INTERACTIONS OF A MULTI-LIMB PUSH-PULL TASK

by 6402

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INTRODUCTION

In every task requiring the use of muscles, energy is expended to perform the task. Various methods have been used to measure the energy used in doing physical work, so that physical cost to the person involved could be determined. Many tests have been conducted to measure human reaction to performance of various common tasks, so that physical cost to humans in one work situation might be used to predict physical cost to a worker performing another similar task. So far as can be determined, little investigation has been made into classifying tasks into fundamental elements according to the energy expenditure required to perform them.

Much information is available concerning limited-scope tests of human reaction to various environmental and work factors, but apparently these results must be applied to real-life work situations in a piece-meal fashion. Usually physiological tests are limited in the number of variables tested, so little is known concerning human reaction to simultaneous changes in two or more variable work factors. If, for example, increasing light intensity in a given work situation increases productivity, as does decreasing temperature, what would be the inter-action effect on productivity if both light intensity and temperature were changed? A systematic approach to the application of knowledge of human work factors to task design is needed. A task designer should be provided methods of relating the various environmental and work factors to create an optimal task design, without resorting to the expensive and time-consuming process of building mock-ups or actual equipment for testing workers under simulated conditions of a proposed task design.

The foundation of a systematic approach to motion study was laid by the Gilbreths (1924) when they attempted to codify the elementary subdivisions of human work. The resulting seventeen subdividions, called "therbligs," when used in a variety of combinations, with varying frequency, may be used to describe virtually all manual work. After a step-by-step analysis of the fundamental motions of a task has been made, time and effort of task performance can often be reduced by eliminating unnecessary motion. The work done by the Gilbreths resulted in other research studies to determine work economy principles. One investigator was Barnes (1968), who has done a considerable amount of research in the area of human work. One of his contributions was to organize his opinions and the opinions of others into twenty-two principles of motion economy. These principles were designed to be detailed enough to avoid abstractness, yet general enough to have wide application. Application of the principles of motion economy make increased production of specific tasks possible, with minimal energy expenditure.

The studies noted have concentrated on fundamental motions and the best ways to apply them to performance of human tasks. Other approaches to taxonomy of human physiological response factors are needed, so that the energy expenditure required to perform tasks may be predicted. The work measurement techniques commonly used are primarily concerned with the method by which work is done, but do not predict or measure the energy expenditure involved in performing a task. One approach to codifying human manual labor might be to classify fundamental motions by the physical cost to the individual, for a given work output. One benefit would be that a task designer would be able to predict the amount of operator energy which would be expended by the proposed task design, or conversely, he would be able to design the task to fit the physical capabilities of a given operator. Some method of determining the effectiveness of a task design is needed, which is based on the energy expended in performing the task.

Since the term "fundamental motion" as used in literature does not denote any physical cost consideration, the term "motion cost" will be used in this study to indicate physical cost of work output for human fundamental work motions. Codifying motion-costs appears to be extremely difficult because numerical relationships would need to be developed between human physical responses, environmental factors, and psychophysical work factors. The problem is compounded by the fact that the human body responds many ways to many stimuli, and the responses vary within a human, and among humans. Another difficulty in codifying motion-costs lies in the virtually infinite number of combinations of environmental factors and work factors which exist. The sheer size of the problem of relating human energy expenditure to task performance is enormous, but work in this area would help to change the presently used trial-and-error approach to task design.

One problem which immediately arises in determining motion-cost is in selection of a measurement of physical cost. Many measures of human work have been proposed, but research is still being conducted to find easy, reliable measurement methods. One of the most valid measurements of energy cost is through measurement of the calories consumed during task performance. The caloric value of food ingested can be measured, along with the amount of oxygen consumed. These factors may be used to calculate the metabolic rate of a person, for performing a task. The difference between a person's metabolic rate and his basal metabolic rate indicates the energy expended to perform a task. There are several drawbacks involved in measurement of metabolic rate as an indicator of energy expenditure: (1) The type food consumed will determine the amount of heat liberated, (2) The basic metabolism is measured with the subject completely relaxed, after he has fasted for 12-14 hours, and (3) A spirometer, to measure the oxygen consumed, is not always readily available outside a laboratory. Measurement of caloric consumption as an energy expenditure indicator is valid, but not always easy to accomplish.

