# DESIGN OF A DUAL-FUNCTION PEDAL
# USING FORCE AND TORQUE AS CRITERIA

by 2235

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

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# INTRODUCTION

The last two decades have witnessed a significant shift toward placing a greater reliance upon systematic research and reduced emphasis upon human experience as the basis for developing principles and data to be applied in adapting equipment, work space and environment for human use. This shift has led to the rapid development of the field of "human factors" - a branch of applied science aimed at matching machines and tasks with the abilities of their human operators, designing tools and equipment so people can use them effectively and creating environments that are suitable for human living and work.

The current development of complex man-machine systems such as missiles, space ships, surveillance systems, and automated production systems has produced myriads of mundane products and items of equipment that need more attention to their human factors aspect. It has been found, often through unhappy experience, that some of these devices are not appropriately designed to be used effectively by their operators; human errors are excessive and many accidents occur because of mistakes which are attributed to design deficiencies.

The role of the driver, in relation to his vehicle, typifies the interaction of a man-machine system. As automobile usage increased, the automobile became a greater hazard on the highways.

Time magazine expressed the hazard of being on an American road in a car in 1967 as "Automobiles are intended to be used in an environment in which a traffic death occurs every eleven minutes and an injury every nineteen seconds". The motor vehicle has become central to our way of life, profoundly influencing our living, working and playing patterns and providing a variety of gratifications. These conveniences and gratifications, however, have been reached at a high price. Automobile accidents cost the American economy $14.2 billion in 1968, up $1.8 billion or 14% over the 1967 figure of $12.4 billion according to the Insurance Information Institute. There were a record of 55,500 traffic deaths; 4.5% more than the 1967 toll of 53,100. The problem is immense and deserves a careful analysis so that remedies can be suggested.

At present the driver is expected to compensate for the limitations and deficiencies of his vehicle, the highway, and other drivers. Most drivers are able to do so most of the time. However, at least once each year approximately 25% of all drivers and 41% of drivers under the age of 20 do not cope successfully with the demands made upon them (Accident Facts 1966, NSC). There is thus an imbalance between the technology of the motor vehicle transportation system and the demands made upon driver capabilities. Even the normally competent, careful and responsible driver occasionally will be careless, irresponsible, distracted, fatigued, ill, upset or preoccupied. The normally competent driver is then a variable element in the system. Even the normally well-engineered, controlled access, properly-signed and uncongested highway occasionally will be slick with ice, obscured by fog or congested with a mix of vehicles. The motor vehicle system is variable in its demands upon driver capabilities. Figure 1 shows the hypothesis that a localized system failure, or so called accident, occurs when the system demands exceed driver capability (Blumenthal, 1968). A U. S. Department of Commerce analysis of road safety concludes that: "Drivers are being asked to make judgments that they cannot make well, to make decisions faster than humanly possible, and to make changes in direction and speed more accurately than they possibly can". (Miller, 1966).

Needless to say, traffic safety is a problem with technological, behavioral, sociological and value dimensions. The solution must be many-faceted. From a human engineering point of view, reducing system demands, especially motor vehicle control systems demands, seems to be the most economical way of improving safety. One of the parameters which affects safety is the operator's permissible margin of error. The greater this margin, the less the chances of an accident (or less the severity of an

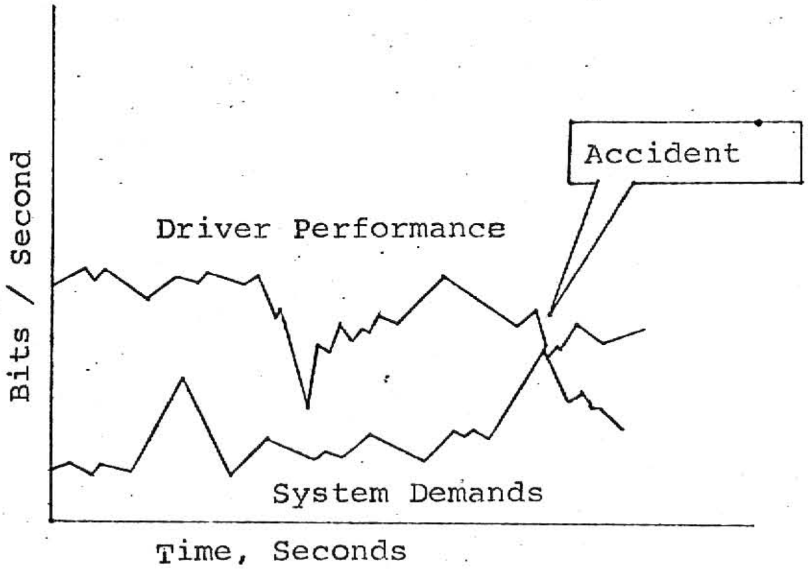


Figure 1. Hypothetical Localized System Failure

accident). This margin is dependent upon design and one of the facets of design is the permissible time lag between the decision of the controller and the actuation of the control. This time lag, elements of which are reaction time and travel time of the control,is the time between the appearance of a stimulus and the completion of operator's response to the presented condition.

It is assumed that the shorter the actual time lag, the greater is the permissible margin or error. This axiom is based on the premise that the greater the time available for the automobile to attain a specified condition (that of lower or zero speed) from another given condition (that of moving at a certain higher speed), the greater is the possibility of automobile's achieving it.

Reaction time, as referred above, is defined as the delay between the occurrence of a stimulus and the initiation of a response, whereas travel time of the control is defined as the period from the start of a response to its completion by the operator. Reaction time, as defined here, comprises:

1. Sensing time: The time required to sense a signal. This is a function of the properties of the signal (size, intensity, duration, etc.).
2. Decision time: The time required to complete the neurological process of selection of the

correct response to the presented stimulus. This depends upon the complexity of the decision to be made and the number of times the situation has been practiced.

3. Response time: The time required to respond to a signal. This depends on the limb used, the distance to be moved and the accuracy required for the move.

Travel time, as defined here, comprises the actual time of movement of the control. This time is a function of the complexity of the response (e.g. force, displacement and precision requirements) and the body member being used.

If any of these factors can be so controlled that their time of execution is reduced, the actual time lag will be decreased and the permissible margin of error increased.

A desirable approach to designing controls would consider the distribution of actual forces and torques exerted by an operator when using the control. Knowledge of the magnitude and direction of these forces and torques, as well as their duration, would permit calculation of physiological costs for alternative control configurations. As a result of this new approach to methods engineering, the development of an effective methodology for measuring physiological costs of work is receiving considerable attention. Davis and Miller (1962) suggest two reasons for the urgency to better understand the demands of jobs and the capabilities of people:

1. Due to increased mechanization and automation, the individual has more impact on the system, and hence, the repercussions of a poor job design now become more severe and costly.
2. The rapid advances which have occurred in the life sciences and the field of electronics promote the attainment of physiological data.

Perfection of an efficient, well-founded technique for measuring the costs of work in a natural working environment would conceivably provide analysis with a basic tool for predicting the nature of operator performance. Such a technique lends itself to the solution of problems concerning the evaluation of alternative work methods and the reduction of physiological fatigue and work stress. Consequently, the purpose of this research was to investigate the design considerations of a dual-function pedal as a function of the physiological cost measured by a force platform.

# LITERATURE REVIEW

The literature review has been divided into three parts. The first part describes the work done on single action pedals. The second part deals with the experiments conducted on dual-function pedals at Kansas State University. The third part traces the history of the various techniques used to estimate physiological cost.

## Single Action Pedals

The first efforts to determine an optimal foot pedal design were made by Barnes, Hardaway and Podolsky in 1942. The five pedals investigated differed only in the location of the fulcrum. The pedals were operated from the seated position that felt most comfortable. All pedals were operated as a trip type such as would be found on a punch press. Fifteen operators (twelve male and three female) performed the routine twice, first using the pedals in the order 1, 2, 3, 4, 5, and the second time in the reverse order. Using a 90 second session of continuous up and down movement, it was found that the foot pedal with the fulcrum at the heel had 109 milliseconds for the downward stroke; the worst pedal had 137 milliseconds.

Utilizing a force platform,Lauru (1957) investigated the lateral, vertical and frontal forces involved in activating pedals from a seated position. In comparison with Barnes and his associates (1942), who had found that a pedal pivoted at the heel yielded the least time per cycle, Lauru found both the least time per cycle and least force requirements for a pedal pivoted at the axis of the tibia. Neither report presented complete data on the design of the pedals.

McFarland (1966) recommended that for pedal forces over 20 pounds the long axes of the foot and lower leg should form a 90 degree angle, since this angle required least muscular effort to hold the foot in position. For small pedal forces (under 20 pounds), the knee angle should be at least 90 degrees - preferably 135 degrees or more.

Ayoub and Trombley (1967) used reaction time to a visual stimulus and the time of travel to a fixed stop as the criteria for optimality for foot pedal design. Five subjects performed the experiment in a single session requiring approximately two hours and fifteen minutes. The position of the fulcrum at the heel, with the load attached at the ball of the foot, gave minimum time of 247 milliseconds; the worst pedal had a time of 258 milliseconds. The optimum range of foot tibia angle was found to be from 78 to 96 degrees; however, 84 degrees was the recommended angle.

## Dual-Function Pedals

Versace (1966) at the Human Factors Department at the Ford Motor Company conducted some preliminary studies of dual brake-accelerator devices on automobiles but failed to show any unusual advantage over the conventional two pedal system.

One type of "one-pedal control" of a car was developed by Humphrey, Inc., (1968). In this method various degrees of braking are accomplished by simply letting up on the accelerator pedal. Three distinct braking zones are provided; an upper proportional braking zone, a middle neutral zone or coasting zone, and a lower acceleration zone. However, this design has the limitation that the driver has to keep his foot constantly on the pedal. If due to fatigue or some other reason, he removed his foot from the pedal, the car will come to a panic stop.

Fenton and Montano (1968) reported having used a hand-operated control stick which was installed in a test vehicle to replace the steering wheel, accelerator pedal and brake pedal. This spring loaded stick was located in front of the driver and displacement from the neutral position was proportional to the applied force. The vehicle was steered by moving the control stick head to the left or right, accelerated by moving it forward and braked by pulling it back.

A series of ten experiments conducted at Kansas State University is briefly described below. (Chawla, 1969) (Konz, Wadehra, Sathaye and Chawla, 1969).

In the first experiment, (Konz and Daccarrett, 1967) relative quickness of activating a control by hand and foot were compared for 12 subjects. The following four conditions were studied:

1. Honk horn; starting position - hand on the horn rim.
2. Honk horn; starting position - hand on steering wheel.
3. Depress brake; starting position - left foot on brake.
4. Depress brake; starting position - right foot on depressed accelerator.

The times for actuation in condition 1 (.38 seconds) and 3 (.39 seconds) were not significantly different from each other but were significantly faster than in conditions 2 (.56 seconds) and 4 (.59 seconds).

The advantage obtained in conditions 1 and 3 was primarily due to elimination of the movement of the limb from one location to another location. Two possible design feasibilities emerged from the experiment; 1. design the control so that the effector limb is able to be poised on it for actuation at all times. This control could be properly positioned for left foot actuation as the left foot is free in nearly 80 per cent of the cars on the road. 2. One of the other three limbs (right foot, right hand, left hand) would be given the additional task of braking along with its present job. This could be achieved by some integrated control. From the design point of view, in the second alternative, it would be easier to combine the braking function with the accelerator pedal than with the steering wheel because the foot is in a relatively fixed position while hands move and are already busy with many tasks.

The second experiment (Konz and Daccarrett, 1967) on 121 subjects, was done on a combined brake and accelerator pedal designed by Mr. C. N. Winkleman, (U. S. Patent No. 2,878,908) because of its availability. There have been at least 16 other patents granted to various inventors on dual-function pedals since 1924.

This pedal activated the accelerator when the toe was pressed down and activated the brake when the heel was pressed down. There was an interlock between the two controls to prevent simultaneous actuation of both controls. Figure 2 shows a sketch of this device.

Eleven of the 12 subjects in experiment 1 (Konz and Daccarrett, 1967) also participated in experiment 2 (Konz and Daccarrett, 1967). The time for actuation of the eleven subjects was .62 seconds for condition 4 of experiment 1; the .41 seconds when using the combined control was significantly ($p < .01$) lower.

In experiment 3 (Konz and Daccarrett, 1967) an American Automobile Association (AAA) reaction timer comprising a conventional system of clutch, brake and accelerator pedal was compared with the Winkleman integrated control for 25 subjects. It was observed the 0.29 seconds when using the left foot poised on the control was significantly ($p < .05$) less than the 0.36 seconds of the integrated control and the 0.36 seconds was significantly less than the 0.45 seconds when using the right foot from the accelerator.

The preceeding three experiments conducted in a laboratory indicated some of the potential advantages of the integrated control. The next experiment (Konz, Koe and Kalra, 1968) therefore was conducted on the highway. The integrated control was mounted in a 1960 Rambler. It was made interchangeable with the conventional accelerator and brake pedals and the two were tested for reaction times while driving on a highway. Thirteen subjects drove two miles on a two lane highway without intersections with one control and then drove back with the other control in place. The average reaction time for the combined control (.47 seconds) was significantly ($p < .01$) lower than for the conventional system (.57 seconds).

In the fifth experiment, back in the laboratory, a new dual-function pedal prototype (without interlock) was used. (Konz, Koe and Kalra, 1968). The reaction times for 72 subjects were tested for the AAA reaction timer on a parked 1960 Rambler equipped with automatic transmission, and the new dual-function pedal mounted on a test box. The dual-function pedal with a reaction time of 0.323 seconds was found to be significantly ($p < .01$) faster than both the AAA reaction timer (0.483 seconds) and the 1960 Rambler conventional (0.432 seconds). The dual-function pedal had the minimum learning effect.

Experiment 6 was run to determine the effect of varying some of the parameters in the design of the dual-function pedal. (Konz, Koe and Kalra, 1968; Kalra, 1968) More specifically, the distances between the heel of the pedal to the brake and accelerator shaft were altered (See Figure 2). The criterion was minimum reaction time. No specific values of these variables or any combination were better than others, within the tested range of d (.5" to 2.5") and L (5" to 9").

Experiment seven (Wadhera, 1968) was conducted to determine minimum reaction time with varying pedal angle with the floor, brake force, accelerator force and seat reference distance (SRD).

The value of the brake force was varied between 13 to 21 pounds, without losing more than 15 milliseconds. A range of 4

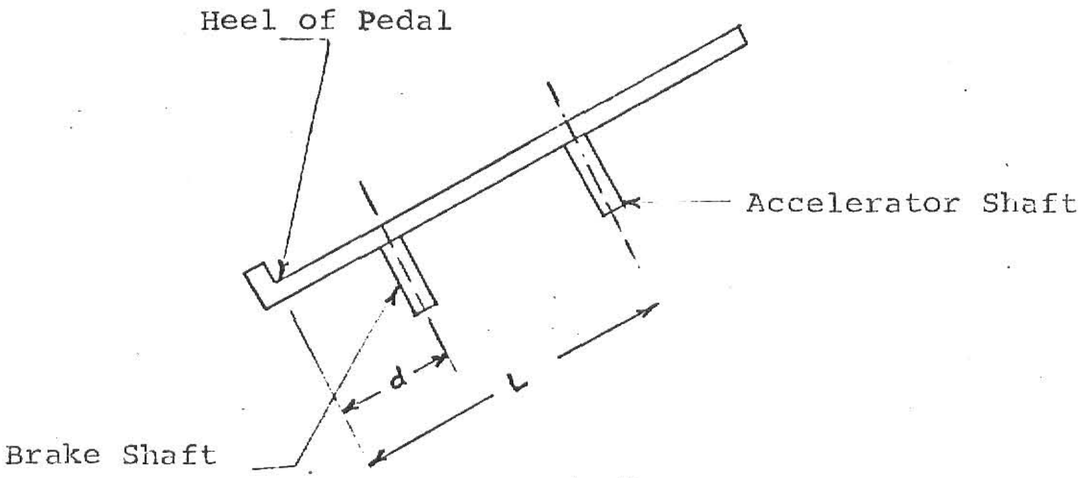


Figure 2. Dual-function Pedal

to 8 pounds was found to be optimum for accelerator force. The recommended optimum range of pedal angles was between 30 to 40 degrees. SRD seemed to be optimum between 45 to 55 per cent of the subject's height.

Experiment eight (Sathaye, 1969) was conducted to obtain an optimum design of the dual-function pedal, with respect to four parameters: , inclination of the foot pedal with the automobile floor; SRD, the distance between heel of the pedal and intersection of seat surface with the back rest of the pedal, and , the angle by which the pedal assembly was rotated in the clockwise direction around the vertical axis. Reaction time was used as the criterion. Four subjects were used and the experiment was conducted in a parked 1956 Chevrolet automobile with its engine running. The optimum angle for was found to lie between 30 to 45 degrees without losing more than 10 milliseconds within that range. The optimum SRD was between 40 to 50 per cent of the subject's height without losing more than 15 milliseconds. The optimum value of seat height was nine inches; however a range from 8 to 10 inches could be used without affecting the reaction time by more than 10 milliseconds. The angle of twist, , when varied from 0 to 14 degrees did not have a significant effect on the reaction time. A reaction time of 290 milliseconds was found for the optimum design.

Experiment nine (Chawla, 1969) was conducted to investigate the effect of varying , and SRD, while keeping the seat height fixed at 9 inches. Four staff members from Kansas State University, each having at least 40 years of driving experience, were used as subjects. In addition 50 subjects (male and female) were used from an Engineering Open House (March 15, 1969) to compare reaction times of the dual-function pedal to that of the conventional system.

