial classification Model I design was used in this study. The following is the mathematical model and description of the terms:

$$Y = \mu + S(I) + L(J) + C(K) + SL(IJ) + LC(JK) + SC(IK) + \epsilon(IJKL) \quad (1)$$

$$I = 1 \dots 10$$

$$J = 1, 2$$

$$K = 1, 2, 3$$

μ	=	average effect in the absence of any treatment effects
$S(I)$	=	subject effect
$L(J)$	=	load effect
$C(K)$	=	crank length effect
$SL(IJ)$	=	interaction effects of subjects and loads
$LC(JK)$	=	interaction effects of loads and crank lengths
$SC(IK)$	=	interaction effects of subjects and crank lengths
$\epsilon(IJKL)$	=	error

The assumption was that the $\epsilon(IJKL)$ was NID $(0, \sigma^2)$, i.e., the errors were normally and independently distributed with homogenous variance over subjects and treatments.

The mathematical model shows that any observed value (Y) is the sum of four parts: an overall mean (μ), main effects, interaction effects, and a random element from a normally distributed population with mean zero and standard deviation σ .

RESULTS

Data Analysis

Gross heart rates, incremental heart rates, ratings of perceived exertion, oxygen consumptions, and oxygen-consumption-based energy expenditures are presented in Table 8 through Table 12. The incremental heart rates were calculated by subtracting the basal heart rates from the gross heart rates for each subject. The subjects' basal heart rates are shown in Table 13. The oxygen-consumption-based energy expenditure values were calculated from the oxygen consumption data (Grollman, 1969) by converting to Standard Temperature and Pressure by means of Equation 2,

$$V_{\text{stp}} = V_{\text{obs}} \left(\frac{BP_{\text{obs}}}{760 \text{ mm Hg}} \right) \left(\frac{273^{\circ}\text{C}}{273^{\circ}\text{C} + t_{\text{obs}}} \right) \quad (2)$$

where

V_{stp} is the volume of oxygen consumed as measured by the spirometer and corrected to Standard Temperature and Pressure (760 mm Hg, + 273°C).

V_{obs} is the volume of oxygen consumed as measured by the spirometer.

BP_{obs} is the observed barometric pressure.

t_{obs} is the observed temperature in degrees centigrade.

and using this V_{stp} to calculate energy expenditure in kcal/min by using

TABLE 8

Gross Heart Rate Data (beats/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
1	.86	108	112	110	110.00
	1.50	142	124	136	134.00
	Mean	125	118	123	122.00
2	.86	94	94	96	94.67
	1.50	114	100	100	104.67
	Mean	104	97	98	99.67
3	.86	114	98	120	110.67
	1.50	142	138	142	140.67
	Mean	128	118	131	125.67
4	.86	126	128	126	126.67
	1.50	148	148	150	148.67
	Mean	137	138	138	137.67
5	.86	128	124	136	129.33
	1.50	170	174	148	164.00
	Mean	149	149	142	146.67
6	.86	104	110	110	108.00
	1.50	130	120	128	126.00
	Mean	117	115	119	117.00

TABLE 8 (continued)

Gross Heart Rate Data (beats/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
7	.86	110	112	116	112.67
	1.50	164	134	154	150.67
	Mean	137	123	135	131.67
8	.86	96	92	94	94.00
	1.50	114	114	116	114.67
	Mean	105	103	105	104.33
9	.86	106	110	120	112.00
	1.50	140	116	130	128.67
	Mean	123	113	125	120.33
10	.86	116	114	122	117.33
	1.50	156	142	144	147.33
	Mean	136	128	133	132.33
Means for rows by columns	.86	110.2	109.4	115.0	111.53
	1.50	142.0	131.0	134.8	135.93
Column means		126.1	120.2	124.9	123.73

TABLE 9

Incremental Heart Rate Data (beats/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
1	.86	40	44	42	42.00
	1.50	74	56	68	66.00
	Mean	57	50	55	54.00
2	.86	20	20	22	20.67
	1.50	40	26	26	30.67
	Mean	30	23	24	25.67
3	.86	38	22	44	34.67
	1.50	66	62	66	64.67
	Mean	52	42	55	49.67
4	.86	40	42	40	40.67
	1.50	62	62	64	62.67
	Mean	51	52	52	51.67
5	.86	50	46	58	51.33
	1.50	92	96	70	86.00
	Mean	71	71	64	68.67
6	.86	36	42	42	40.00
	1.50	62	52	60	58.00
	Mean	49	47	51	49.00

TABLE 9 (continued)

Incremental Heart Rate Data (beats/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
7	.86	40	42	46	42.67
	1.50	94	64	84	80.67
	Mean	67	53	65	61.67
8	.86	46	42	44	44.00
	1.50	64	64	66	64.67
	Mean	55	53	55	54.33
9	.86	34	38	48	40.00
	1.50	68	44	58	56.67
	Mean	51	41	53	48.33
10	.86	36	34	42	37.33
	1.50	76	62	64	67.33
	Mean	56	48	53	52.33
Means for rows by columns	.86	38.0	37.2	42.8	39.33
	1.50	69.8	58.8	62.6	63.73
Column means		53.9	48.0	52.7	51.53

TABLE 10

Rating of Perceived Exertion Data

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
1	.86	12	11	11	11.3
	1.50	14	13	14	13.7
	Mean	13.0	12.0	12.5	12.5
2	.86	10	9	11	10.0
	1.50	13	12	13	12.7
	Mean	11.5	10.5	12.0	11.3
3	.86	12	11	13	12.0
	1.50	15	13	14	14.0
	Mean	13.5	12.0	13.5	13.0
4	.86	10	11	10	10.3
	1.50	13	13	14	13.3
	Mean	11.5	11.5	12.0	11.8
5	.86	14	10	17	13.7
	1.50	18	13	14	15.0
	Mean	16.0	11.5	15.5	14.3
6	.86	13	12	14	13.0
	1.50	16	10	15	13.7
	Mean	14.5	11.0	14.5	13.3

TABLE 10 (continued)

Rating of Perceived Exertion Data

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
7	.86	9	10	11	10.0
	1.50	12	12	14	12.7
	Mean	10.5	11.0	12.5	11.3
8	.86	13	10	12	11.7
	1.50	13	14	15	14.0
	Mean	13.0	12.0	13.5	12.8
9	.86	9	7	11	9.0
	1.50	15	11	13	13.0
	Mean	12.0	9.0	12.0	11.0
10	.86	13	11	12	12.0
	1.50	16	15	16	15.7
	Mean	14.5	13.0	14.0	13.8
Means for rows by columns	.86	11.5	10.2	12.2	11.3
	1.50	14.5	12.6	14.2	13.8
Column means		13.0	11.4	13.2	12.5

TABLE 11

Oxygen Consumption Data (liters/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
1	.86	1.70	1.83	1.86	1.80
	1.50	1.89	1.99	1.90	1.93
	Mean	1.80	1.91	1.88	1.86
2	.86	1.47	1.48	1.47	1.47
	1.50	1.88	1.48	2.10	1.82
	Mean	1.67	1.48	1.79	1.65
3	.86	1.58	1.58	1.70	1.62
	1.50	2.01	1.70	1.92	1.88
	Mean	1.79	1.64	1.81	1.75
4	.86	1.69	1.39	1.48	1.52
	1.50	1.69	2.62	2.04	2.12
	Mean	1.69	2.00	1.76	1.82
5	.86	1.50	1.14	1.22	1.29
	1.50	1.82	2.02	1.97	1.94
	Mean	1.66	1.58	1.59	1.61
6	.86	1.80	1.67	1.95	1.81
	1.50	2.47	1.92	2.08	2.16
	Mean	2.14	1.79	2.02	1.98

TABLE 11 (continued)

Oxygen Consumption Data (liters/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
7	.86	1.54	1.41	1.60	1.52
	1.50	2.12	2.10	2.21	2.14
	Mean	1.83	1.76	1.91	1.83
8	.86	1.45	1.46	1.41	1.44
	1.50	1.63	1.61	1.59	1.61
	Mean	1.54	1.53	1.50	1.52
9	.86	1.49	1.10	1.71	1.43
	1.50	2.12	1.49	1.64	1.75
	Mean	1.80	1.29	1.68	1.59
10	.86	1.41	1.39	1.40	1.40
	1.50	1.97	1.98	2.08	2.01
	Mean	1.69	1.68	1.74	1.70
Means for rows by columns	.86	1.56	1.44	1.58	1.53
	1.50	1.95	1.89	1.96	1.94
Column means		1.76	1.67	1.77	1.73

