A CINEMATOGRAPHICAL ANALYSIS OF THE LEG ACTION OF CYCLING

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ABSTRACT

A CINEMATOGRAPHICAL ANALYSIS OF THE
LEG ACTION OF CYCLING

By

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The purpose of this study was to analyze and compare the leg movements of six selected subjects with the leg movements recommended in most cycling literature.

Using the cinematographic technique described by Cureton, the projected image of each of the subjects was used to determine movement patterns while he or she was riding the rollers, a mechanical device for indoor training that accommodates both the rider and his bicycle. Mechanics of the bicycle that directly relate to the performance of the cyclist and mechanics of the leg action were analyzed. A comparison of the subjects' performance with theories commonly found in bicycle literature was made.

Basically, the recommended adjustments of the bicycle commonly found in most cyling literature did not vary significantly from those of rider comfort.

The leg supplying the driving force is the most important concern of cycling. Maximum knee extension

occurred at an average angle of 161.2° and maximum foot extension at the 169.5° crank position. Knee flexion began at 171° and flexion of the foot at 205°. The range of knee movement was from 57° to 73°. The range of movement was from 19° to 45° for the ankle.

The average area in which force could be applied effectively in the first half of the pedal revolution was through a range of 41° to 180°. The area of least force was at 90° and those crank positions most nearly approaching this point.

The findings of this study, generally, were in agreement with the recommendations most commonly found in cycling literature. There were differences, however, with regard to the foot being in a horizontal position at 90°. The degree of ankling which would be most efficient could not be determined.

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By

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CHAPTER I

INTRODUCTION

Since the inception of the bicycle in the 1800's, man has incorporated its use for work, recreation, and competitive sport. There have been and will continue to be refinements of a machine that, all in all, has withstood the censures of time.

There has been limited scientific inquiry of a person's mechanical relationship to the bicycle. A test was conducted by Scott (7) in the 1890's with a special pedal adaptation to record the force applied during a pedal revolution. Singh (17) explored the mechanical adjustment of cycling for safety, comfort, and speed. The main cycling publication in the United States, American Cycling, features a monthly technical section by DeLong. He has briefly discussed a large number of aspects of both the bicycle and the cyclist. Certain theories have been formed as to the mechanics of cycling, but no cinematographic evidence was found to support these theories.

Statement of the Problem

Man cannot rely on observation alone. Aided by high speed photography, anatomical data, mechanics, and moments of force, the writer tried to provide a scientific base to substantiate present conceptions commonly found in most cycling literature. That is, (a) there is an important relationship between the rider and his bicycle, especially at the three points of contact: the handlebars, the seat, and the pedals; (b) the most critical factor in cycling is the leg action; (c) the degree of ankling contributes to the rider's efficiency.

The writer was interested in determining whether or not there were any appreciable differences between the subjects' leg movements and the related riding techniques commonly described in bicycling literature. Stated briefly, the toe is raised at the top of the stroke, presses the pedal forward, and is in a horizontal position when the crank is at 90°. The toe points downward and draws the pedal back at the bottom of the stroke.

Pertinence of the Study

For the serious-minded cyclist, there are a limited number of publications relating to the sport available in the United States. There is a dependence on other countries, especially Great Britain, for books and periodicals in this subject area.

In most references regarding past research, the writer was unable to determine the scientific base upon which conclusions were drawn. There has been recently, however, an increase in the number of studies being conducted and other technical data available.

Cycling is a common experience, and with the growing amount of leisure time and the present stress on physical fitness, the demand for such a lifetime sport becomes even more important. Once the initial investment of the machine is assumed, it is an inexpensive form of recreation and sport by riders of all ages. One can participate with a group, as a family, or individually anyplace in the world. After the rider has learned a certain degree of proficiency he or she will experience an extremely pleasurable form of activity.

The writer has had much contact with cyclists of all skill levels. It was hoped that by better understanding the technical implications of cycling the writer would be better able to share useful information with other cycling enthusiasts.

Delimitations

While the writer was primarily concerned with the mechanical principles of the cyclist, there were mechanics of the bicycle alone that had to be considered. No attempt was made to ascertain the correct fit and adjustment of the bicycle to the rider as it has been covered by Singh (17), DeLong (8, 9), and others. By necessity, each subject rode the bicycle of his or her own choosing. The selection of seat, handlebar, and gear ratio adjustments were also left up to the individual.

No muscular analysis or physiological requirements are explained in this study. The primary concern is the mechanical function of the leg. Relationships with other parts of the body and the bicycle are discussed only as necessary.

Limitations

1. It cannot be assumed that the camera speed was held perfectly constant.

2. There may have been some unknown lens and camera irregularities.

3. There was a small and not truly random sample.

4. The bicycle adjustments for seat, handlebar, and gear ratio were set according to rider comfort and not recommended adjustments. A comparison was made to see if there was great variation between recommended adjustments and those governed by comfort.

5. Variables may have been present that were not known to the writer.

6. While the rollers, a mechanical device for indoor training, are used during the winter season to perfect pedalling technique by racing cyclists, variables may have been either introduced or lacking that would ordinarily be found while riding under road conditions.

7. The principles of physics cannot be applied to the human being perfectly.

8. The study was limited by the maximum speed of the camera.

Definition of Terms

1. Ankling. The use of one's ankles to vary the flexion and extension of the feet throughout the pedal revolution to permit smoother pedalling with less effort.

2. Bicycle. A machine with a tubular frame, two wheels 27" x 1 1/4", dropped handlebars, saddle, and metal pedals upon which a rider balances and propels himself forward by pushing on the pedals.

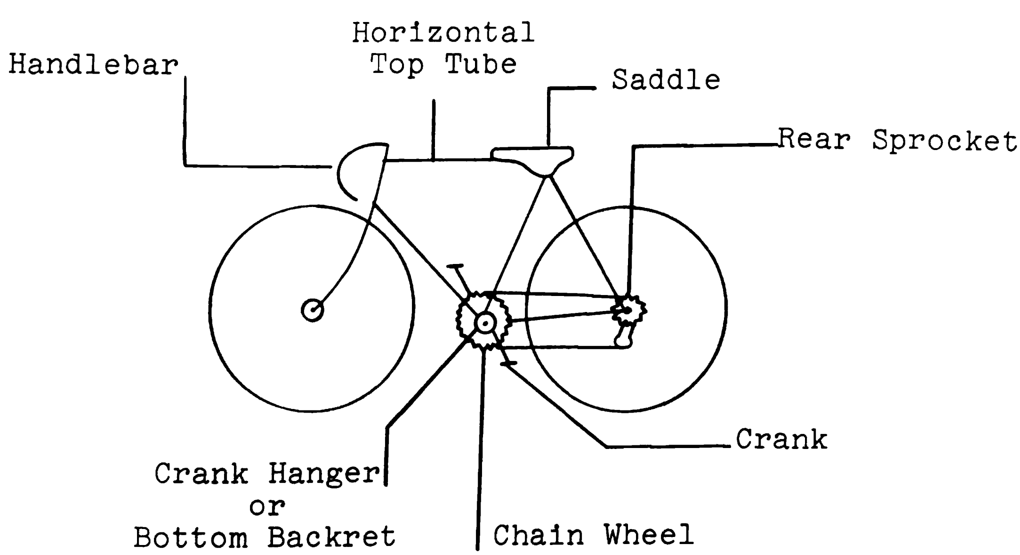


Figure 1.--Basic bicycle components.

3. Cleats. Metal pieces of varying designs containing slots to fit over the metal rat trap pedal. They are attached to the sole of the cycling shoe.

4. Cycling Shoes. A lightweight, leather shoe with a special reinforced sole to equalize pressure on the ball of the foot.

5. Cyclist. For purposes of this paper, a cyclist is any person riding a light-weight, multi-geared bicycle for pleasure and/or recreation.

6. Dead Centers. "Near the top and bottom of each stroke the rider's weight can no longer be used for propulsion...These points are called 'dead centers'" (7, p. 20).

7. Gear Ratio. A ratio of the number of teeth on the front chain wheel to the number of teeth on the rear sprocket. When multiplied by the diameter of the wheel times pi, would represent the distance travelled for each turn of the crank.

8. Handlebars. They are an underslung type of bar that reduces pressure on the saddle,permits the back to bend forward which relaxes the spine, distributes the body weight more evenly between the front and rear wheels, and permits the upper body to assist with propulsion (1).

9. Rat-trap Pedals. This type of pedal is made of metal, is lighter than rubber pedals, and because of a toothed surface provides a better grip for cycling shoes.

10. Rollers. Three cylinders, two at the rear and one at the front, are placed so they will accommodate a cyclist and his machine. The bicycle is placed atop the rollers, and with careful balance the rider can practice pedalling technique indoors within a limited area.

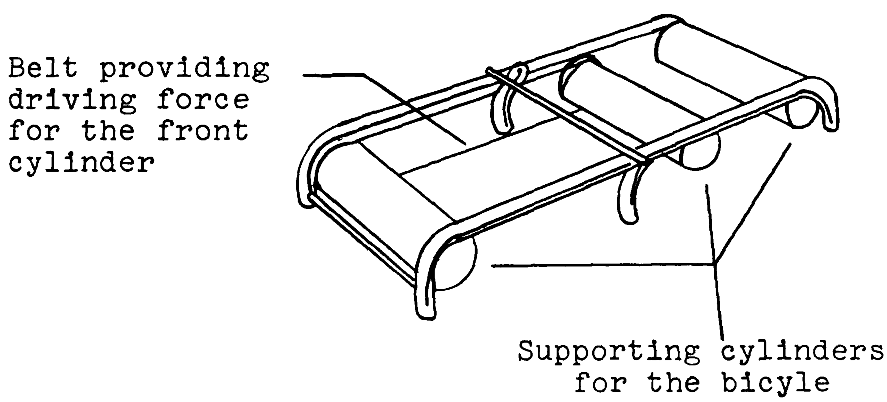


Figure 2.--Rollers for indoor training.

11. Saddle. A narrow, leather, unsprung unit designed to permit free movement of the thighs.

12. Toe Clips and Straps. These attach to the rat-trap pedal to prevent the foot from sliding too far forward and to assist in the upward motion of pedalling.

CHAPTER II

REVIEW OF THE LITERATURE

Limited availability of literature in the United States related to bicycling necessitates dependence on other countries for much of that which is procurable. It has been established, however, that:

> A bicycle is a mechanical aid to allow an individual to convert muscular energy into motion. Unless its rider is so disposed that his muscular team is most effectively utilized, premature fatigue, discomfort, or loss of performance will result (9, p. 16).

There seems to be common agreement that bicycling is an act requiring balance and the most efficient use of one's body and machine. The term ankling is referred to as an efficacious means of accomplishing this very thing in almost all literature pertaining to cycling.

> The pedal is the point at which the energy of the rider is transmitted to the cycle, and so forms the chief connecting link between the cyclist and the wheel. The degree of perfection with which the connection is made goes far to determine the whole character of one's riding. . . . (13, p. 70)

Shaw (16) and the Philadelphia AYH (1) state simply that in ankling the toes are raised on the upstroke, the foot is in an almost horizontal position when it is half way around, and the toes begin to press back on the pedal at the bottom of the stroke.

The Athletic Institute, in cooperation with the Bicycle Institute of America and the Amateur Bicycle League of America (2), wrote of ankling with more clarity. With the foot moving in a clockwise direction the recreational rider most effectively applies power to the pedals from just after twelve o'clock all the way around to past six o'clock--more than half way around for each foot. The heel is dropped as the foot rises. Force application starts just after twelve o'clock by extending the ankle--applying forward power to the pedal. The ankle continues a steady extension until it is fully extended at the bottom of the stroke where backward pressure is applied to the pedal.

The racing cyclist, aided by toe clips, can exert a pull between six o'clock and twelve o'clock enabling power to be applied all the way around. There is, of course, more strength on the downstroke.

Varied degrees of proficiency are possible, and many who pose as good riders, states Porter, have poor ankle action.

> With good pedalling the rider will be able to apply power through one half, or more, of each revolution, and perfect pedalling will permit him to do so to an even greater extent. . . Also, the heel must rise uniformly as the crank decends so that half way around the toe and heel

> are level and the power is applied to the end of the crank at exactly right angles where the work is easiest and most effective.
>
> By acquiring good ankle motion instead of exerting pressure with each foot through only one hundred and fifty to one hundred and eighty degrees, it becomes possible to apply power through two hundred to two hundred twenty degrees and it also applies the power more effectively throughout the whole distance (13, pp. 76,80).

R. P. Scott (7), in the 1890's, developed a pedal which could measure the force applied to it and record it on a spring wound rotation drum. There was a fall-off of effort at the top and bottom of the stroke. When effort is greatest, such as during hill-climbing, the variation is greatest. In one section he considered only the vertical uniform pressure and found that ". . . only 13% of the effort is effective in the top and bottom 30° of rotation, 37% in the second and fifty 30° and 50% in the center third of the pedal stroke" (7, p. 21).

The crank is the means of transferring the rider's driving power to the bicycle, but there is little scientific evidence as to proper crank length. DeLong (10) cites the contribution of several men. First, Mons. Perrache stated as a rule of thumb that crank legnth should be 1/10th the rider's inside leg measurement. Mons. Bourlet calculated that the maximum crank length a rider can effectively use is one half his thigh bone length. Both these men made their contributions near the turn of the century.

> Professor Sharp in England (1896) pointed out . . . that the shorter the crank length in proportion to the rider's leg length, the more nearly the rider's knee motion approaches simple harmonic motion. This is to say, in simplicity, the starting, acceleration, deceleration and stopping of the knee motion becomes a smoother function (10, p. 14).

Milton Morse, an interested cyclist, asked the following questions in his contribution to the question of crank length: "Which is more tiring--the short crank with rapid cadence, or the slow, powerful strokes of the long crank?" (12, p. 15). He and his wife gradually increased crank lengths over a long period of time from 6.5 inches to over 8 inches. As the crank length increased, up to 7.75 inches, so did the number of miles they were able to ride each day. Gearing was changed as crank length was increased. They found the 7.75 inch crank length most satisfactory and found that daily distances actually decreased with cranks longer than 7.75 inches. They preferred long cranks and slow, powerful strokes.

Vaughn Thomas (18) of England conducted a study in which he tried to standardize the mechanical variables of the bicycle into one parameter which was the saddle height.

The subjects rode with a heavy work load (500 kg/m), and the subjects were timed in performing this work load at four different saddle heights. The experiment showed quite conclusively that the most efficient saddle height is 109% of the inside leg measurement. He found that the better the rider (in terms of racing ability) the more he tends to have his saddle set to the recommended height.

Another study of significance was conducted by Singh concerning the mechanical adjustment of cycling for safety, comfort, and speed.

> He concluded that no two persons would have the mechanical adjustment on their bicycles the same way; that the cyclist should know how to select the bicycle according to individual body needs and to be able to ride the machine correctly; and be able to adjust it as required for safety, comfort, and minimum power loss. (17, p. 95)
>
> First of all, the height of the bicycle depends on the height of the cyclist. The height of the frame . . . to the axis of the bottom bracket should be about 10" less than that of the rider's inside leg measurement. . . . (17, p. 29)

Singh (17) further stated that the saddle should be adjusted for rider comfort so that the pedal can be reached at its lowest point. Also, the top of the handlebars should be about two inches lower than the saddle.

A Schwinn Bicycle Company pamphlet (8) stresses the importance of fitting the bicycle to the rider. Figure A1 in the Appendix gives reference to the points of measurement for determining correct fit of the bicycle. Their first recommendation was that the frame size should be such that the top horizontal bar permits the rider to just straddle it with both feet flat on the ground. If the frame is too small it will not permit proper setting of the saddle and handlebars.

The nose of the saddle should be set two inches behind an imaginary line drawn through the center of the crank hanger. Then, by placing the heel on the pedal at its lowest point and sitting on the saddle, the leg should be straight. When in the proper riding position, the knee will have a very slight bend.

The saddle top should be level and not at an angle. Portuesi (14) adds further emphasis to this. If tipped down, extra pressure is applied to the arms and wrists to keep from sliding forward in the saddle. While Schwinn (8) says the angle should be neither up nor down, Portuesi (14) says the saddle top should be level or with a very slight tip-up.

Schwinn (8) continues on to say that the top of the handlebars should be no higher than the top of the saddle. The distance of the bars from the seat should be such as to permit a natural arm position with the back inclined approximately 45° forward.

> Ankling permits the rider to take full advantage of the principles of leverage. The heel should be dropped to give an increasing forward push to the pedal with the thrust reaching full force when the foot is in its most forward position (17, p. 98).

Though only several sources have what might be considered a true scientific base, Scott's study (7) in 1890 and Porter's (13) in 1895, would seem to have set forth the principles of cycling.

Once the bicycle is properly adjusted, the cyclist should be ready to learn more cycling techniques of which cadence is a part. Research, says Schwinn (8), has shown that a person operates most efficiently in the pedal speed range of 55 to 85 revolutions per minute. For normal riding, pedal speed should be to the middle or higher side of this range. Yet another individual reports (6) varied laboratory studies have been made which would indicate greater muscular efficiency at from 42 to 60 revolutions per minute.

CHAPTER III

METHODS OF PROCEDURE

This study used the cinematographic technique as described by Cureton (4) for analyzing the mechanics of leg action in cycling. By using projected images as a guide for plotting the movement patterns for each subject, pertinent data could then be obtained.

Research Method

The subjects performed their cycling techniques while riding the rollers. As shown in Figure 3, the rear wheel of the bicycle is placed over two closely spaced cylinders. Rotation of the back wheel provides the turning force for these cylinders. They in turn are connected to the front cylinder by a belt thereby causing the front cylinder and the front wheel of the bicycle to rotate.

Three practice trials were given to the cyclists who could already ride the rollers and five or more for the inexperienced cyclists several weeks before the filming. All but one had achieved complete independence of a spotter by the time of the filming.

The rollers were placed on the University of Akron gym floor near the wall on which a plain background paper

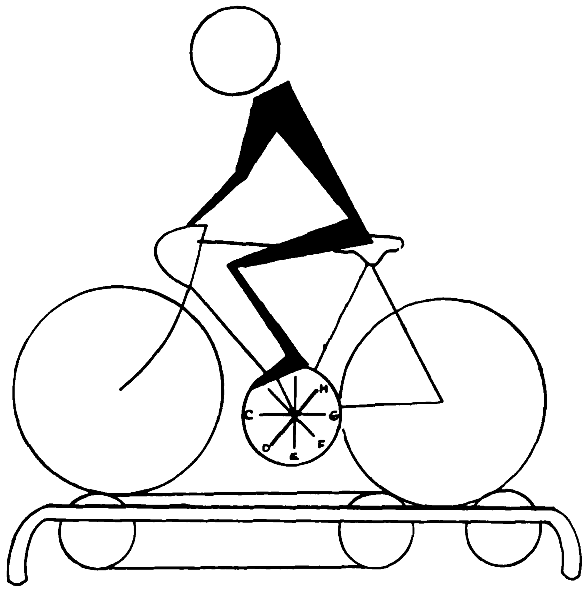


Figure 3.--Cyclist riding rollers.

had been hung. Vertical and horizontal measures were placed in the camera field of view by the rollers, and their positions were checked with a level. A cardboard disc, sub-divided into eight parts, was attached to the bicycle behind the crank of each rider for later referral to crank positions and to provide an unobstructed view of foot actions. It was only used, however, to provide an unobstructed view of the foot.

Since rides on the rollers are usually of short duration, no warm-up was given. Rather, those desiring it, rode laps around the gym. The three-minute riding time given each subject was divided into three one-minute segments with filming being done near the end of each minute.

The camera, a motor driven Bell and Howell 16mm, Model 70J was set 36 feet 11.5 inches from the subjects. The camera was aimed at the hip joint as measurements were to be taken from all joint centers of both the upper and lower limb segments. Measuring from the center of the lens the camera was placed at a height of 4 feet. A 1:2.4 Pan-Cinor Zoom Lens was used at f/5.6 and the camera speed set at 64 frames per second. Each frame was .03023 of a second using the ball drop procedure suggested by Cureton (4).

Beginning with the crank in a vertical position, each location of the crank was recorded as were several surface landmarks put on the subjects prior to filming to indicate joint centers. The location of the surface landmarks and the determination of the centers of gravity were found by using techniques proposed by Williams and Lisner (19).