For the four experimental subjects a reaction time of 270 milliseconds was found for the optimum design; the conventional brake-accelerator system required 519 milliseconds. For fifty Engineering Open House visitors, the dual-function pedal averaged 280 milliseconds and the conventional system 470 milliseconds.

The optimum pedal angle was between 30 and 40 degrees. The optimum seat reference distance was estimated to be between 40 to 50 per cent of the subject's height. Beyond this region a change of 1 per cent in SRD increased reaction time approximately 7 milliseconds per per cent of seat reference distance. The angle of twist, when varied between 90 to 115 degrees, did not have a significant effect on the reaction time. Negative angles (less than 90 degrees) increased the reaction time. At the best condition the mean reaction time of the older subjects (average age: 60 years) used in this experiment was less than that of the young students (average age: 23 years) used in experiment eight (Sathaye, 1969). This might be due to the fact that older subjects had nearly ten times more driving experience than young students.

Experiment ten (Amar and Arora, 1969) was conducted to optimize the variables d and L using reaction time and travel time as the criteria. This study confirmed that the criterion of reaction time did not act as a constraint in the tested ranges of d(.5" to 3.5") and L(6" to 9"), a result already observed in experiment six. However, using travel time as a criterion, the recommended optimum range for d was between 1.5" and 3", and for L, it was between approximately 7" and 8.75".

### Predicting Physiological Cost

Over the years considerable research has been conducted in an effort to find a physiological factor that varies with the intensity of muscular work and is adaptable to noncomplex measurement and recording procedures. Advances in the field of electronics have yielded many noteworthy improvements in the techniques used to predict energy expenditure. A brief review of these techniques for industrial on-the-job use is given below.

Work energy requirements have been measured by many different and elaborate methods all of which have their own particular advantages and disadvantages. Green, Morris and Wiebers (1959) and Ingenhol (1959) discuss various techniques. Most of the equipment is costly and requires the subject to be attached to the instrument in some way. For instance, in a gasometer investigation by Green and Morris (1958), exhausted air from an individual was collected and its contents analyzed. From the $CO_2$ content of the exhausted air a relationship was established to the amount of energy used. Of course the gas mask had a physical as well as a psychological effect on the worker's performance. Another problem is that the oxygen "debt" incurred has a time lag which makes it difficult to assign a quantitative value to energy used (expended) on a specific part of the task. (Konz and Day, 1966)

Frederik (1959), in determining the best heights and weights for lifting, used the previously mentioned method of indirect calorimetry which utilizes the measurement of oxygen converted into carbon dioxide over and above that for the basic metabolism. This method requires appreciable physical force to be exerted. Ingenhol says oxygen consumption crosses a threshold when the weight lifted exceeds approximately 10 kilograms (22 pounds). Below this threshold the difference between metabolism while working and the basic metabolism is not detectable by $CO_2$ measurements. For example, the minimum weight lifted in Frederik's experiment was 20 pounds which is near this threshold.

Nichols and Amrine (1959) measured energy expenditure by using the heart rate and assuming that a faster heart rate was associated with more effort or energy exerted. Fahnestock, Boyes, Sargent, Springer and Siler (1963) point out, however, that there is not a linear relationship between the energy and heart rate. Fahnestock's subjects pedaled a bicycle ergometer at 30 rpm for several hours and he found that the heart beat rate rises for approximately 30 minutes after the start of work even though a constant amount of energy is being exerted. After 30 minutes, the heart rate was relatively constant.

### Design of Force Platform

Many of these measurement problems can be overcome by the use of the force platform. This device was developed by Lauru (1957), improved by Greene and Morris (1959), and further modified by Barany (1961) with the aid of a grant from the National Science Foundation. It detects forces as small as a heart beat in three independent perpendicular planes. No attachments are required to be made between the subject and the apparatus. Lauru's device consisted of a triangular platform balanced in space by means of piezo-electric quartz crystals in a manner such that they simultaneously detected changes in force in the vertical, frontal and lateral directions. The crystals converted minute variations in pressure to proportional variations of electric current which was amplified and recorded photographically on an oscilloscope. Lauru did not report evidence that the proposed measure of bodily movements was in fact a measure of physiological cost. However, he did imply from his studies that the larger the area under the reaction force trace, the more effort required for the given task (Lauru, 1957).

The force-platform constructed by Greene and Morris (1959) consisted of a rigid equilateral triangular top frame balanced in space by steel balls that rested on cantilever beams. The beams were suspended from a steel subframe. An externally applied force resulted in a proportional beam deflection which, in turn, was converted into a proportional amount of electrical voltage by means of Linear Variable Differential Transformers (LVDT) and were recorded on three channels of a Brush Recorder.

In 1964 Greene's platform was improved by Barany and Whetsal (Whetsal, 1964). They used three additional cantilever beams to preload the three beams acting upward so that forces acting up could be detected as well as those acting down. The three additional beams were supported at the tips of a second triangle rotated 60 degrees with respect to the first, making a hexagon shapeded platform.

A major improvement, torque measurement about the three axes, was introduced by Konz and Hearn (Hearn and Konz, 1968). The method selected to measure the torques about the three axes was quite simple. Two extra LVDT's for each axis were placed on the lower platform with their lines of action located an equal distance on either side of the torque axis. The lines of action of these transformer cores also lie in a plane which is perpendicular to the associated axis. The electrical connection of the two transformers is such that any variation of the position of one transformer relative to that of the other will give a resulting output. At the same time, both the cores may move along their lines of action by the same amount, remain in balance and thus have no output signal.

## Meaning of Output of Force Platform

Using his platform, Greene (1957) investigated the hypothesis that the force traces indicate the actual physiological costs to a worker as measured by oxygen comsumption. A foot ergometer task was used at four levels of force and four different work paces for four different subjects. The results yielded correlations between force-time recordings and oxygen consumption of 0.79, 0.23, 0.75, and 0.76 for each subject, respectively, and pooled correlation of 0.78, disregarding the second individual's regression coefficient. Although the correlations were significant, Greene discredits the results by declaring that because distance was fixed, better correlations were obtained than if distance had been made a variable in the experiment. According to Greene, the force-platform yields only a continuous record of the force, and no more; hence it is impossible for the platform alone to measure mechanical work, since work is defined as force times distance. One possible solution to this problem, suggested by Greene, would be to relate platform forces to calorie cost by means of a family of curves for each task, one curve for each distance. Different tasks could possibly be divided into three groups; one group for those tasks utilizing leg motions, one for arm motions, and a third for hand motions (Yoder, 1964).

Brouha (1960) used a Lauru platform to obtain continuous and quantitative records of all the dynamic forces and elements of motion. Using this apparatus, he studied the relation between the forces recorded by the platform and the oxygen consumption needed to do the work. The task consisted of raising and lowering the arms from shoulder level to full extension above the head while lifting either a zero load, a 2.2 pound weight, or a 4.84 pound weight. Force platform records were taken only in the vertical plane, and oxygen consumption was measured during both work and recovery. The results revealed a 0.83 correlation between vertical force-time area and oxygen cost for three subjects performing the task at three loads and at various paces. The results are limited to the assumption that the body's reaction forces to the lifting task were entirely vertical in direction. Although this study gave a good indication that reaction forces developed on a platform approach metabolic measurements, it was by no means conclusive on this point.

Physiological work, however, is entirely different from mechanical work (Karpovich, 1962). As was mentioned before, mechanical work is derived simply by multiplying force by distance. Physiological work, on the contrary, may not be nearly so sensitive to changes in distance as to changes in weight lifted or force exerted. For example, to carry 50 pounds a distance of 50 feet constitutes a feasible human task and represents 2500 foot-pounds of mechanical work, but the same amount of mechanical work would be computed when 1,000 pounds is carried a distance of 2.5 feet -- an impossible human task! In fact, certain types of physiological work (static work) require no movement whatsoever. For example, if a man holds ten pounds while his arm remains motionless and extended, he is not doing any mechanical work, yet he quickly gets tired. Thus, it is clear that some sort of modified effort formula is required in order to correctly employ force applied, distance, and time as criteria in describing exactly to what extent a force-sensitive device measures physiological work.

Any attempt to derive an exact effort formula consisting of the directly measurable components of distance, force and time would appear futile for the following reasons: (Yoder, 1964)

1. The factors are not of equal status and importance. There is a greater sensitivity of the human metabolism to weights than to distance or even to speed of work (Ingenohl, 1959).

2. The factors cannot be combined into a mathematical product alone. One factor, such as bodily movements, can be fixed to zero while another, such as weight lifted, is varied; and still, even though a product of these factors would yield a zero, energy is expended.

Therefore, any evaluation of a force-sensitive device to measure human work should be based strictly on energy expenditure. Statistical methods can then be used to specify which factors produce a significant effect upon the amount of force exerted and the energy expended during the performance of an experimental task. The consistency with which the factors affect force exerted in relation to their effects on physiological work can then be examined by comparing the experimental results (Yoder, 1964).

## Application of Force-Platform

Several investigations have been carried out on the force platform since Lauru's work in 1957.

Jacobson (1960) studied a dynamic evaluation of a force platform. The force platform had sufficient sensitivity to measure

1/2 pound force in the frontal axis and 1 pound force in the lateral axis. He concluded that this minimum force sensing capability was unaffected by frequencies of force application from 50-200 cpm or by variation in subject weight from 100 to 200 pounds.

Barany (1963) investigated the nature of individual differences in bodily forces exerted by a group of subjects who performed a simple motor task. He concluded that:

1. A very large portion of the variation in the amount of force exerted per cycle can be attributed to individual differences.
2. There was no relationship between any one of the anthropometric measurements (arm reach, chest circumference, height and weight) and the force exerted per unit of production.

Barta (1962) investigated the existence of a relationship between the external force (measured by the force platform) exerted by a worker and time as the criterion for work measurement. He found that the three components of external force, measured by the force platform, increased at a much greater rate than the increase in time as the weight handled increased from 0.35 to 12.92 pounds.

Dunnington (1961) and Hudson (1962) studied the effect of work place dimensions on the physiological cost as measured by the force platform. The task contained a variety of motions and simulated a drilling operation. They found that adjusting the work place to fit the subject's anthropometric measurements significantly reduced the effort (lb-sec. of area) to perform the task.

Konz and Day (1966) varied the height and handle orientation of a push-pull task performed on the force platform in the standing condition. The subjects operated the push-pull device at each of the five handle heights (knee, hip, waist, chest, and eye). Even though the force required for the task itself did not vary, changing the height of the handle forced each subject to exert a force to maintain his own body position. This force exerted by the subject was minimum when the handle was at chest height.

Wu (1965) (Konz ,1967) investigated the effect of direction of movement and height of the work station. The seated subject moved a two pound weight with the right hand from a central point to a peripheral point 15 inches away; five different heights of work station and five different angles were considered. Physiological cost as measured by the force platform was used as the criterion. He found that an optimum vertical distance was at 0.85 L, L being the length of the upper arm of the individuals.

Jeans (1966) studied the physiological cost of simultaneous and symmetrical motions. The subject moved a two pound weight in each hand between the specified points 18 inches apart under three experimental conditions. It was concluded that the outward motions of both hands required more force than the inward motions.

Sankaran (1968) studied the optimum height of a work table for simple arm movements while sitting. The criterion used was the physiological cost as measured by the force platform. Ten female subjects were used and five heights (+3, 0, -3, -6, -9 cm. from the elbow) were studied. There was a significant difference between heights. The work table height at three centimeters below the elbow level required the minimum physiological cost while the table level set at nine centimeters below the elbow required the maximum physiological cost. It was found that there was a significant difference between the inward and outward movements, the outward having less cost than the inward for the table heights below the elbow level. But for the table heights above the elbow level, the inward movements required less physiological cost than the outward movements.

# PROBLEM

To date, ten experiments have been conducted on dual-function pedals at Kansas State University. The first five of these experiments explored the potentials of this innovation in the controls for an automotive accelerator-brake system. These experiments demonstrated that the dual-function pedal, although not the best in theory, was better than the existing system. The last five of these experiments investigated the effect of varying different parameters in the design of the dual-function pedal. These experiments used minimum reaction time or travel time as the criterion of optimality. The question then is, is time alone a satisfactory criterion of optimality?

Physiological cost, in addition to time, is an important factor in an effective design of a man-machine control system. The criterion of minimum time may optimize the design of a machine or a task but it may fail to match it with the ability of its human operator. On the other hand, the criterion of minimum physiological cost takes into consideration the human factor aspect and aims at reducing the physiological fatigue and work stress. Since the criterion of minimum time has been thoroughly investigated in the previous studies, the present research was undertaken to investigate the effect of varying some of the design parameters of the dual-function pedal on the physiological cost of human subjects. The physiological cost was measured in terms of force and torque recorded by a force platform.

Since the response required is primarily an extensor movement of the entire leg, the placement of the fulcrum of the pedal may be a significant variable. Konz, Koe, and Kalra (1968) concluded that reaction time did not change significantly as d was varied from .5" to 2.5" and L was varied from 5" to 9". The present study was conducted to determine experimentally the best values of d and L, using force and torque associated with the application of the brake as criteria. The purpose of this study was to evaluate the suitability of force and torque as criteria for evaluating the alternative design configurations of man-machine control systems.

# METHOD

## Experimental Arrangement

The experimental arrangement shown in Plate I was similar to that of Kalra (1968), except for the addition of the force platform and three recorders. The apparatus for the present experiment consisted of the following:

A. Control switch

B. 100 watt electrical lamp covered with red cellophane

C. Three 2-channel Texas Instrument Oscillographic recorders

D. D. C. supply source

E. Dual-function pedal test box

F. Actuation indicator bulbs

G. Biomechanic chair

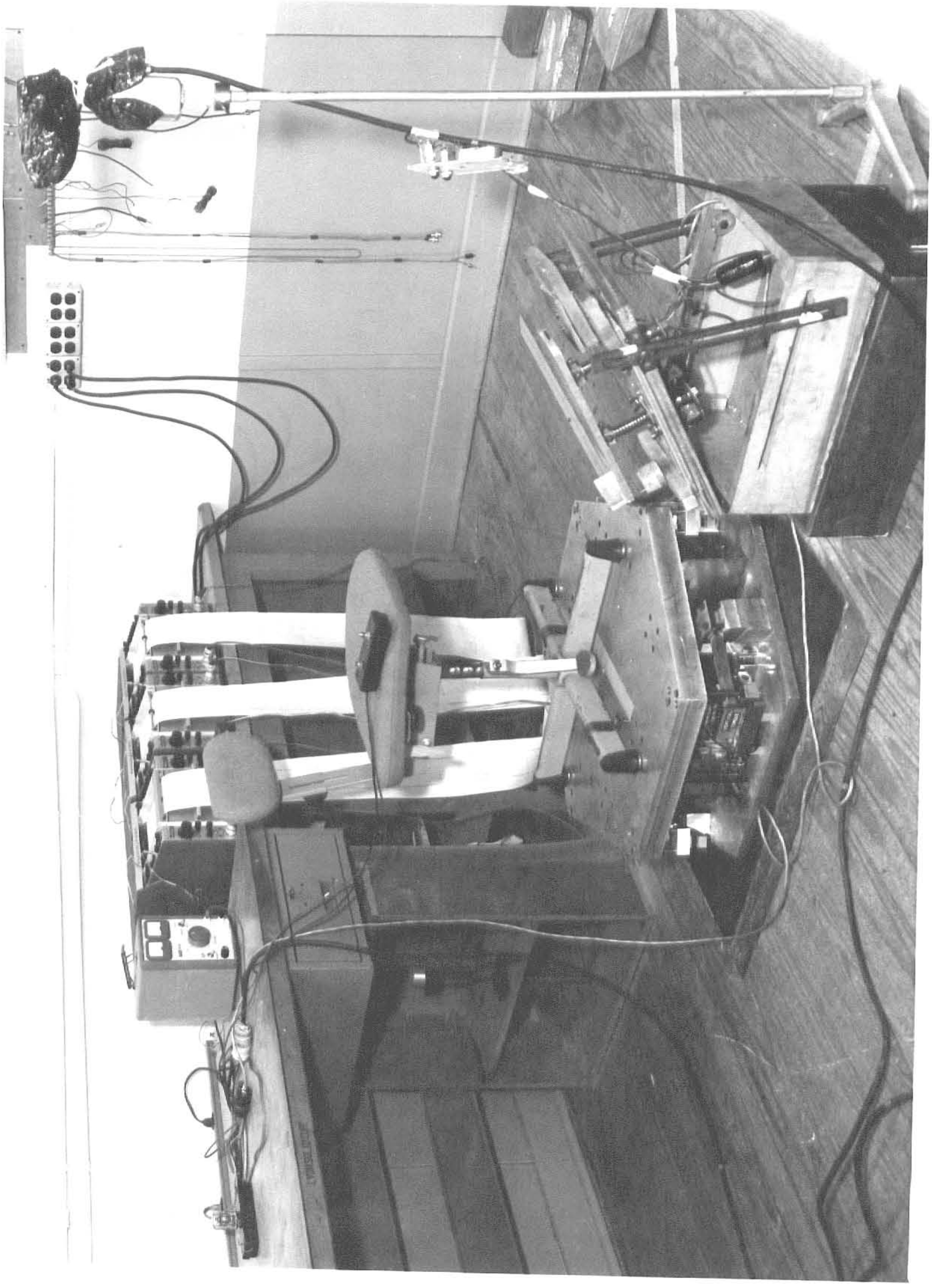
H. Force platform

The distances of the two shafts from the heel of the pedal can be adjusted easily. The foreshaft acts as a fulcrum when the pedal is pressed by the heel and the rear shaft acts as a fulcrum when the pedal is pressed by the toe. The motions could be used for accelerating and braking a car. Plate II gives a side view of the dual-function pedal.