TABLE 12

Energy Expenditure Calculated from Oxygen Consumption (kcal/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
1	.86	8.22	8.84	8.95	8.67
	1.50	9.13	9.61	9.15	9.30
	Mean	8.68	9.23	9.05	8.98
2	.86	7.07	7.14	7.10	7.10
	1.50	8.81	7.14	10.16	8.70
	Mean	7.94	7.14	8.63	7.90
3	.86	7.63	7.64	8.21	7.83
	1.50	9.68	8.21	9.28	9.06
	Mean	8.66	7.92	8.74	8.44
4	.86	8.15	6.69	7.13	7.32
	1.50	8.17	12.67	9.86	10.23
	Mean	8.16	9.68	8.49	8.78
5	.86	7.26	5.47	5.87	6.20
	1.50	8.79	9.76	9.51	9.35
	Mean	8.02	7.62	7.69	7.78
6	.86	8.69	8.05	9.42	8.72
	1.50	11.92	9.24	10.06	10.41
	Mean	10.31	8.65	9.74	9.56

TABLE 12 (continued)

Energy Expenditure Calculated from Oxygen Consumption (kcal/minute)

Subject	Load (kcal/min)	Proportion of crotch height			Mean
		.17	.20	.23	
7	.86	7.42	6.82	7.71	7.32
	1.50	10.21	10.12	10.68	10.34
	Mean	8.82	8.47	9.20	8.83
8	.86	6.98	7.04	6.82	6.95
	1.50	7.85	7.76	7.67	7.76
	Mean	7.42	7.40	7.25	7.36
9	.86	7.17	5.29	8.25	6.90
	1.50	10.22	7.17	7.93	8.44
	Mean	8.70	6.23	8.09	7.67
10	.86	6.80	6.69	6.74	6.74
	1.50	9.50	9.57	10.06	9.71
	Mean	8.15	8.13	8.40	8.23
Means for rows by columns	.86	7.54	6.97	7.62	7.38
	1.50	9.43	9.13	9.44	9.33
Column means		8.48	8.05	8.53	8.35

TABLE 13

Basal Heart Rates (beats/min)

<u>Subject</u>	<u>Rate</u>
1	68
2	74
3	76
4	86
5	78
6	68
7	70
8	50
9	72
10	80

the following relationship:

$$M = V_{\text{stp}} \left(\frac{\text{liter}}{\text{minute}} \right) \left(4.825 \frac{\text{kcal}}{\text{liter}} \right)$$

where

M is the oxygen-consumption-based energy expenditure in kcal/minute.

The respiratory quotient (RQ) is assumed to be 0.82.

Carbohydrates and fat are the fuel for working muscle. The percentage participation of these two fuels in the energy metabolism is assessed by the determination of the nonprotein respiratory quotient (RQ) which is the following ratio:

$$\frac{\text{CO}_2 \text{ volume produced}}{\text{O}_2 \text{ volume utilized}}$$

Since the carbon dioxide is not measured, the respiratory quotient cannot be calculated, but an RQ of 0.82 is usually assumed (Grollman, 1969). For this RQ the caloric value of oxygen is 4.825 kcal/liter.

Gross heart rate, incremental heart rate, rating of perceived exertion, and energy expenditure were statistically analyzed by means of analysis of variance (ANOVA). The Kansas State University Department of Statistics and Computer Science "AARDVARK" Program was utilized. Using the fixed model analysis, significance was established at the 0.05 level. All the significant variables and their interactions were further tested by Duncan's Multiple Range Test at the 0.05 level.

For all measures, the ANOVA utilized the following variables: ten subjects (S), two load conditions (L), and three proportional crank length conditions (P). All variables and interactions are tested and all significant effects ($p < 0.05$) are identified.

Additionally, the correlation coefficient relating knee angles with crank lengths was calculated. The knee angle was measured with the pedal in the top position in line with the saddle post. The purpose of calculating this correlation was to test the validity of using a proportion of crotch height as a substitute for knee angles in determining the crank lengths. A regression analysis was then performed to allow the leg angle formed during each condition to be predicted from the crank length.

Correlation coefficients were also determined for every pairwise combination of the four measurement variables. This was done to determine the reliability and accuracy of these measures.

Gross Heart Rate

The ANOVA summary of gross heart rate is given in Table 14. There were significant effects for load conditions, proportional crank length conditions, and subjects. The interaction between the load and proportional crank length conditions was also significant.

Load conditions. Table 15 presents the results of Duncan's Multiple Range Test for the two load conditions. The gross heart rate at the larger load was higher and significantly different than the gross heart rate at the smaller load.

Proportional crank length conditions. Table 16 shows the results of Duncan's Multiple Range Test for the three proportional crank lengths.

TABLE 14

Analysis of Variance of Gross Heart Rate at Two Loads at Three
Proportional Crank Lengths for Ten Subjects

<u>Source of Variance</u>	<u>df</u>	<u>MS</u>	<u>F</u>
Subjects (S)	9	1250.78	24.76**
Loads (L)	1	8930.38	176.81**
Crank Length Proportions (P)	2	194.47	3.85*
S x L	9	113.51	2.25
S x P	18	25.21	.50
L x P	2	209.40	4.15*
Error	<u>18</u>	50.51	
Total	59		

* $p < .05$

** $p < .01$

TABLE 15

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Two Loads on Gross Heart Rate

Load	Means (beats/min)
L(2)	135.93
L(1)	111.53

* Non-significant groupings connected by column of asterisks

L1 .86 kcal/min

L2 1.50 kcal/min

TABLE 16

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three
Proportional Crank Lengths on Gross Heart Rate

Proportion	Means (beats/min)		
P(1)	126.10	*	
P(3)	124.90	*	*
P(2)	120.20	*	

* Non-significant groupings connected by column of asterisks

P1 .17

P2 .20

P3 .23

The shortest length crank produced gross heart rates that were higher and significantly different than the gross heart rates produced by the middle length crank. The shortest length crank produced a higher but not significantly different gross heart rate than the longest length crank.

Subjects. There were individual differences among the subjects as shown in Table 17.

Load conditions by proportional crank length conditions. Table 18 gives the results of Duncan's Multiple Range Test for the interaction of load conditions by proportional crank length conditions. For the larger load conditions, the shorter crank produced higher and significantly different gross heart rates. There were no significant differences between the gross heart rates at the smaller load conditions.

Incremental Heart Rate

Table 19 gives the ANOVA summary of incremental heart rate. There were significant effects for load conditions, proportional crank length conditions, and subjects. There was also significant interaction of load conditions by proportional crank lengths.

Load conditions. Table 20 presents the results of Duncan's Multiple Range Test for the two load conditions. The incremental heart rate for the larger load was higher and significantly different than the incremental heart rate at the smaller load.

Proportional crank length conditions. Table 21 shows the results of Duncan's Multiple Range Test for the three proportional crank lengths. The shortest length crank produced incremental heart rates that were higher

TABLE 17

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Ten Subjects on Gross Heart Rate

Subject	Means (beats/min)		
S(5)	146.67		
S(4)	137.67	*	
S(10)	132.33	*	*
S(7)	131.67	*	*
S(3)	125.67		*
S(1)	122.00		*
S(9)	120.33		*
S(6)	117.00		*
S(8)	104.33		*
S(2)	99.67		*

* Non-significant groupings connected by column of asterisks

TABLE 18

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Two Loads (L) by Three Proportional Crank Lengths (P) on Gross Heart Rate

Entry	Means (beats/min)	
LP(2,1)	142.00	
LP(2,3)	134.80	*
LP(2,2)	131.00	*
LP(1,3)	115.00	*
LP(1,1)	110.20	*
LP(1,2)	109.40	*

* Non-significant groupings connected by column of asterisks

L1 .86 kcal/min

L2 1.50 kcal/min

P1 .17

P2 .20

P3 .23

TABLE 19

Analysis of Variance of Incremental Heart Rate at Two Loads at Three
Proportional Crank Lengths for Ten Subjects

<u>Source of Variance</u>	<u>df</u>	<u>MS</u>	<u>F</u>
Subjects (S)	9	733.36	14.52**
Loads (L)	1	8930.36	176.80**
Crank Length Proportion (P)	2	194.47	3.85*
S x L	9	113.51	2.25
S x P	18	25.21	.50
L x P	2	209.40	4.15*
Error	<u>18</u>	50.51	
Total	59		

* $p < .05$

** $p < .01$

TABLE 20

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Two Loads on Incremental Heart Rate

Load	Means (beats/min)
L(2)	63.73
L(1)	39.33

* Non-significant groupings connected by column of asterisks

L1 .86 kcal/min

L2 1.50 kcal/min

TABLE 21

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Proportional Crank Lengths on Incremental Heart Rate

Proportion	Means (beats/min)		
P(1)	53.90	*	
P(3)	52.70	*	*
P(2)	48.00	*	

* Non-significant groupings connected by column of asterisks

P1 .17

P2 .20

P3 .23

and significantly different from the incremental heart rates produced by the middle length crank. The shortest length crank produced an incremental heart rate that was higher but not significantly different than the longest length crank.