There was one unaccountable source of error. There appeared to be a shortening of the leg and crank at the top and at the bottom of the pedal revolution. This was present in all male subjects and in the female subjects to a lesser degree. It was not significantly present in the upper part of the body for any of the subjects. One possible explanation was that surface landmarks may have been improperly positioned enough to cause a slight shift when the leg was in different positions. Another explanation may be that the leg may have turned away from the camera at these points in the revolution causing an angle change in relation to the lens.

Subjects

Six cyclists from the Akron Bicycle Club volunteered for this study. All were selected because: (a) of the limited number of subjects available, and (b) one was experienced in riding the rollers, three had limited experience, and the other two had a willingness to learn.

The subjects are referred to alphabetically as subjects A through F. Subject A, Jim Beres, was the model against whom the other cyclists were compared. He used to compete professionally and, not including other accomplishments, won the Budapest-to-Vienna 200 mile race four times--once in nine hours, 22 minutes and 38 seconds, a record that still stands. He has logged over 500,000 miles in his yet unfinished career. All other subjects were recreational/touring cyclists.

CHAPTER IV

PRESENTATION OF DATA

Motion pictures were taken of six cyclists riding rollers to analyze the mechanics of cycling and to compare the results with recommended techniques in most cycling literature. First to be considered, was the mechanics of the bicycle as directly related to the performance of the cyclist. Second, the mechanical analysis of the leg action during pedal rotation was studied. Third, a comparison was made between the leg actions of the subjects and theories commonly found in bicycle literature.

Analysis of the Bicycle

Bicycle Adjustment

Often recommended bicycle adjustments were compared with the actual adjustments, shown in Table 1, of each rider whose bicycle was set according to personal comfort. Recommended adjustments, as found in most cycling literature (1-3, 8-9, 13-17), are as follows:

1. The rider should be able to just straddle the top horizontal bar with both feet flat on the ground if the frame size is correct.

TABLE 1.--Comparison of bicycle adjustments.

	Subjects					
	A	B	C	D	E	F
Frame size (clearance from crotch of subject to top tube)	.25"	.50"	1.0"	0.00"	.50"	.75"
Crank length	6.75"	6.75"	6.75"	6.75"	6.75"	6.5"
Saddle 1	leg straight	leg straight	leg straight	leg straight	Slight bend	leg straight
Saddle 2						
Actual	34.0"	35.0"	35.5"	33.5"	34.75"	33.5"
109%	34.0"	34.8"	36.5"	32.3"	34.8 "	34.0"
Nose of saddle	2.0"	2.25"	2.5"	2.0"	2.75"	2.0"
Handlebars						
Height (in rela- to top of saddle)	Slightly below saddle	Slightly below saddle	2.5" below saddle	even with saddle	Slightly below saddle	even with saddle
Back (degrees from horizontal)	56°	56°	55°	39°	48°	58°
Arms (elbow flexion)	20°	1°	Hyper-extended	5°	19°	10°

2. For Saddle 1 position the leg should be straight when the heel is on the pedal and the pedal is at its lowest point of 180°.
3. Saddle 2 position, measuring from the pedal to the top of the saddle, is set at Vaughn Thomas' (18) ideal saddle height of 109% of the inside leg measurement.
4. The saddle nose should be approximately two inches behind the midline of the crank hangar or bottom bracket.
5. The top of the handlebars should be level or at a point not to exceed two inches below the saddle.
6. The angle of the trunk should be approximately 45° and was measured from the projected image.
7. The arms should be in a natural position and not stiff.

Table 1 presents the actual bicycle adjustment for each rider. Remembering the aforementioned recommended adjustments this table presents the actual measurements for each cyclist and his machine.

All but one of the bicycles were diamond frame models, that is, the men's model in which there is a horizontal top bar. The exception was of mixte frame design in which the top tube is placed at an angle slightly higher than that commonly seen on a girl's model bicycle. Frame size for that bicycle was judged by taping a piece of wood to the place where a horizontal top tube would be attached. The .75 and 1 inch clearances on Subjects C and F might be considered as being outside the range of just barely clearing the top tube.

Crank length is a controversial issue in cycling circles. Unless it is a custom-made bicycle, built with regard to individual measurements as were the bicycles of Subjects A and F, the crank length is pre-determined by the manufacturer.

All of the subjects but one had straight legs when their heel was placed on the pedal at its lowest point of 180°. Such an adjustment should provide a saddle height that permits a slight bend of the leg when the ball of the foot is placed on the pedal. This adjustment and the subject's position of comfort were in agreement.

When the subjects' actual saddle position was compared with Vaughn's (18) 109% of the inside leg measurement (from the crotch to the floor while in stocking feet) no great deviation was found for most subjects. The saddle heights very nearly approached the recommended 109% measurement although Subjects C and D had their saddle 1 inch too low for this standard.

There was variation of the nose of the saddle with half of the subjects having a distance greater than 2 inches. Also, the height of the handlebars was within suggested levels for all subjects. The men all had their handlebars below the saddle whereas both women had theirs even with the top of the saddle.

All subjects but one deviated considerably from the recommended 45° body lean. The riders may wish to experiment with various stem height and length combinations so they can more nearly achieve the 45° riding angle. On the other hand, the recommended lean of 45° may be incorrect.

Deviations from any of these standards did not mean that the adjustments were incorrect and thereby invalidate the data. Deviations from the recommended norms were caused by individual preferences and physical characteristics. However, too great a deviation in any one area should be given closer scrutiny to see if it would be advantageous to make adjustments nearer to those recommended.

Bicycle Resistances

Once the bicycle was set in motion, the rider had to overcome resistances that would affect performance. The figures for these resistances, derived from a study by Fred DeLong, Technical Editor of American Cycling Magazine (5), were used because this particular set of figures coincided with other technical data available and the fact that this area would be a separate study in itself.

"At 20 miles per hour bearing friction uses about 10.2 foot-pounds per second or 7.3% of the total energy supplied by the rider at this speed. Chain and sprocket losses--15 foot-pounds per second or 10%" (5 , p. 21).

The Goodyear Tire and Rubber Company, one of the leading tire manufacturers, ran a test on a Schwinn touring tire to determine its rolling resistance in terms of the number of pounds resistance per 100 pounds of vertical weight (11). Under their test conditions, the rolling resistance was .72/100 pounds. Table 2 shows a comparison of these resistances calculated for all riders (see Appendix for calculation of formulas). It was found that variations in the rolling resistance of the tire, .72/100 pounds, was due to energy loss and tire histeresis and because of differences in vehicle-rider weight.

While bearing, chain, and sprocket losses were assumed constant on all bicycles, there were differences due to the per cent of rolling resistance and the forces necessary to overcome them.

Variations in the ratios of wheel to pedal revolutions were due to different gear ratios between bicycles. The gear ratio is the number of teeth on the front chain wheel to the number of teeth on the rear sprocket. (This term also is used to represent the number of teeth in the chain wheel to the number of teeth on the rear sprocket multiplied by the diameter of the wheel. This latter is the figure most frequently referred to in cycling literature and that with which most cyclists are familiar.)

TABLE 2.--Bicycle resistances.

	Subjects					
	A	B	C	D	E	F
Ratio of wheel to pedal revolution	3.0	3.063	3.50	3.57	3.57	3.063
Rolling resistance lbs./100 lbs.	1.74	1.54	1.584	1.159	1.50	1.138
Rolling circumference of the tire	13.17	13.42	13.21	13.13	13.25	13.45
Pedal radius	6.75	6.75	6.75	6.75	7.0	6.5
Force to overcome rolling resistance	10.19	9.37	10.85	8.05	10.14	7.213
Force for bearing, chain and sprocket losses	16.03	14.74	17.07	12.66	15.95	11.35
Lbs. force needed to maintain momentum	26.22	24.11	27.92	20.71	26.09	18.56

The rolling circumference was a measurable distance and another area of consideration at this time. The tire was marked and, with the rider sitting on the saddle, the beginning and ending points of one wheel revolution were marked on the ground. The rolling circumference was the distance between these two marks. The differences were due to changes in tire deflection which is dependent on total weight even though all rims were the same size.

Crank lengths, or pedal radius, were determined, for the most part, by the manufacturer. Four subjects had identical crank lengths of 6.75 inches, one had a crank length of 7.0 inches, and another had a crank length of 6.5 inches.

Momentum

Forces Affecting Momentum

Newton's first law states: "A body at rest will remain at rest and a body in motion will continue in motion with constant speed in a straight line, as long as no unbalanced force acts on it" (15, p. 50).

On the basis of all the resistances previously mentioned, the amount of force needed to maintain momentum was determined and is as follows: Subject A - 26.22 lbs.; Subject B - 24.11 lbs.; Subject C - 27.92 lbs.; Subject D - 20.71 lbs.; Subject E - 26.09 lbs.; and Subject F - 18.56 lbs. This was the amount of force needed to maintain constant velocity, irregardless of pedal position, once momentum was established. Because the two female cyclists, Subjects D and F, required less force to overcome chain, sprocket, bearing and rolling resistances that involved body weight, they needed less overall force to maintain momentum.

The maximum force due to weight which can be applied, assuming both feet are on the pedals, is the individual's weight minus the weight of one leg. This maximum force occurs when the rider is lifted completely off the seat and the non-driving leg is merely dead weight. The maximum force, or net weight, for each subject under these conditions was as follows: Subject A - 131.3 lbs.; Subject B and C - 155.5 lbs.; Subject C - 165.7 lbs.; Subject D - 118.1 lbs.; and Subject F - 111.9 lbs. While cyclists do not stand while riding the rollers, some do when climbing hills and for changes of position on long rides.

The greatest amount of effective force due to weight for all cyclists was needed when the crank was at approximately 40° and 160° from the vertical position. Before and after these points, force in excess of that which could be applied was required. Points at the top and bottom of the revolution (0° and 180°) are called "dead centers" (7) and depend on momentum of the system of the entire bicycle to carry the crank through.

Optimum force, whether standing or sitting, is applied when the pedal nears 90° and the weight of the person affects this force proportionally. The force of the rider at the three points of contact--handlebars, seat and pedal--were determined mathematically for each frame of the projected image. A force drawing using these original drawings was made for each recorded crank position of the first half of the pedal revolution. Figure 4 shows the necessary points of measurement for this. Figures A3, A4, and A5 in the Appendix shows the resultant figures determined from the force drawings. Related formulas may also be found in the Appendix.

Table 3 compares the body weight on the seat, handlebars and pedals of all subjects at four important areas in the crank rotation. Complete data for each recorded crank position may be found in the Appendix. All subjects were seated.

The forces on the handlebars varied for all subjects. It was assumed for purposes of this study that the force on the handlebars remained constant and that changes were due to extraneous body movement.

Forces on the seat varied with leg motion. There was unweighting on the seat when the crank was near the top of its revolution. As the leg pushed nearer to the 135° crank position there was a small but gradual increase in the amount of weight on the seat. A decrease in weight appeared again as the crank moved from the 135° to the 180° crank position. It could not be determined as

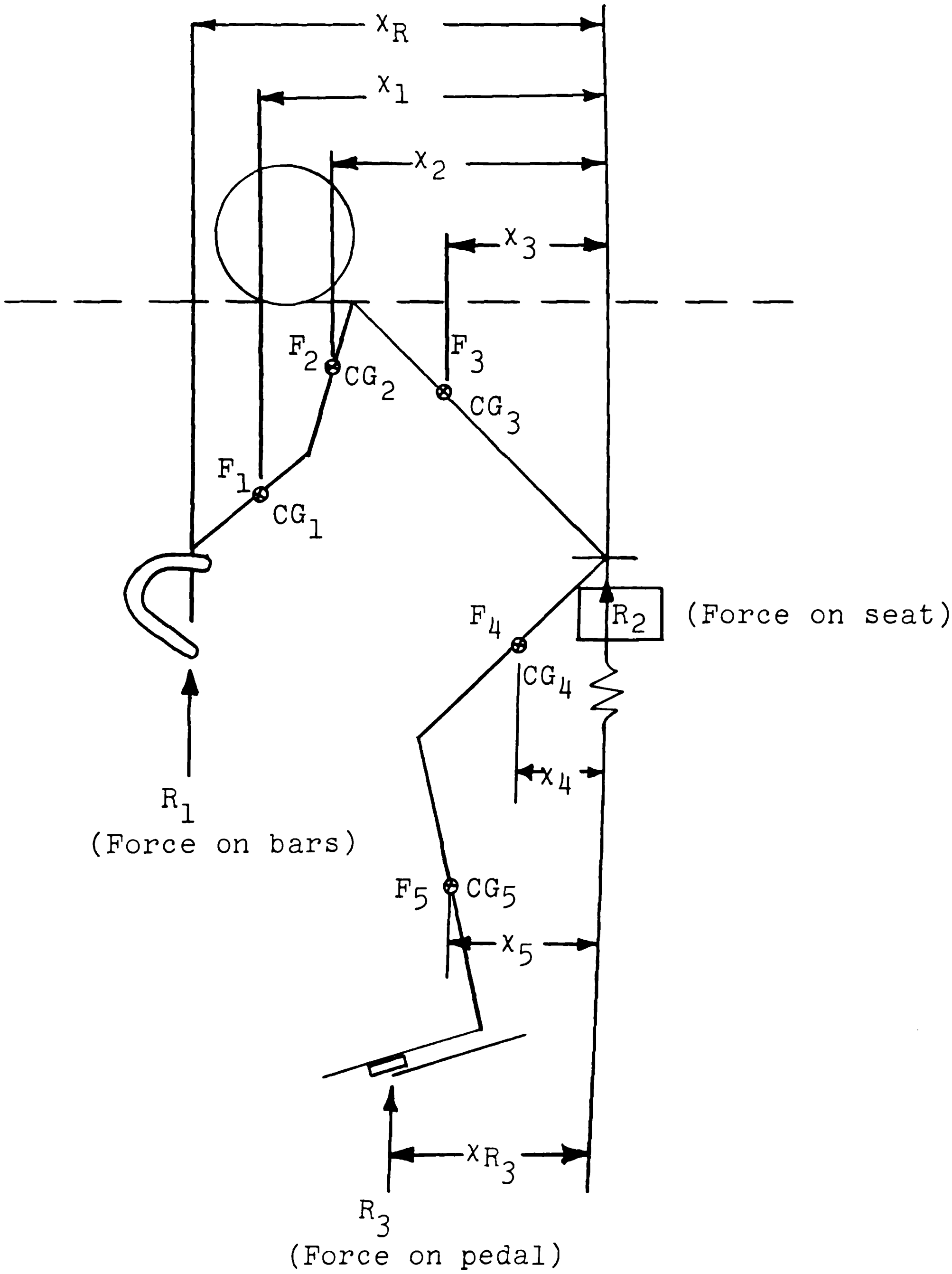


Figure 4.--Force diagram for determining moments.

TABLE 3.--Body weight on handlebars, seat and pedals.

Force (Rider Seated)	Subjects A	B	C	D	E	F
Total Body Weight	156	185	197	140	185	133
% Net Body Weight on Handlebars						
45°	13.7	11.6	12.1	15.8	12.0	13.4
90°	12.9	11.5	12.0	15.2	13.2	13.3
135°	12.9	11.0	11.7	15.3	13.1	13.3
180°	12.9	11.0	11.7	15.3	13.1	12.8
% of Net Body Weight on Seat						
45°	53.6	59.6	61.9	51.4	60.0	54.0
90°	57.6	65.7	64.7	56.6	60.5	59.4
135°	62.3	66.3	67.2	58.6	62.9	61.7
180°	60.6	63.0	64.1	52.3	61.4	60.0
% of Net Body Weight on Pedal						
45°	12.0	10.7	10.9	11.5	12.1	10.8
90°	10.2	8.7	8.1	8.7	9.0	8.4
135°	8.5	8.4	7.2	7.6	8.0	7.5
180°	9.3	10.0	8.7	8.3	8.7	8.5
Actual Net Body Weight on Pedal in lbs.						
45°	18.8	20.9	21.4	16.1	22.4	14.4
90°	16.0	15.9	16.0	12.2	16.7	11.4
135°	13.2	15.5	14.2	10.7	14.6	10.1
180°	14.6	18.5	17.2	11.6	16.0	11.7

to how much the opposite leg affected the changes in weight on the seat.

Load on the pedal varied due to the severe changes in the horizontal crank position. As force is applied to the pedal to maintain velocity, the force that the rider has available is due only to his ability to transfer his weight from the seat to the driving leg.

Velocity

The pedalling rate in the study refers to the speed with which the crank rotated. The speed used was such that it permitted good balance on the rollers but was not so fast as to cause undue fatigue. One influencing factor on speed was the gear ratio used. Too high a gear ratio would increase the pedal resistance and raise the amount of force necessary to maintain momentum.

Too low a gear ratio would lower the force necessary to maintain momentum. In that case, the subject in trying to keep steady pressure on the pedals would have to spin the cranks too fast. This would cause bouncing on the seat and random movements throughout.

Each subject used a gear ratio that permitted him to have enough speed to maintain good balance and yet not tire before the end of his three-minute filming period. The gear ratio chosen and the resulting speeds are shown in Table 4.

TABLE 4.--Pedalling rate and velocity.

Subject	Subjects					
	A	B	C	D	E	F
Gear ratio	3.11:1	3.06:1	3.50:1	3.57:1	3.57:1	3.06:1
No. of frames for one revolution	30	32	37	45	48	39
Time/sec. of pedal Revolution for one frame	.907	.967	1.119	1.36	1.451	1.18
Revolutions per minute	66.15	62.05	53.80	44.13	41.35	50.85
Miles per hour	15.56	15.06	14.70	12.26	11.67	12.71

It was previously stated in the Review of Literature that one source maintains that a person operates most efficiently at 55 to 85 revolutions of the crank per minute (RPM) (8). Another source indicated greatest muscular efficiency at from 42 to 60 RPM (6). While this is an area of study in itself, it might be interesting to note that the lowest RPM for the subjects was 41.35 and the highest 66.15. This would seem to indicate that some of the subjects were not operating efficiently according to either criterion. However, all subjects were riding a higher gear ratio on the rollers than they would under normal riding conditions. It must be assumed that, under normal riding conditions, the subjects would be riding one to two gear ratios lower. This would permit an easier and faster pedalling rate referred to by cyclists as "spinning." This might well permit the riders to fall into the suggested RPM ranges for maximum efficiency previously mentioned.

The velocity of each change in crank position was found for each rider and interpreted in terms of feet per second. Figures 5 through 10 show the velocity patterns during one pedal revolution of each rider. The irregularities were due in part to measurement error and were averaged out in some sections of the graph. The first 50°, 100° to 200° and from 275° to 360° represented the areas of greatest fluctuation. It should be noted that Subject A, the best rider, had the least overall variation in velocity. This, of course, was expected. Every change in velocity represents an individual expenditure of energy according to Newton's second law. Subject A was the most efficient rider according to his velocity curve.

Analysis of the Cyclist

Analysis of Knee Action as Related to Crank Position

Subject A was compared to each of the other six subjects in regard to knee action relative to crank position.