The shafts were connected to two cut out switches, which were connected to two "actuation indicator bulbs", one green and the other red. A D. C. power supply (12v/200 mA) was used in

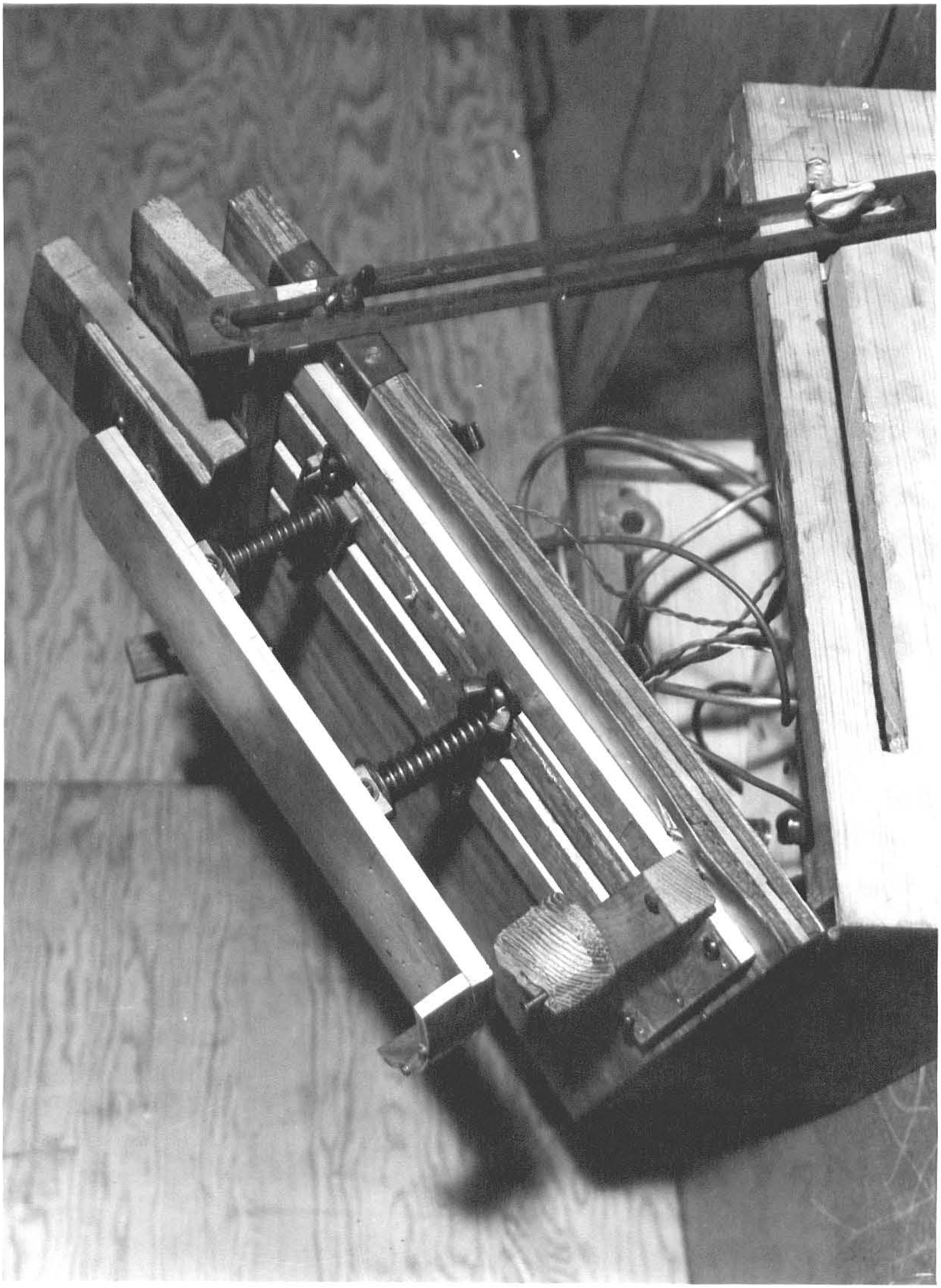
# PLATE I

Experimental Arrangement



## PLATE II

A Side-View of The Dual-Function Pedal



the circuit. The bulbs were off when no shaft was pressed. When the accelerator was depressed, the green bulb came on, and when it was released and the brake depressed, the green bulb went off. If, by mistake, both shafts were depressed, the red bulb would go on and a buzzer would sound, indicating faulty operation to the subject.

The chair used had a cushioned seat and back. The red cellophane paper covering the 100 watt lamp was to simulate the tail light of a car.

The force platform used was designed and constructed by Hearn and Konz (1968). Three 2-channel recorders were used to record forces on three perpendicular axes and their associated torques. The force trace originates from an established zero mark and deviates up or down. The distance deviated is directly proportional to the force or torque exerted in the specific plane.

## Design of Experiment

A searching technique called EVOP (Evolutionary Operation of Processes) (Box and Hunter, 1959) was used for optimizing the d and L values. The basic elements in the technique are:

1. Introduction of systematic small changes in the level of the parameters.
2. Analysis of the result of these changes so that a direction of steepest ascent (descent) can be approx-

imated and new changes in parameters incorporated to move toward the maximum (minimum) in the next phase of testing.

In EVOP a single performance of a complete set of operating conditions is called a cycle and the repeated running through of a cycle of operating conditions is called a phase. A new phase of EVOP begins when new conditions are explored, involving different levels of the same variables or different variables.

To study the effects of any change, it is required that the process be run for some number of cycles at one level of variables. The result, or response surface, is determined and then new changes are introduced. The "evolution", thus, is a step by step process, each change representing a new step and with the direction of the step so selected as to lead to the optimum.

A $2^2$ factorial design with a center point, Figure 3, was used for this experiment. The variables d and L were selected as shown in Figure 4, giving 5 conditions for the experiment.

For evaluating the output of the force platform, at least two analysis techniques can be used:

1. The total area under the trace (i.e. energy) can be calculated either by using a planimeter or by feeding the LVDT signal into an analog integrating circuit (Energy is considered to be the average force exerted over a period of time).

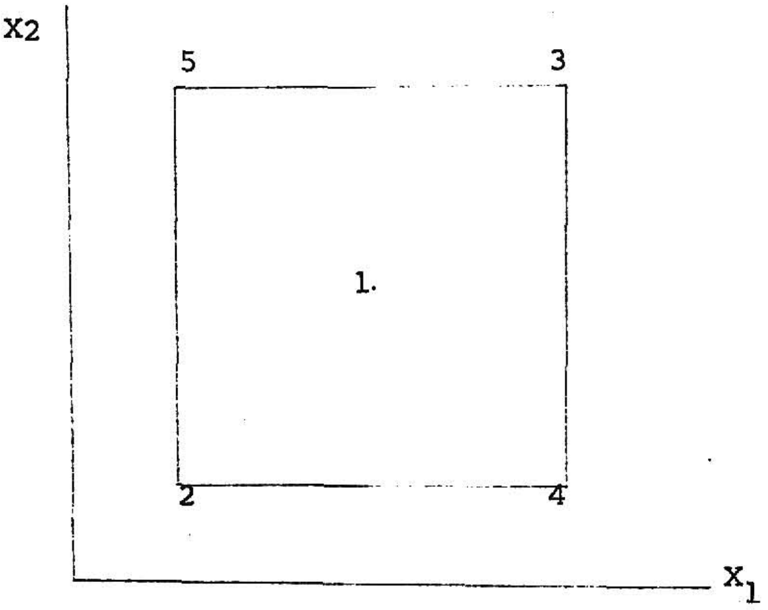


Figure 3. Factorial Design with a Center Point

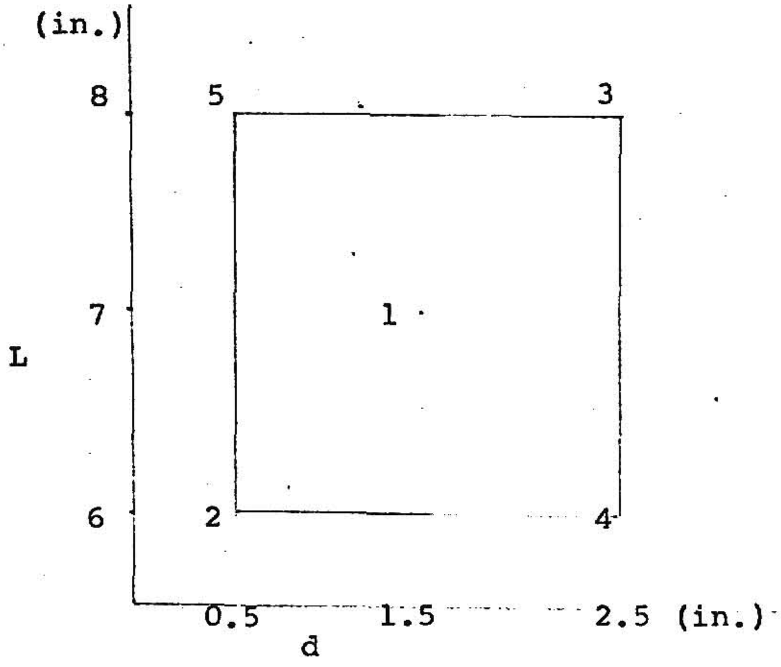


Figure 4. Pattern of Variables for Phase I

2. The maximum height of the trace can be used as an index of the forces or torques exerted by the operator when performing the task.

If the energy exerted is required, the total area analysis should be used; if only the maximum force or torque exerted is required, measuring the maximum height of the line is sufficient. In the present experiment, displacement of the pedal was kept fixed for all subjects by placing stops below the toe and heel of the pedal. Since the trial was a very short duration ( one second), the work pace could not be standardized for all subjects. The subjects were asked to operate the pedal as naturally as they would do in an actual driving condition. It was expected that the variables under study would significantly affect the maximum level of external forces and torques exerted by the subjects. Since the time for which the brake or accelerator was kept pressed was not important, it was decided to use the maximum heights of the LVDT outputs for analyzing the data. The arithmetic sums of the three components of force or torque thus measured were used as representative indices of the total amount of force or torque exerted. The reasons for using the arithmetic sum are:

1. It is simple.

2. If vectorial sum was used, it would cancel forces in opposite directions.

## Experimental Procedure

The value of seat reference distance (SRD), the inclination of the pedal to the floor ($\alpha$), the chair height, and the angle of twist ($\beta$) were taken as optimized by Chawla (1969). SRD was adjusted as 40 per cent of the subject's height. The value of $\alpha$ was set at 35 degrees and $\beta$ at 0 degrees. Seat height was fixed at 9" above the heel of the pedal. The brake (15 pounds) and accelerator (6 pounds) spring forces were kept constant. The brake spring was 2.44" long with a spring constant of 66.67 pounds/unit inch and the accelerator spring was 2.56" long with a spring constant of 10.42 pounds/unit inch. A weight of two hundred pounds was placed on the platform and the calibration of the force platform was then made for this two hundred pounds, standard weight. Each subject was weighed and when he sat on the chair, additional weights were placed on the platform to bring the total weight on the platform to 200 pounds. This eliminated the requirement of adjusting the transformers for each individual subject's weight. By calibration with known weights, the scale factors, which give the amount of force in pounds per mm of deflection on the output paper for the force axes and the amount of torque in inch-pounds per mm of deflection on the output paper for the torque axes, were determined for each axis. Granger (1967) demonstrated this specific force platform to be linear within a 200 pound range and to be repeatable with an accuracy of 0.1 pound. The variability due to subjects and conditions far exceeded this measurement error. This, plus the repeated measurements, indicate the device was sufficiently accurate for this experiment.

The subject was told the purpose of the experiment. He was seated on the chair with his back resting against the back rest and hands in his lap. The center of the pedal was offset 8" from the center of the chair on the right side of the seated subject. The subject sat in a relaxed position with his left foot on the platform and right foot on the floor of the test box. He was asked to look at the red lamp in front. The recorder was turned on for one or two seconds to record the normal reading for the subject. The reference line is marked R in Figure 5. After a few seconds, the control switch was turned on to light the lamp. The subject lifted his right foot and pressed the accelerator shaft. The trace between $A_1$ and $A_2$ represents the force or torque exerted for this activity. The line $R_A$ shows the condition when the subject was pressing on the accelerator against a fixed stop. The control switch was turned on again and the subject released the accelerator and pressed the brake against a fixed stop. The line $B_1$ $B_2$ shows this interval. From $B_2$ to $B_3$ the subject kept pressing on the brake. The subject was then asked arbitrarily to release the brake and come back to the normal position R'. The establishment of these benchmarks reduced the problem of any electronic drift of the equipment as well as other miscellaneous errors. It is possible to use either baseline; the subject sitting with his right foot on the floor of the test box (R R') or the subject with his right foot pressing on the accelerator against a fixed stop ($R_A$). The former (R) was used for this experiment so the output could be interpreted as the total force or torque required (above that required to sit in the chair) for applying the brake. Once the force and torque outputs had been plotted on the recording charts, it was necessary to measure the ordinates on each axis. Since the axes had been calibrated, it was possible to convert the millimeters of peak ordinate readings into pounds and inch-pounds of forces and torques respectively.

In the initial condition of the depressed accelerator, it was made certain by the experimenter that both the controls were not in the depressed condition. If both controls were pressed simultaneously after the presentation of the stimulus, the red indicator bulb came on and the buzzer sounded and the data were disregarded.

The subjects were given three to five practice trials at each condition. Ten force platform outputs were recorded for each condition for a subject before the condition was changed to the next one. The time between two successive stimuli (four to seven seconds), selected randomly, was sufficient to prevent the

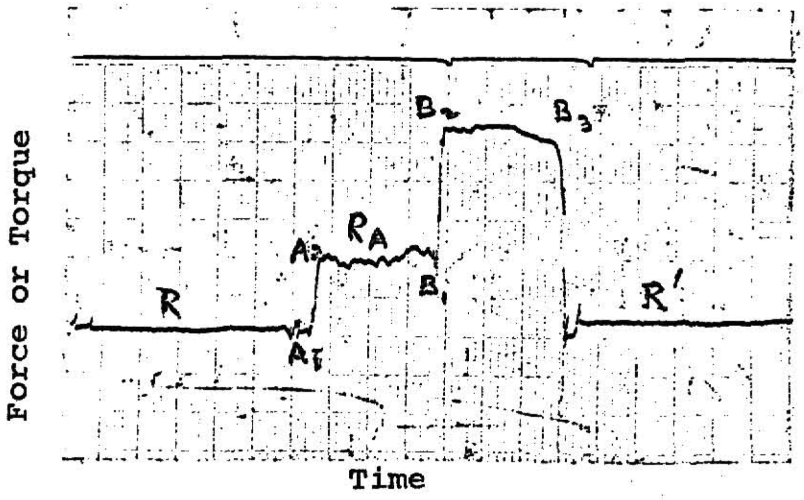


Figure 5. Pattern of Force Platform Output

treating of them by the subject as a single stimulus (Welford, 1960) or his anticipative response to a signal about to occur (Morgan, et al., 1963). While the condition was being changed, the subject was idle. No other rest time was allowed.

Each phase of the experiment was run in two parts. In the first part, the subject was seated on the force platform and the pedal unit was placed on the floor (Plate III). In the second part, the pedal unit was placed on the force platform and the subject was seated on the floor (Plate IV). In the remainder of the thesis, the first part will be referred to as subject on platform and the second part will be referred to as pedal on platform.

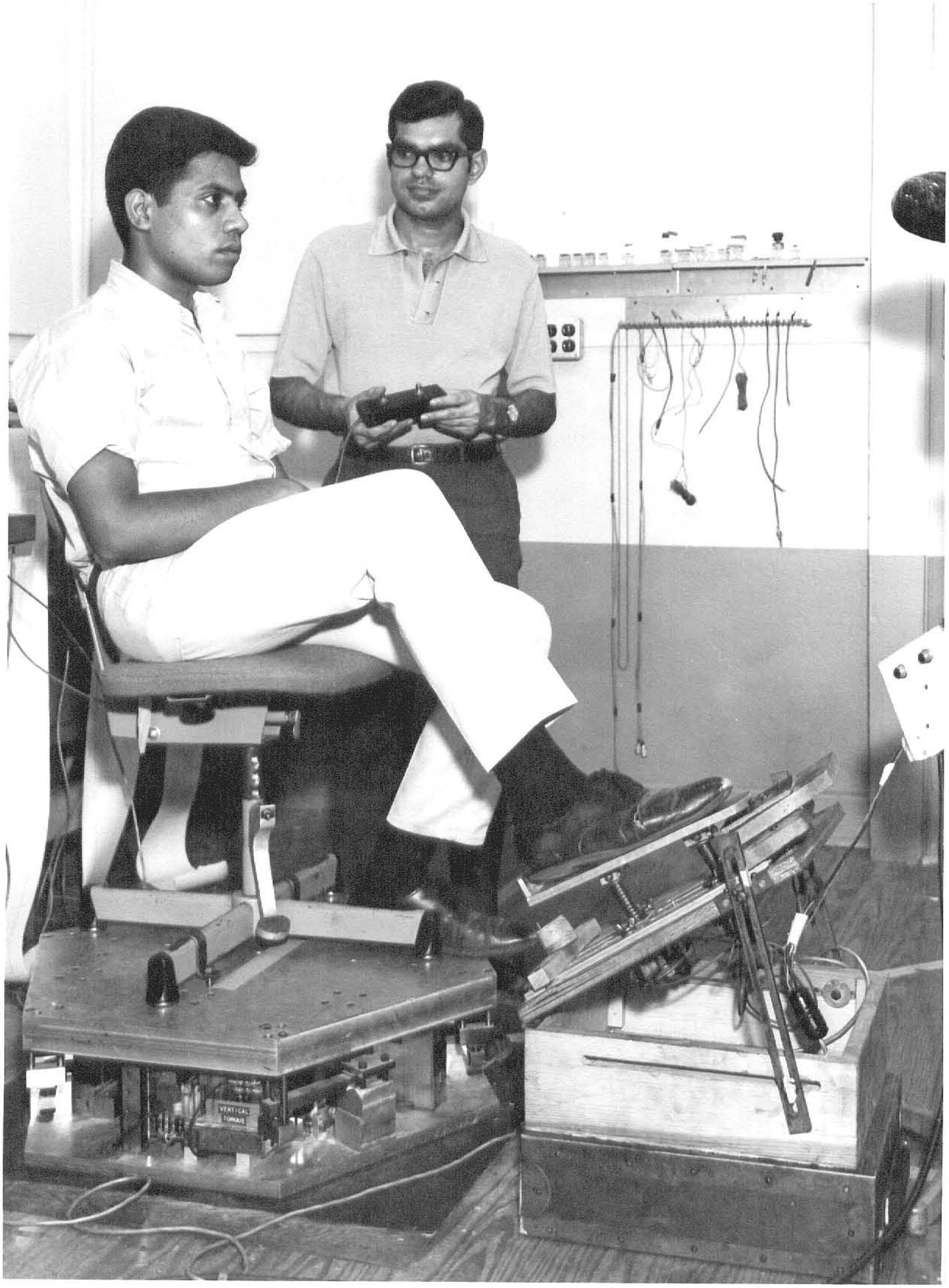
## Subjects

Four subjects, selected from an available population of male graduate industrial engineering students at Kansas State University,were paid by the hour. The subjects had driving experience varying from 1 to 4 years. Their ages varied from 24 to 31 with an average of 26.7 years; their heights varied from 63" to 73.5" with an average of 68.9".