Subjects. There were individual differences among the subjects as shown in Table 22.

Load conditions by proportional crank length conditions. Table 23 gives the results of Duncan's Multiple Range Test for the interaction of load conditions by proportional crank length conditions. For the larger load conditions, the shorter crank produced a higher and significantly different incremental heart rate. There were no significant differences between the incremental heart rates at the smaller load conditions.

Rating of Perceived Exertion

Table 24 gives the ANOVA summary of the subjects' ratings of perceived exertion. There were significant effects for load conditions, proportional crank length conditions, and subjects. There were no significant interactions.

Load conditions. Table 25 presents the results of Duncan's Multiple Range Test for the two load conditions. The rating of perceived exertion at the larger load was higher and significantly different than the rating of perceived exertion at the smaller load.

Proportional crank length conditions. Table 26 shows the results of Duncan's Multiple Range Test for the three proportional crank lengths. Both the shortest and longest length cranks produced ratings of perceived

TABLE 22

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Ten
Subjects on Incremental Heart Rate

Subject	Means (beats/min)
S(5)	68.67 *
S(7)	61.67 * *
S(8)	54.33 * *
S(1)	54.00 * *
S(10)	52.33 *
S(4)	51.67 *
S(3)	49.67 *
S(6)	49.00 *
S(9)	48.33 *
S(2)	25.67

* Non-significant groupings connected by column of asterisks

TABLE 23

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Two Loads (L) by Three Proportional Crank Lengths (P) on Incremental Heart Rate

Entry	Means (beats/min)	
LP(2,1)	69.80	
LP(2,3)	62.60	*
LP(2,2)	58.80	*
LP(1,3)	42.80	*
LP(1,1)	38.00	*
LP(1,2)	37.20	*

* Non-significant groupings connected by column of asterisks

L1 .86 kcal/min

L2 1.50 kcal/min

P1 .17

P2 .20

P3 .23

TABLE 24

Analysis of Variance of RPE at Two Loads at Three Proportional
Crank Lengths for Ten Subjects

<u>Source of Variance</u>	<u>df</u>	<u>MS</u>	<u>F</u>
Subjects (S)	9	7.73	4.67**
Loads (L)	1	91.27	55.13**
Crank Length Proportions (P)	2	19.47	11.76**
S x L	9	1.49	.90
S x P	18	1.63	.99
L x P	2	1.27	.77
Error	<u>18</u>	1.66	
Total	59		

** $p < .01$

TABLE 25

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Two Loads on Rating of Perceived Exertion (RPE)

Load	Means
L(2)	13.77
L(1)	11.30

* Non-significant groupings connected by column of asterisks

L1 .86 kcal/min

L2 1.50 kcal/min

TABLE 26

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Proportional Crank Lengths on Rating of Perceived Exertion (RPE)

Proportion	Means	
P(3)	13.20	*
P(1)	13.00	*
P(2)	11.40	

* Non-significant groupings connected by column of asterisks

P1 .17

P2 .20

P3 .23

exertion that were higher and significantly different than the ratings of perceived exertion that resulted from the middle length crank. They were not significantly different from each other.

Subjects. There were individual differences among the subjects as shown in Table 27.

Oxygen-Consumption-Based Energy Expenditure

Table 28 gives the ANOVA summary of the energy expenditure as calculated from the oxygen consumption of the subjects. There were significant effects for load conditions and subjects, but not for proportional crank lengths. There were no significant interactions.

Load conditions. Table 29 presents the results of Duncan's Multiple Range Test for the two load conditions. The energy expenditure at the larger load was higher and significantly different than the energy expenditure at the smaller load.

Subjects. There were individual differences among the subjects as shown in Table 30.

Correlation of Knee Angle with Proportional Crank Length

Table 31 shows the knee angle versus crank length data for each proportion and each subject. The correlation coefficient was calculated to be - 0.81, which is significant with $p < 0.001$.

The regression analysis yielded the following linear regression equation:

$$Y = 114.28 - 2.16 X \quad (4)$$

TABLE 27

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Ten
Subjects on Rating of Perceived Exertion (RPE)

Subject	Means				
S(5)	14.33	*			
S(10)	13.83	*	*		
S(6)	13.33	*	*	*	
S(3)	13.00	*	*	*	*
S(8)	12.83	*	*	*	*
S(1)	12.50		*	*	*
S(4)	11.83			*	*
S(2)	11.33			*	*
S(7)	11.33			*	*
S(9)	11.00				*

* Non-significant groupings connected by column of asterisks

TABLE 28

Analysis of Variance of Oxygen-Consumption-Based Energy Expenditure at
Two Loads at Three Proportional Crank Lengths for Ten Subjects

<u>Source of Variance</u>	<u>df</u>	<u>MS</u>	<u>F</u>
Subjects (S)	9	2.86	2.75*
Loads (L)	1	57.30	55.06**
Crank Length Proportions (P)	2	1.41	1.35
S x L	9	1.41	1.35
S x P	18	.74	.71
L x P	2	.17	.16
Error	<u>18</u>	1.04	
Total	59		

* $p < .05$

** $p < .01$

TABLE 29

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Two Loads on Oxygen-Consumption-Based Energy Expenditure (kcal/minute)

Load	Means (kcal/min)
L(2)	9.33
L(1)	7.38

* Non-significant groupings connected by column of asterisks

L1 .86 kcal/min

L2 1.50 kcal/min

TABLE 30

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Ten Subjects on Oxygen-Consumption-Based Energy Expenditure (kcal/min)

Subject	Means (kcal/min)
S(6)	9.56 *
S(1)	8.98 * *
S(7)	8.83 * *
S(4)	8.78 * *
S(3)	8.44 * * *
S(10)	8.23 * * *
S(2)	7.90 * *
S(5)	7.78 * *
S(9)	7.67 * *
S(8)	7.36 *

* Non-significant groupings connected by column of asterisks

TABLE 31

Knee Angle Versus Crank Length Data

<u>Proportion of</u> <u>Grotch Height</u>	<u>Subject</u>	<u>Knee Angle</u> <u>(degrees)</u>	<u>Crank Length</u> <u>(cm)</u>
.17	1	84	14.75
	2	82	15.75
	3	79	14.75
	4	87	13.75
	5	83	13.50
	6	88	15.25
	7	83	15.25
	8	79	14.75
	9	88	15.00
	10	84 (83.7)	13.25
.20	1	76	17.50
	2	72	18.50
	3	74	17.50
	4	81	16.25
	5	79	15.75
	6	80	18.00
	7	78	17.75
	8	73	17.50
	9	78	17.50
	10	73 (76.4)	15.50
.23	1	67	20.00
	2	70	21.50
	3	70	20.00
	4	70	18.75
	5	77	18.25
	6	76	20.75
	7	74	20.50
	8	67	20.00
	9	67	20.25
	10	72 (71.0)	18.00

where

Y is the predicted knee angle in degrees

X is the proportional crank length in centimeters

Correlations Between Energy Expenditure Measures

The correlations between the four energy expenditure measures are given below.