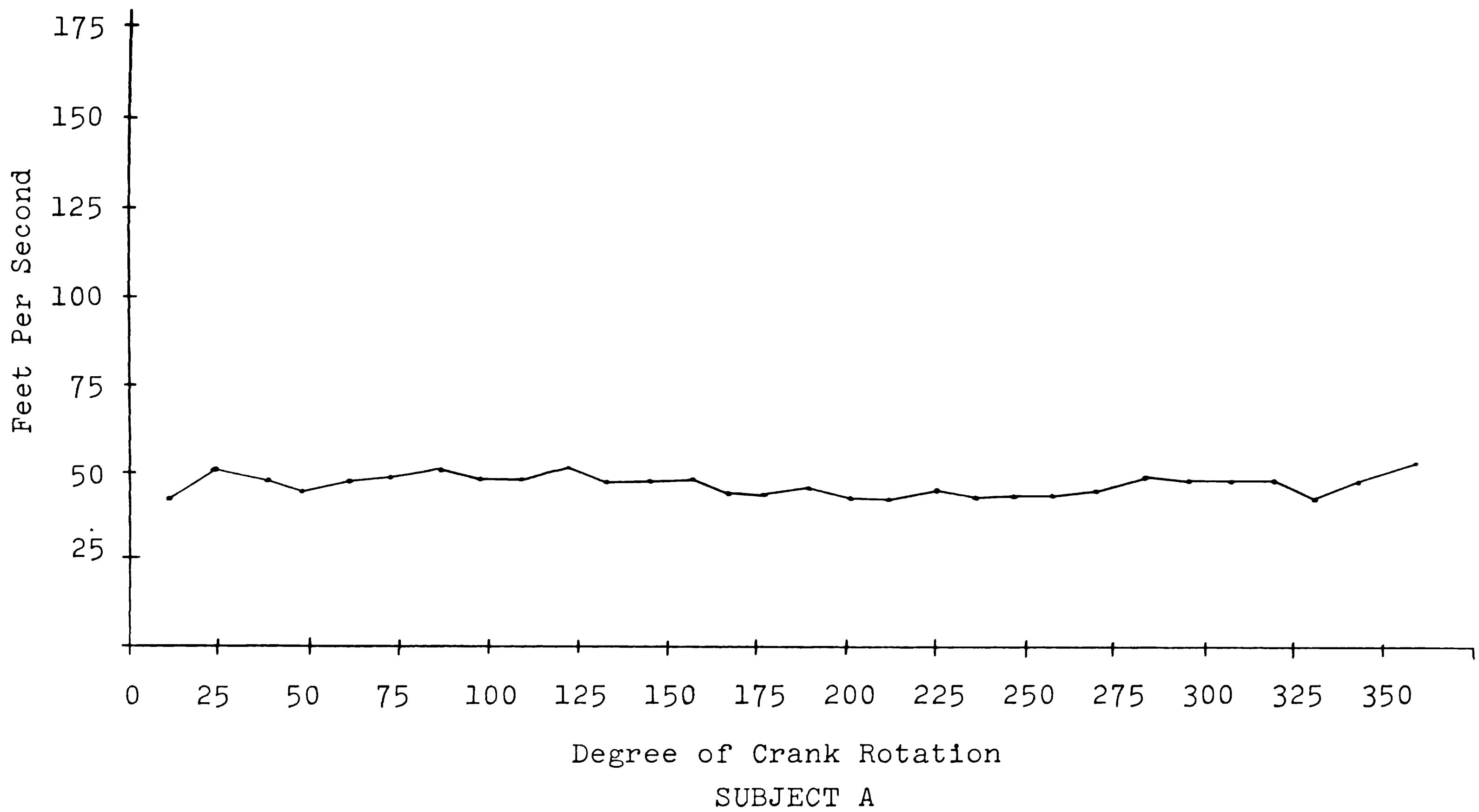


Figure 5.--Velocity of crank rotation.

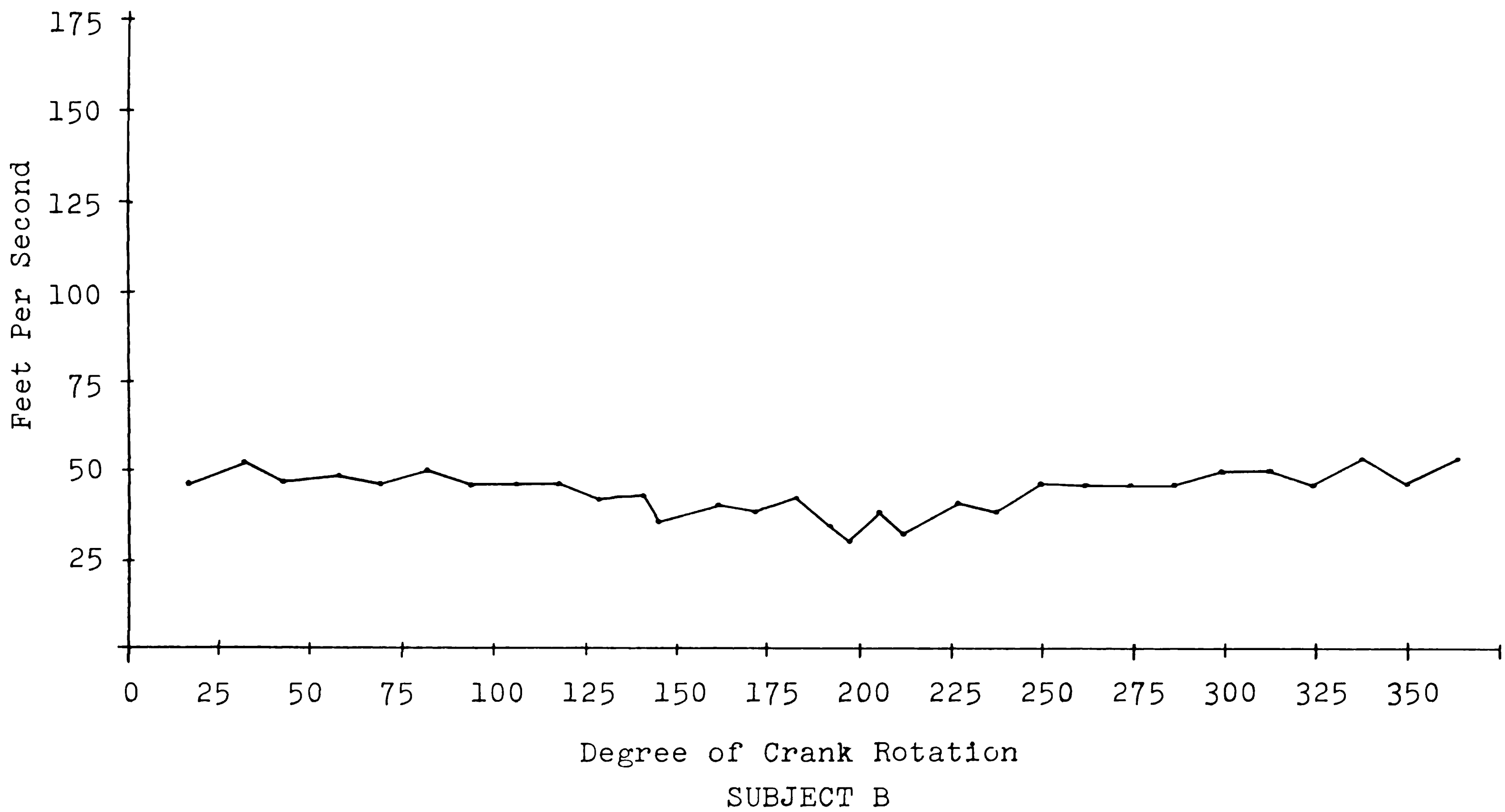


Figure 6.--Velocity of crank rotation.

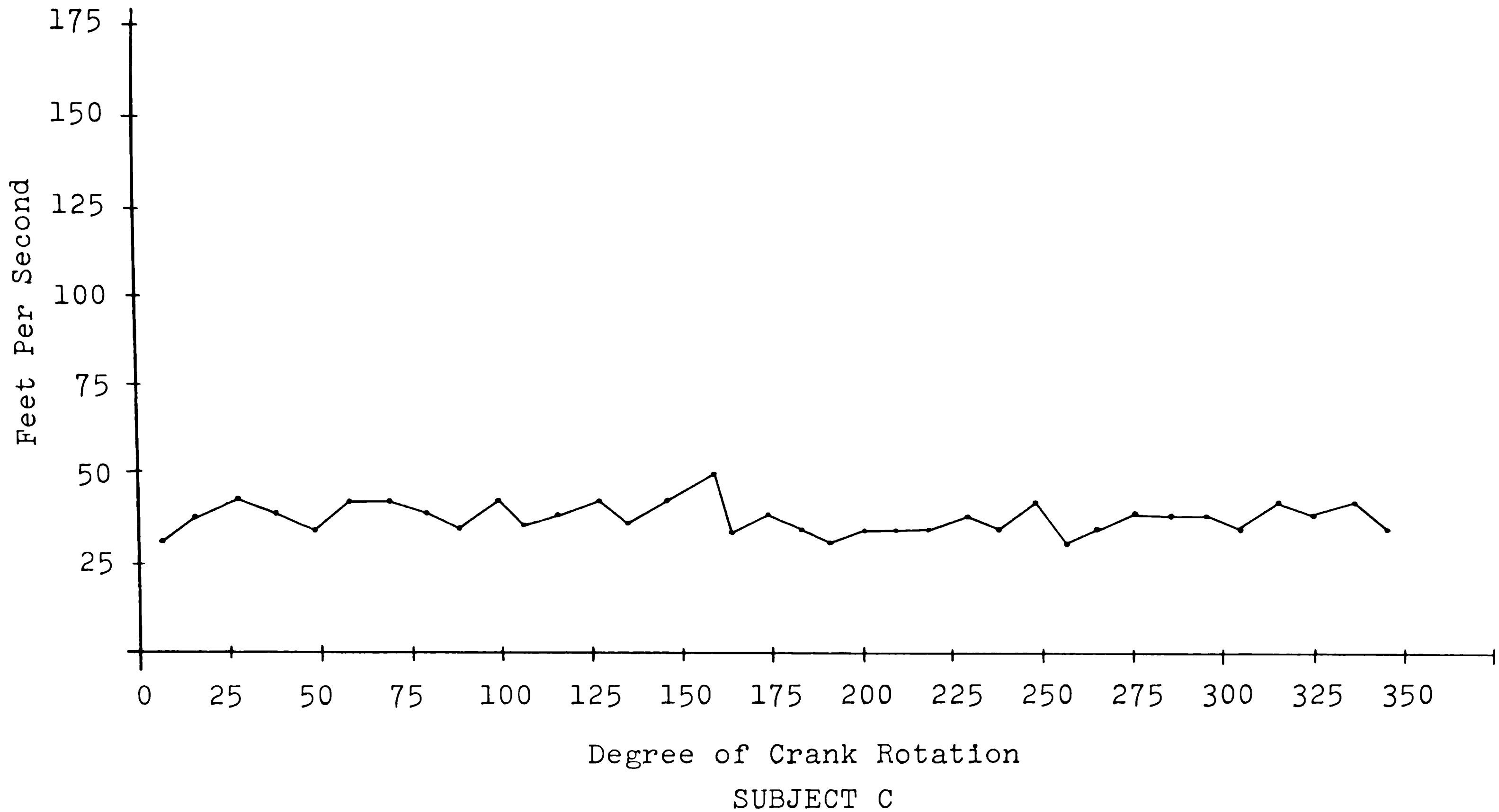


Figure 7.--Velocity of crank rotation.

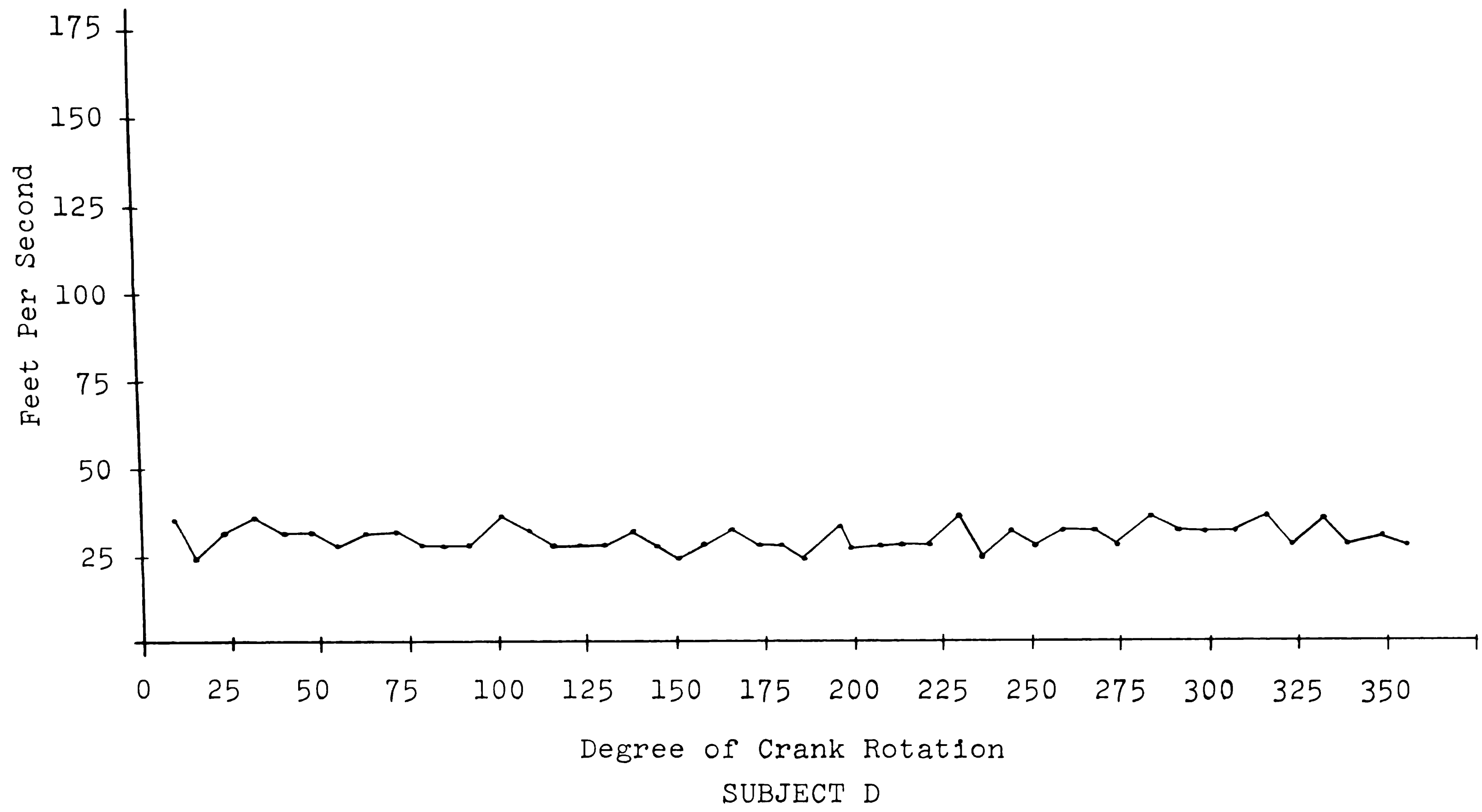


Figure 8.--Velocity of crank rotation.

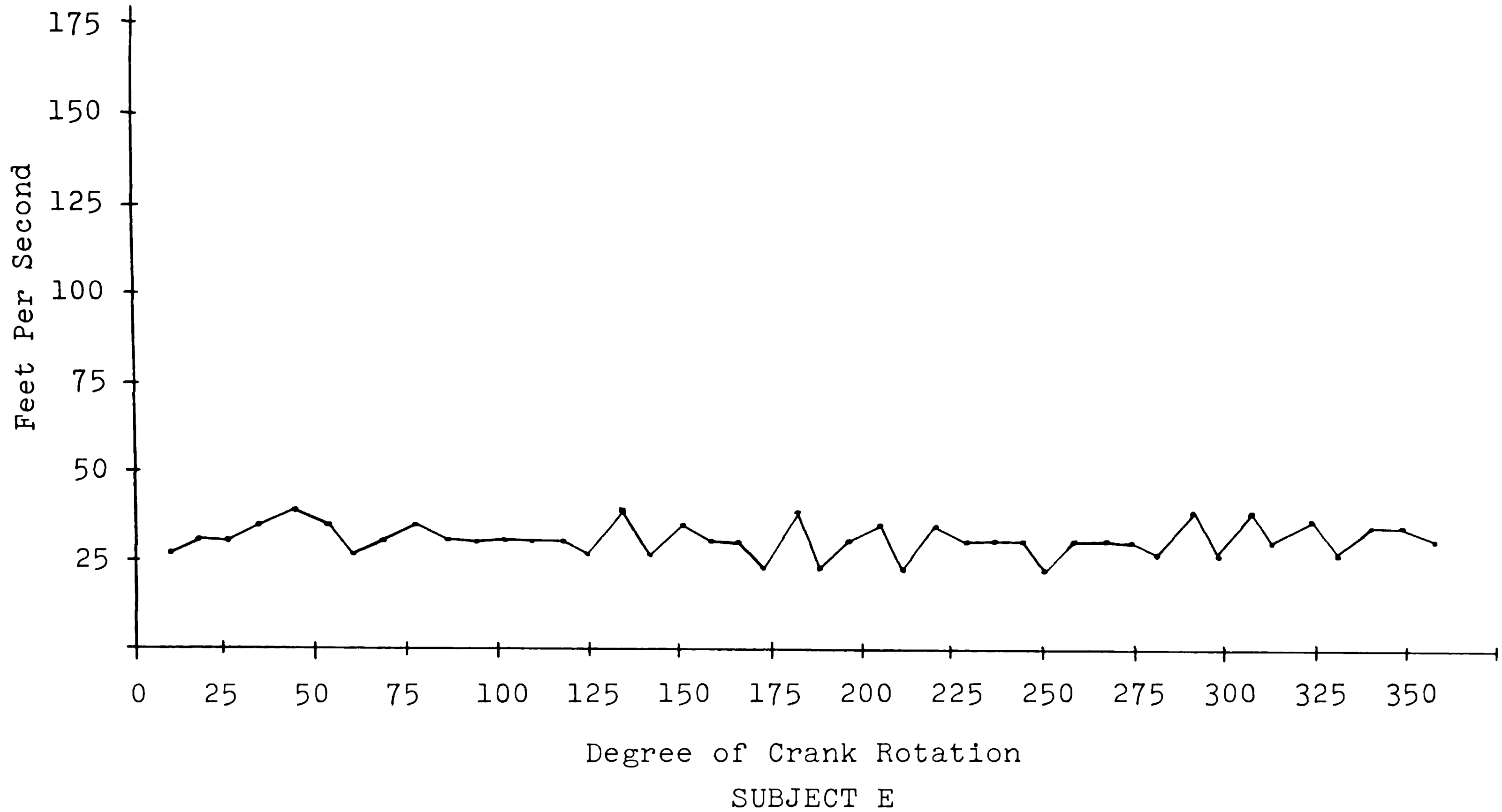


Figure 9.--Velocity of crank rotation.

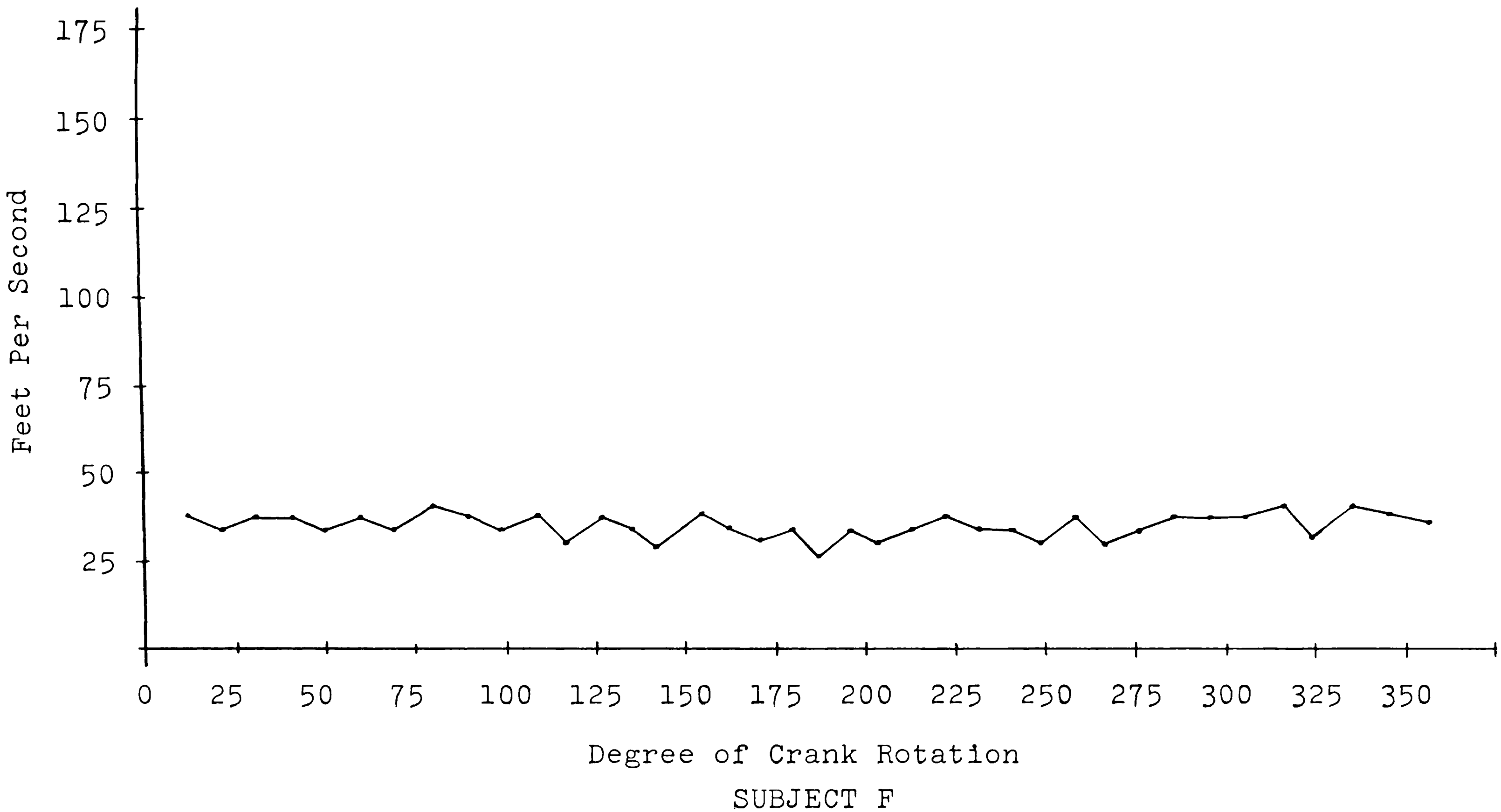


Figure 10.--Velocity of crank rotation.