The sequence of treatment administration was randomized for each subject. Finally, the output traces for all subjects were selected for measurement so that it was not known which treatment

PLATE III

A subject performing the task with subject seated on the platform


VERTICAL
TORQUE

## PLATE IV

A subject performing the task with pedal on the platform


VERTICAL
TORQUE

was being analyzed. This reduced any chance of unconscious bias on the part of the analyst.

# EXPERIMENTAL RESULTS

The range of variables was studied in three phases. The results of Phase I were used to determine the conditions for Phase II. Similarly, the results of Phase II were used to determine the conditions of Phase III.

EVOP (Evolutionary Operation of Process) was used to evaluate the significance of main effects (d and L) and the interaction effect (d x L). Running average $Y_i$'s (i identifying the conditions 1, 2, .....5) were calculated after obtaining mean forces and torques for each subject. Sample calculations for the four cycles of a phase illustrating the use of EVOP in calculating $Y_i$'s, the d, L and d x L effects and the 95% error limits for these effects are given in the Appendix. The effects were calculated as follows:

$$\text{d effect} = \tfrac{1}{2}(Y_3 + Y_4 - Y_2 - Y_5)$$

$$\text{L effect} = \tfrac{1}{2}(Y_3 + Y_5 - Y_2 - Y_4)$$

$$\text{d x L interaction} = \tfrac{1}{2}(Y_2 + Y_3 - Y_4 - Y_5)$$

The results of the three phases are presented below.

## Phase I

The values selected in Phase I for the parameters d and L were 1.5" and 7", .5" and 6", 2.5" and 8", 2.5" and 6" and .5" and 8", identified as conditions 1 through 5 respectively in Figure 4. Total composite forces and torques for the subject on

Table 1

Mean peak force (pounds) of ten trials in Phase I,

Subject on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 63.5 | 72.3 | 63.7 | 56.0 | 101.2 | 71.4 |
| R. K. | 56.9 | 85.4 | 65.4 | 58.9 | 79.0 | 69.0 |
| R. M. | 65.2 | 68.2 | 42.3 | 32.7 | 80.1 | 57.7 |
| G. G. | 61.3 | 35.6 | 45.5 | 26.8 | 76.3 | 49.0 |
| Mean | 61.7 | 65.4 | 54.2 | 43.6 | 84.1 | 61.8 |

Table 2

Mean peak torque (inch-pounds) of ten trials in Phase I

Subject on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 943.4 | 1207.4 | 1267.6 | 619.4 | 1745.5 | 1156.6 |
| R. K. | 949.0 | 1297.9 | 1253.6 | 1217.3 | 1235.4 | 1190.6 |
| R. M. | 1047.7 | 1177.4 | 953.2 | 563.1 | 1181.2 | 984.6 |
| G. G. | 921.2 | 933.7 | 899.0 | 598.4 | 1022.5 | 815.0 |
| Mean | 965.4 | 1079.1 | 1093.3 | 749.5 | 1296.1 | 1036.6 |

Table 3

Mean peak force (pounds) of ten trials in Phase I,

Pedal on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 62.9 | 70.8 | 71.6 | 44.9 | 74.7 | 64.9 |
| R. K. | 61.6 | 66.6 | 64.5 | 47.8 | 73.9 | 62.8 |
| R. M. | 71.6 | 73.4 | 38.5 | 35.9 | 68.7 | 57.6 |
| G. G. | 49.8 | 63.2 | 53.6 | 33.4 | 67.9 | 53.7 |
| Mean | 61.4 | 68.7 | 57.0 | 40.5 | 71.3 | 59.7 |

Table 4

Mean peak torque (inch-pounds) of ten trials in Phase I,

Pedal on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 373.4 | 447.3 | 464.9 | 364.1 | 492.6 | 428.4 |
| R. K. | 582.5 | 565.2 | 597.1 | 552.5 | 705.7 | 600.6 |
| R. M. | 525.8 | 650.9 | 511.6 | 488.3 | 673.8 | 570.4 |
| G. G. | 595.4 | 426.7 | 527.5 | 493.0 | 627.5 | 534.0 |
| Mean | 519.4 | 522.5 | 525.2 | 474.4 | 624.9 | 533.2 |

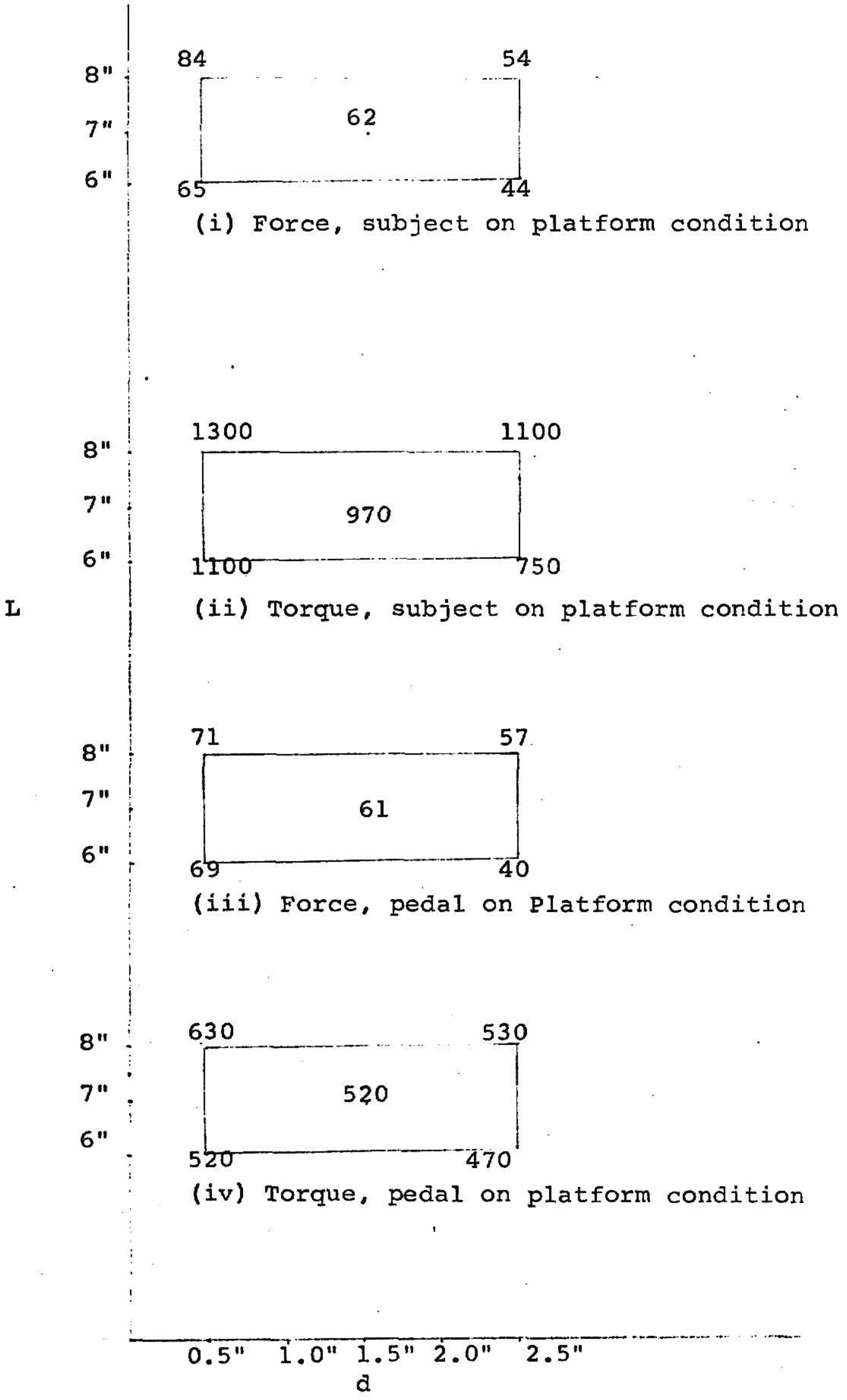
Table 5

Consolidated main effects and 95% error limits for

Phase 1

| | | | Cumulative Effects | | | |
|---|---|---|---|---|---|---|
| Condition | Criterion | Cycle No. | d | L | dxL | 95% Error Limits |
| Subject on Platform | Force, lb | 2 | -23.4* | 9.2 | -2.1 | ± 14.9 |
| | | 3 | -27.9* | 9.7 | -1.8 | ± 11.8 |
| | | 4 | -25.8* | 14.6* | -4.1 | ± 11.8 |
| Subject on Platform | Torque,"lb | 2 | -282.0 | 290.0 | 52.2 | ±468.7 |
| | | 3 | -328.4 | 258.9 | 99.2 | ±441.9 |
| | | 4 | -266.2 | 280.4 | 63.4 | ±329.1 |
| Pedal on Platform | Force, lb | 2 | -14.3* | 13.7* | 8.1* | ± 4.2 |
| | | 3 | -20.8* | 8.8 | 6.6 | ± 9.3 |
| | | 4 | -21.2* | 9.5* | 6.9* | ± 6.9 |
| Pedal on Platform | Torque, "lb | 2 | -58.0* | 82.8* | -10.1 | ± 40.3 |
| | | 3 | -92.8* | 62.9* | -6.7 | ± 48.2 |
| | | 4 | -73.8* | 76.6* | -25.7 | ± 56.9 |

* $p < .05$



(i) Force, subject on platform condition

(ii) Torque, subject on platform condition

(iii) Force, pedal on Platform condition

(iv) Torque, pedal on platform condition

Figure 6. Mean peak values of force (pounds) and torque (inch-pounds) for conditions of Phase I

platform condition for the four subjects are summarized in Table 1 and Table 2 respectively. Similar values for the pedal on platform condition are given in Table 3 and Table 4. The forces, given in pounds, and the torques, given in inch-pounds, are the mean peak values of the ten readings taken for each condition. The mean peak values of the forces and torques are illustrated in Figure 6 for the four different criteria.

The results in calculations after each cycle for Phase I are consolidated in Table 5. The 95% error limits are also shown for the various effects.

Subject on Platform - As can be seen from the Table 5, d andL had a significant effect on force at the completion of Phase I, subject on platform. The surface sloped downwards from 0.5 inch by 12.9 pounds per inch. In other words, the force exerted decreased at a rate of 12.9 pounds per inch of increase of d. A change of 2 inches in L changed the response by 14.6 pounds; the surface sloped upward from 6 inches by 7.3 pounds per inch. As can be seen from Table 5, using torque as the response, there were no significant main or interaction effects at the completion of Phase I, subject on platform.

Pedal on Platform - Table 5 shows that the main effects of d and L and the interaction effect had a significant effect on force at the end of Phase I, pedal on platform. A change of 2 inches in d changed the response by 21.2 pounds; the surface sloped downward from 0.5 inch by 10.6 pounds per inch. A change of 2 inches in L changed the response by 9.5 pounds; the surface sloped upward from 6 inches by 4.8 pounds per inch. The significant d x L interaction effect showed that effect of d was dependent upon L. The main effects of d and L were found significant for torques also. A change of 2 inches in d changed the response by 73.8 inch-pounds, the surface sloped downward from 0.5 inches by 36.9 inch-pounds per inch. A change of 2 inches in L changed the response by 76.6 inch-pounds; the surface sloped upward from 6 inches by 38.3 inch-pounds per inch.

The results of Phase I suggested that the area of search for Phase II include larger values of d and smaller values of L; that is, the minimum was "southeast" of the area searched in Phase I.

## Phase II

The new values of variables selected are shown in Figure 7. One point of Phase I was replicated in Phase II. The mean peak forces and torques per cycle for the subject on platform condition for the four subjects are tabulated in Table 6 and Table 7. Table 8 and Table 9 give similar values for the pedal on platform condition. Table 10 shows the cumulative effects and 95% error limits for various effects. Figure 8 illustrates the average peak

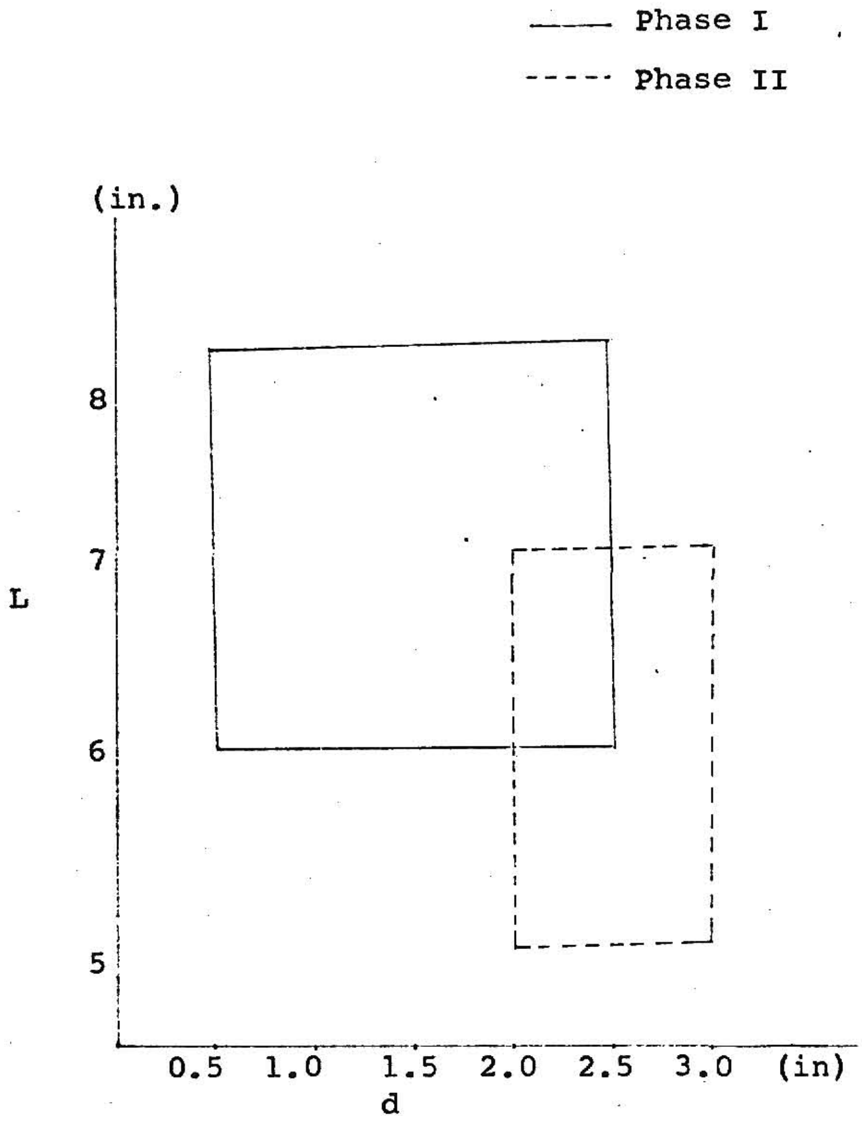


Figure 7. Pattern of variables for Phase I and Phase II

values of the forces and the torques for the four criteria.

Subject on Platform - As seen from the Table 10, d had a significant effect on force at the completion of Phase II, subject on platform. A change of 1 inch in d changed the response by 10.8 pounds; the surface still sloped downward from 21 inches. The results of torques at the end of Phase II, subject on platform condition, also indicated that d had a significant effect on torque. A change of 1 inch in d changed the response by 227.1 inch-pounds; the surface sloped downward from 2 inches.

Pedal on Platform - The results show that the main effects of d and L were significant. A change of 1 inch in d changed the response by 9.8 pounds; the surface sloped downward from 2 inches. A change of 2 inches in L changed the response by 5.3 pounds; the surface sloped upward from 5 inches by 2.7 pounds per inch. As seen from the Table 10, there were no significant main or interaction effects at the completion of Phase II, pedal on platform condition using torque as the criterion.

The overall results of Phase II indicated that the best direction to move was by increasing d and reducing L; that is, southeast.