Another indicator of physiological cost is the measurement of the change in the rate of oxygen consumption from the resting level to the working level. Oxygen consumption measurement is a cumbersome and expensive process. The oxygen consumption is directly related to the basal metabolic rate, but it is difficult to measure, and the consumption rate may vary widely from time to time in an individual, and may vary widely from person to person. In general, as physical work output is increased, the oxygen consumption is also increased, but Barnes (1968) has stated that certain factors which cause physiological stress, such as temperature, humidity, and clothing, can not be properly evaluated by oxygen consumption alone. Another problem with oxygen consumption measurement is that a fairly high level of physical effort is required before the difference between basal oxygen consumption and working oxygen consumption can be distinguished.

Another study (Datta and Ramanathan, 1969) was made of data obtained on energy expenditure, pulmonary ventilation, and heart rate of subjects who carried loads up a flight of stairs. Regression equations indicated that both parameters provide acceptable estimates of energy expenditure. Statistically, the energy cost computed from pulmonary ventilation was closer to observed values, although the slope of the two equations was the same. It was inferred that pulmonary ventilation is relatively more suitable than heart rate for assessing human energy cost of homogeneous groups, with sufficient precision for field and industrial studies.

One of the most frequently measured indicators of physical exertion is the heart beat rate since, in general, as physical exertion increases, heart rate also increases. As Barnes (1968) points out, the heart rate increases from some basal rate when work is performed, to some relatively steady state at a higher rate. Upon stopping work, the heart rate gradually decreases to about the rate in being prior to beginning the task. The increase in heart rate induced by performing the work may be used as an index of the physiological cost of the job. Another index of physiological cost sometimes used is the recovery time required to return from the work-induced heart rate to the basal-level heart rate. Several of the studies noted above have shown acceptable correlation between heart rate and energy expenditure. The main attraction of the use of heart rate as an index of energy expenditure is that the data is easy to take. The heart rate can be recorded by electromechanical means, or can be taken manually by the use of a stethoscope and stopwatch. Many studies of human reaction to stress have been made, using heart rate as an index, giving a common base for comparison of results.

An experiment (Sharkey, McDonald, and Corbridge, 1966) was conducted to attempt to correlate heart rate and ventilation rate to oxygen consumption, to infer the relative usefulness of those two criteria in determining physiological cost of work. The ventilation rate and heart rate data for six treadmill tasks were used to derive regression equations for oxygen consumption, for each subject. The subjects then walked on a treadmill while carrying a static load, cycled a bicycle ergometer, and hand-cranked a bicycle ergometer. After the oxygen consumption rate was measured, the previously derived regression equations for relating heart rate and oxygen consumption were found to overestimate oxygen consumption in some cases by over 30 per cent, while ventilation rate equations were found to be more accurate in predicting oxygen consumption. The most accurate results were obtained when the activity measured reasonably approximated the activity for which the equation was written.

Experiments which have been conducted to determine the heart rate induced by various tasks have indicated that heart rate is affected by many different factors. A three-dimensional "environmental cube" has been described by Rohles (1969), which is a representation of the variables which must be controlled or otherwise defined and specified when conducting tests of human reaction to environmental variables. A total of 25 physical, organismic, and reciprocative factors, which can be broken down into 82 sub-factors are listed, all of which could affect human reaction to stimuli, including changes in heart rate. Some examples of research done on the effects of stress on the human mind and body will serve to point out some of the common environmental factors which must be controlled.