Reference to Figures 11 through 16 and Figure A2 in the Appendix will facilitate understanding of the movement patterns made by the knee and foot as related to the crank positions during one pedal revolution.

The amount of knee flexion at the top of the pedal revolution was very nearly 75° for all subjects. Beginning with the pedal in a vertical position, the leg action of Subject A was smooth and continuous throughout. Maximum knee extension was at the crank position of 145° whereupon the leg angle remained constant as the crank rotated through another 22°.

Maximum knee extension was reached at a different crank position for each subject but was, in all cases, before reaching the halfway point in the pedal revolution. On the basis of information taken from the graphs in Figures 11 through 16, the black bar in Figure 17 presents a comparison of these points in the pedal revolution.

Table 5 shows that Subject A reached maximum knee extension at the 145° crank position and Subject C did so at the 174° crank position. All other subjects reached maximum knee extension within the range of the 145° and 174° positions of Subjects A and C.

Knee flexion for all subjects but one was begun before the 180° crank position. Subject C was the exception at 186°. Both Subjects A and D began knee flexion at the

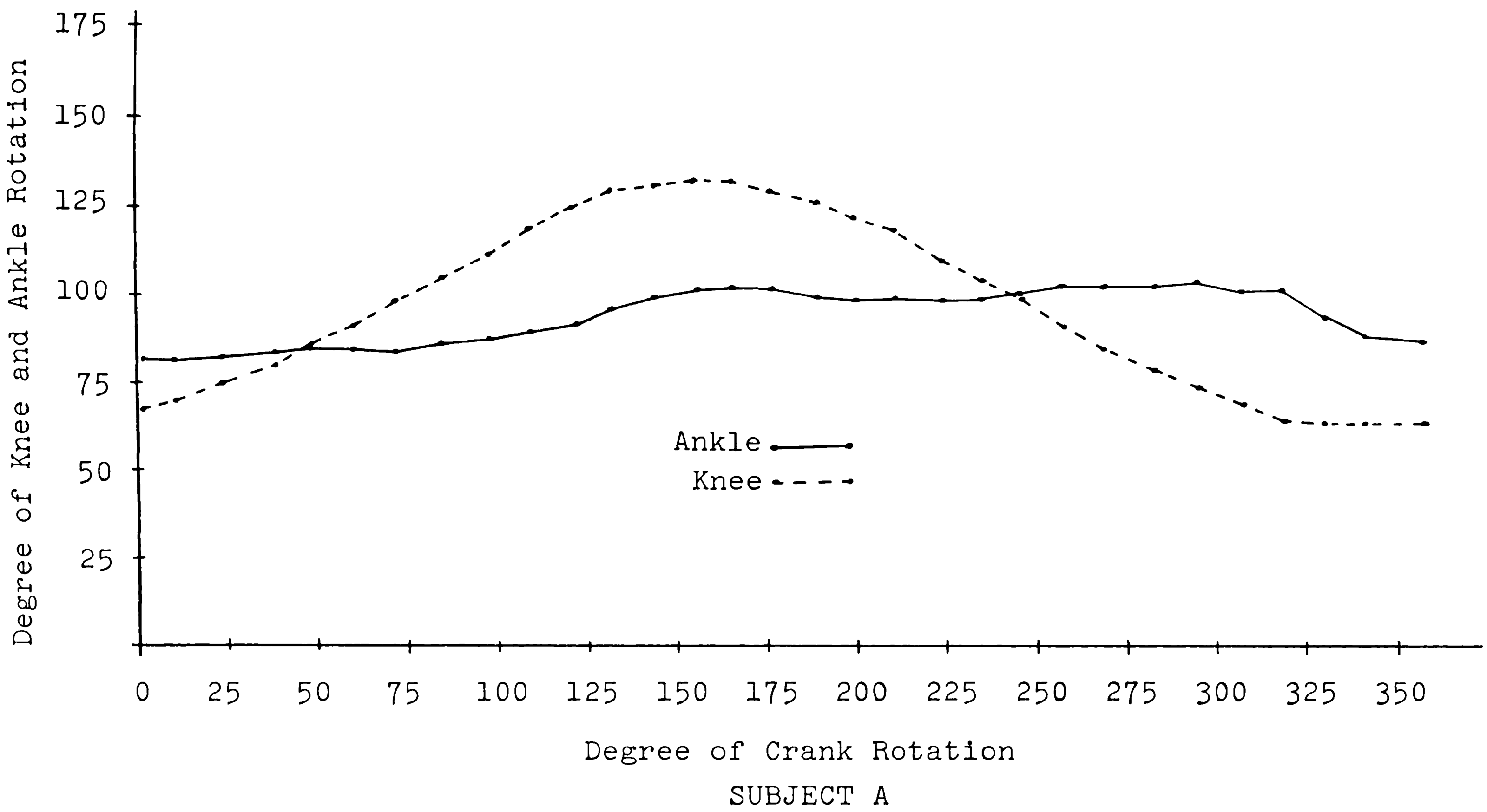


Figure 11.--Relation between knee, ankle, and crank positions.

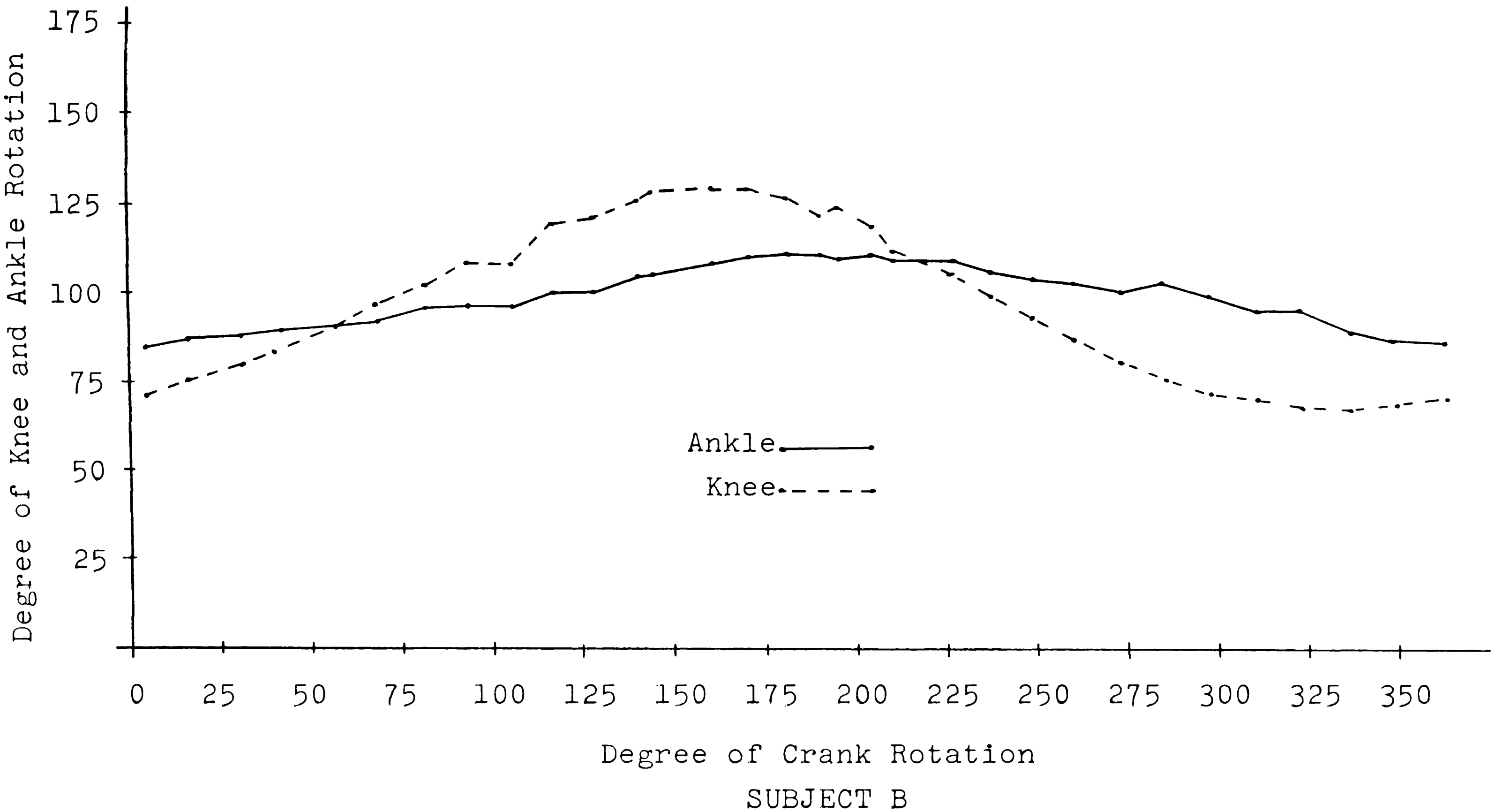
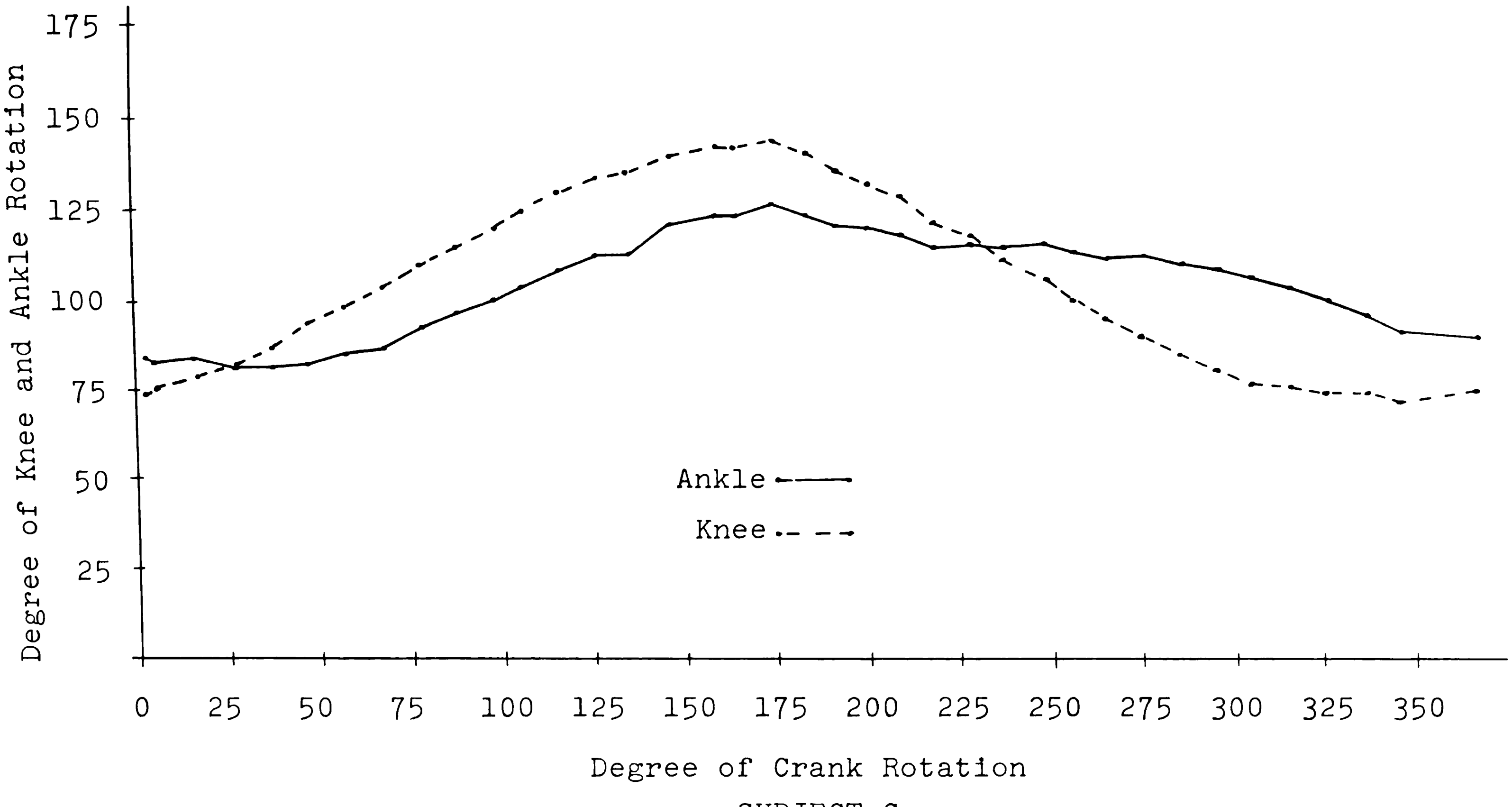


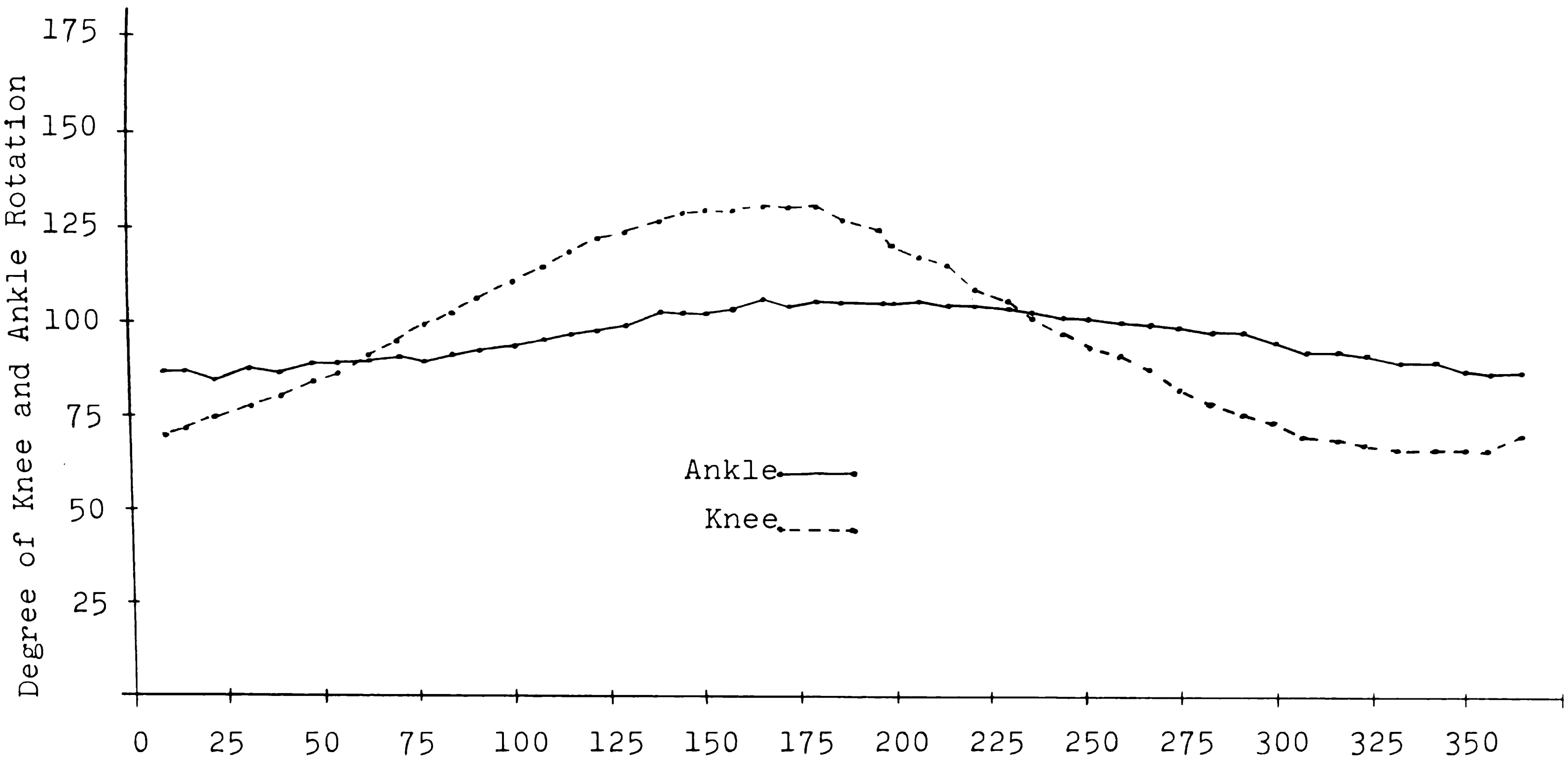
Figure 12.--Relation between knee, ankle, and crank positions.



SUBJECT C

Figure 13.--Relation between knee, ankle, and crank positions.

Figure 14.--Relation between knee, ankle and crank positions.



SUBJECT E

Figure 15.--Relation between knee, ankle, and crank positions.

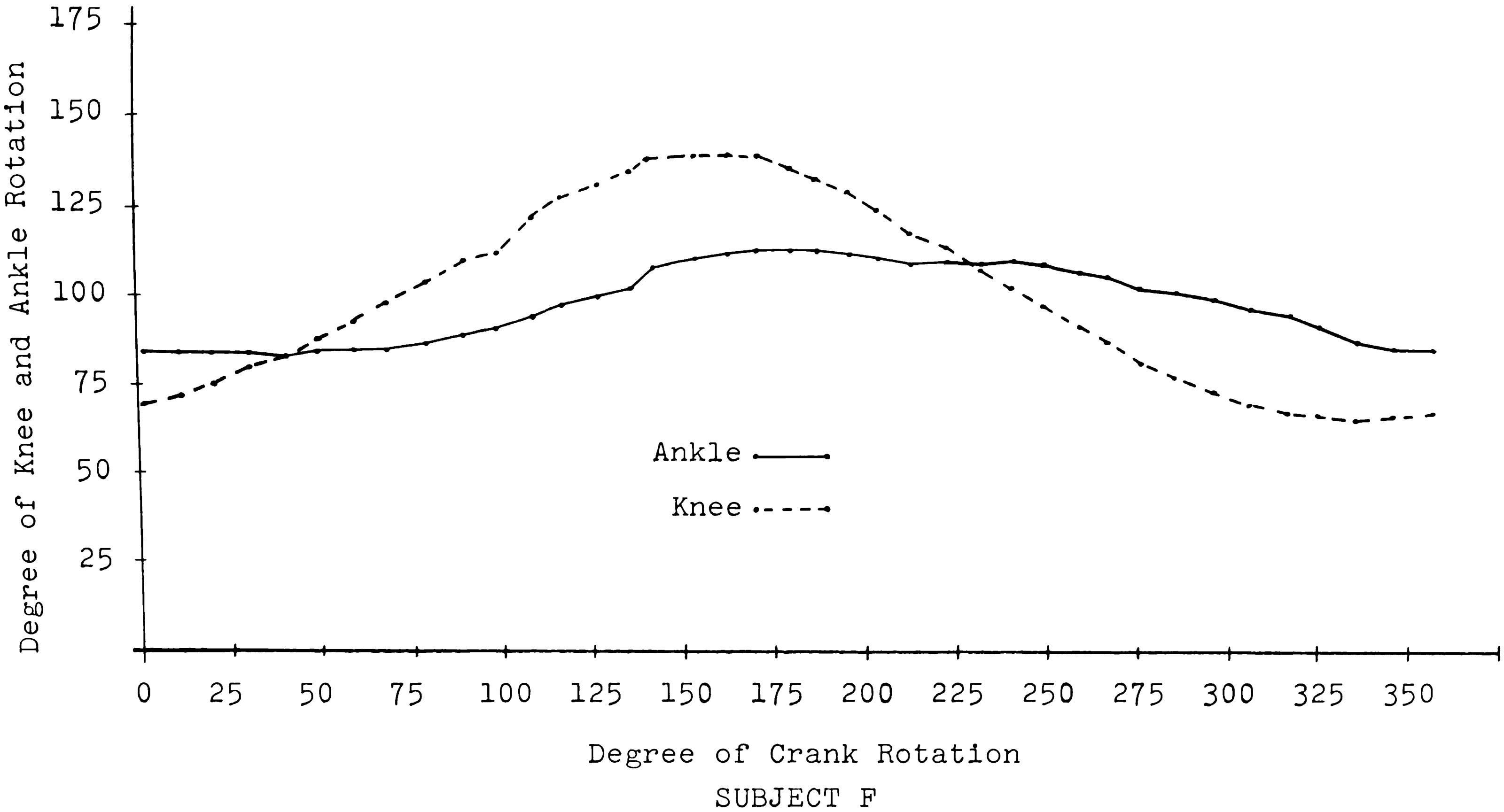


Figure 16.--Relation between knee, ankle, and crank positions.