## Phase III

The present design of the pedal was such that further simultaneous increase in the values of d and decrease in the value of

Table 6

Mean peak force (pounds) of ten trials in Phase II,

Subject on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 46.1 | 43.6 | 37.6 | 27.3 | 48.2 | 40.6 |
| R. K. | 43.8 | 43.3 | 28.2 | 32.8 | 48.8 | 39.4 |
| R. M. | 63.7 | 51.3 | 35.5 | 46.3 | 49.6 | 49.3 |
| G. G. | 27.8 | 35.7 | 35.0 | 26.2 | 31.9 | 31.9 |
| Mean | 45.4 | 43.5 | 34.1 | 33.2 | 45.4 | 40.3 |

Table 7

Mean peak torque (inch-pounds) of ten trials in Phase II,

Subject on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 834.6 | 773.4 | 690.0 | 519.0 | 931.0 | 749.6 |
| R. K. | 862.8 | 891.0 | 649.2 | 555.0 | 997.2 | 791.0 |
| R. M. | 994.8 | 870.6 | 539.4 | 710.4 | 811.2 | 785.3 |
| G. G. | 596.4 | 606.0 | 543.0 | 510.6 | 653.4 | 581.8 |
| Mean | 822.2 | 785.2 | 605.4 | 573.8 | 848.2 | 727.0 |

Table 8

Mean peak force (pounds) of ten trials in Phase II,

Pedal on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 44.3 | 44.2 | 38.3 | 28.6 | 53.9 | 41.9 |
| R. K. | 36.4 | 39.2 | 37.2 | 26.9 | 43.3 | 36.6 |
| R. M. | 51.0 | 44.5 | 42.6 | 37.7 | 43.7 | 43.9 |
| G. G. | 31.4 | 39.4 | 30.9 | 23.2 | 35.3 | 32.0 |
| Mean | 40.8 | 41.8 | 37.3 | 29.1 | 44.1 | 38.6 |

Table 9

Mean peak torque (inch-pounds) of ten trials in Phase II,

Pedal on Platform condition

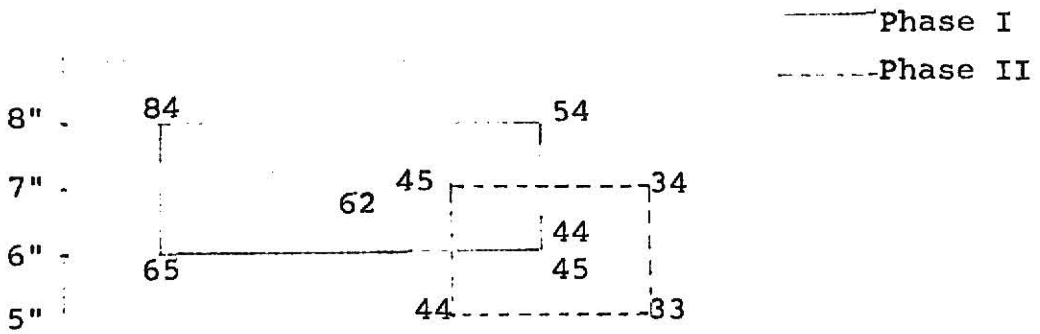
| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 273.6 | 270.2 | 319.3 | 243.2 | 386.1 | 298.5 |
| R. K. | 398.3 | 261.4 | 402.0 | 332.8 | 344.8 | 347.9 |
| R. M. | 533.5 | 482.3 | 445.5 | 408.2 | 428.6 | 459.6 |
| G. G. | 402.2 | 481.5 | 435.8 | 384.6 | 428.3 | 426.5 |
| Mean | 401.9 | 373.8 | 400.7 | 342.2 | 397.0 | 383.1 |

# Table 10

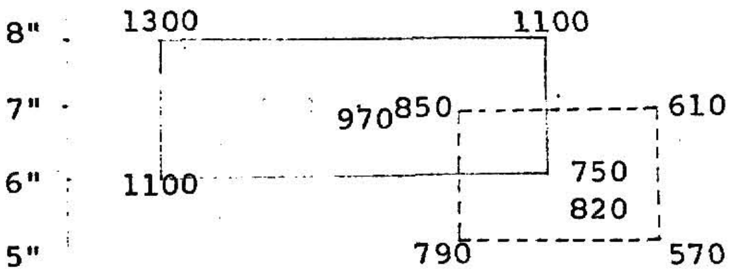
# Consolidated main effects and 95% error limits for Phase II

| | | Cumulative Effects | | | | |
|---|---|---|---|---|---|---|
| Condition | Criterion | Cycle No. | d | L | dxL | 95% Error Limits |
| Subject on Platform | Force, lb | 2 | -14.5* | 3.9 | -1.1 | ± 6.3 |
| | | 3 | -12.9* | 5.5 | -2.3 | ± 6.0 |
| | | 4 | -10.8* | 1.4 | -0.5 | ± 6.6 |
| Subject on Platform | Torque, "lb | 2 | -294.9* | 132.3* | 3.5 | ±67.0 |
| | | 3 | -268.6* | 49.8 | -18.4 | ±90.6 |
| | | 4 | -227.1* | 47.3 | -15.7 | ±80.8 |
| Pedal on Platform | Force, lb | 2 | -12.4* | 8.5* | 1.6 | ± 4.1 |
| | | 3 | -9.6* | 6.3* | 1.9 | ± 4.7 |
| | | 4 | -9.8* | 5.3* | 3.0 | ± 3.9 |
| Pedal on Platform | Torque, "lb | 2 | 8.7 | 86.2* | -13.5 | ±70.2 |
| | | 3 | -3.8 | 54.7 | 6.2 | ±58.0 |
| | | 4 | -14.0 | 40.9 | 17.7 | ±52.1 |

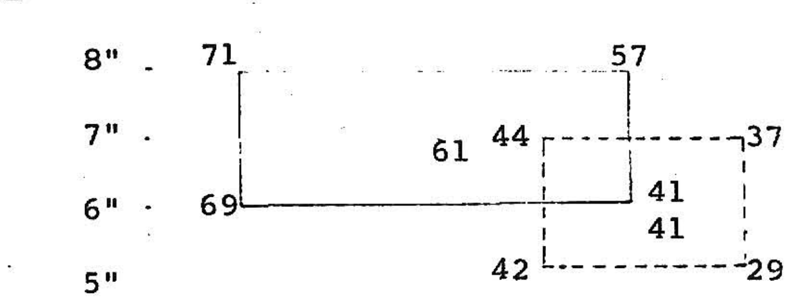
* $p < .05$



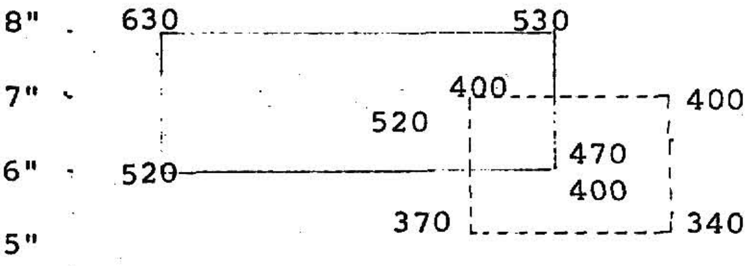
(i) Force, subject on platform condition



(ii) Torque, subject on platform condition



(iii) Force pedal on platform condition



(iv) Torque, pedal on platform condition

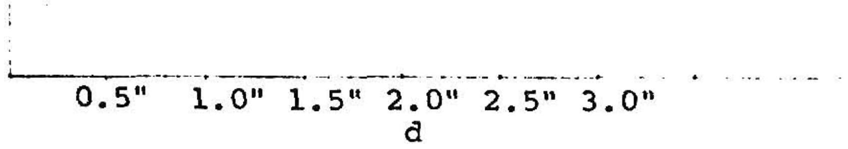


Figure 8. Mean peak values of force (pounds) and torque(inch-pounds) for conditions of phase I and phase II

L would result in a collision of the springs attached to the two shafts. The results of the first two phases showed that it was more beneficial to increase the values of d than to decrease the value of L. Therefore, in Phase III, values of d and L were increased resulting in the conditions shown in Figure 9. One point of Phase II was replicated in Phase III.

Tables 11 through 14 list the mean forces and torques per cycle for Phase III. Table 15 shows the cumulative effects and 95% error limits for the various effects. Figure 10 illustrates the average peak values of the forces and torques for the four criteria.

At the completion of Phase III, the main effects of d and L were significant. It seemed that increasing d and reducing L would lead to a still better operating range, but the physical limitations of the pedal did not permit further change in the operating conditions. The search was terminated after Phase III as the feasible surface had been scanned. In the range explored, the most favorable point was the point 4 (d=4", L=6") in Phase III. For this point the value for the subject on platform condition of force was 18 pounds; the value of torque was 324.9 inch-pounds; the value for the pedal on platform condition of force was 19 pounds; and the value of torque was 333 inch-pounds.

Figures 11 through 14 show the overall results for the three phases using the four criteria; force subject on platform, torque subject on platform, force pedal on platform, and torque pedal on platform. The common points of the three phases showed no definite learning effect. The approximate shape of the response surface showing its contours is also shown in these figures. It was observed that as the two shafts were moved closer, the forces and torques exerted decreased. The four criteria of physiological cost, when plotted against (L-d) are shown in Figures 15 through 18. It is interesting to note that the difference (L-d) seems to be a valid index in selecting the values of d and L. However the two variables d and L appear to give the best results as is evident from Figures 11 through 14.

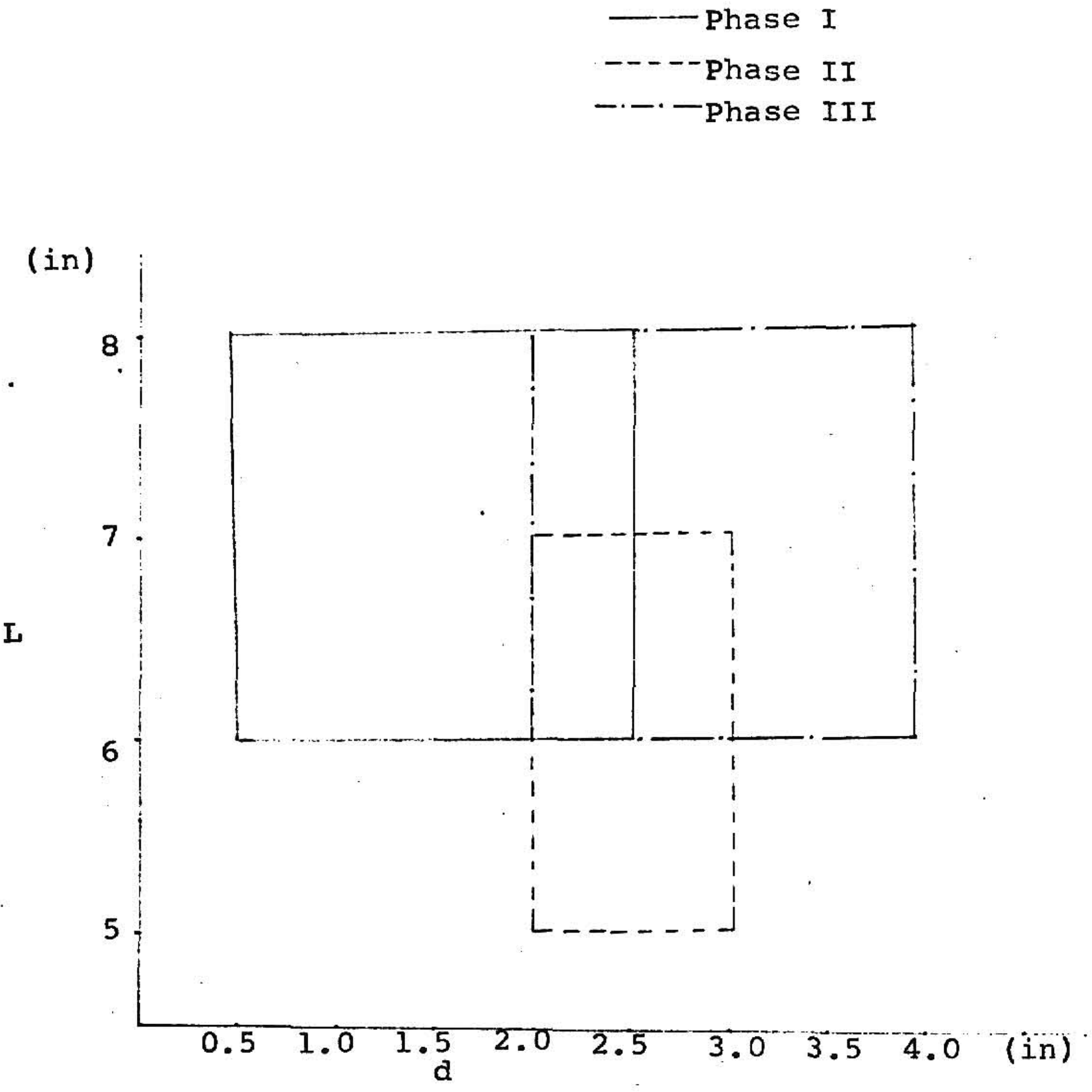


Figure 9. Pattern of variables for Phase I, Phase II and Phase III

## Table 11

Mean peak force (pounds) of ten trials in Phase III

Subject on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 38.9 | 45.0 | 46.5 | 22.9 | 64.1 | 43.5 |
| R. K. | 26.4 | 40.1 | 29.1 | 11.7 | 45.5 | 30.6 |
| R. M. | 35.4 | 32.5 | 30.3 | 21.8 | 29.6 | 29.9 |
| G. G. | 30.6 | 40.2 | 19.6 | 15.8 | 51.2 | 31.5 |
| Mean | 32.8 | 39.5 | 31.4 | 18.1 | 47.6 | 33.9 |

## Table 12

Mean peak torque (inch-pounds) of ten trials in Phase III

Subject on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 659.8 | 856.2 | 730.4 | 370.8 | 1132.2 | 749.9 |
| R. K. | 558.6 | 754.4 | 430.6 | 241.2 | 900.2 | 577.0 |
| R. M. | 680.7 | 675.0 | 552.1 | 352.8 | 643.4 | 580.8 |
| G. G. | 676.0 | 820.8 | 493.0 | 330.8 | 1094.6 | 683.0 |
| Mean | 643.8 | 776.6 | 551.5 | 323.9 | 942.6 | 647.7 |

Table 13

Mean peak force (pounds) of ten trials in Phase III, Pedal on Platform condition

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 39.5 | 40.3 | 36.5 | 32.5 | 40.5 | 37.9 |
| R. K. | 38.8 | 41.4 | 27.4 | 22.9 | 45.7 | 35.2 |
| R. M. | 30.3 | 29.1 | 25.4 | 15.6 | 33.9 | 26.9 |
| G. G. | 33.1 | 26.6 | 17.1 | 6.8 | 46.3 | 26.0 |
| Mean | 35.4 | 34.4 | 26.6 | 19.5 | 41.6 | 31.5 |

Table 14

Mean peak torque (inch-pounds) of ten trials in Phase III Pedal on Platform condition

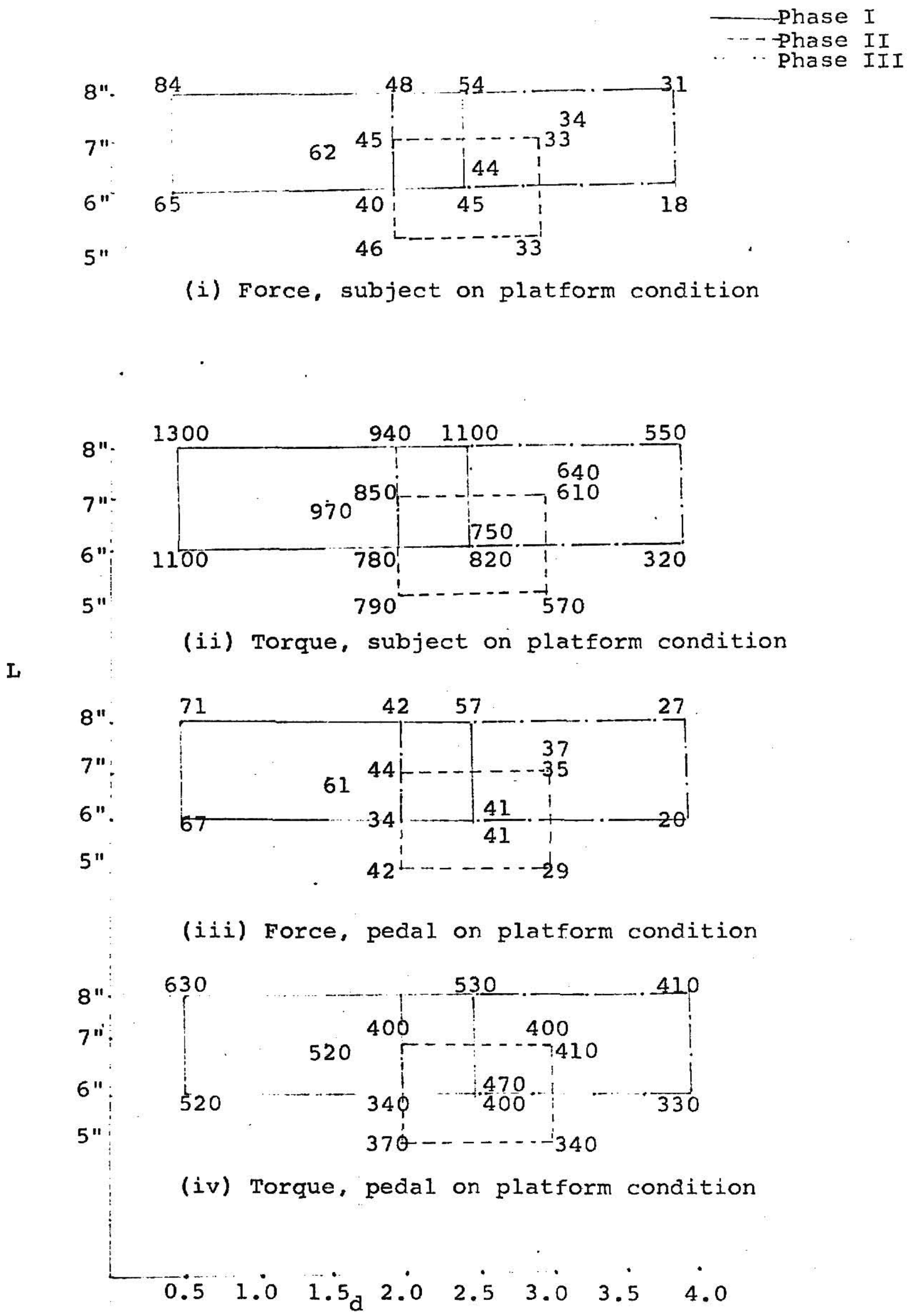
| | Condition | | | | | |
|---|---|---|---|---|---|---|
| Subject | 1 | 2 | 3 | 4 | 5 | Mean |
| A. A. | 312.0 | 275.2 | 371.8 | 260.5 | 353.6 | 314.6 |
| R. K. | 403.1 | 347.3 | 446.6 | 347.0 | 431.2 | 395.0 |
| R. M. | 464.9 | 415.2 | 443.5 | 404.5 | 488.4 | 443.3 |
| G. G. | 466.0 | 311.4 | 394.3 | 321.2 | 378.6 | 374.3 |
| Mean | 411.5 | 337.3 | 414.1 | 333.3 | 413.0 | 381.8 |