Bateman, Goldsmith, Jackson, Smith, and Mattocks (1970) concluded that heart rate of airline pilots was raised under stressful conditions, particularly during take-off and landing, when a high degree of skill was required, or an element of danger was present. In an experiment involving threat of shock, (Hodges and Spielberger, 1966) those high-anxiety subjects who expressed moderate to extreme fear of shock responded to threat of shock with a significant mean increase in heart rate over the increase of those low-stress subjects who reported little or no fear of shock. It was concluded that the subjects' cognitive appraisal of an experimental situation was an important determinate of psychophysiological responses to stress.

A study (Edwards, Jones, Oppenheimer, Hughes, and Knill-Jones, 1969) of the effects of conditioning subjects to the task to be used, using a group of conditioned bicycle riders and a group of sedentary subjects was made to study development of fitness. After performing a submaximal cycle ergometer exercise, the trained group was found to have lower values for ventilation, heart rate, cardiac output, respiratory exchange ratio, and blood lactate. It may be concluded that repeated performance of a physiological task over a period of time may cause a decrease in the commonly measured physiological responses.

According to a study by Elliott and Thysell (1968), smoking may cause an elevation in heart rate of about 20 beats per minute. The increased heart rate dissipates more slowly for the subject who smokes continuously than for the subject who smokes a single cigarette, after abstaining from smoking for a few hours. The heart rate response to smoking could seriously affect the outcome of an experiment involving heart rate measurement.

A study (Andreassi and Whalen, 1967) was conducted on physiological activity resulting from "new learning," "over-learning," and "double over-learning" of verbal materials (nonsense syllables). Heart rate increased with new learning, decreased with over-learning and decreased further with double over-learning. It was concluded that the drop in heart rate was due to habituation of this response when the subjects were no longer required to learn new material, and to a reduction in apprehensiveness as the experiment progressed. The results of this study has definite application to experiment design, if heart rate measurement error induced by apprehensiveness is to be avoided.

A study was conducted by Brenner and Mothersall (1967) to determine the relationship between respiration rate and the control of heart rate. Under conditions of paced and unpaced respiration, subjects were able to learn to increase or decrease their own heart rates, when presented with an auditory feedback of the degree of success achieved. The study also concluded that heart rate control may occur independently of change in respiratory behavior. It was thought possible that the observed heart rate control was performed through learned changes in muscle tension. The ability to voluntarily or involuntarily change heart rate could have detrimental effects on the outcome of heart rate studies if not provided for in the process of data collection.

The studies noted above serve to indicate some, but by no means all, of the common environmental factors which may affect heart rate, when measurement of heart rate is used as an index of energy cost to humans during task performance. Many other measures of physiological cost have been used, such as calorimetry, electromyograms, lactate production, and pyruvate production. All the various cost measurements noted have certain advantages and disadvantages, but all are used in an effort to determine the quantity of "work" done in performing tasks.

The next problem encountered in classifying fundamental motions of work by physical cost to the individual for a given work output is in the multitude of factors involved in the task design. The field of ergonomics in concerned partially with task performance which results in least physiological cost to the worker. As is stated in an ergonomics vademecum (Kellermann, van Wely, and Willems, 1963) "Ergonomics points the way to optimum utilization of the most valuable means of production, the working human." The table of contents of this vademecum indicates the elemental considerations of task design: Dimensions of the human body, man as a source of energy, noise reduction, lighting, climate, information displays, controls, panels, and paced work. Other factors include physical condition of the subjects, load intensity, position of the subject, motions involved in performing the task, and other parameters. Since physical "work" can take so many forms, usually a few simple physical tasks, which are hopefully representative of more complex physical tasks, are tested for physical cost indications. A wealth of information is available concerning physical cost for minute, isolated, incremental tasks, but not a great deal is available concerning how to put these results together for a quick, accurate estimation of physical cost of a task design.