	OC	RPE	IHR
GHR	0.52*	0.58*	0.63*
IHR	0.55*	0.89*	—
RPE	0.55*	—	—

*p < .001

GHR = Gross heart rate

IHR = Incremental heart rate

RPE = Rating of perceived exertion

OC = Oxygen Consumption

Correlation Between Subject Characteristics and Energy Expenditure Measures

The correlations between various subject characteristics and the four energy expenditure measures were calculated. In addition, the correlations between height, weight, and crotch height were calculated. All of these correlation coefficients are tabulated below:

	A	W	H	CH
GHR	0.38	-0.64*	-0.90**	-0.81**
IHR	0.11	-0.51	-0.77**	-0.71*
OC	0.36	0.11	-0.07	0.11
RPE	0.18	-0.15	-0.22	-0.24
W	—	—	0.87**	—
CH	—	—	0.92**	—

*p < .05

**p < .01

GHR = Gross heart rate

IHR = Incremental heart rate

OC = Oxygen consumption

RPE = Rating of perceived exertion

A = Age

W = Weight

H = Height

CH = Crotch height

DISCUSSION

Before the substantive results of the study are discussed, the relationships among the four measurement criteria will be investigated.

Reliability and Accuracy of Measures

One of the reasons for taking multiple measurements in this study was to make it possible to test the reliability and accuracy of each measure. All four criteria were estimates of the same variable, that is, the energy expended by each subject for each condition. Three of these were physiological measurements, including gross heart rate, incremental heart rate, and oxygen consumption. The other measure, rating of perceived exertion, was a psychological measurement which asked for a subjective judgment from the subject. One important indicator of the degree of reliability and accuracy of the measurements is the correlation which exists between them.

Correlation between gross heart rate and rating of perceived exertion.

The correlation coefficient relating the rating of perceived exertion measurements with the gross heart rate measurements for both loads was calculated to be 0.58 ($p < .001$). This compares favorably with results obtained in previous studies. Gamberale (1972) found correlations of 0.53 and 0.57 between gross heart rate measurements and rating of perceived exertion measurements for two load conditions similar to the ones used in the present study.

The objective of Gamberale's study was to investigate the relation

between perceived exertion and physiological indicators of exertion during exercise. He recorded gross heart rate, oxygen uptake, blood lactate concentration, and rating of perceived exertion at different work loads for twelve subjects. The subjects performed three different tasks: working with a wheelbarrow, lifting weights, and pedaling a bicycle ergometer. Gamberale found that rating of perceived exertion is related to gross heart rate in a fairly linear way regardless of the type of task. Differences in the level of perceived exertion in relation to gross heart rate were found between the different kinds of work. These differences were related, to some extent, to the amount of oxygen uptake and blood lactate concentration.

The rating of perceived exertion values that he obtained were about one-tenth of the corresponding gross heart rate values. These results were in support of other studies which used this same measure (Borg, 1962; Borg and Linderholm, 1967; Skinner, et al., 1970). By comparing the gross heart rates in Table 8 with the ratings of perceived exertion in Table 10, it appears that the results of this study generally support these previous findings. For example, the grand mean for Load 1 is 111.53 beats/minute for gross heart rate and 11.3 for rating of perceived exertion. Likewise, the grand mean for Load 2 is 135.93 beats/minute for gross heart rate and 13.8 for rating of perceived exertion. In both of these examples, the rating of perceived exertion means are about one-tenth of the gross heart rate means.

Correlation between rating of perceived exertion and incremental heart rate. An interesting result occurred when the rating of perceived exertion measure was correlated with the incremental heart rate measure. A correla-

tion coefficient of 0.89 ($p < .001$) was found. This is higher than the coefficient found between gross heart rate and rating of perceived exertion. This seems to indicate that the subjects were actually reporting changes of exertion rather than gross levels of exertion. Gamberale did not make this comparison in his study.

These results indicate that the subjects could accurately judge how hard they were exerting themselves. With the use of this scale or something similar, it is possible to use these subjective responses as accurate measures of physiological response to various tasks.

Correlation between gross heart rate and incremental heart rate.

The correlation coefficient relating gross heart rate with incremental heart rate was 0.63 ($p < .001$). This indicates that by filtering out some of the effects due to differences in individual heart rates, a somewhat different energy expenditure curve results. The fact that some of the effects due to subjects have been removed in the incremental heart rate measure is illustrated when Table 14 and Table 19 are compared. The sample standard deviation for subjects using the incremental heart rate measure is 27.1 beats/minute while the sample standard deviation for subjects using the gross heart rate measure is 35.4 beats/minute.

Correlations between oxygen-consumption-based energy expenditure and the other energy expenditure measures. The correlations between the oxygen-consumption-based energy expenditure data and the other three measurement criteria were all low, ranging from 0.52 to 0.55 ($p < .001$). This suggests that the oxygen-consumption-based energy expenditure data may be somewhat inaccurate. In comparing the overall magnitude of the oxygen

consumption data found in other studies, it appears that the magnitude of this study's oxygen consumption data is too high. Figure 4 compares the gross heart rate data, oxygen consumption data, and rating of perceived exertion data found by Gamberale (1972) to the corresponding data resulting from the present experiment. This is the same study described previously. Figure 4 shows that a high correspondence exists between Gamberale's oxygen consumption and gross heart rate data. The gross heart rate data from the present study is shown to be notably similar to the gross heart rate data from the Gamberale study. However, the oxygen consumption data in the present study were substantially higher.

Gamberale used a much more sophisticated technique to measure oxygen uptake than was used in the present study. He collected expired air in a Douglas bag during the last minutes of every exercise period. He then measured the volume with a spirometer and analyzed the gas according to the Haldane technique. From this information, oxygen uptake was calculated. The present study measured only the volume of oxygen consumed by spirometry.

For these reasons, it is felt that the oxygen consumption data obtained in this study are not as accurate as the heart rate and rating of perceived exertion data. The oxygen consumption data in Table 11 and the oxygen-consumption-based energy expenditure data in Table 12 show mean values that are relatively consistent with the mean values for the other measures of energy expenditure except for magnitude. However, as reported in the results section, not as many significant effects were found by the oxygen-consumption-based energy expenditure measure as were found by the other measures of energy expenditure.

**THIS BOOK
CONTAINS
NUMEROUS PAGES
WITH DIAGRAMS
THAT ARE CROOKED
COMPARED TO THE
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INFORMATION ON
THE PAGE.**

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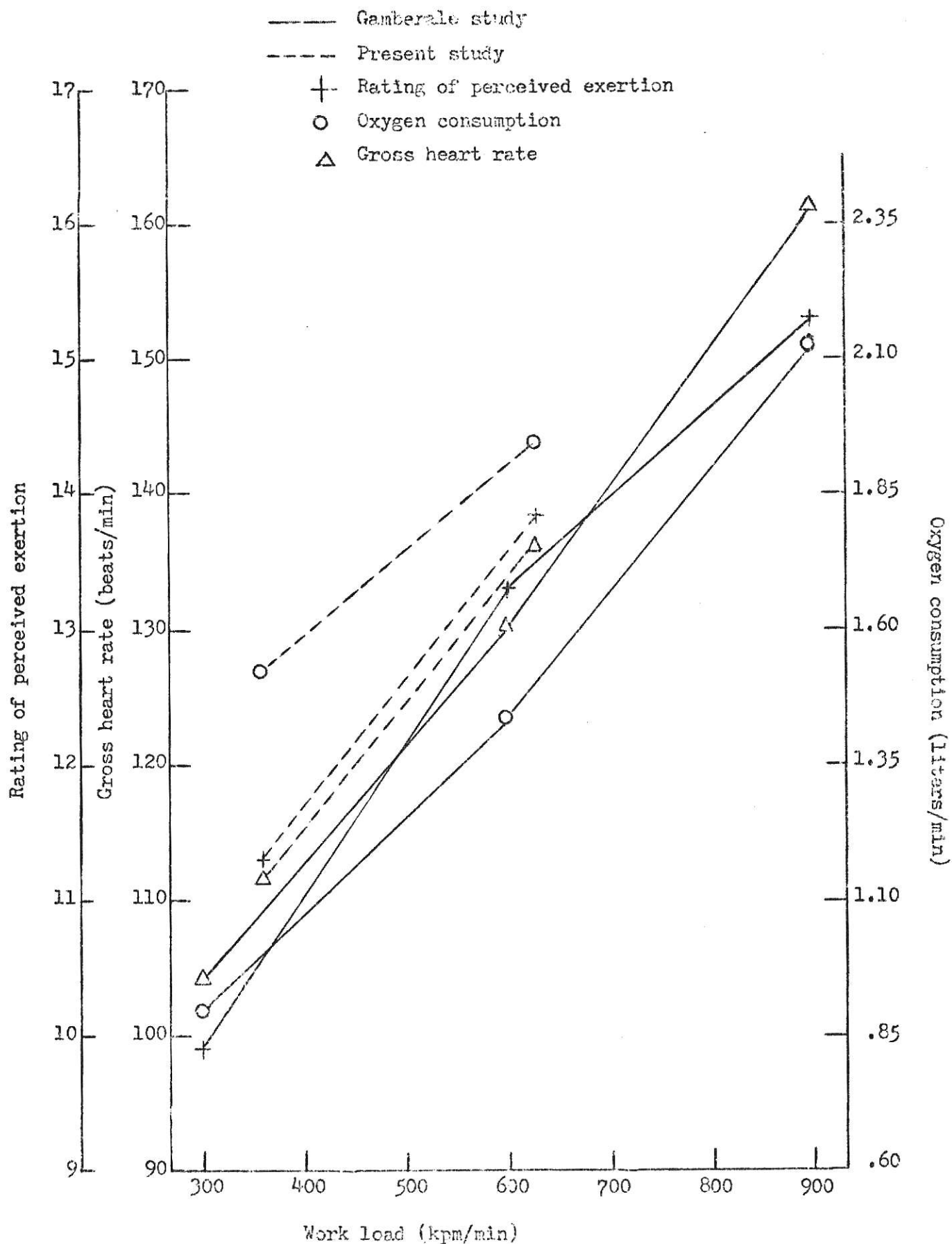