Table 15

Consolidated main effects and 95% error limits for Phase III

| | | Cumulative Effects | | | | |
|---|---|---|---|---|---|---|
| Condition | Criterion | Cycle No. | d | L | dxL | 95% Error Limits |
| Subject on Platform | Force, lb | 2 | -21.2* | 16.4* | 4.2 | ± 5.8 |
| | | 3 | -15.8* | 11.9* | 4.7 | ± 8.2 |
| | | 4 | -18.8* | 10.7* | 2.6 | ± 7.4 |
| Subject on Platform | Torque, "lb | 2 | -467.5* | 242.7* | 31.8 | ±84.0 |
| | | 3 | -380.6* | 189.7* | 59.7 | ±120. 5 |
| | | 4 | -421.9* | 196.8* | 30.8 | ±106. 3 |
| Pedal on Platform | Force, lb | 2 | -12.2* | 3.3 | 1.1 | ± 6.2 |
| | | 3 | -11.7* | 4.6* | 1.5 | ± 3.6 |
| | | 4 | -15.0* | 7.2* | -0.1 | ± 5.0 |
| Pedal on Platform | Torque, "lb | 2 | 4.7 | 93.3* | 12.2* | ± 8.0 |
| | | 3 | -6.2 | 80.9* | 2.4 | ±17.6 |
| | | 4 | -1.5 | 78.3* | 2.6 | ±25.0 |

* $p < .05$



(i) Force, subject on platform condition

(ii) Torque, subject on platform condition

(iii) Force, pedal on platform condition

(iv) Torque, pedal on platform condition

Figure 10. Mean peak values of force (pounds) and torque (inch-pounds) for conditions of Phase I, Phase II and Phase III

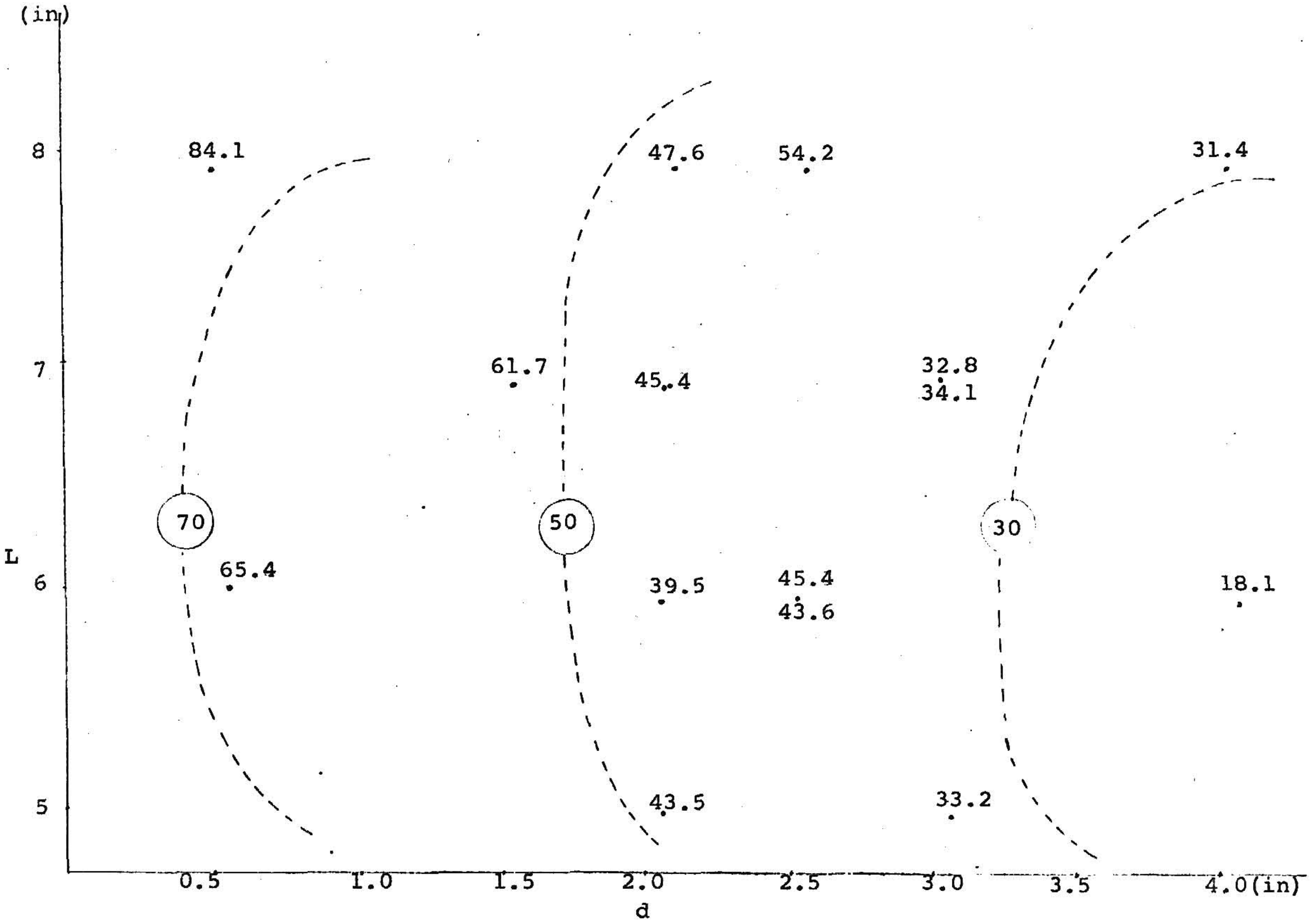


Figure 11. Mean values of force (pounds) of three phases, subject on platform condition

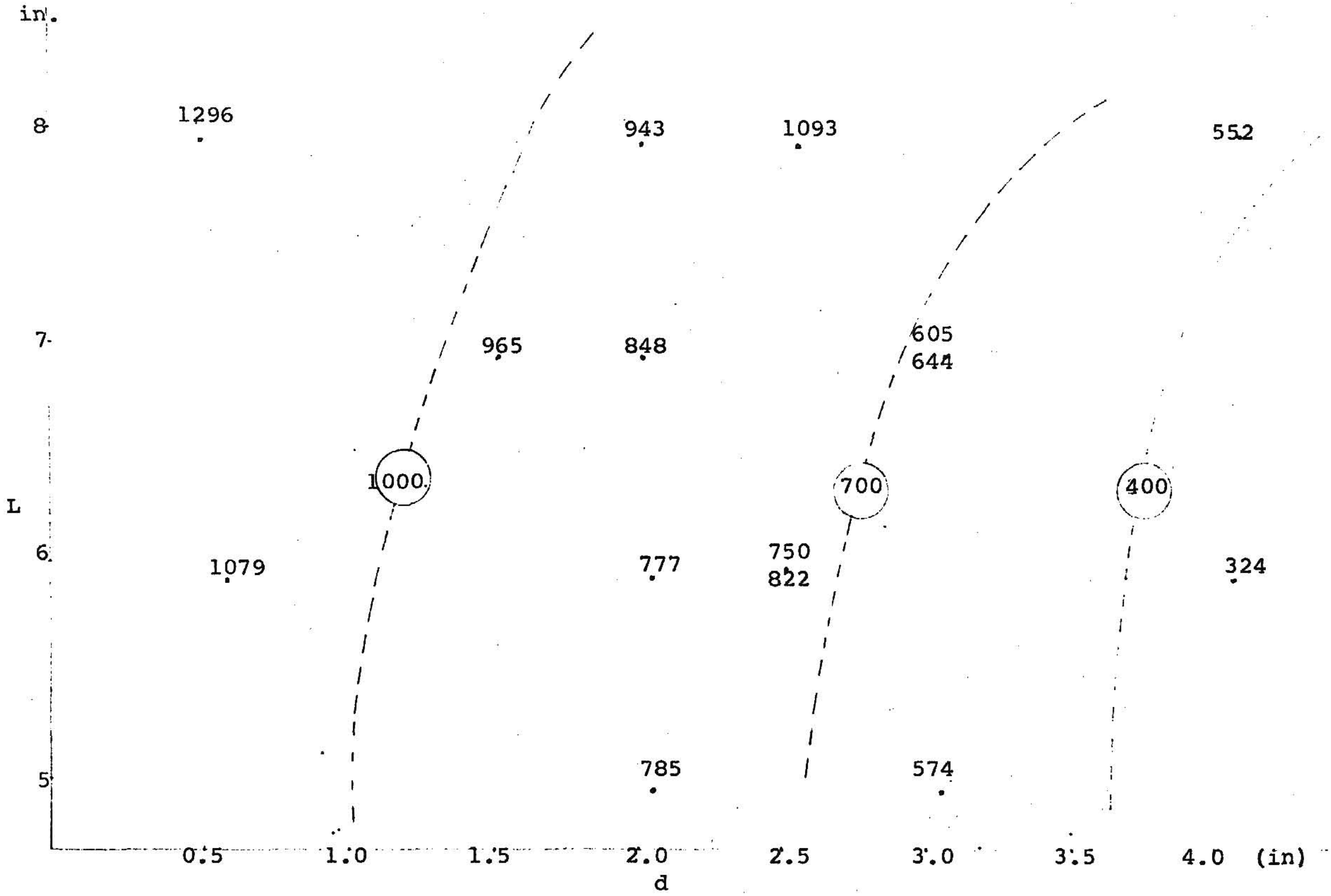


Figure 12. Mean values of torque (inch-pounds) of three phases, subject on platform condition

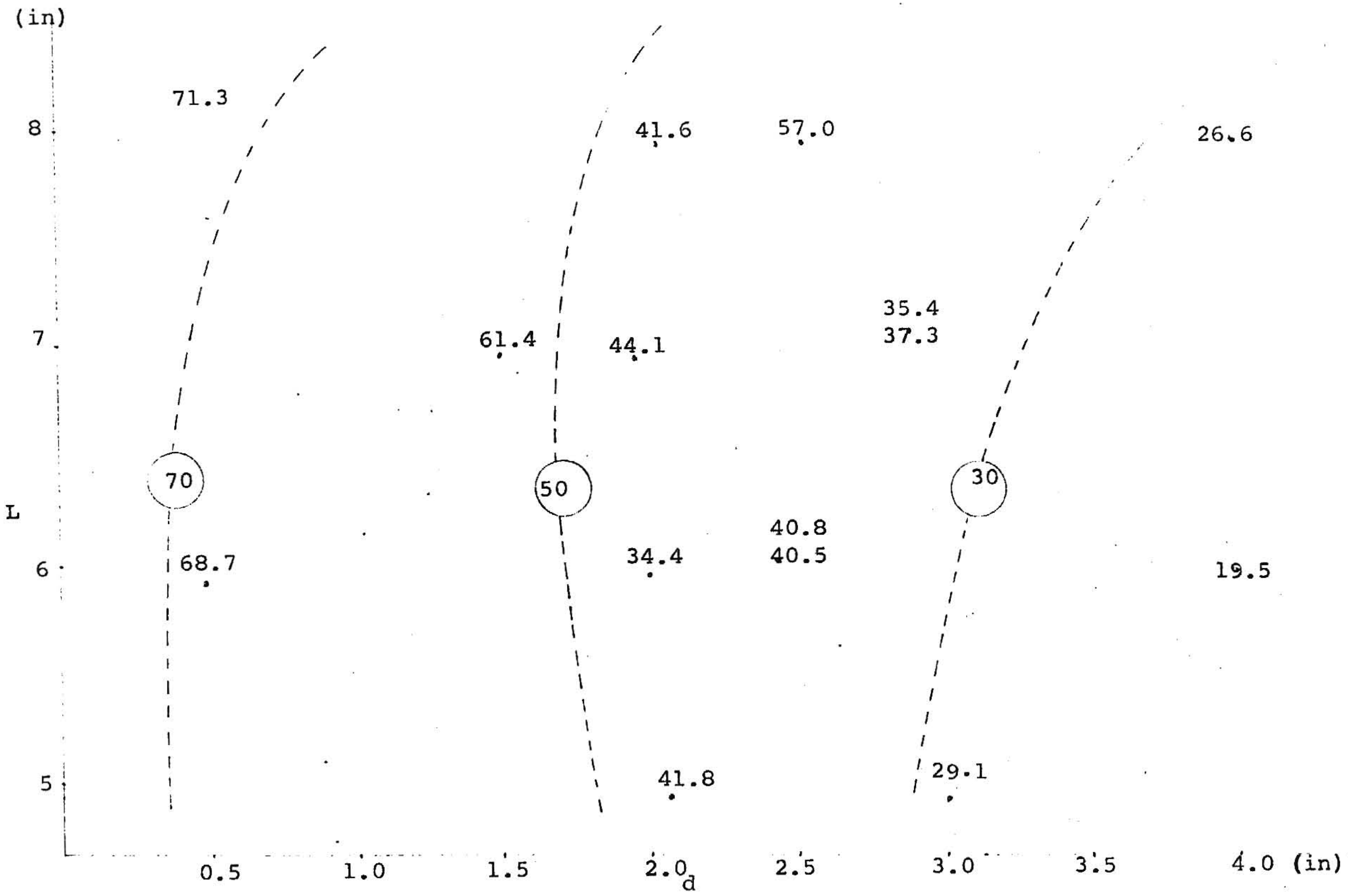


Figure 13. Mean values of force (pounds) of three phases, pedal on platform condition

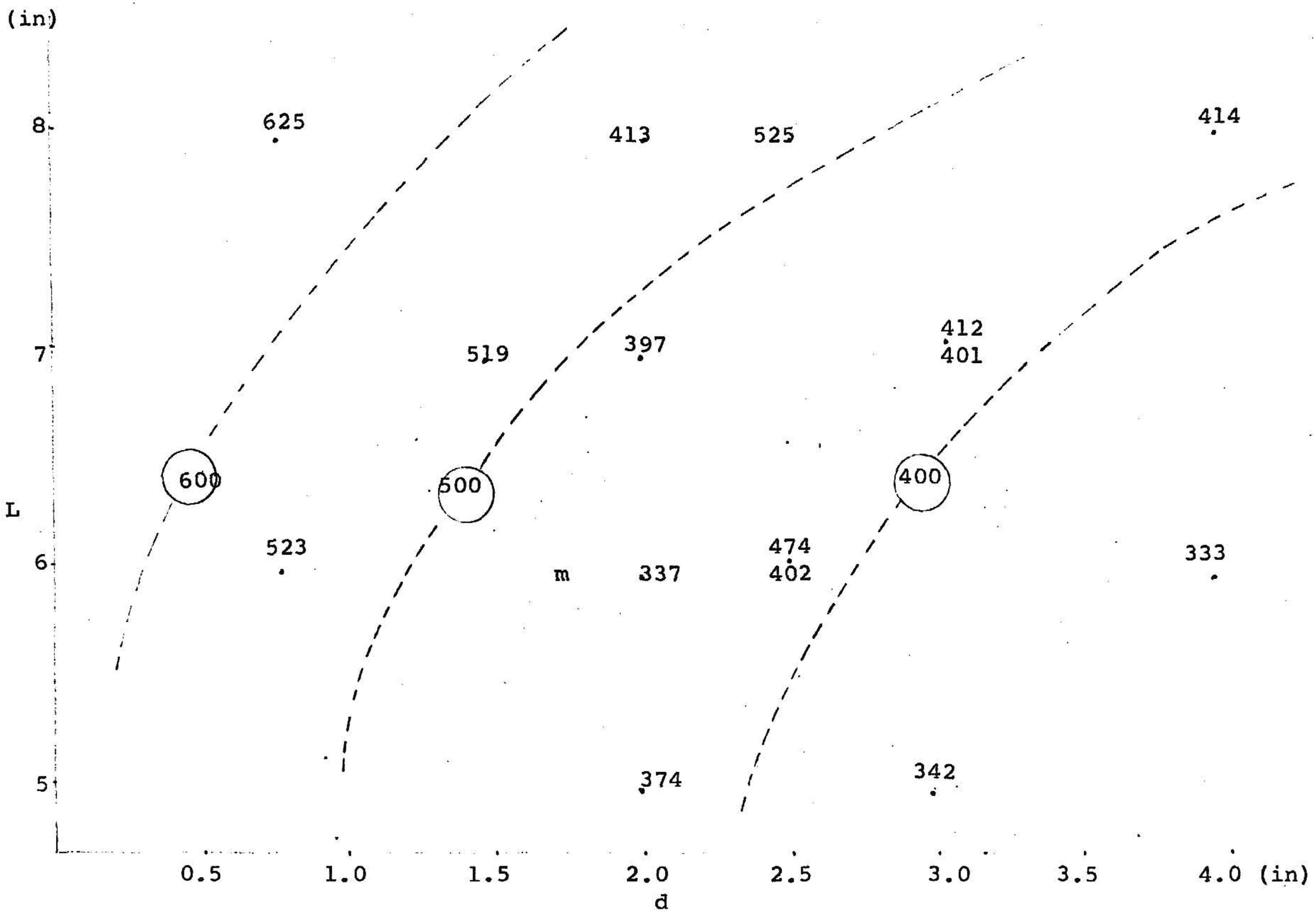


Figure 14. Mean values of torque(inch-pounds) of three phases, pedal on platform condition