Some examples of research on optimal body positions for manual tasks will serve to illustrate the limits of many pieces of physiological reaction research. Day (1965) found that when subjects performed push-pull hand tasks while standing, that minimum force was required to perform the task when the handle was at chest height, when the alternative handle heights were at eye, chest, waist, hip, and knee levels. Hastings (1966) found that the optimum height of the table for a sitting operator is at elbow level. The results of these two studies do not provide enough information to deduce the optimal height of a push-pull task for a sitting operator. Changes in muscle loading and energy expenditure may cause an interaction between vertical body position and the push-pull motion, resulting in an optimal handle position somewhere between elbow level and chest height. The task design can greatly influence the energy cost of performing a task.

A knowledge of the amount of energy expenditure induced by each basic increment, or motion-cost, of a task would provide insight into needs for task design improvement. Task design would be simplified by knowing whether the motion-costs of a complex task can be simply added together to determine the overall task energy expenditure, or if a multiplying factor exists. Some work has been done in this area of investigation. For example, Scule and Goldman (1969) studied the effect of weight and its placement on soldiers. It was found that weight may be carried on the hands and on the head at an only slightly greater energy cost than for equivalent body weight increases, but that weight carried on the feet greatly increased the energy cost. This information could be used to redesign soldier's load placement, to achieve the present goals with less fatigue.

Andrews (1967(b)) investigated the principle of work economy that the two hands should begin as well as complete their motions at the same time. Static and dynamic tasks were performed at various work output rates, with one arm and both arms. A comparison was made, for various external work loads, of incremental energy expenditure rates for left-armed and right-armed performance, and for one-armed and two-armed performance. The results of this test indicate that there is no statistically significant difference in the incremental energy expenditure rates for left and right arms, for both the static and dynamic tasks. Less energy was expended when both hands, rather than one hand, were used in performing the static-load tasks, as was true for the dynamic-load tasks greater than 25 watts (0.36 kilocalories/ minute). For a similar productive work situation, a logical choice in method of accomplishing the task can now be made.

A study (Andrews, 1966) was conducted in which the net energy expenditures for separate simple physical tasks were summed and compared with the energy expenditure for the simultaneous performance of the same tasks. Three tasks were used: one-armed cranking of an ergometer, one-armed static pulling against resistance, and walking. The energy expenditures for these tasks were summed for all eight possible two-task and three-task sets. Results of the test indicated that for seven of the eight task sets, the sum of the net energy expenditure rates for the simple physical tasks significantly exceeded the net energy expenditure rate for the same tasks performed simultaneously. The significant differences ranged between three and thirty-three per cent. Andrews concluded that any valid system of standard metabolic data would have to make provisions for the interactions between the muscular patterns of simultaneously performed components.

PROBLEM

The value of a study such as the one made by Andrews (1966) could be increased by examining a simple physical task in greater detail to determine the energy cost for separate parts of the simple task, and the relationship of contributions to the energy cost of the overall task. A desirable vehicle for study would be a simple task involving all four limbs, separately and simultaneously, with the same work output for each limb. For a given work output, the optimal limb combination could be determined, in terms of minimized energy expenditure. Interactions of energy expenditure resulting from various limb combinations could be detected, to determine whether energy expenditure is additive for the limbs involved, or if a multiplying factor exists. A study which forms the basis for this thesis is made on a simple four-limb sitting-type task to determine: (1) the physical cost, in terms of mean increased heart rate, for all possible limb combinations, (2) if differences exist between the means of the incremental heart rates of all possible limb combinations, for a given work output, (3) the combinatorial coefficients required to predict the energy expenditure of a task by combining the energy expenditures of the sub-elements of the task, and (4) the "best" 1-limb, 2-limb, 3-limb, and 4-limb combination, in terms of minimized induced heart rate increase, for accomplishing a given work output.