Figure 4. Comparison of Gamberale's gross heart rate, rating of perceived exertion, and oxygen consumption results with the present study results.

Load Effect

Load effect was highly significant ($p < .01$) for all measures. For example, both the data from the gross heart rate and incremental heart rate measures (Table 8 and Table 9) show a difference of 24.4 beats/minute between the grand mean for Load 1 (.86 kcal/min) and the grand mean for Load 2 (1.50 kcal/min). Table 10 shows this difference to be 2.5 for the rating of perceived exertion measure. This is about 10% of the magnitude of the difference of the gross heart rate measure.

The two loads which were selected simulated two work loads which would be found in an actual bicycle riding situation. Because these loads were substantially different from each other in magnitude, this significant difference was expected.

Proportional Crank Length Effect

The proportional crank length effect was significant for all measures except oxygen-consumption-based energy expenditure. The smallest mean value for each significant measure occurred for the middle length crank which was 20% of the operator's crotch height. Table 16 shows that the middle length crank resulted in a mean gross heart rate which was about six beats/minute lower than the mean for the shortest proportional crank length and about four beats/minute lower than the mean for the longest proportional crank length. Table 21 shows that the middle length crank resulted in a mean incremental heart rate which was about six beats/minute lower than the mean for the shortest proportional crank length and about five beats/minute lower than the mean for the longest proportional crank length. Table 26 shows that the middle length crank resulted in a mean

rating of perceived exertion which was 1.6 lower than the mean for the shortest proportional crank length and 1.8 lower than the mean for the longest proportional crank length.

These results do indicate that the length of the crank does affect the energy expenditure of the operator. This concurs with the study by Morehouse and Miller (1948) which concludes that one of the variables which affects the mechanical efficiency of muscular movements is the angle of the pull by the muscle relative to the muscle's point of attachment.

All of the studies mentioned earlier concerning the leg strength at various knee angles are also supported. These studies (Carpenter, 1938; Clarke, et al., 1950; Woodson, 1960; Linford and Rarick, 1968) all found that the knee has a minimum angle of about 120 degrees beyond which the maximum strength decreases. These studies investigated only maximum strength at static load conditions. There is probable a minimum knee angle which corresponds to a dynamic, sustained, submaximal cranking motion. Although there has been no research done specifically to determine this angle, the results from this study show (Table 31) this angle to be approximately 76 degrees. This is the average angle formed for all subjects with the middle proportional crank length.

Proportional Crank Length by Load Interaction

One of the hypotheses of this study was that the proportional crank length which resulted in the least energy expenditure would vary with the load. This hypothesis was confirmed by both the gross heart rate and incremental heart rate measures. The load by proportional crank length interaction was significant for both of these measures (Table 14

and Table 19). For the heavier load, the shortest length crank produced a mean heart rate that was 7 beats/minute higher than the mean heart rate for the longest length crank and 11 beats/minute higher than the mean heart rate for the middle length crank. Table 18 and Table 23 show these significant differences. For the lighter load, the longest length crank produced a mean heart rate that was 5 beats/minute higher than the mean heart rate for the shortest length crank and 6 beats/minute higher than the mean heart rate for the middle length crank. This load by proportional crank length interaction effect is illustrated in Figure 5 and Figure 6.

Figure 5 is a plot of incremental heart rate versus crank length as a proportion of crotch height. Second degree regression equations were calculated and the curves were plotted from these equations. For all the equations, Y is the predicted incremental heart rate in beats/minute. X is the proportion of crotch height in equations 5 and 6. X is the proportion of stature height in equations 7 and 8.

For load 1 (.86 kcal/minute) the regression equation is:

$$Y = 163.07 - 1338.68X + 3546.72X^2 \quad (5)$$

The standard deviation for this curve is 8.7 beats/minute. For load 2 (1.50 kcal/minute) the regression equation is:

$$Y = 410.82 - 3400.11X + 8200.27X^2 \quad (6)$$

The standard deviation for this curve is 16.2 beats/minute.

Figure 6 is a plot of incremental heart rate versus crank length as a proportion of stature height. For this situation, the regression equation for load 1 is:

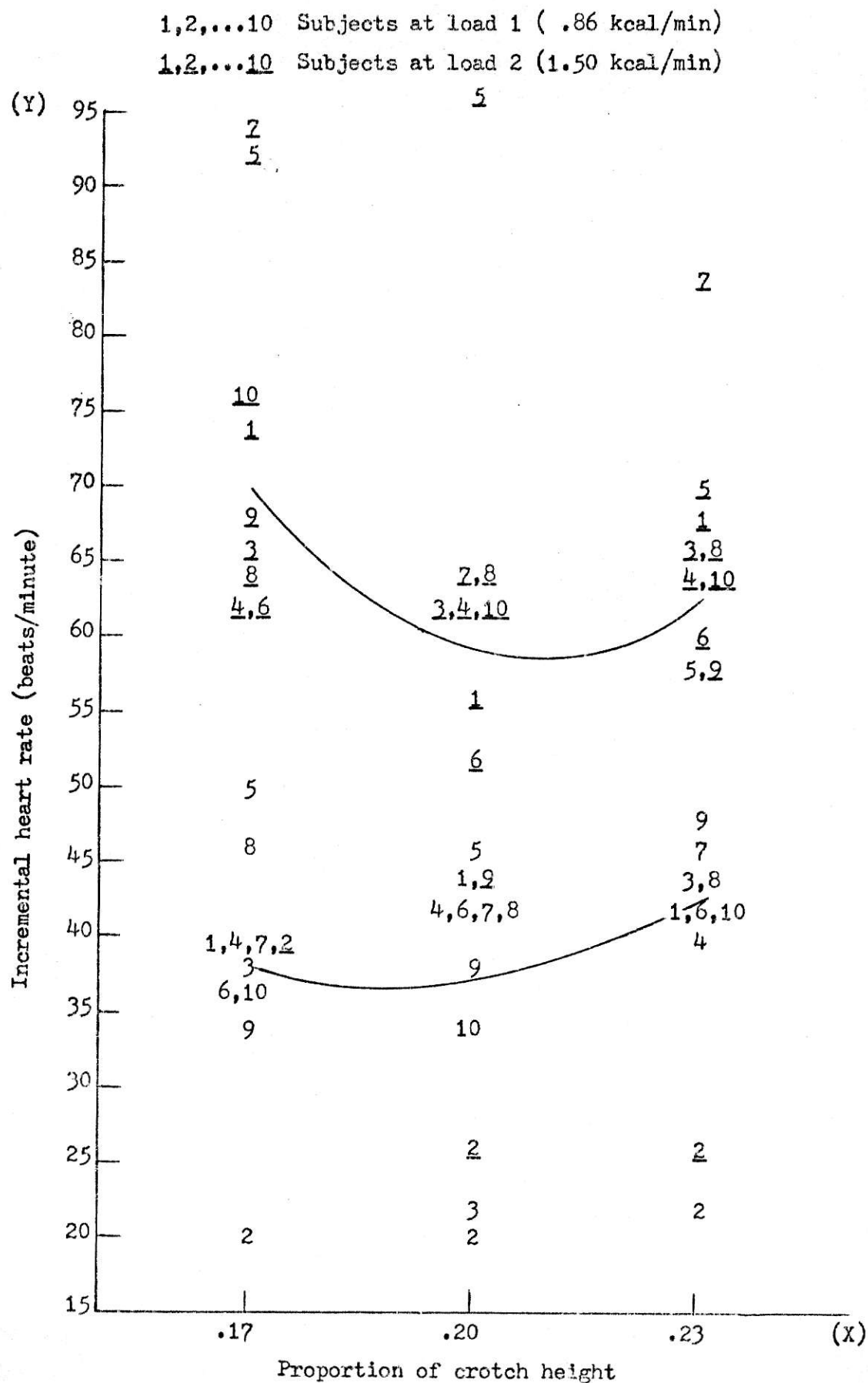


Figure 5. Relationship between incremental heart rate and crank lengths that are proportions of crotch height (at two loads).