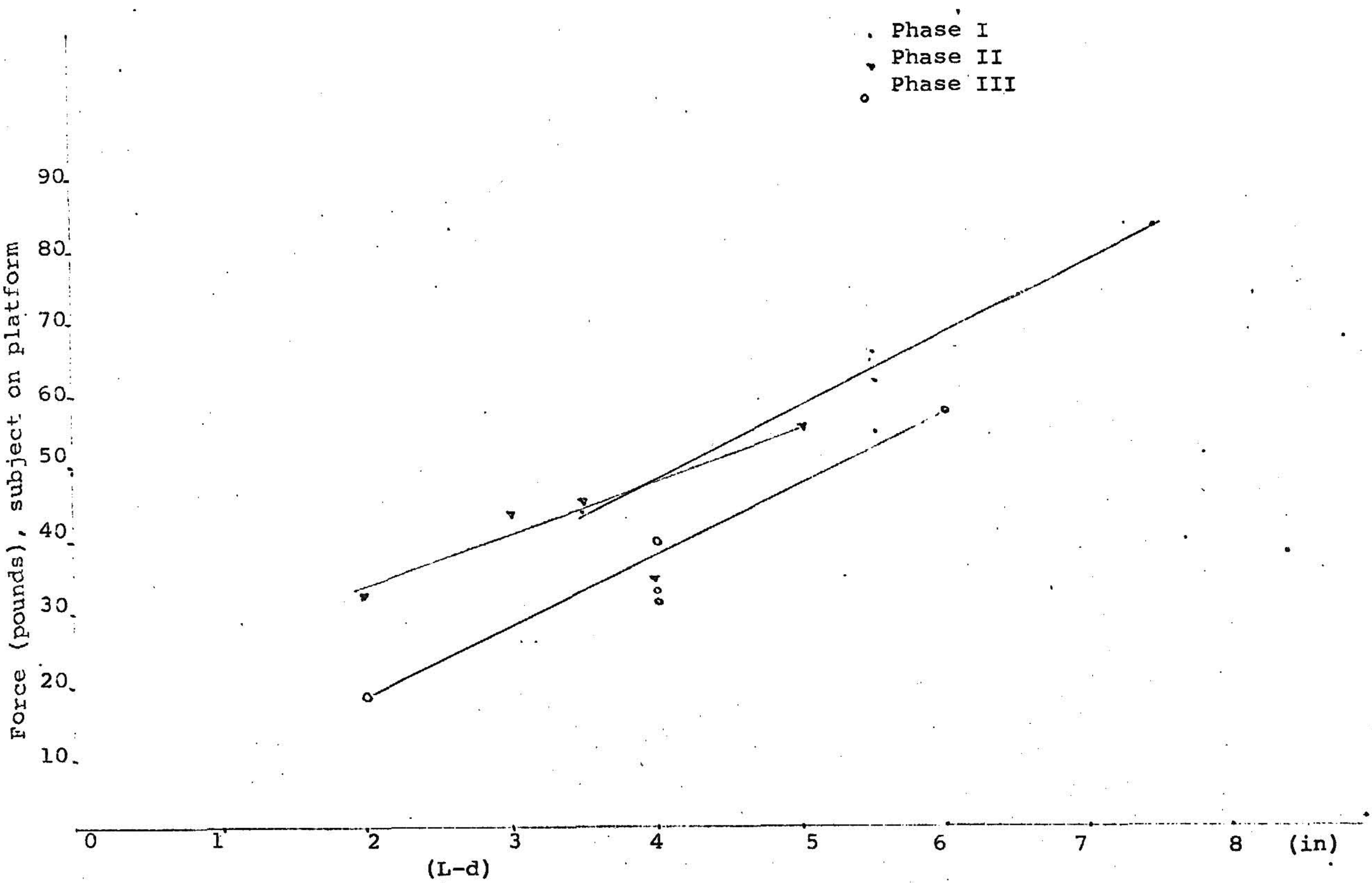


Figure 15. Effect of (L-d) on force, subject on platform condition

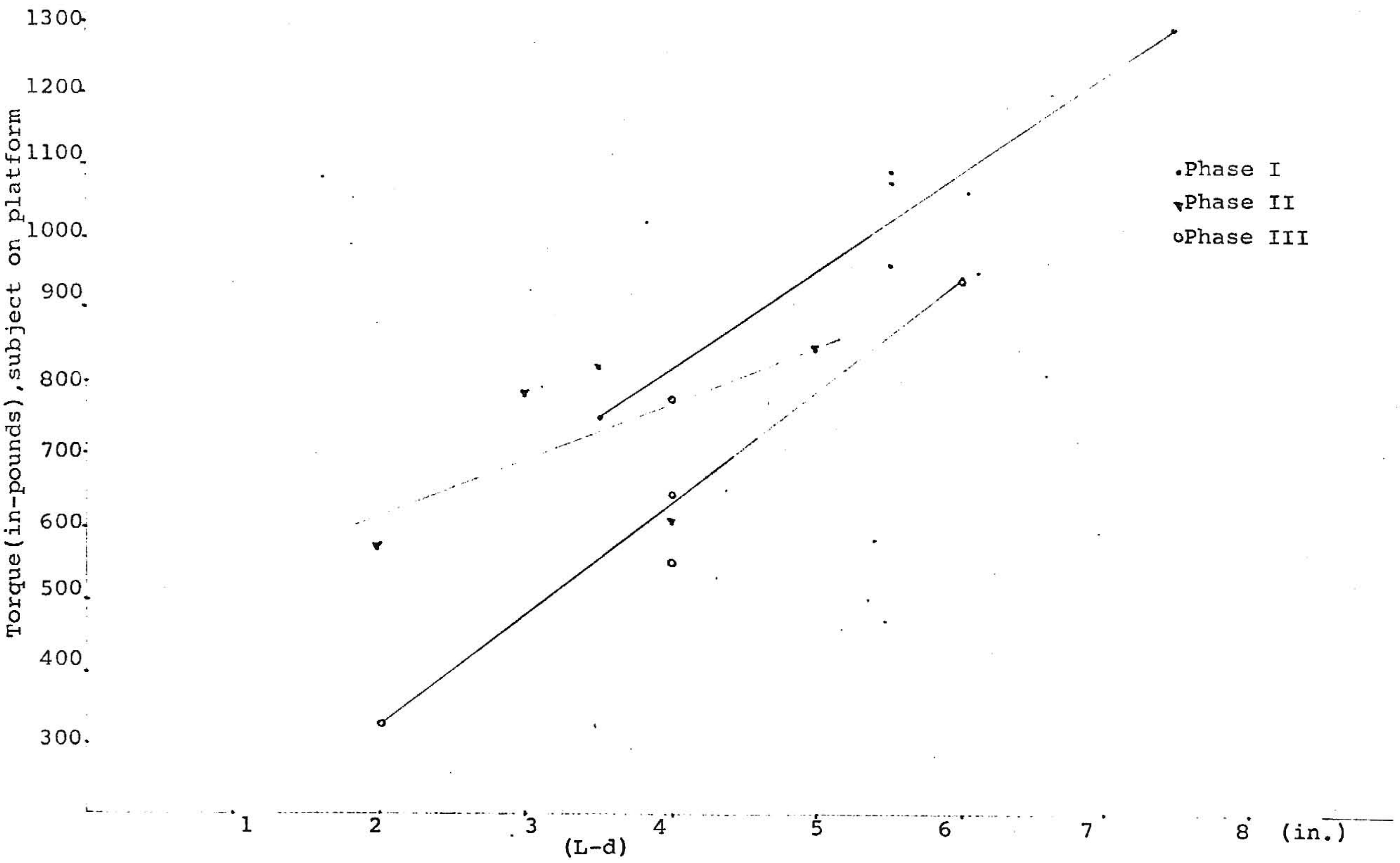


Figure 16. Effect of (L-d) on torque, subject on platform condition

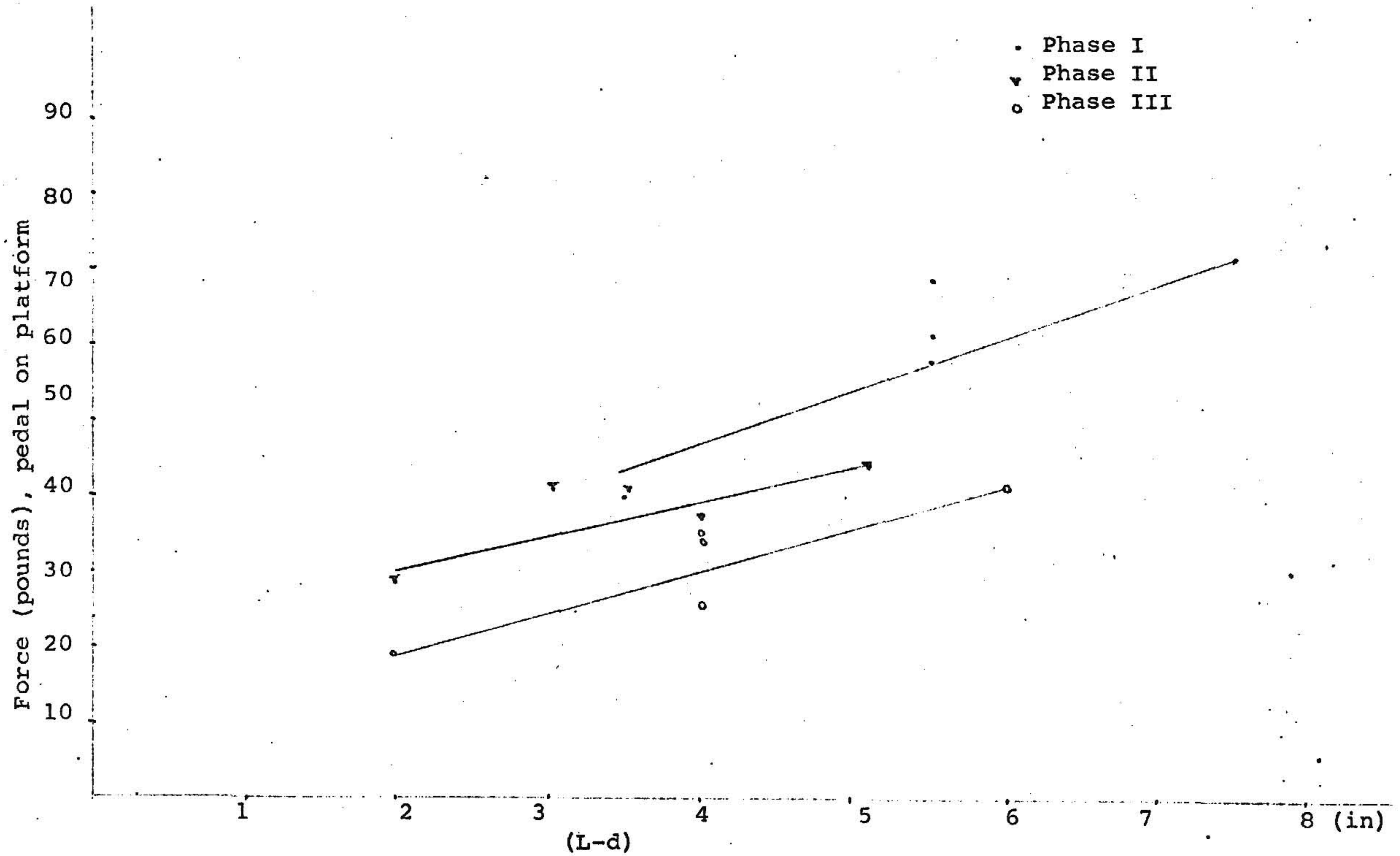


Figure 17. Effect of (L-d) on force, pedal on platform condition

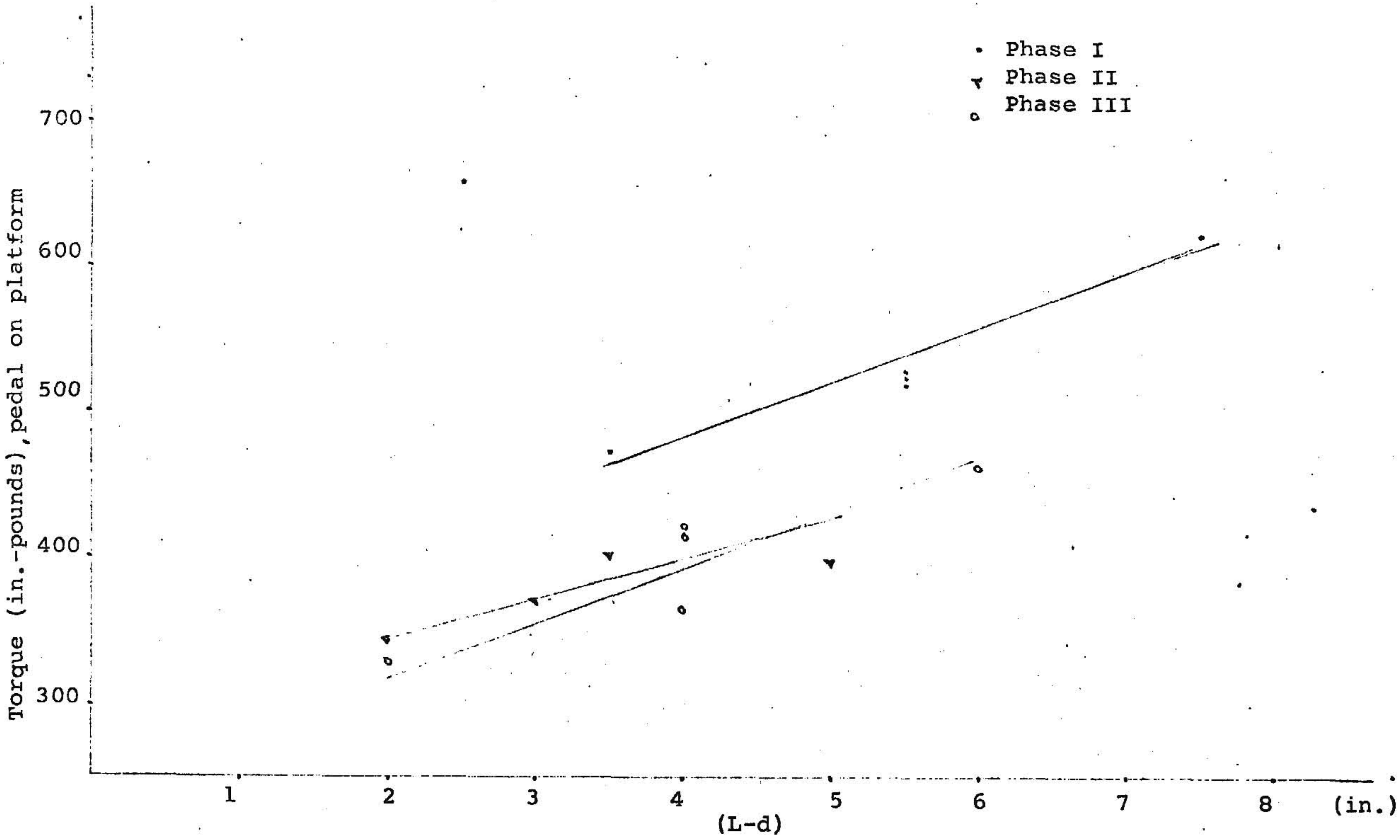


Figure 18. Effect of (L-d) on torque, pedal on platform condition

# DISCUSSION

In order to evaluate effectively the implications of the experimental results, a few important points will be discussed in this section. Consideration will be given first to the statistical analysis which leads to an optimum working range of the variables studied. This will be followed by a number of specific comments made concerning each phase of the findings associated with the characteristics of this experiment.

The results revealed a significant relationship between the outputs as measured by the force platform and the variables d and L of the dual-function pedal. Referring to Figures 11 through 14, it appears that within the tested range of d (.5" to 4") and L (5" to 8"), the optimum value of d lies between 3.5" and 4" and the optimum value of L lies between 5.5" and 6" approximately. However, d=4" and L=6" was the best point. It is noteworthy that for the dual-function pedal, the single variable (L-d) was found to be effective in selecting the best values of d and L. The smaller the value of (L-d), the less the forces and torques exerted, as is obvious from the Figures 15 through 18. This may lead to the conclusion that the best operating point will be when (L-d) = 0. However this condition is not desirable because when L=d, the subject will not know what shaft he is pressing while operating the pedal. In general, experimental findings revealed that (L-d) gave a good indication of the overall performance of various operating conditions. Therefore, this single variable could be used in some studies as the index of operator cost. However, use of both d and L would give still more information. Experiments six (Konz, Koe and Kalra, 1968) and ten (Amar and Arora, 1968) had demonstrated that the reaction time did not act as a constraint in selecting the variables d and L and experiment ten revealed that while travel time did affect these variables, the results were too limited and they showed that the surface was flat in a wide range. The findings of the present study showed that physiological cost as measured by the force platform was a sensitive criterion for the evaluation of alternative design configurations of a dual-function pedal.