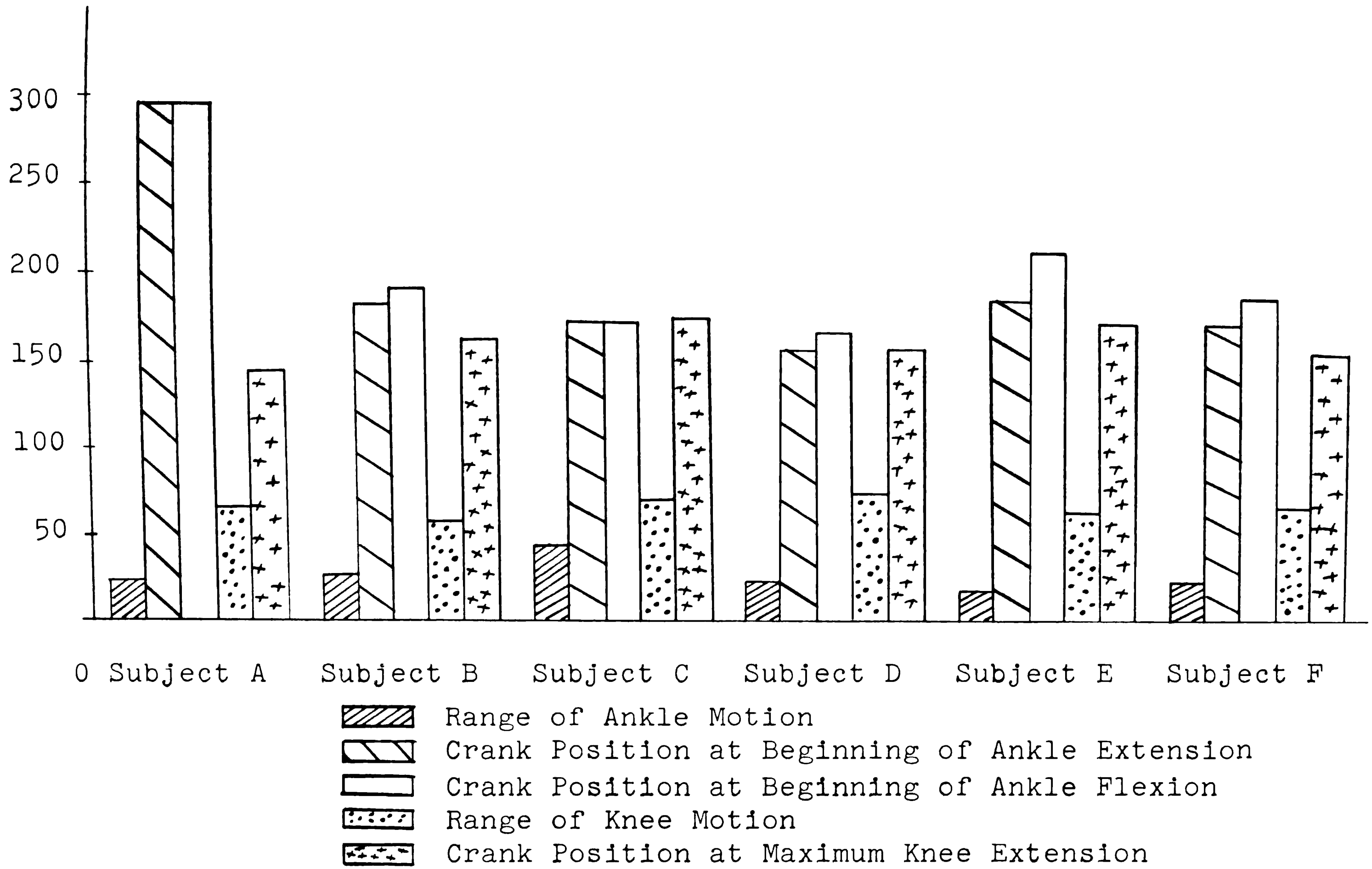


Figure 17.--Comparison of important points of flexion and extension of the knee and ankle in degrees.

TABLE 5.--Comparison of knee flexion and extension.

Crank Positions in Degrees	Subject A	B	C	D	E	F
Crank position of maximum knee extension	145	162	174	159	173	154
Crank position at start of knee flexion	167	172	174	167	186	171
Range of movement during maximum knee extension	22	10	0	8	13	16

167° crank position. Subject F started knee flexion at a position of 171° and Subject B at 172°.

Except for Subject C, all other subjects held a constant angle during maximum knee extension as the crank continued its rotation. This range of movement varied from the 8° of Subject D to 10° by Subject B, 13° by Subject C, 16° by Subject F and 22° by Subject A.

It should be noted that Subject A reached maximum knee extension earlier and maintained that position longer than any of the other subjects. Very likely, these are two characteristics of efficient cycling.

Comparison of the range of knee extension from its flexed position at the top of the pedal revolution to its point of maximum extension may be found in Figure 17. Subject A extended his leg over a range of 65°, to 58° by

Subject B, 70° by Subject C, 69° by Subject D, 61° by Subject E and 67° by Subject F.

At the approximate crank position of 90°, three of the subjects--B, D and F--broke the continuous flow of knee extension and either held the same knee angle as the pedal continued on around or changed only slightly. The other three subjects held a smooth knee extension pattern.

During the last half of the pedal revolution, Subject A's movements were still smooth and continuously changing until approximately 320°. The knee flexion on the recovery, or last half of the pedal revolution, covered a range of 180° to 320°. For the remaining 40° of the pedal rotation a constant knee flexion of 65° was maintained.

All of the other cyclists had one or more position changes interrupting the pattern of gradually increasing flexion. The pattern did, however, continue smoothly in between these deviations. Subject F had such an irregularity at 223° and Subject B had one at 192°. Subject C experienced such irregularities at four points--220°, 248°, 304° and 325°; D slightly at 251° and 291°; E fluctuated throughout the entire last half of the pedal revolution.

Maximum knee flexion was achieved for three subjects at a crank position of 320° to 325°. Subject E experienced this at 332", F at 336° and Subject C at 345°. As

Figures 11-17 show, this maximum flexion was not held through to the top of the stroke except in the case of Subject A. All other subjects began leg extension before the full 360° of the pedal revolution had been achieved.

Analysis of Ankle Action as Related to Crank Position

At the top of the pedal revolution, Subject A had the ankle flexed to a greater degree than at any other place in the stroke. This dropped the heel and raised the toe. As the pedal rotated, extension of the foot was very gradual until the approximate crank position of 73°, whereupon it became more pronounced. The graph in Figure 11 shows that the ankle continued to extend in an almost stairstep pattern until the 296° crank position which marked the point of maximum ankle extension. The heel made a pronounced drop at 320° as it neared the top of the revolution. Subject A reached maximum foot extension later and maintained the process of foot extension longer than the other cyclists.

At 48° and 248° the foot and knee of Subject A were at almost identical angles with each other. These were also the approximate points where the amount of force on the pedals required to maintain momentum began to level off and approach a minimum value and where more effective propulsive force might begin to be applied.

All the other subjects followed the same pattern of greatest ankle flexion at the top of the stroke. As the foot extended there was a slight heel drop preceding each change in extension. Maximum extension was reached by Subject D at 167°, by C at 174°, by F at 187°, by B at 206° and E at 214°. Maximum ankle extension could be said to begin at an average 206° crank position. Graphic comparisons may be found in Figure 17.

Subject C had the greatest range of ankle motion with 45°. His foot extension began at 69° and continued until his maximum value was reached at 174° which was slightly later than that of the others. His heel drop began immediately after reaching this peak. At 215° the abrupt change steadied and a more gradual flexion finished the revolution. Comparison of these points of ankle flexion may also be found in Figure 17.

From this study, it would appear that the magnitude of ankling is not as important as the duration of ankling.

Analysis of Leg and Foot Action in Relation to Crank Position

Combining the two, both the knee and ankle are flexed at the top of the crank revolution and as the leg extends so does the foot. The toe of the foot presses down as the heel lifts. The knee reaches maximum extension before the half way point of the revolution or at approximately 161.2°. It does not really change position as it passes through the bottom part of the stroke and as the foot presses down and back.

The foot did not reach full extension until near the bottom half of the revolution. Subject A, however, reached full extension later in the stroke. The heel was raised and the toe pointed downward as the foot pulled up. The foot can pull up more effectively with cycling shoes equipped with cleats, toe clips, and straps. The foot flexes in a sudden change near the end of the stroke to get the foot behind the pedal so as to assist in pushing it into the next revolution. This is also the point where the knee has reached maximum flexion.

It must be assumed that the other leg has identical action. Thus, while the left leg and foot is at its point of maximum flexion when the crank is at zero degrees, the right knee has already begun flexion for the recovery part of the stroke. The foot is pressing back and is near its maximum extension with the right crank at 180°.

The pressing back and pulling up with one foot and pressing forward and down with the other combine to carry the momentum of the pedals past the dead centers and to make the recovery leg effective over a wider range. For example, instead of stopping at 180° or before, the foot can pull up until 320° to 345° before dropping the heel in preparation for the next crank rotation.

Leg Action Comparison with Other Cycling Literature

The Athletic Institute publication (2) presents detailed ankling techniques for the recreational rider and the racing cyclist. The first half of the stroke is supposed to be the same for both, but the racing cyclist, aided by toe clips and straps, is able to pull up on the second half of the revolution. The recreational rider having no toe clips is unable to exert an upward pull. The subjects in this study all used toe clips and straps and were compared to the racing cyclist.

The publication stated that power was applied just after twelve o'clock, or at 15°, to a point more than half way around. Considering the amount of force which could effectively be applied, Table 6 shows that the subjects in this study could not apply force until later in the pedal revolution. They were unable to apply effective force until an average 41° crank position, 44° if Subject A was considered. Subject A could not apply effective force until 61° which was even later still. His whole range of effective force was not as great as the other subjects and, being at the extreme range in relation to the other subjects, was figured separately in the overall average.

They were unable to apply force effectively past an average of 180° insofar as actual pounds of pressure

TABLE 6.--Range of effective force during first 180°.

Degrees of Force	Subjects					
	A	B	C	D	E	F
Beginning of effective force	61	43	38	45	40	41
End of effective force	167	183	174	183	180	180
Range	106	140	136	138	140	139

were concerned, except for Subject A who only went to 167°. If all six subjects were considered the bottom range of effective force would be 178°.

Another area of comparison was in ankle extension. The Athletic Institute (2) said that the ankle was fully extended at 180°. The findings of this study, however, revealed that all of the subjects reached maximum ankle extension at different crank positions. Two subjects--Subject D at 167° and Subject C at 174°--reached maximum ankle extension before the 180° crank position. Subjects A at 296°, E at 214°, B at 206° and by F at 187° all reached maximum ankle extension after the 180° crank position. Ankle flexion began in varying degrees immediately after these points of maximum extension. Maximum ankle extension could be said to begin at an average 206° crank position.

The other sources related the process of ankling more simply (1, 3). In essence they stated that the toe is raised on the upstroke and presses the pedal forward. At approximately 90° the foot is horizontal. The toe is pointed down at the bottom of the stroke and draws the pedal back.

Shaw (16) carried it further by adding that actual pressure on the pedal begins just before reaching the top. The leg begins to straighten at the same time the foot presses forward and downward. He too says the foot is in a horizontal position at approximately 90°. The foot begins to press back with the toes while the leg continues to push downward. Also, the better the angle through which the foot moves in relation to the lower leg the more it contributes to the success of the process of ankling.

These sources did not interpret what is meant by the foot being in a horizontal position at 90°. It is assumed that the 90° angle represents the crank position. But, it is questionable as to whether this means for the foot to be horizontal with regard to a horizontal reference line or horizontal in relation to the lower leg. Irregardless of position, the statement with regard to this study can be construed as incorrect. The heel was elevated above a horizontal reference line in each subject enough so that it could not be truly considered to be horizontal at 90°.

Table 7 compares the position of the foot in relation to the lower leg at the point at which the crank was closest to 90°. Subject A would most closely conform to this 90° position, but overall there was too great a difference for the foot to be considered horizontal at 90°.

TABLE 7.--Comparison of crank and ankle positions closest to 90°.

Category (in degrees)	Subjects					
	A	B	C	D	E	F
Crank position (in degrees) closest to 90°	86	94	88	94	92	90
Angle of ankle in relation to lower leg	87	81	77	83	77	75
Crank position at 90° ankle angle	111	12	66	21	59	85
Angle of ankle in relation to lower leg closest to 90°	90°	90°	93°	90°	90°	91°

The other comparison was of the ankle position closest to 90° and its related crank position. The figures in Table 7 show that the foot does reach a 90° angle in relation to the lower leg but the crank position, on the whole, could not even be considered to be closely approaching 90°. There was a wide range of crank positions for all subjects. Subject F, however, very nearly approaches a 90° ankle position when the crank was at 90°.

It must be assumed then that the subjects in this study did not achieve a true horizontal foot position when the crank was at 90°--either with regard to a horizontal reference line or in relation to the lower leg.

Porter (13) stated that the cyclist was able to apply force through one half or more of the crank rotation. At 90° the toe and heel are level, and that was the point where work was the easiest and most effective. He also stated that without good ankle action, power is applied through only 150° to 180°; but with good ankling, force could be applied through 200° to 220°.

The actual force that could be applied effectively did not appear to be one half or more of the pedal rotation in this study. The majority of the subjects approached a range of only 140° of the pedal rotation. The amount of force at the bottom of the stroke as the foot pressed back and as it pulled up during the last half of the revolution could not be determined within this study.

Porter (13) devised a pedal from which he could record the force being applied to the pedal. This writer had to assume that, during the last half of the pedal revolution, the subjects were, in fact, pressing back and pulling up to help carry the foot past the 180° crank position. The foot continued to pull up until the point of heel drop anywhere from 320° to 345°.

Assuming no momentum, Figures 18 and 19 show how much force had to be applied at each crank position within the area of effective force of each rider. The female cyclists had a lower overall force requirement than did the male cyclists, but their individual weights were also lower.

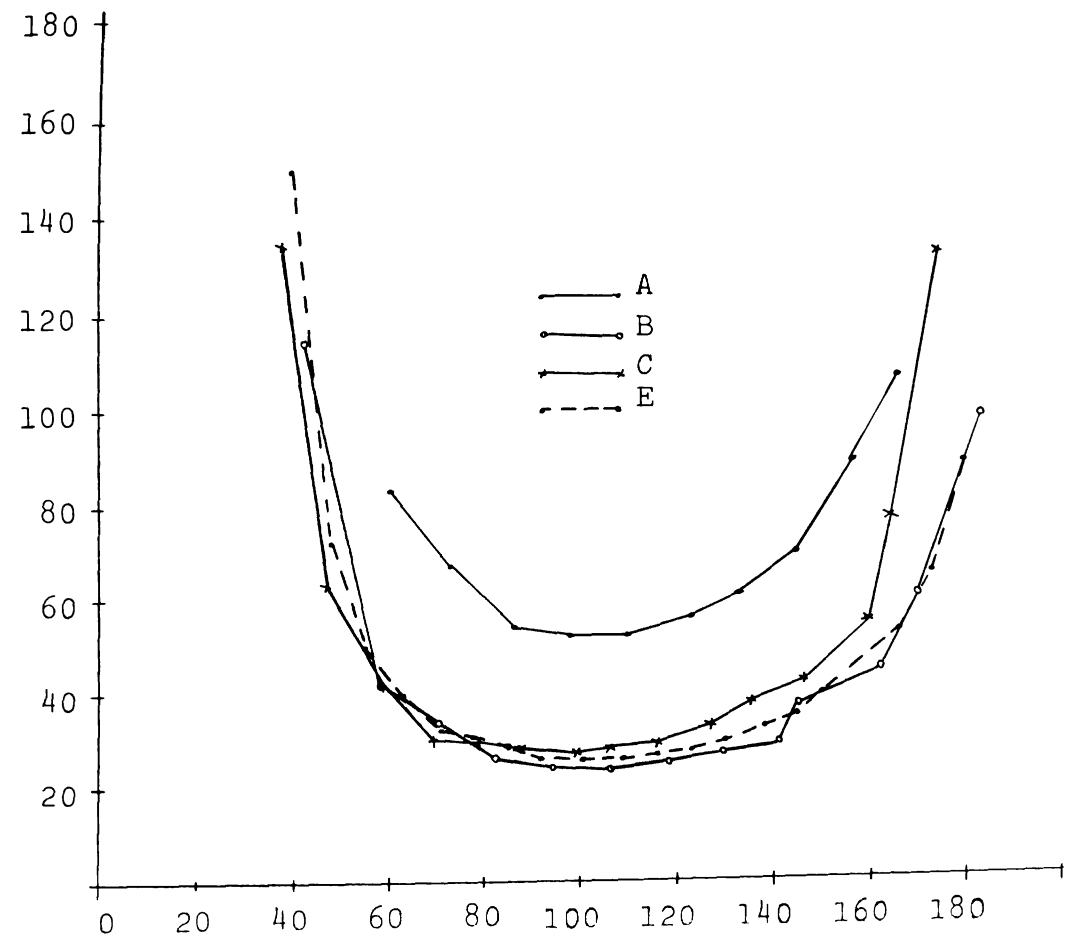


Figure 18.--Force needed to overcome resistances when there is no momentum male cyclists.