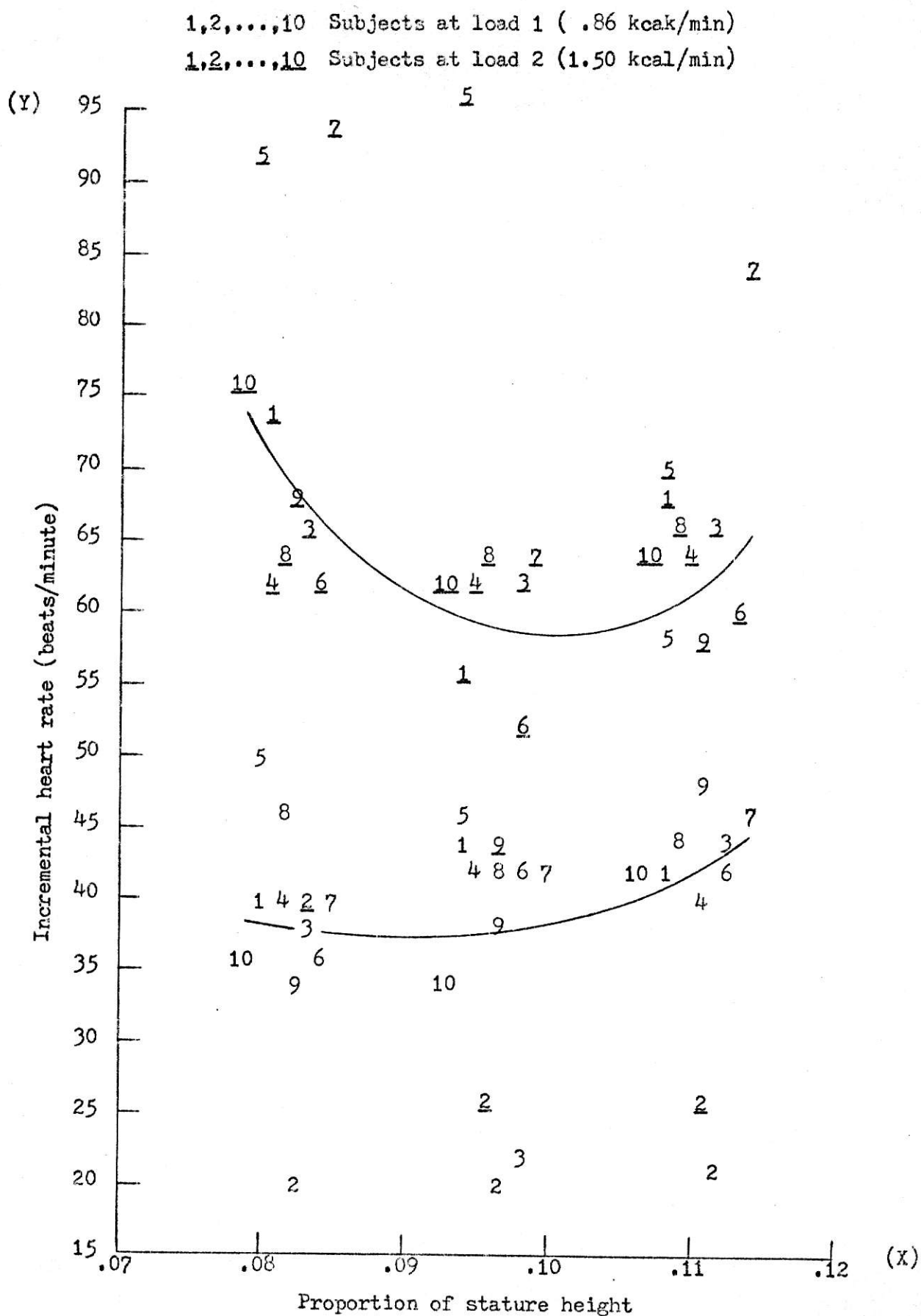


Figure 6. Relationship between incremental heart rate and crank lengths that are proportions of stature height (at two loads).

$$Y = 142.74 - 2329.59X + 12851.53X^2 \quad (7)$$

The standard deviation from this curve is 8.8 beats/minute. For load 2 the regression equation is:

$$Y = 394.31 - 6717.77X + 33593X^2 \quad (8)$$

The standard deviation for this curve is 16.1 beats/minute.

This interaction can be explained according to the same explanation given for the significant proportional crank length effect. Because the efficiency of the leg muscles depends on an optimal combination of load, speed, and distance moved (Morehouse and Miller, 1948), the optimal crank length is probably going to change as one of the other variables changes (load in this case).

Specifically, these results show that under light load conditions the proportion used to determine crank length from crotch height should be approximately 0.20 although this proportion can vary in either direction without much effect on the energy expenditure. For the heavier load conditions the proportion used to determine the crank length should be about 0.20 of crotch height or slightly larger. That is, for heavier loads a longer length crank is more efficient.

Subject Effect

The subject effect was significant for all four measures. The incremental heart rate measure reduced the effect substantially but not to the level of statistical insignificance that Andrews (1967) obtained.

Many of the correlations between the anthropometric characteristics

of the subjects and two of the energy expenditure measures were significant. These anthropometric measures were weight, height, and crotch height. The energy expenditure measures were gross heart rate and incremental heart rate. The table presenting these correlation coefficients is reproduced below:

	A	W	H	CH
GHR	0.38	-0.64*	-0.90**	-0.81**
IHR	0.11	-0.51	-0.77**	-0.71*
OC	0.36	0.11	-0.07	0.11
RPE	0.18	-0.15	-0.22	-0.24
W			0.87**	
CH			0.92**	

* $p < .05$

** $p < .01$

GHR = Gross heart rate

IHR = Incremental heart rate

OC = Oxygen consumption

RPE = Rating of perceived exertion

A = Age

W = Weight

H = Height

CH = Crotch height

These correlations show that as the height and weight of the subjects increased, the gross and incremental heart rates decreased.

The reason for this relationship may be due to the fact that only the differences in the mass of the legs need to be lifted against gravity. In pedaling the bicycle ergometer, the weight of the body is supported by the seat and handlebars. One study (Wyndham, et al., 1963) found that for tasks where the body weight was not lifted against gravity that the oxygen consumption of the heavier man and the lighter man will be similar. The heavier man will use less oxygen per kilogram of body weight and operate at a lower percentage of his maximal level. The heavier man would therefore be under less physiological strain, and thus, have a lower heart for a given load. Because of the high correlation between subject height and weight of 0.87 ($p < .01$), it is difficult to distinguish a separate effect due to subject height.

When this sample was selected, no special precautions were taken to select any particular age group. Astrand and Rodahl (1970) found that, at a given submaximal load, bicycling demands about the same energy output regardless of the subject's age. The fact that no significant correlations were found between age and any of the energy expenditure measures in this study supports their finding. The age range in this study, however, was limited to ages from 21 to 31.

It was also interesting to see that none of the anthropometric measures were correlated significantly with the rating of perceived exertion measure. This result suggests that this subjective measure of energy expenditure may be less affected by individual differences than the physiological measures of energy expenditure.