METHOD

Experimental Tasks

The weight-and-pulley task machine used for this study, and pictured in Figure 1, consisted of a left-hand and a right-hand pull-handle, and a left-foot and a right-foot pedal. A drawing of the essential features is shown in Figure 2. Each pull-handle was attached to a ½-inch diameter nylon rope which passed through a horizontal nylon grommet oriented toward the rear of the machine, over a 1¼-inch pulley, and down to a lead weight. Each foot pedal rotated about a pin at the heel, and a load was provided by means of a ½-inch nylon rope attached to the toe of the pedal, which passed upward and over a 1¼-inch pulley to a lead weight. An adjustable typist's chair, with the rollers and armrests removed, was provided as a seat for the subject. After the chair was fitted to the subject, he adjusted the chair on the platform for comfortable leg-reach to the pedals while the pedals were fully depressed. The pull-handles were adjusted vertically and horizontally for a comfortable grip with the arms fully extended and with the center of the handles 2 inches below the top of subjects shoulder joint. A metronome set at 60 beats per minute was placed at eye level on a shelf between the hands of the subject.

The arm task was to pull the hand grip horizontally toward the shoulder joint until the cable stop prevented further displacement, then to relax the arm until the weight attached to the cable pulled the hand grip back to its original position. The leg task was to depress the pedal to the platform, then to flex the leg vertically until the weight attached to the pedal pulled the pedal back to its extreme upward

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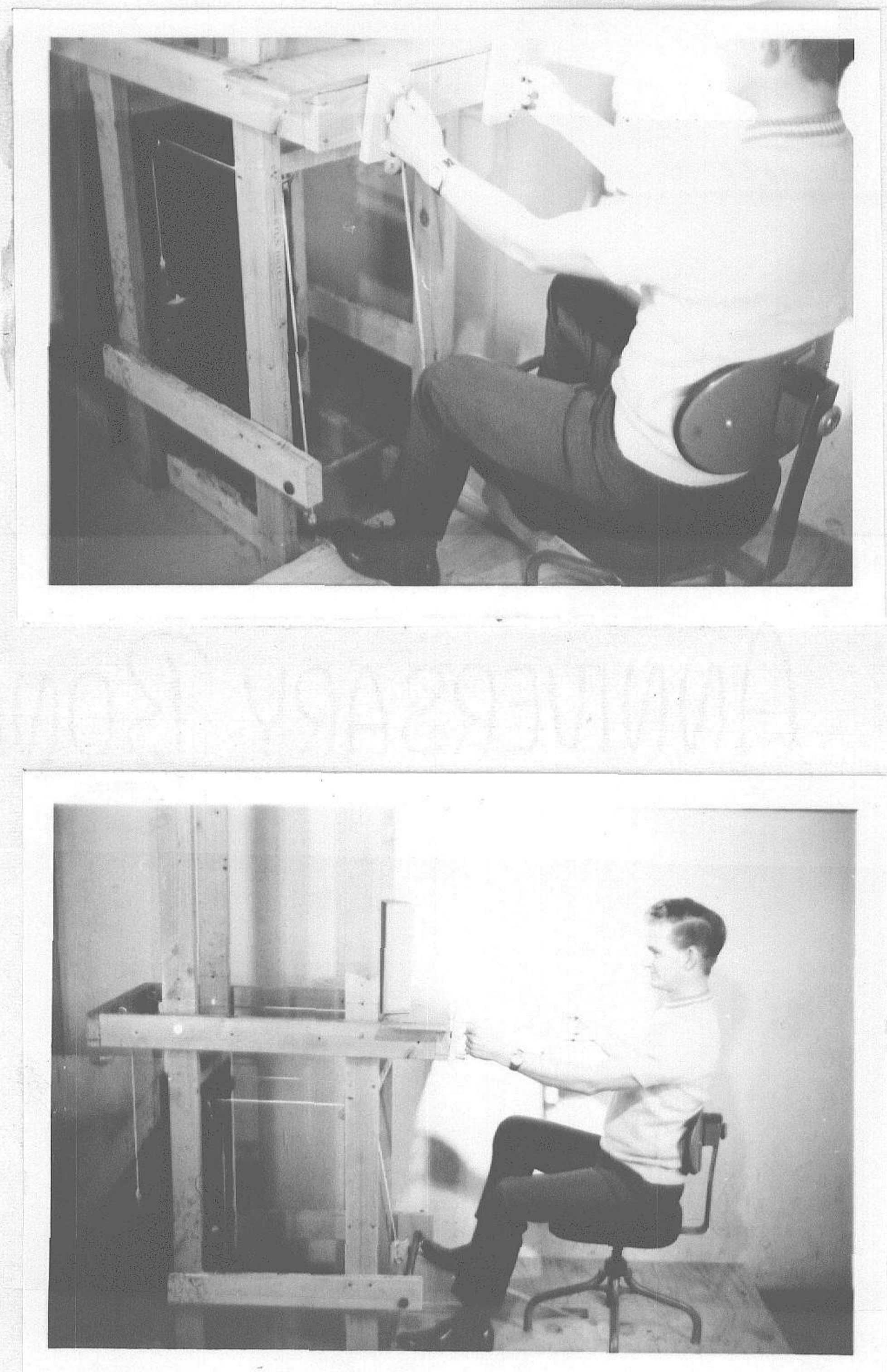