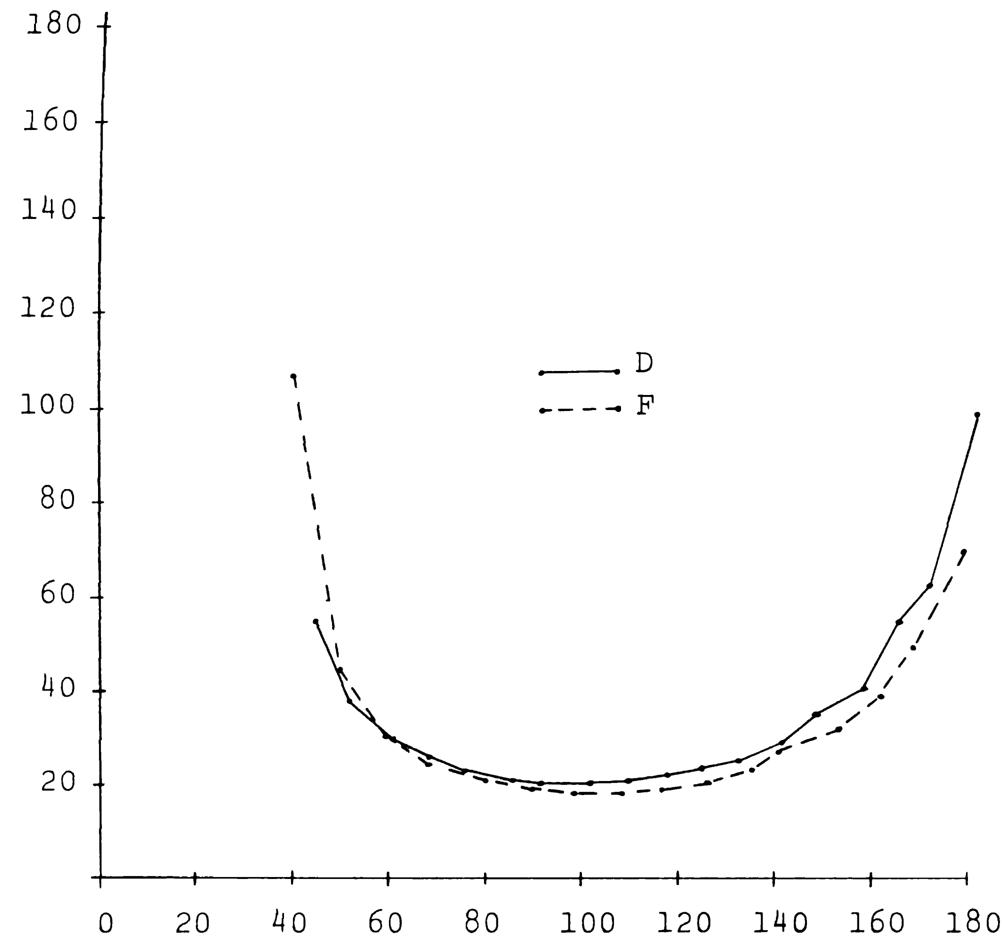


Figure 19.--Force needed to overcome resistances when there is no momentum female cyclists.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Certain theories have been formed as to the mechanics of cycling, but no evidence was found to support these theories using a cinematographic analysis. Conceptions commonly found in most cycling literature are that (a) there is an important relationship between the rider and his bicycle, especially at the three points of contact--the handlebars, seat and pedals; (b) the most critical factor in cycling is the leg action; and (c) the degree of ankling contributes to the rider's efficiency.

Six subjects from the Akron Bicycle Club volunteered and were filmed for the study. The cyclists rode on rollers, a mechanical device for indoor training. The film was analyzed frame by frame with the patterns of the leg action plotted on white paper.

Conclusions

On the basis of observations and data taken from this study, the following conclusions were drawn:

1. The recommended bicycle adjustments and those of rider comfort did not vary significantly.
2. The leg, supplying the driving force was, of course, the most important part of cycling.
3. The degree of knee extension and flexion was dependent on the seat height, crank length, and amount of ankling.
4. Maximum knee extension was reached before the halfway position of crank rotation--at approximately 161.2°.
5. Maximum knee flexion was reached at 167° and 186°.
6. For most subjects the maximum knee extension was reached before the halfway position of crank rotation or 180°.
7. Discounting the rider at the extreme end of the range of knee movement, the average range of motion was 69.4°.
8. In relation to the lower leg, the foot is at its greatest degree of flexion when the pedal is in a vertical position.
9. Changes in foot extension form a stair-step pattern rather than a smooth one. The heel drops slightly prior to each increase in foot extension.

10. Maximum foot extension was reached at an average 206° crank position.
11. All riders ankled to some degree wiht the range of ankle motion 19° to 45°.
12. Flexion of the foot began at an average 205°. With the exception of one subject, the maximum foot extension was held briefly as the crank continued to rotate.
13. Again discounting the rider at the extreme range, the subjects were able to effectively apply force at an average 41° crank position.
14. The cyclists were unable to apply force effectively past an average of 180° insofar as actual pounds of pressure could be determined.
15. The average area in which actual pounds of force could be effectively applied was 41° to 180°.
16. It must be assumed that the subjects in this study did not achieve a true horizontal foot position when the crank was at 90°--neither in relation to a horizontal reference line nor in relation to the lower leg.
17. No valid means of establishing the skill level of the cyclists could be determined.
18. There was no significant difference between male and female cyclists.

19. The degree of knee and ankle motion that would be most efficient could not be reliably determined within this study as was originally intended. However, it would appear that the magnitude of ankling is not as important as the duration of ankling.

20. The "dead center" at the top of the stroke encompasses an area of 40° on the first part of the stroke but could not be reliably determined for the other areas.

Basically, the findings of this study are in agreement with the recommendations most commonly found in cycling literature. There was a discrepancy, however, with regard to the foot being in a horizontal position at 90°. Considering the angle of the foot in relation to the lower leg, the foot approaches the 90° position. But, when the foot is, in fact, in a true 90° position the crank is not.

The effective pressure which may be applied begins at an average 41° and not 15° as suggested by one authority, even though the foot is pressing forward. The amount of pressure which could be applied throughout the full revolution could not be reliably determined. As a result, even though it was found that all subjects experience some degree of ankling, its actual range of effectiveness could not be determined.

Recommendations

On the basis of this study of the leg action and related areas of cycling, the following recommendations are made:

1. It would facilitate timing the film if a timer were placed within the field of view of the test area.
2. Keep both the vertical and horizontal reference objects on the same plane.
3. Pictures taken from the side and the front would provide more opportunity to observe any random movements that might occur.
4. A larger sample might be considered more truly representative of the population.
5. A pedal adaptation that would record the amount of force applied to the pedal would more reliably relate the effectiveness of ankling.
6. Other areas of study are as follows:
    a. Determine what is the proper crank length.
    b. Determine how much force can be applied to the pedals under various conditions.
    c. Determine the degrees of ankling which would be most efficient.
    d. Do the same kind of study with a higher speed camera--400 frames/second.

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APPENDIX

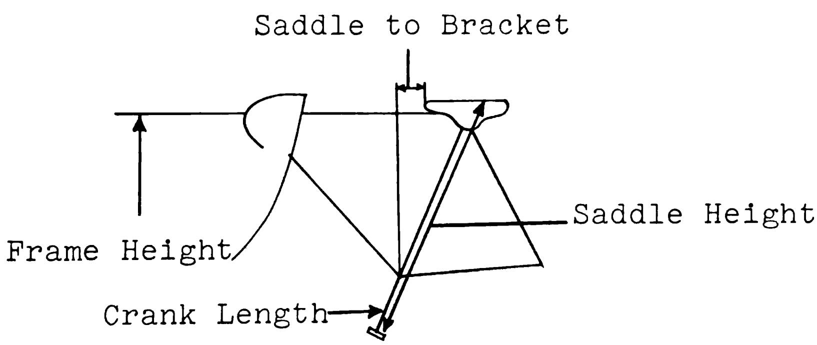
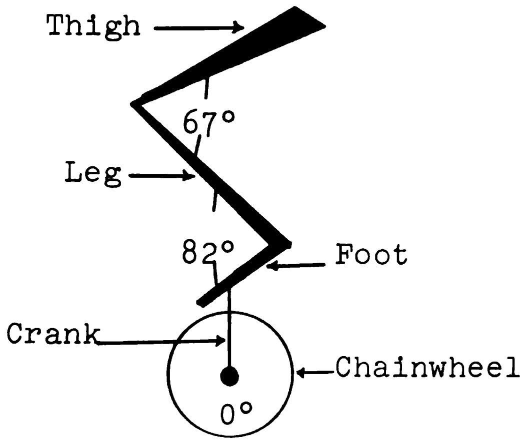
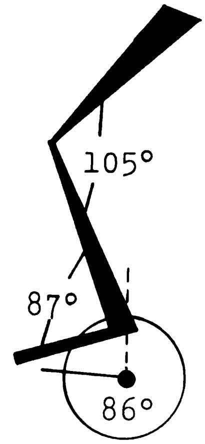


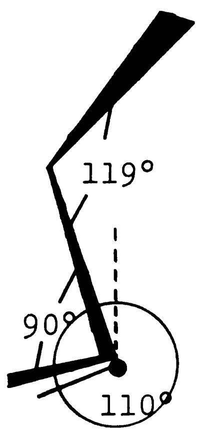
Figure A-1.--Points of measurement on bicycle.



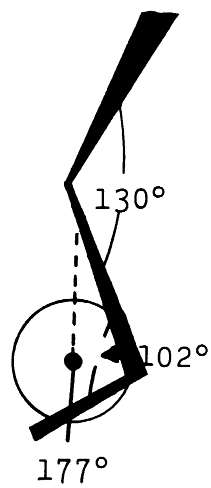
1. Leg Position When Crank is Vertical.



2. Leg Position When Crank Angle Nearest to 90°.

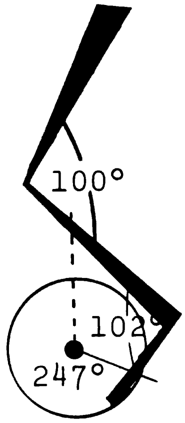


3. Leg Position When Ankle Angle Nearest to 90°.

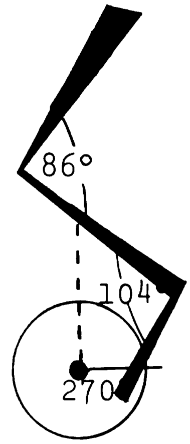


4. Leg Position When Crank Nearest 180°.

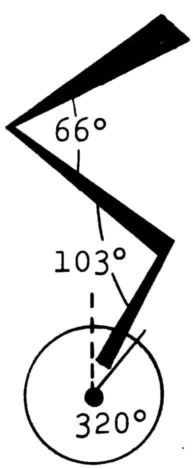
Figure A-2.--Leg action of subject A at different crank angles.



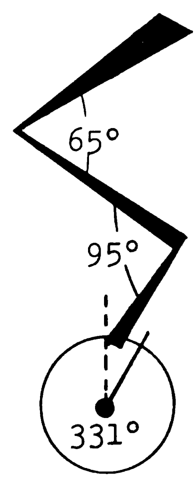
5. Leg Position When Crank Angle 247°.



6. Leg Position When Crank Angle Again at 90° (270°) to the Vertical.

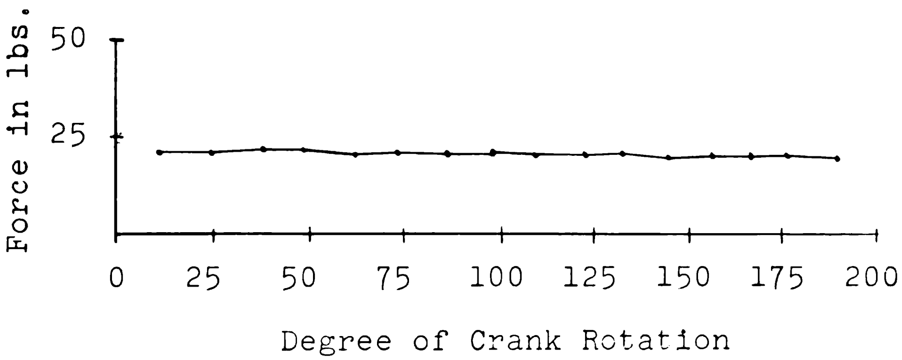


7. Leg Position Prior to Beginning of Ankle Flexion.

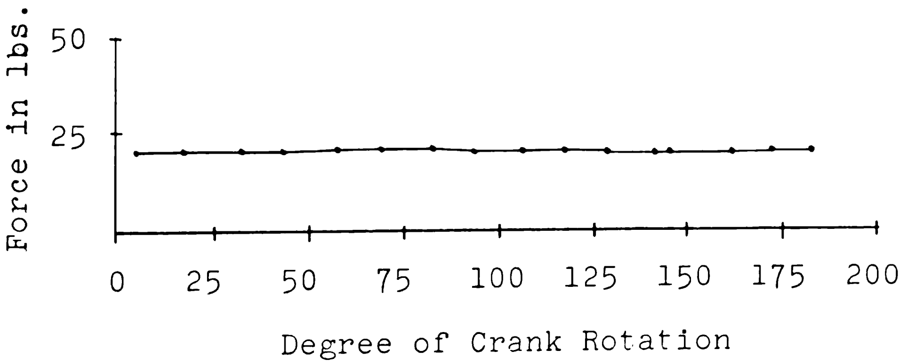


8. Leg Position As Ankle Flexion Begins.

Figure A-2.--(Continued)



SUBJECT A



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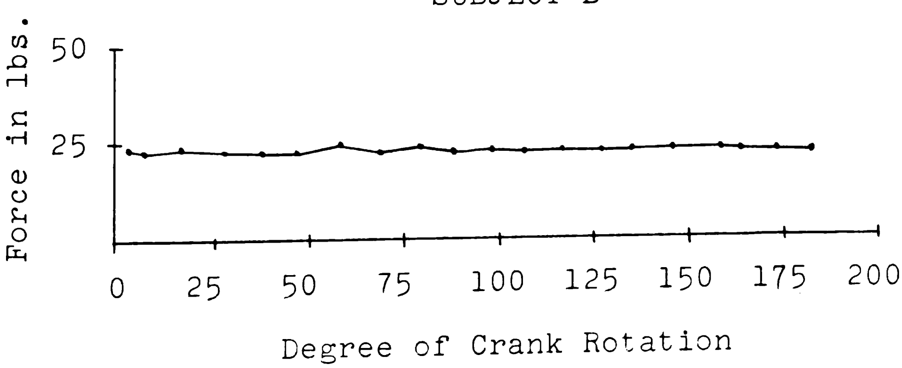
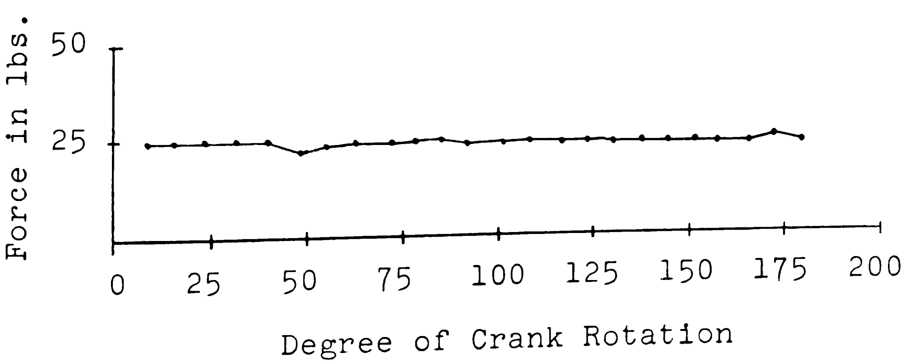
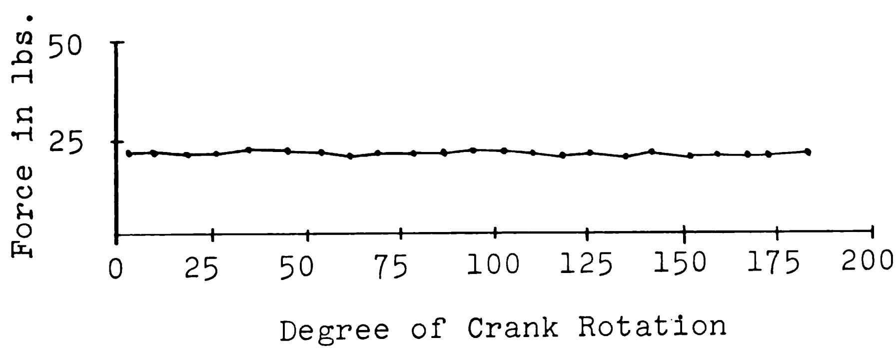


SUBJECT C

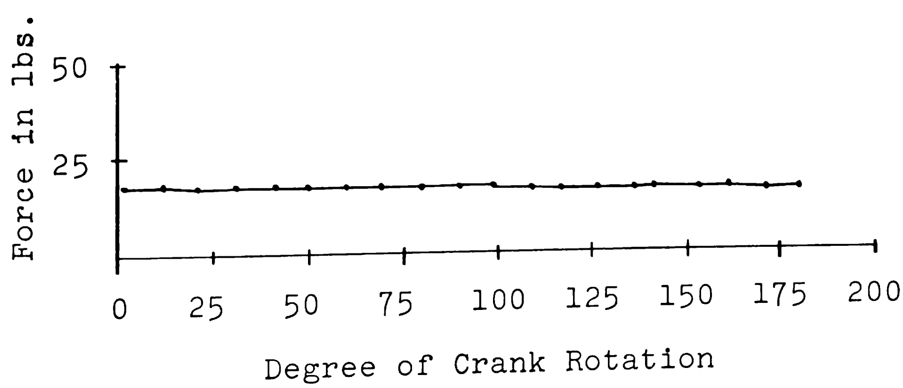


SUBJECT E

Figure A-3.--Comparison of net body weight on handlebars-male cyclists.

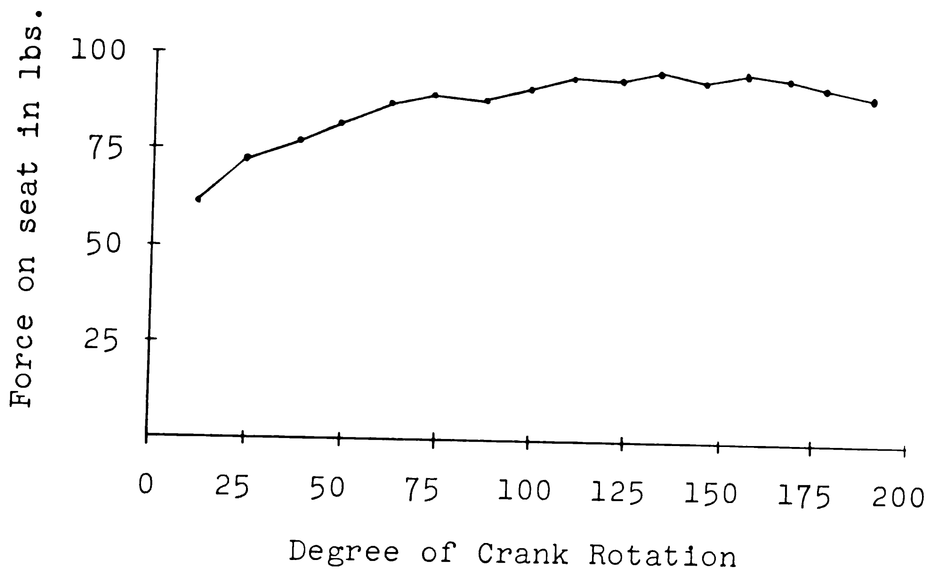


SUBJECT D

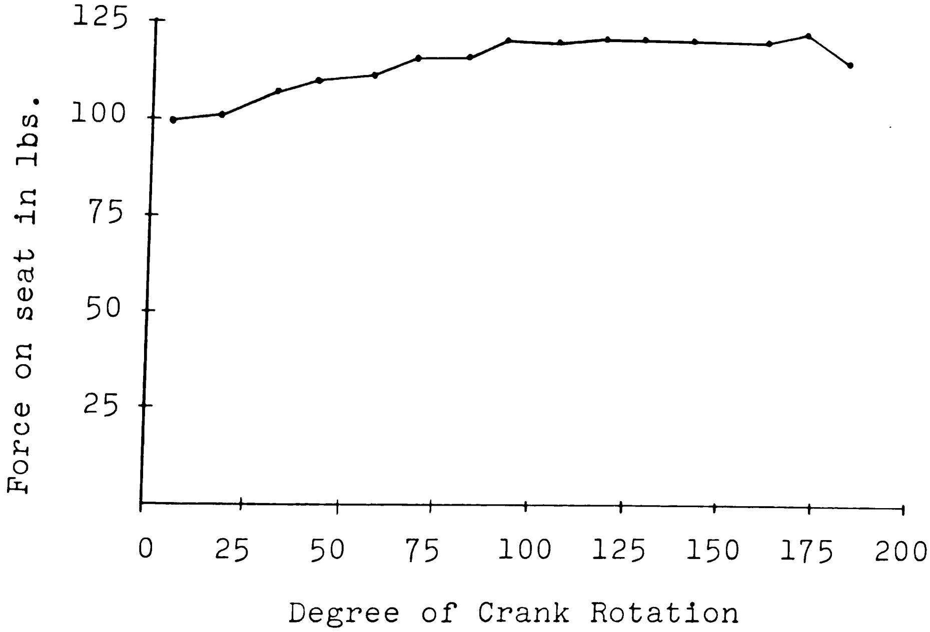


SUBJECT F

Figure A-4.--Comparison of net body weight on handlebars-female cyclists.