Relation Between Proportional Crank Length and Knee Angle

Because of the difficulties and inaccuracies involved in setting the crank length directly from a specified knee angle, it was necessary to use a proportion of the crotch height as a substitute for knee angle. From an earlier pilot study (Gross, 1974), it was determined that this was a valid substitution. A high correlation of -0.96 ($p .01$) was found between these two measures. In the present study, the correlation coefficient was calculated and again it proved to be high at -0.81 ($p .01$). In order to relate back to the knee angle criterion, a regression equation

$$Y = 114.28 - 2.16X \quad (4)$$

where

Y is the predicted knee angle in degrees

X is the proportional crank length in centimeters

was computed and the regression of knee angle on crank length is plotted in Figure 7.

Because of the high correlation found between stature height and crotch height (0.92 , $p .01$), the crank lengths may also be expressed in terms of proportion of stature height. Figure 6 shows that the optimal proportion of stature height is approximately 0.10 . This proportion gives the lowest incremental heart and thus the lowest energy expenditure.

Comparison of Proportional Crank Lengths With Standard Crank Length

The curves in Figure 8 show the relationship between the standard crank length and the optimal proportional crank length of 20% of crotch height over both the male (White, 1966) and female (Clauser, 1972)

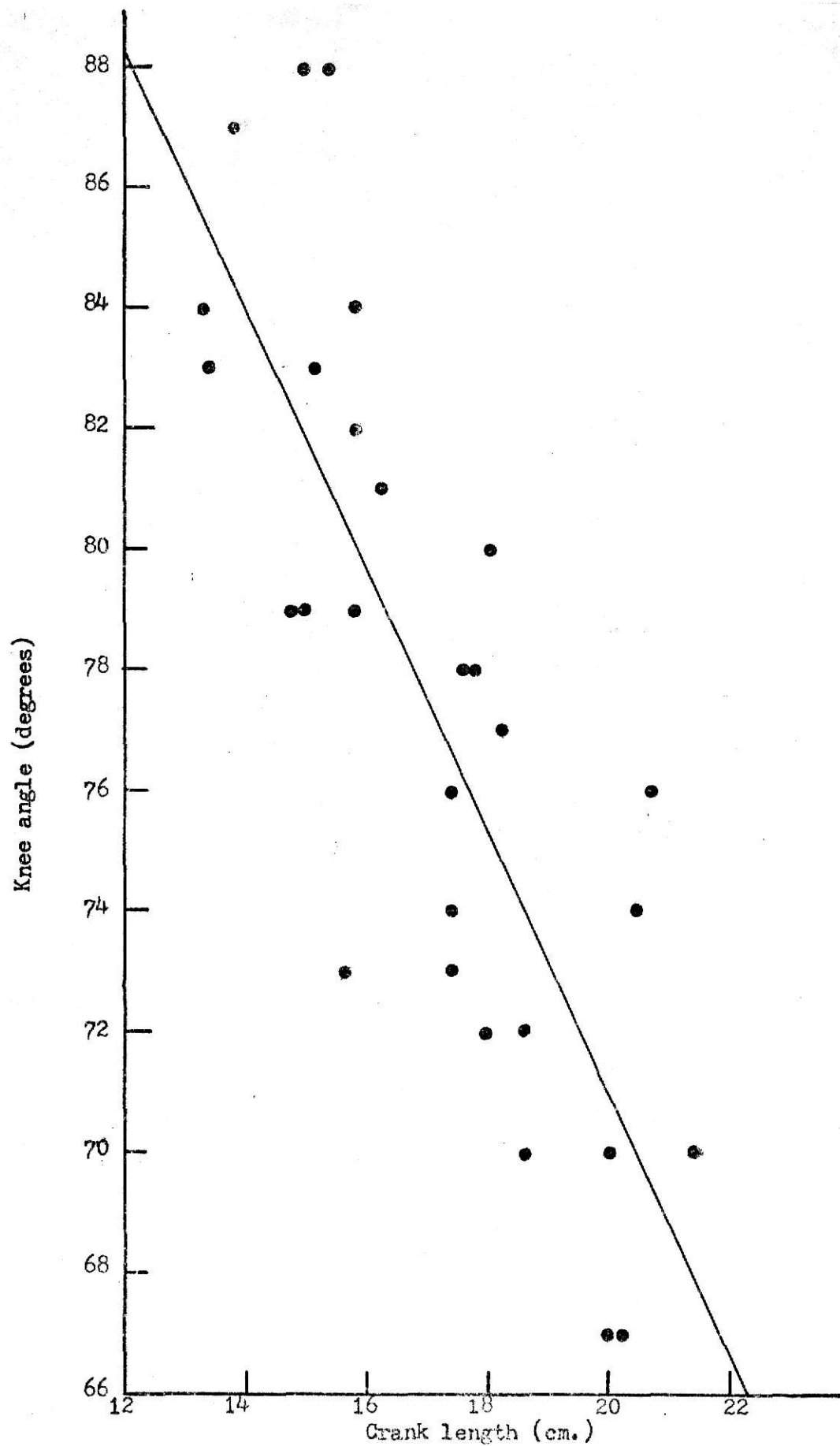


Figure 7. Regression of knee angle on crank length.

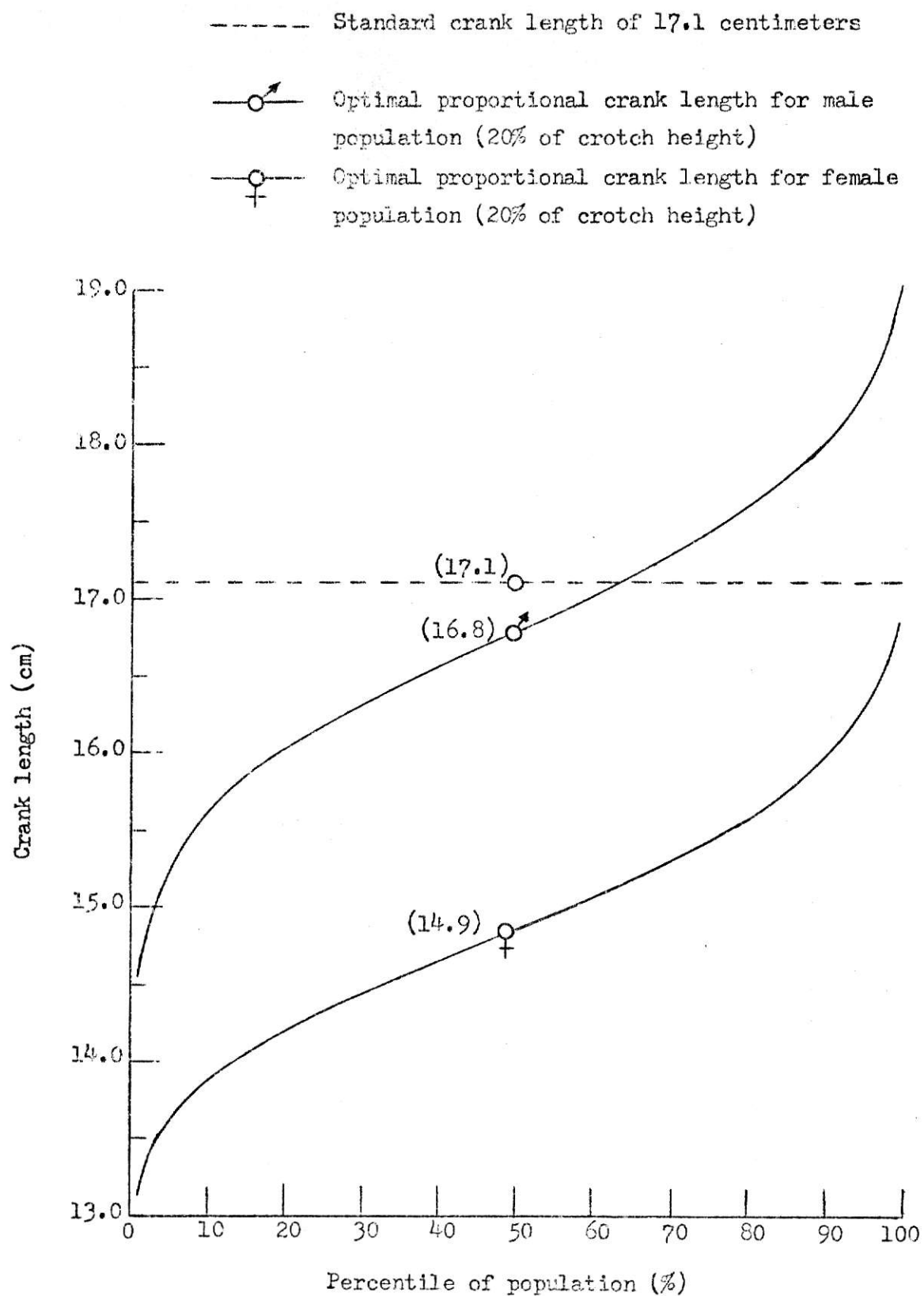


Figure 8. Comparison of optimum proportional crank length with standard crank length over the male and female range of crotch heights.

population ranges of crotch heights. The curves show that the fiftieth percentile man with a crotch height of 83.91 centimeters should be using a crank length of 16.8 centimeters rather than the standard crank length of 17.1 centimeters. This difference, however, is not large (0.3 centimeters). The standard crank length for the fiftieth percentile man corresponds to about 21% of his crotch height.