Figure 1. Weight-and-pulley task apparatus.

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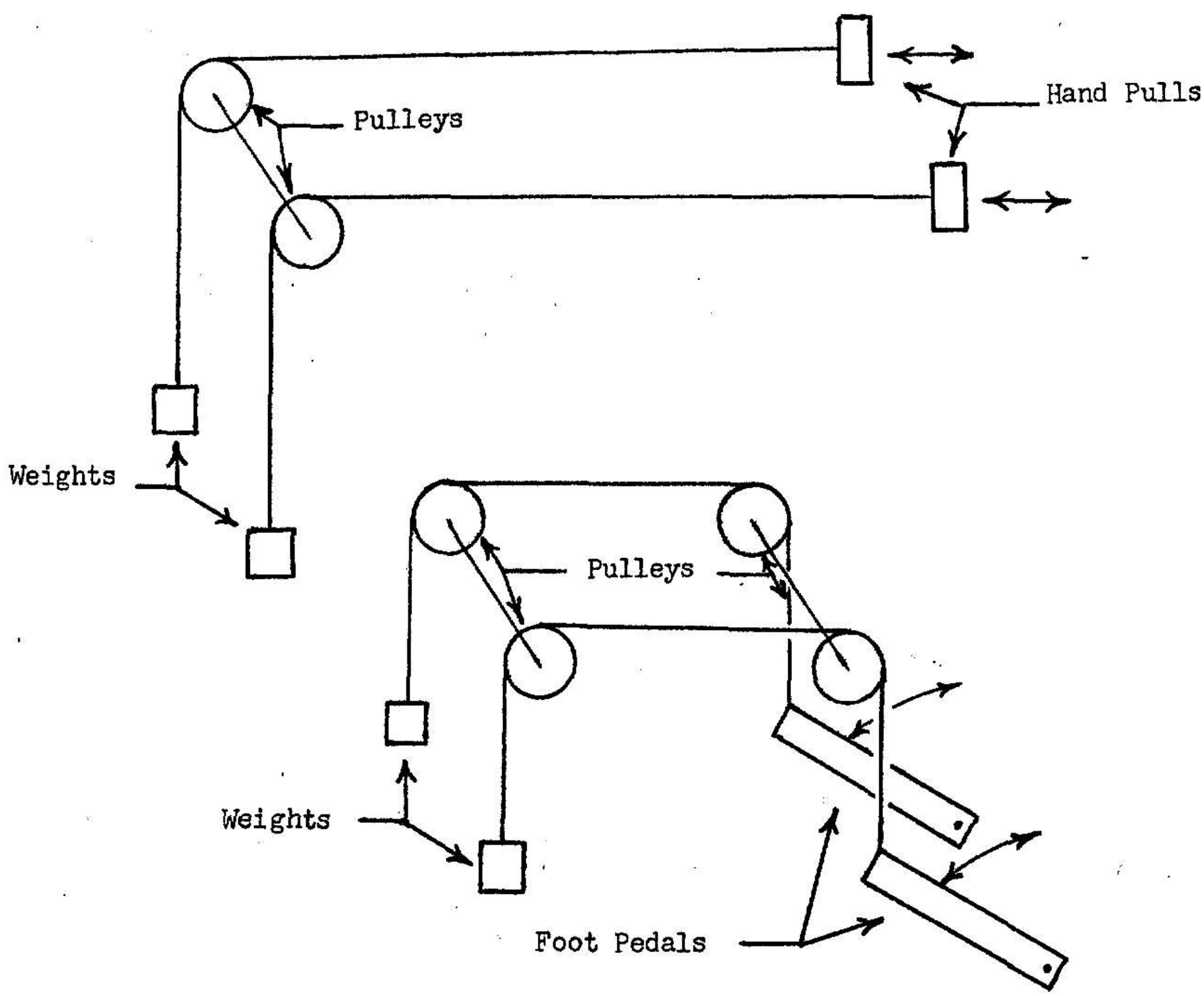