On the other hand, generalizations regarding the accurate measurements of physiological cost for the present task cannot be made on the basis of this experiment since the results exposed large variability and individual differences. Some subjects applied the control quickly and with a jerk while others applied it gradually and smoothly. Since the jerky motions record more peak forces and torques, the individual differences resulted in a large variability. Anthropometric measurements, especially the length of the leg, might affect the force applied. The way a subject shifted his weight on the various parts of the body, while operating the control, may have caused some error in the forces and torques recorded. The easy conditions requiring less force and torque were intermingled with the difficult ones requiring higher forces and torques. The levels of easier conditions may have become trivial in contrast with those of difficult ones.

Another interesting facet of the study is the nature of the forces and torques exerted in operating a foot pedal control. To the author's knowledge, no published work exists which gives a quantitative analysis of the forces and torques imposed on the operator for such a task. Figure 19 shows a specimen of the forces and torques exerted for the two different arrangements (subject on the platform and pedal on platform) tested. It is interesting to note that although the forces were only slightly higher in the former, the difference was considerable for torques. Konz and Day (1966) point out that the total energy required for a task is composed of two components: a. The energy required to do the task itself and, b. The energy required to position and control the body while doing the task. It is this second component which was not fully transmitted to the force platform in the pedal on platform condition, and because of this partially missing component, torques recorded by the force platform were considerably lower. In fact, the torques recorded in the pedal on platform condition were reduced to almost half of the torques

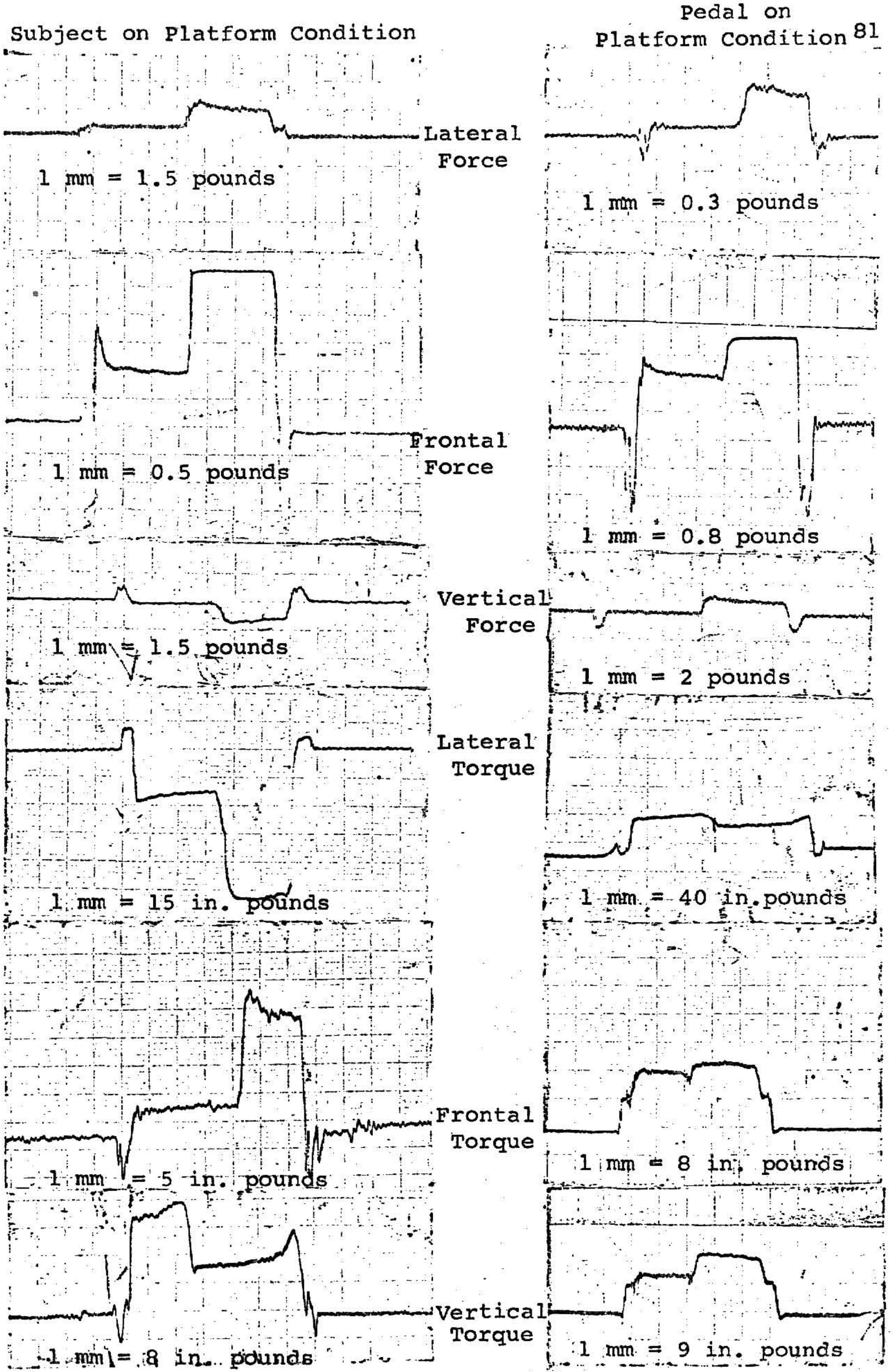


Figure 19. Force platform outputs for d=4" and L= 8" for subject R.M.

recorded in the subject on platform condition. The individual components of torque, however, did not vary consistently. The summersault (lateral torque) in the pedal on platform condition varied between 30% to 50% of the summersault in the subject on platform condition. The cartwheel (frontal torque) in the pedal on platform condition varied between 35% to 55% of the cartwheel in the subject on platform condition. The twist (vertical torque) in the pedal on platform condition varied between 40% to 150% of the twist in the subject on platform condition. Thus it is not possible to explain the total variation on the basis of any one individual component.

It is interesting to note that despite all of the individual differences and large variability, the common points showed good repeatability when the averages of the four subjects were considered. In general, forces gave more consistent results than the torques. No logical explanation of this disparity can be given at this time. Since no previous studies on optimum design of controls have used torque as a criterion, additional experimentation is recommended in this area.

This experiment, by no means, provides an answer to an optimum design of a dual-function pedal. It merely suggests a range of just one set of variables. Other variables of design are inclination of the control pedal from the floor, height of control pedal from floor, seat reference distance, seat height and spring rates for fore and aft shaft. Again, the testing of these variables can use different criteria. Force and torque associated with the application of the brake are only two criteria. Other criteria could be force and torque required on the accelerator. What is the effect of (L-d) on accelerating force? Does the accelerating force increase with the increase in braking force? Further research is needed to answer these questions.

In conclusion, physiological cost is a sensitive criterion in evaluating the alternative design configurations of a man-machine control system; force and torque are affected by the location of shafts of the dual-function pedal; braking force and torque are minimized when the shafts are closer and under the center of the foot; the conclusions are the same with force or torque, and the conclusions are the same with the subject on the platform or the pedal on the platform.

# CONCLUSION

The study undertaken in this thesis leads to some useful information on the design considerations of a dual-function pedal using force and torque as criteria. Previous studies had used reaction time or travel time as criteria of optimality. Force and torque exerted by the subject and as measured by the force platform were found to be more sensitive criteria than reaction time or travel time. Future studies using these criteria for work evaluation should find this thesis of some use.

In particular the following conclusions can be drawn:

1. Within the tested range of d(.5" to 4") and L(5" to 8"), the optimum value of d lies between 3.5" and 4" and the optimum value of L lies between 5.5" and 6" approximately. However, d=4" and L=6" was the best point in the range of variables studied. This result is important in contrast to that of Konz, Koe and Kalra (1968) who concluded that reaction time did not change significantly as d was varied from .5" to 2.5" and L was varied from 5" to 9".

2. It was noted that the smaller the value of (L-d), the lower were the forces and torques, in each phase of testing.

3. It is hard to justify whether the subject should be seated on the force platform or the pedal be placed on the force platform while operating the control pedal. Although

the torques in the pedal on platform condition were reduced to half of the torques in the subject on platform condition, the ranking of points in one condition generally agreed with the ranking in the other condition.

4. Common points showed no learning effect. Results were reproduceable when the averages of the four subjects were considered.

5. A large variability was observed in the forces and torques recorded because of the individual differences. In general, force gave more consistent results than the torque.

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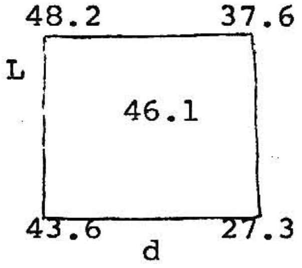
# APPENDIX



## TWO VARIABLE EVOLUTIONARY OPERATION PROGRAM

## CALCULATION WORK SHEET

Cycle $n = 1$

Project: Dual Function Pedal

Response: Force (pounds) S on P

Phase: II

| Operating Conditions | Calculation of Averages | | | | | Calculation of Standard Deviation | |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | | |
| (i) Previous Sums | | | | | | Previous Sum S | = |
| (ii) Previous Averages | | | | | | Previous Average S | = |
| (iii) New Observations | 46.1 | 43.6 | 37.6 | 27.3 | 48.2 | New s = Range x $f_{k, n}$ | = |
| (iv) Differences (ii)-(iii) | | | | | | Range | = |
| (v) New Sums | 46.1 | 43.6 | 37.6 | 27.3 | 48.2 | New Sum S | = |
| (vi) New Averages | 46.1 | 43.6 | 37.6 | 27.3 | 48.2 | New Average s = $\frac{\text{New Sum S}}{n-1}$ | = |

Calculation of Effects

'd' effect = $\frac{1}{2}(Y_3 + Y_4 - Y_2 - Y_5) = -13.5$

'L' effect = $\frac{1}{2}(Y_3 + Y_5 - Y_2 - Y_4) = 7.5$

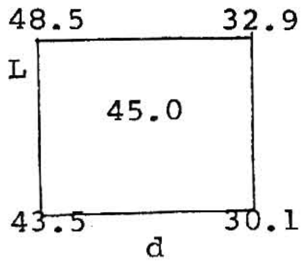
'd x L' interaction = $\frac{1}{2}(Y_2 + Y_3 - Y_4 - Y_5) = 2.9$

Calculation of 95% Error Limits

For New Averages = $\frac{2s}{\sqrt{n}} = \pm$

For New Effects = $\frac{2s}{\sqrt{n}} = \pm$

# APPENDIX



## TWO VARIABLE EVOLUTIONARY OPERATION PROGRAM

## CALCULATION WORK SHEET

Cycle n = 2 Project: Dual Function Pedal

Response: Force (pounds) S on P Phase: II

| Operating Conditions | Calculation of Averages | | | | | Calculation of Standard Deviation | |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | | |
| (i) Previous Sums | 46.1 | 43.6 | 37.6 | 27.3 | 48.2 | Previous Sum S | = |
| (ii) Previous Averages | 46.1 | 43.6 | 37.6 | 27.3 | 48.2 | Previous Average S | = |
| (iii) New Observations | 43.8 | 43.3 | 28.2 | 32.8 | 48.8 | New s = Range x $f_{k,\ n}$ | = 4.5 |
| (iv) Differences (ii)-(iii) | 2.3 | 0.3 | 9.4 | -5.5 | -0.6 | Range | =14.9 |
| (v) New Sums | 89.9 | 86.9 | 65.8 | 60.1 | 97.0 | New Sum S | = 4.5 |
| (vi) New Averages | 45.0 | 43.5 | 32.9 | 30.1 | 48.5 | New Average s = $\frac{\text{New Sum S}}{n-1}$ | = 4.5 |

Calculation of Effects

'd' effect = $\frac{1}{2}(Y_3 + Y_4 - Y_2 - Y_5) = -14.5$

'L' effect = $\frac{1}{2}(Y_3 + Y_5 - Y_2 - Y_4) = 3.9$

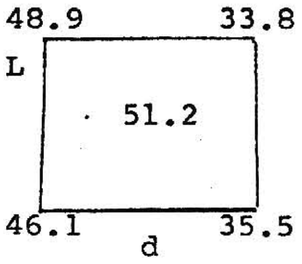
'd x L' interaction = $\frac{1}{2}(Y_2 + Y_3 - Y_4 - Y_5) = -1.1$

Calculation of 95% Error Limits

For New Averages = $\frac{2s}{\sqrt{n}} = \pm 6.3$

For New Effects = $\frac{2s}{\sqrt{n}} = \pm 6.3$

# APPENDIX



## TWO VARIABLE EVOLUTIONARY OPERATION PROGRAM

## CALCULATION WORK SHEET

Cycle n = 3 Project: Dual Function Pedal

Response: Force (pounds) S on P Phase: II

| Operating Conditions | Calculation of Averages | | | | | Calculation of Standard Deviation | |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | | |
| (i) Previous Sums | 89.9 | 86.9 | 65.8 | 60.1 | 97.0 | Previous Sum S | = 4.5 |
| (ii) Previous Averages | 45.0 | 43.5 | 32.9 | 30.1 | 48.5 | Previous Average S | = 4.5 |
| (iii) New Observations | 63.7 | 51.8 | 35.5 | 46.3 | 49.6 | New s = Range x $f_{k,\ n}$ | = 6.2 |
| (iv) Differences (ii)-(iii) | -18.7 | -7.8 | -2.6 | -16.2 | -1.1 | Range | = 17.6 |
| (v) New Sums | 153.6 | 138.2 | 101.3 | 106.4 | 146.6 | New Sum S | = 10.7 |
| (vi) New Averages | 51.2 | 46.1 | 33.8 | 35.5 | 48.9 | New Average s = $\frac{\text{New Sum S}}{n-1}$ | = 5.4 |

Calculation of Effects

'd' effect = $\frac{1}{2}(Y_3 + Y_4 - Y_2 - Y_5) = -12.9$

'L' effect = $\frac{1}{2}(Y_3 + Y_5 - Y_2 - Y_4) = 5.5$

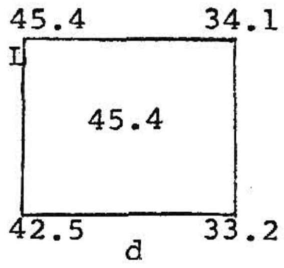
'd x L' interaction = $\frac{1}{2}(Y_2 + Y3 - Y_4 - Y_5) = -2.3$

Calculation of 95% Error Limits

For New Averages = $\frac{2s}{\sqrt{n}} = \pm 6.0$

For New Effects = $\frac{2s}{\sqrt{n}} = \pm 6.0$

# APPENDIX



## TWO VARIABLE EVOLUTIONARY OPERATION PROGRAM

## CALCULATION WORK SHEET

Cycle n = 4

Project: Dual Function Pedal

Response: Force (pounds) S on P

Phase: II

| Operating Conditions | Calculation of Averages | | | | | Calculation of Standard Deviation | |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | | |
| (i) Previous Sums | 153.6 | 138.2 | 101.3 | 106.4 | 146.6 | Previous Sum S | = 10.7 |
| (ii) Previous Averages | 51.2 | 46.1 | 33.8 | 35.5 | 48.9 | Previous Average S | = 5.4 |
| (iii) New Observations | 27.8 | 35.7 | 35.0 | 26.2 | 34.8 | New s = Range x $f_{k,\ n}$ | = 9.1 |
| (iv) Differences (ii)-(iii) | 23.4 | 10.4 | -1.2 | 9.3 | 14.1 | Range | = 24.6 |
| (v) New Sums | 181.4 | 173.9 | 136.3 | 132.6 | 181.4 | New Sum S | = 19.8 |
| (vi) New Averages | 45.4 | 43.5 | 34.1 | 33.2 | 45.4 | New Average s $= \frac{\text{New Sum S}}{n-1}$ | = 6.6 |

### Calculation of Effects

'd' effect = $\frac{1}{2}(Y_3 + Y_4 - Y_2 - Y_5) = -10.8$

'L' effect = $\frac{1}{2}(Y_3 + Y_5 - Y_2 - Y_4) = 1.4$

'd x L' interaction = $\frac{1}{2}(Y_2 + Y_3 - Y_4 - Y_5) = -0.5$

### Calculation of 95% Error Limits

For New Averages $= \frac{2s}{\sqrt{n}} = \pm 6.6$

For New Effects $= \frac{2s}{\sqrt{n}} = \pm 6.6$

# DESIGN OF A DUAL-FUNCTION PEDAL USING FORCE AND TORQUE AS CRITERIA

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# ABSTRACT

A force platform was used to study the effect of varying the location of the brake and accelerator shafts of a dual-function pedal. Four subjects performed the task using two different arrangements: a. the subject seated on the force platform with the pedal on the floor and, b. the subject seated on the floor with the pedal on the force platform. The distance between the heel of the pedal and the accelerator shaft (d) and the distance between the heel of the pedal and the brake shaft (L) were varied in a five point experimental design which brings out the effect of interactions. The arithmetic sums of the three components of forces and torques were used as the criteria of optimality. An optimum searching technique called EVOP (Evolutionary Operation of Processes) was used to analyze the data.

Within the tested range of d(.5" to 4") and L(5" to 8"), the optimum value of d was between 3.5" to 4" and that of L was between 5.5" and 6" approximately. However d = 4" with L= 6" was the best point. The smaller the value of (L -d), the better was the operation of the pedal, in each phase of testing. Although the torques in the pedal on platform condition were reduced to half of the torque in the subject on platform condition, the ranking of points in one condition generally agreed with the ranking in the other condition.