For the fiftieth percentile female the difference between the optimal proportional crank length and standard crank length, however, is much larger (2.1 centimeters). In this case, a crank length of 14.9 centimeters would be optimal. The standard crank length for the fiftieth percentile female corresponds to about 23% of her crotch height. These comparisons show that the standard crank length presently used on most bicycles is too long for about 60% of the adult male population and almost 100% of the adult female population.

Implications for Future Research

To the author's knowledge, this is the only experimental study that has been conducted in this area. There needs to be more study done to investigate the effect of crank length and load on the energy expenditure of the operator. This study showed that the energy expenditure of the subject can be changed by roughly one kcal/minute with a change in the crank length of three percentage points of crotch height. This can be seen in Table 18 where the significant difference between the shortest length crank and the middle length crank was about eleven beats/minute at the high load. Ten beats/minute is roughly equal to one kcal/minute (Gamberale, 1972).

Not only should this experiment be replicated, but a narrower range of proportional crank lengths should also be investigated over a narrower range of loads and a wider range of cadences. Likewise, the effect of various physical characteristics of subjects should be investigated more thoroughly. These include height, weight, age, and sex.

Future studies designed specifically to determine how the leg muscle strength and efficiency vary at different knee angles for dynamic, rotary motion would also help explain the crank length and load effects found in this experiment. The effects of saddle height, handlebar height, distance between handlebars and saddle, position of the saddle above the crankshaft, and the lateral distance between pedals should be studied to determine their effect on energy expenditure.

The shape of the drive-chain sprocket is another variable which should be studied. An elliptical-shaped sprocket may allow the leg to operate for a greater proportion of the time at more efficient knee angles during the cranking cycle. Only when all of these variables are matched to the individual characteristics of the people who ride bicycles will the optimal relationship exist.

Future research should also investigate the relationship found in this study between the subject's rating of perceived exertion and incremental heart rate. Perhaps the subject's rating of perceived exertion does measure incremental exertion rather than gross exertion. The finding that there is a lack of a relationship between the individual subjects' anthropometric characteristics and rating of perceived exertion should also be studied further.

Finally, another measurement device that could provide interesting

results is the force platform. This is a device that can detect a wide range of forces in three independent perpendicular planes. The torques about the three axes can also be measured. One important advantage of the force platform is that no attachments are required to be made between the subject and the apparatus. The resultant forces and torques for the various subjects and task conditions could be obtained by mounting a bicycle ergometer on the force platform. These forces and torques could possibly help explain the differences between the various load and crank length combinations. For example, a condition which caused a high energy expenditure may also register a high lateral resultant force by the force platform. This would indicate that much of the force produced by the operator is not being transferred to the mechanical drive system but is being wasted by excess lateral movements, such as maintaining balance and posture.

This study also has important implications for experiments using bicycle ergometers where between-subject comparisons are made. No longer can experimenters claim to make accurate comparisons among subjects with varying physical characteristics when the crank lengths have not been adjusted to the individuals.

Practical Implications

The results of this experiment can be utilized directly both by the bicycle manufacturing industry and private individuals who wish to ride their bicycles more efficiently.

Manufacturers should make a variety of crank lengths available to the consumer. Five crank lengths, varying from fourteen centimeters

to eighteen centimeters in length, would span the population range of crotch heights from the tenth percentile to the ninetieth percentile of adult men and women. Alternatively, the manufacturers could design and produce an adjustable length crank. Either of these suggestions would allow the proper crank length to be selected by almost every individual rider.

CONCLUSIONS

Subjects were able to correctly judge how hard they were exerting themselves. Their subjective ratings had a high correlation with their actual physical activity as measured by the gross heart rate measure (0.58), and an even higher correlation with the incremental heart rate measure (0.89). Thus, this RPE Scale can be substituted as an accurate measure of physiological response to various tasks.

It was also found that this subjective measure of energy expenditure may be less affected by individual differences such as height and weight than are the physiological measures of energy expenditure.

The effect due to subjects was reduced substantially by using incremental heart rate instead of gross heart rate.

Although the loads used in the experiment were representative of loads found during actual bicycling situations, they were substantially different from each other in magnitude (0.86 kcal/minute versus 1.50 kcal/minute). Because of this large difference, a significant load effect resulted for all the energy expenditure measures. For the gross heart rate measure, the larger load produced a heart rate of about 24 beats/minute (roughly two kcal/min) higher than the lower load.

A crank length which was 20% of the operator's crotch height caused an energy expenditure which was about one kcal/minute lower than that caused by the other two proportional crank lengths. This result shows that the energy expenditure of the bicycle rider is affected by the length of the pedal crank, and that the optimal length should be related to the individual anthropometric characteristics of the subjects.

The proportional crank length which resulted in the least energy expenditure by the subject varied slightly with the load. For the heavy work load the proportion of crotch height should be 0.20 or slightly greater. For the lighter work load the proportion of crotch height should be 0.20 although it can vary slightly in either direction without having much effect on the energy expenditure.

Taller and heavier subjects expended less energy than shorter and lighter subjects for the same tasks. Because the weight of the body is supported by the bicycle, the heavier man will use less oxygen per kilogram of body weight and operate at a lower percentage of his maximal level. This results in relatively less physiological strain and, thus, a lower energy expenditure as measured by heart rate. It is difficult to distinguish a separate effect due to subject height because of the high correlation (0.87) between subject height and weight.

Age did not have an effect on the energy expenditure of the subjects. However, only a limited range of ages (21 to 31 years) was used in this study.

The validity of using a proportion of crotch height as a substitution for knee angle was confirmed by the correlation of -0.81 between these two parameters.

The present standard crank length used on most bicycles (17.1 centimeters) is too long for 60% of the male population and almost 100% of the female population.

More research is needed to further investigate the relationship of crank length and load with energy expenditure.

In future experiments using bicycle ergometers, the length of the

crank must be adjusted for each individual. Otherwise between-subject comparisons will not be valid.

A range of crank lengths should be made available to bicycle riders so that they may select the optimal lengths for their individual physical characteristics.

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BICYCLE CRANK LENGTH AND LOAD --- EFFECT
UPON OPERATOR ENERGY EXPENDITURE

by

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In an operator - bicycle relationship, the most efficient system will exist when the bicycle is optimally adjusted to fit the individual characteristics of the operator. This study investigated the effects of pedal crank length and work load on the energy expenditure of the operator. Because the optimal movement of the leg muscles is dependent upon the distance and speed moved and the work load, it was felt that the optimal crank length should be related to the minimum angle formed at the knee during the cranking cycle. Proportion of crotch height was used as an indicator of knee angle.

Ten male subjects, two work loads, and three proportional crank lengths were used in a factorial experimental design. The six conditions were performed in a different random order by each subject pedaling at a constant cadence of 60 revolutions per minute on a bicycle ergometer. A five minute rest period followed each pedaling task. The energy expended by the subjects for each condition was estimated by four different criteria - oxygen consumption, gross heart rate, incremental heart rate, and the subject's own rating of his perceived exertion.

The results showed that a crank length that is about 20% of the subject's crotch height is the most efficient. This proportion does vary significantly with the work load. For a light load that could be encountered in pedaling a bicycle, a slightly shorter crank length is more efficient. For a heavier load, a slightly longer crank length is more efficient. The present standard crank length (17.1 centimeters) used on most bicycles is too long for about 63% of the male population and almost 100% of the female population.