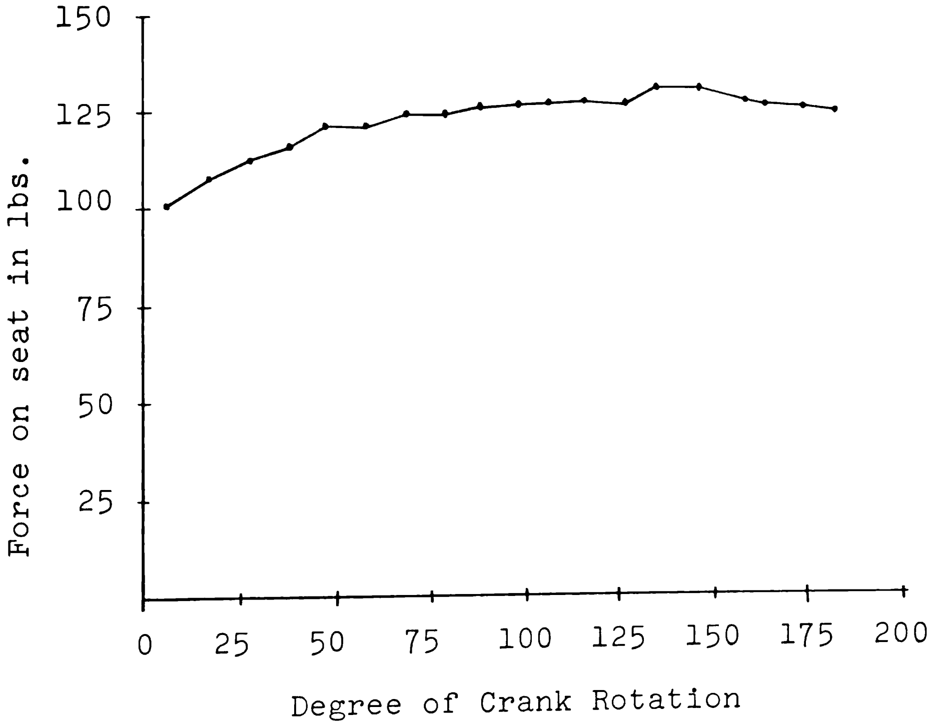


SUBJECT A

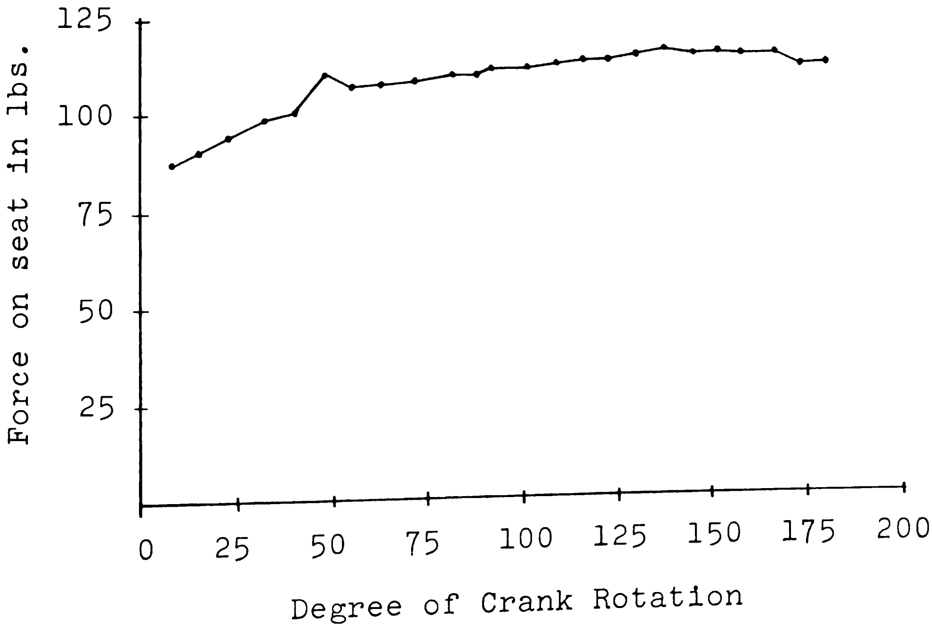


SUBJECT B

Figure A-5.--Comparison of body weight on seat-male cyclists.

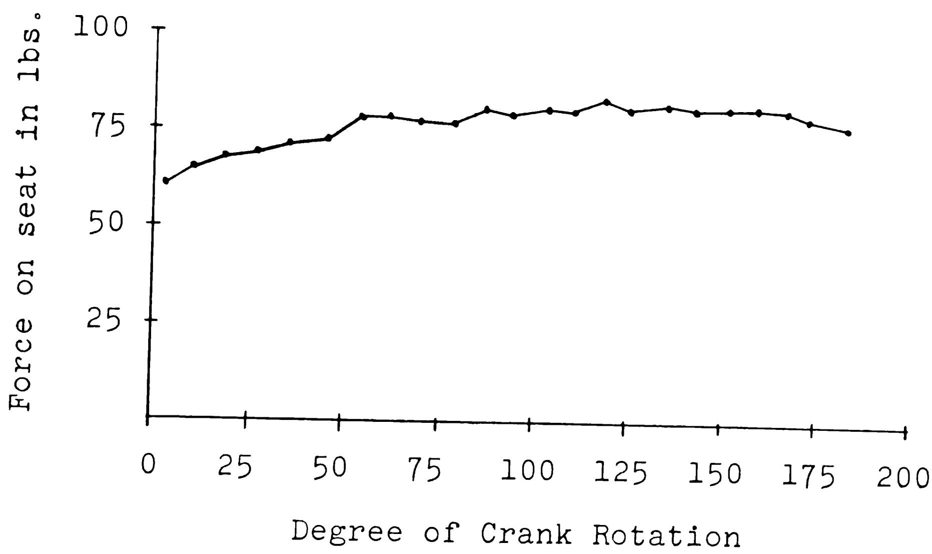


SUBJECT C

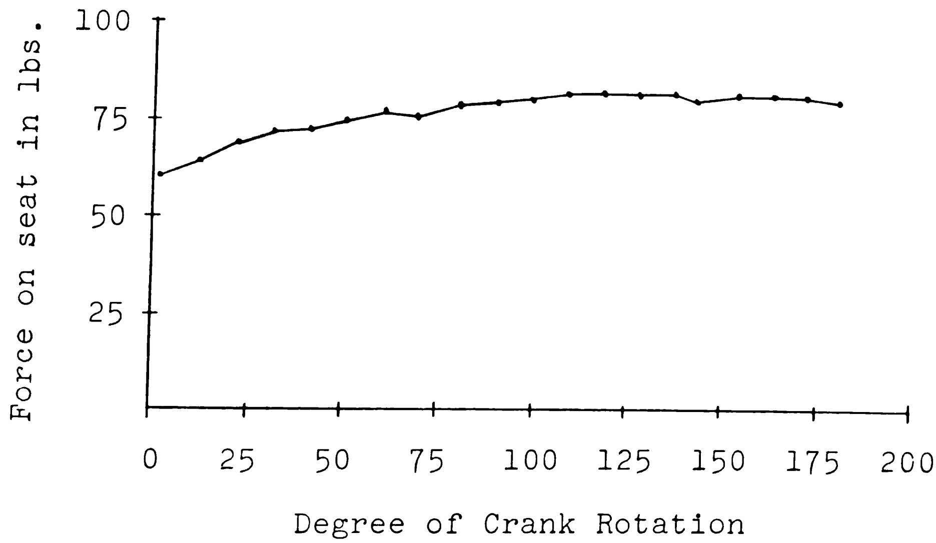


SUBJECT E

Figure A-5.--(Continued)

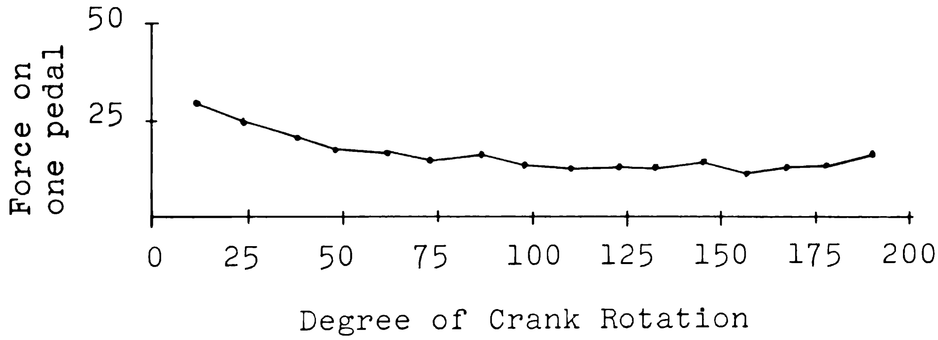


SUBJECT D

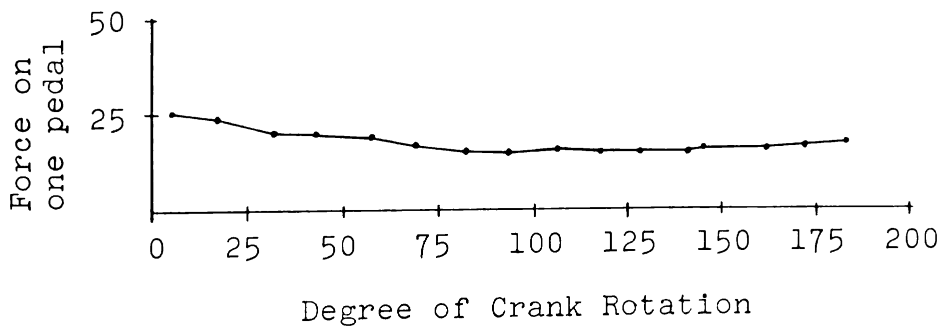


SUBJECT F

Figure A-6.--Comparison of body weight on seat-female cyclists.



SUBJECT A



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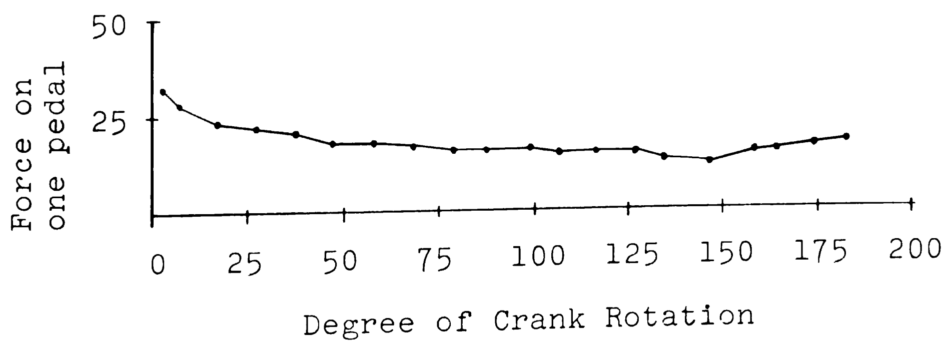

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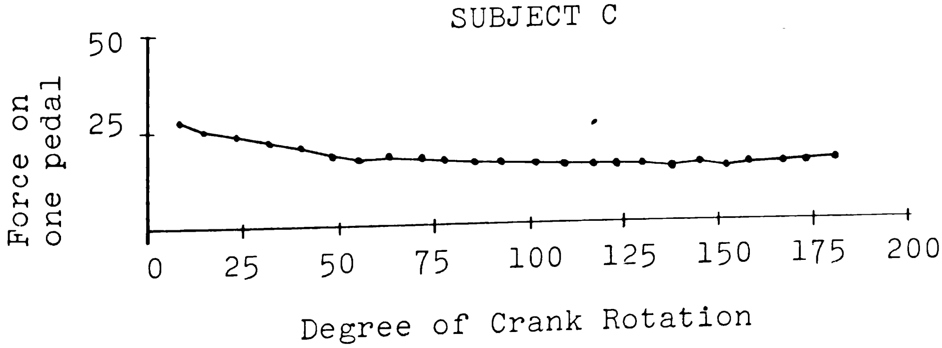
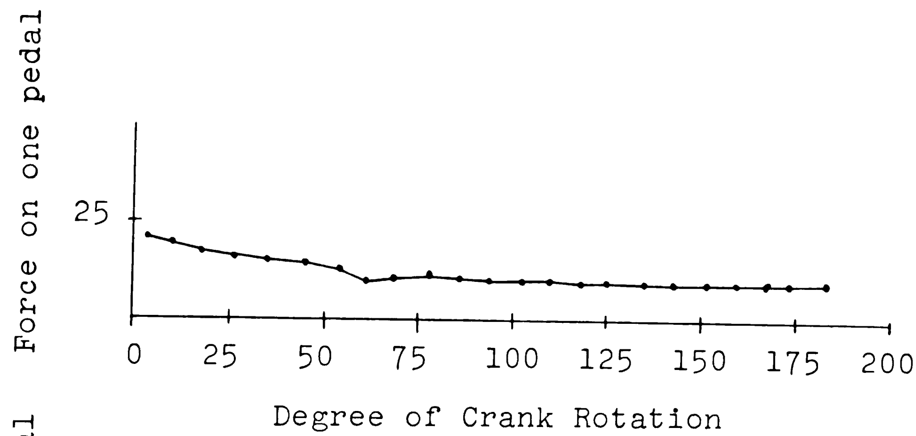
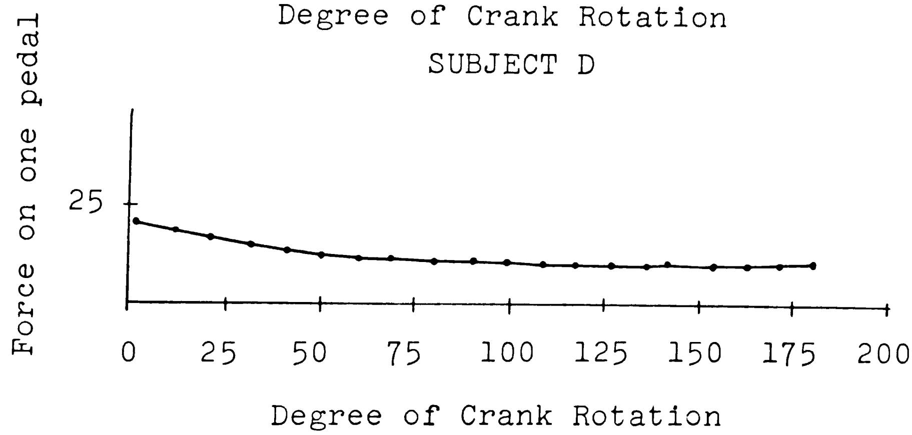


SUBJECT E

Figure A-7.--Comparison of minimum force on pedal (rider seated) male cyclists.

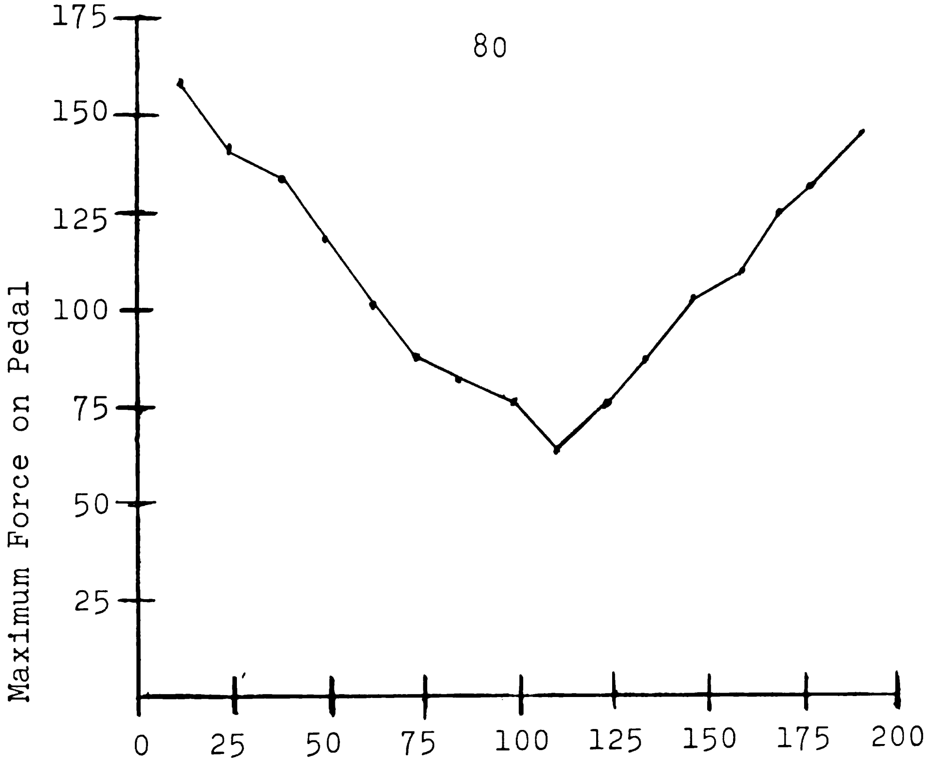


SUBJECT D

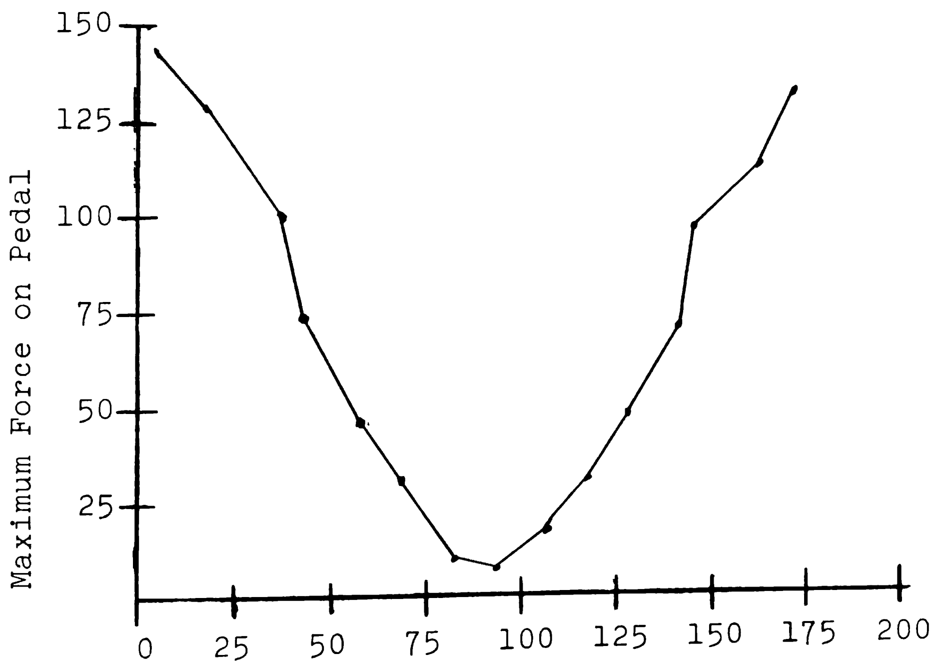


SUBJECT F

Figure A-8.--Comparison of minimum force on pedal (rider seated) female cyclists.

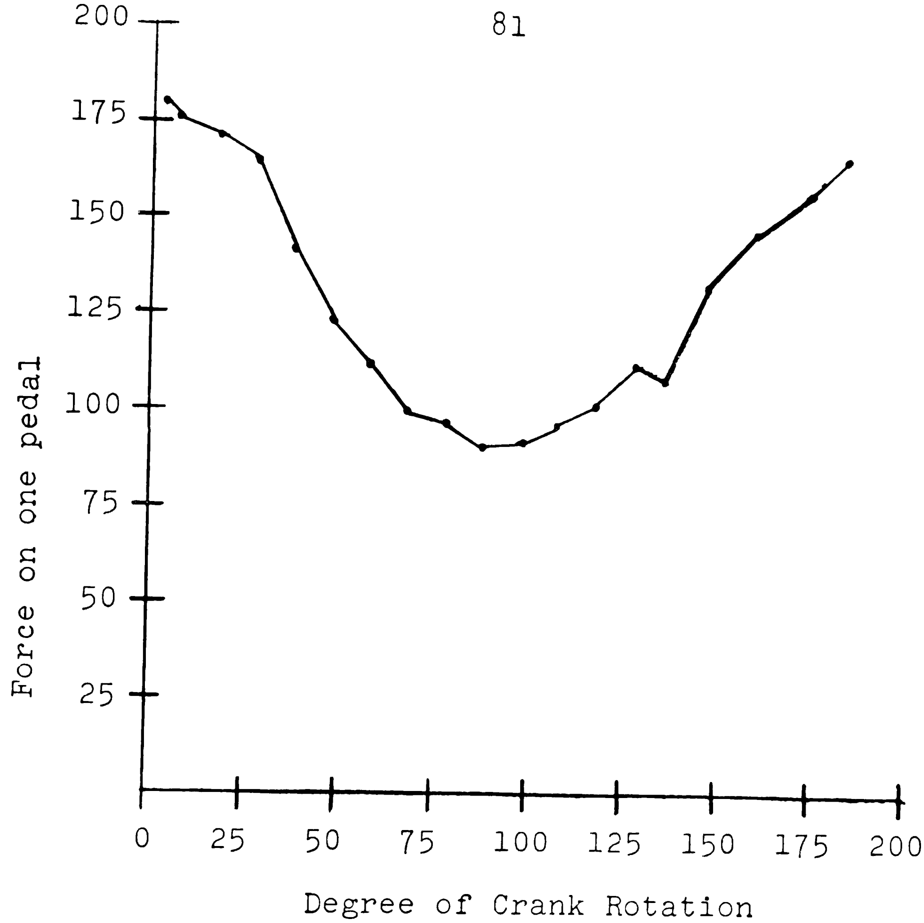


SUBJECT A

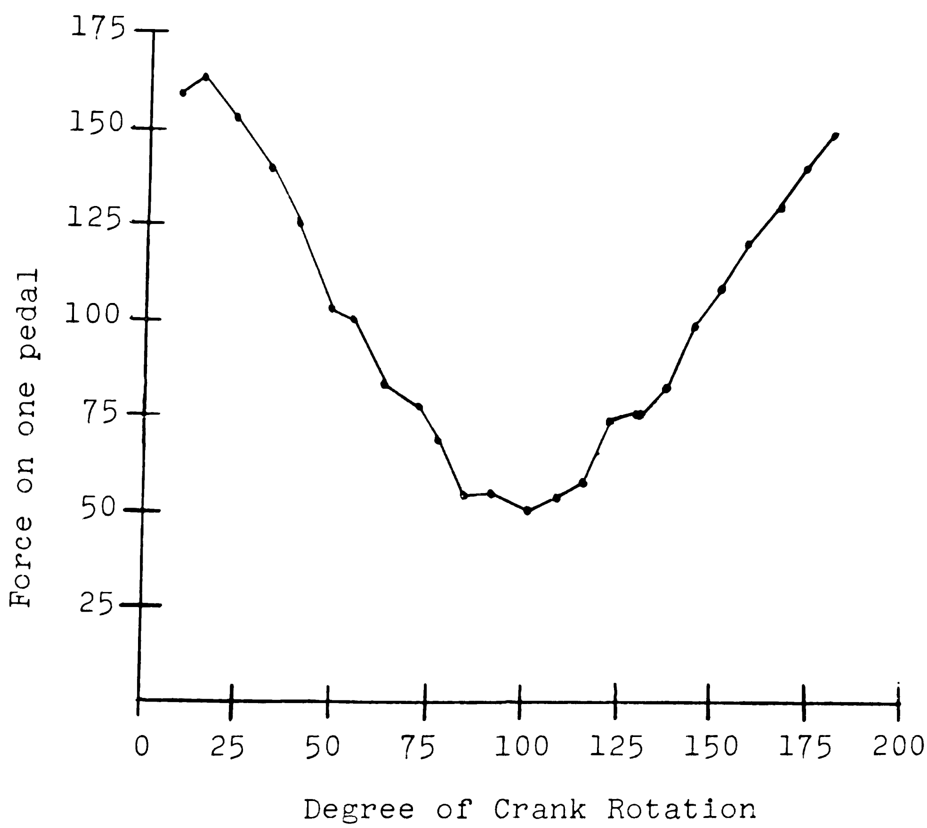


SUBJECT B

Figure A-9.--Comparison of maximum force on pedal
(rider standing)
male cyclists.

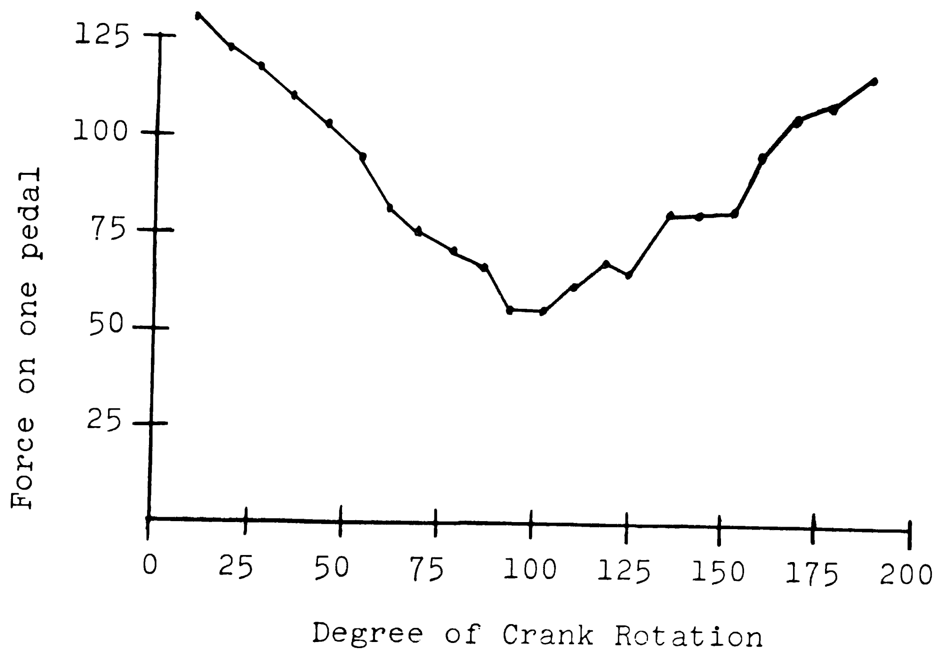


SUBJECT C

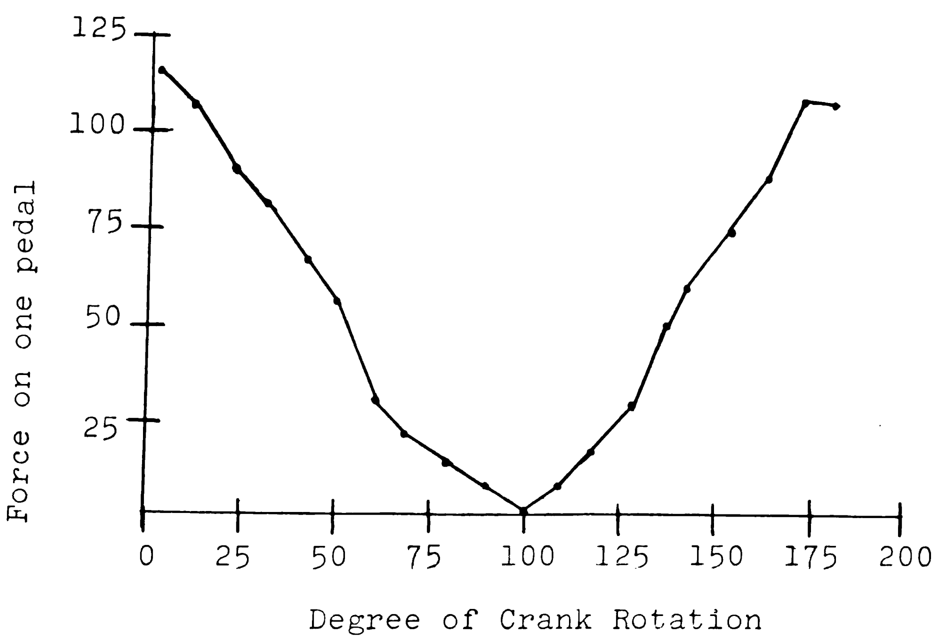


SUBJECT E

9 --(Continued)



SUBJECT D



SUBJECT F

Figure A-10.--Comparison of maximum force on pedal (rider standing) female cyclists.

TABLE A1.--Subject weights and segment lengths.

Category	Subjects					
	A	B	C	D	E	F
Weight in pounds	156	185	197	140	185	133
Segment lengths in inches						
Head, neck and trunk	30.5	30.0	32.5	30.0	30.125	31.625
Arm	11.875	13.0	12.0	9.875	12.5	10.5
Forearm	10.0	10.375	10.625	9.125	10.5	9.125
Thigh	15.625	17.0	15.625	15.625	16.75	16.0
Leg	16.25	17.5	17.5	15.75	16.313	15.5
Foot	9.25	9.188	9.25	8.25	9.25	8.5

TABLE A2.--Bicycle data.

Category	Subjects					
	A	B	C	D	E	F
Bicycle weight (lbs.)	18	29.5	23	21	24	25
No. of teeth for chain-wheel/sprocket	24/8	49/16	49/14	50/14	50/14	49/16
Gear ratio	3.11:1	3.06:1	3.50:1	3.57:1	3.57:1	3.06:1
Gear ratio times the diameter of the rear wheel	84.0	82.7	94.5	96.4	96.4	82.7
Rolling circumferences of the wheel in inches	82.75	84.375	83.0	82.5	83.25	84.5
Length of crank in inches	6.75	6.75	6.75	6.75	7.0	6.5
No. of seconds per frame	.907	.967	1.119	1.36	1.451	1.18
Revolutions/minute	66.15	62.05	53.80	44.13	41.35	50.85
Miles/hour	15.56	15.06	14.70	12.26	11.67	12.71

FORMULAS FOR FIGURING

BICYCLE RESISTANCES

Rolling circumference - A chalk mark is placed on the bike tire plus one on the ground horizontal to the tire. The subject sits on the saddle and moves the bicycle forward for one revolution of the tire. When the mark on the tire is exactly vertical and on the ground again, another chalk mark is put on the floor at this point. The measured distance between these two marks is the rolling circumference.

Rolling resistance = Expressed in foot pounds = .72/100 lbs.

R = The rolling circumference of the tire.

r = The pedal radius.

P = The per cent of rolling resistance of the tire re 100 lbs. pressure.

T_1 = The amount of force required to overcome rolling resistance.

T_2 = The amount of force needed to overcome bearing, chain and sprocket losses.

T = The total amount of force needed on the pedal when the pedal is 90° from the vertical. It is also the amount of force needed on the pedal to maintain momentum under the same conditions.

(Formulas for Figuring
Bicycle Resistances, Cont.

$$k = \frac{\text{No. of teeth in front sprocket}}{\text{No. of teeth in rear sprocket}} = \text{Ratio of wheel to pedal revolution}$$

$$P = .72 \left(\frac{\text{total weight of rider and bike}}{100}\right) = \text{Rolling resistance of tire re 100 lbs. load}$$

$$R = \frac{\text{Rolling circumference of tire}}{2\pi} = \text{Radius of tire}$$

$$r = \text{Pedal radius or crank length}$$

$$T_1 = \frac{k\ P\ R}{r} = \text{Force required to overcome rolling resistance}$$

$$T_2 = \left(\frac{\text{bearing, chain, and sprocket resistances}}{\text{\% Rolling resistance of tire}}\right) T_1 = \text{Force needed to overcome bearing, chain, and sprocket resistance}$$

$$T = T_1 + T_2 = \text{Amount of force needed to maintain momentum}$$

TABLE A3.--Bicycle resistances.

Category	Subjects					
	A	B	C	D	E	F
Ratio of wheel to pedal revolution (k)	3.0	3.063	3.5	3.57	3.57	3.063
Rolling resistance (P)	1.74	1.54	1.584	1.159	1.50	1.138
Rolling circumference (R)	13.17	13.42	13.21	13.13	13.25	13.45
Pedal Radius (r)	6.75	6.75	6.75	6.75	7.0	6.5
Forces to overcome rolling resistance (T_1)	10.19	9.37	10.85	8.05	10.14	7.213
Force to overcome bearing, chain and sprocket losses (T_2)	16.03	14.74	17.07	12.66	15.95	11.35
Lbs. force needed to maintain momentum (T)	26.22	24.11	27.92	20.71	26.09	18.56

FORMULAS FOR FIGURING MOMENTS
SITTING POSITION

MINIMUM LOAD ON PEDALS

Σ Moments 0 - 0 = 0

$$-2\ F_1\ x_1 - 2\ F_2\ x_2 - F_3\ x_3 + 2\ R_1\ x_R = 0$$

R_1 = Total force on handlebars

$2R_1$ = Total force on both handlebars

$\Sigma\ V_F = 0$

$$-2\ F_1 - 2\ F_2 - F_3 + 2\ R_1 + R_2' = 0$$

R_2' = Sum of vertical forces (top half of the body)

$\Sigma\ M = 0$

$$-2\ F_4\ x_4 - 2\ F_5\ x_5 + 2\ R_3\ x_{R_3} = 0$$

R_3 = Total reaction on one pedal

$2R_3$ = Total reaction on both pedals

$\Sigma\ V = 0$

$$-2\ F_4 - 2\ F_5 + 2\ R_3 + R_{2''} = 0$$

$R_{2''}$ = Sum of vertical forces (lower half of body)

$R_2 = R_{2'} + R_{2''}$ = Total forces on seat

FORMULAS FOR FIGURING MOMENTS
STANDING POSITION

MAXIMUM LOAD ON PEDALS

ΣM about the pedal

$$2\ R_1\ (x_R - x_{R_3}) - 2\ F_1\ (x_1 - x_{R_3}) - 2\ F_2\ (x_2 - x_{R_3})$$

$$+ F3\ (x_{R_3} - x_3) + F_4\ (x_{R_3} - x_4) - F_5\ (x_5 - x_{R_3}) = 0$$

$$V = 0$$

$$-2\ F_1 - 2\ F_2 - F_3 - F_4 - F_5 + 2\ R_1 = R_3 = 0$$

R_3 = Sum of the maximum forces about the pedal (standing)

3. FORMULAS FOR REVOLUTIONS

PER MINUTE (RPM's)

$$\frac{\text{No. of seconds per frame}}{\text{No. of frames in one pedal revolution}} = x$$

$$\text{RPM} = \frac{\text{No. of seconds in one minute}}{x}$$

$$\begin{array}{l}\text{No. of}\\ \text{secs./frame}\end{array} = \frac{360^\circ}{\begin{array}{l}\text{No. of degrees crank}\\ \text{is from the vertical}\end{array}} = \sigma$$

$$= \sigma \text{ (no. of frames used)} = y$$

$$= y \text{ (film speed per frame)} = z$$

$$= \frac{\text{no. of secs./min.}}{z}$$

4. FORMULA FOR RADIANS

$$\text{Radians} = \frac{\begin{array}{l}\text{Distance crank travelled from the}\\ \text{vertical minus distance of pre-}\\ \text{vious crank position}\end{array}}{57.3 \text{ (film speed/frame)}}$$

5. $V = \omega r$ Velocity = Radians (crank length)

FORMULA FOR DETERMINING

MILES PER HOUR (MPH)

$$N = \frac{360^\circ}{\text{No. of frames}} = x^\circ$$

$$v = \frac{x^\circ}{360^\circ}\left(\frac{\begin{array}{c}\text{Rolling Circumference}\\ \text{of Wheel}\end{array}}{12''}\right)\left(\frac{60 \text{ MPH}}{88 \text{ Ft.}}\right) = y \text{ MPH}$$

TABLE A4.--Crank angle (in degrees) from the vertical.

Frame No.	Subjects					
	A	B	C	D	E	F
1	11°	5°	3°	3°	9°	2°
2	24	17	7	10	15	12
3	38	32	17	18	23	21
4	48	43	28	26	32	31
5	61	57	38	35	40	41
6	73	69	47	45	48	50
7	86	82	58	54	55	60
8	98	94	69	61	63	69
9	110	106	79	69	71	80
10	123	118	88	78	78	90
11	133	129	99	86	85	99
12	145	141	106	94	92	109
13	157	145	116	102	101	117
14	167	162	127	110	109	127
15	177	172	135	118	116	136
16	190	183	146	125	123	141
17	201	192	159	135	130	154
18	212	196	164	142	138	163
19	225	206	174	151	145	171
20	236	212	183	159	151	180
21	247	228	191	167	158	187
22	258	238	200	173	166	196
23	270	250	209	183	173	204
24	284	262	218	189	180	213
25	296	274	228	197	186	223
26	308	286	237	206	197	232
27	320	299	248	212	200	241
28	331	312	256	221	207	249
29	343	324	265	229	214	259
30	359	338	275	237	221	267
31		350	285	245	230	276
32		364	295	251	236	286
33			304	259	244	296
34			315	267	251	306
35			325	275	259	317
36			336	282	267	325
37			345	292	274	336
38				299	283	346
39				309	291	357
40				313	299	
41				325	307	
42				332	316	
43				341	323	
44				350	332	
45				358	339	
46					349	
47					356	

TABLE A5.--Degrees of knee flexion and extension.

Frame No.	Subjects					
	A	B	C	D	E	F
1	70°	72°	74°	68°	68°	69°
2	75	76	76	71	70	72
3	80	80	79	73	72	75
4	86	84	83	77	75	80
5	92	91	87	81	78	83
6	98	97	94	85	81	88
7	105	103	98	89	84	93
8	112	109	104	93	87	98
9	119	109	110	97	91	104
10	125	120	115	101	95	110
11	130	123	120	106	99	112
12	132	127	125	111	103	122
13	132	129	130	112	107	128
14	132	130	134	120	111	131
15	130	130	136	124	115	135
16	127	127	140	128	119	138
17	123	123	143	132	123	139
18	119	125	143	134	124	139
19	111	119	144	135	127	139
20	105	113	141	137	129	136
21	100	106	136	137	130	133
22	93	100	133	135	130	129
23	86	94	129	132	131	124
24	80	88	122	130	131	118
25	75	82	117	126	131	114
26	70	77	112	122	128	108
27	66	73	106	118	125	103
28	65	71	100	112	121	98
29	65	69	95	108	118	92
30	65	68	90	103	116	87
31		70	85	98	109	82
32		72	81	95	106	78
33			77	89	102	74
34			76	85	97	70
35			74	82	94	68
36			74	78	92	67
37			72	75	87	66
38			75	70	83	67
39			76	69	79	68
40				68	76	
41				65	74	
42				65	70	
43				64	69	
44				64	68	
45				65	67	
46					67	
47					67	

TABLE A6.--Degree of ankle flexion and extension.

Frame No.	Subjects					
	A	B	C	D	E	F
1	82°	85°	84°	91°	88°	84°
2	83	87	83	90	87	84
3	84	88	84	88	87	84
4	85	90	82	89	85	84
5	85	91	82	88	88	83
6	84	93	83	90	87	84
7	87	96	85	92	89	85
8	88	97	87	93	89	85
9	90	97	93	92	90	87
10	93	101	97	93	91	89
11	97	101	100	96	90	91
12	100	105	104	97	92	94
13	102	106	108	100	93	98
14	102	109	113	101	94	100
15	102	111	113	104	96	103
16	100	112	121	106	97	108
17	99	112	124	109	98	111
18	100	111	124	110	99	112
19	99	112	127	111	103	113
20	100	110	124	113	103	113
21	102	110	121	113	103	113
22	104	107	120	111	104	112
23	104	105	118	110	106	111
24	104	104	115	111	105	109
25	105	102	116	112	106	110
26	103	104	115	110	106	109
27	103	100	116	110	106	110
28	95	96	114	108	106	109
29	90	96	112	108	106	107
30	88	90	113	108	105	106
31		88	110	107	105	103
32		87	109	105	104	102
33			107	103	103	100
34			104	103	102	97
35			100	103	102	95
36			96	102	101	92
37			92	101	100	88
38			90	100	99	86
39			86	98	98	86
40				98	97	
41				98	95	
42				96	93	
43				96	93	
44				92	92	
45				92	90	
46					90	
47					88	