Figure 2. Diagram of weight-and-pulley apparatus (not to scale).

position. Both arm and leg tasks were performed at a cyclic rate of 60 repetitions per minute by following the beat of the metronome. The stroke length of each arm task was 1 foot, against a resistive force of 10.3 pounds, for a work output of 0.2 kilocalories per minute. The stroke length of each leg task was 8 inches against a resistive force of 15.45 pounds, which also resulted in a work output of 0.2 kilocalories per minute. The task work output level was designed to produce an external work load of 0.2 kilocalories per minute, since this load produces a substantial heart rate increase, but avoids reaching the maximum ability of the subjects. The work output of 0.2 kilocalories per minute for each limb was external work output since it did not include the work output required to move the limbs themselves. The work output was deliberately kept at a low level so that fatigue manifestations would not be introduced during the 3½-hour test period. For comparison purposes, the energy cost in kilocalories per minute, above the energy cost for sitting idle, is 0.4 for watch and clock repair, 0.45 for seated clerical work, 0.6 for light assembly work, 0.6 for drafting, 0.7 for standing clerical work, 0.8 for hand sewing, and 1.4 for machine sewing.

All possible 1-limb, 2-limb, 3-limb and 4-limb task combinations, at a work output of 0.2 kilocalories per limb, were performed. Table 1 shows a complete array of experimental tasks, along with the task codes which were used throughout the study. The rhythm pattern specified for multiple-limb tasks was that the involved limbs on the same side of the body were to be flexed simultaneously, while the involved limbs on opposite sides of the body were to be flexed alternately. This pattern

TABLE 1

Limb Combinations for Performing Tasks, with Task Codes

	Limbs Involved (x)			
Task Code	Left Arm	Right Arm	Left Leg	Right Leg
1	x			
2		x		
3			x	
4				x
5	x	x		
6			x	x
7	x		x	
8		x		x
9	x			x
10		x	x	
11	x	x		x
12	x	x	x	
13	x		x	x
14		x	x	x
15	x	x	x	x

was selected because it was the one demonstrated most often by subjects during the early stages of task investigation who were asked to select a method of operating various parts of the machine in an easy, natural manner. The pattern specified also allowed subjects to change the number of limbs involved in a task without learning new rhythm pattern relationships among the limbs. During task performance, the non-involved arm was held in a horizontal position with the fingers lightly gripping the pull-handle, while the foot of the non-involved leg was placed on the platform, beside the pedal.

Experimental Trials

Prior to the test day the subject filled out a personal data sheet, as shown in Appendix 1. Personal and environmental data are shown in Table 2. Next he was given a set of written procedural instructions, as shown in Appendix 2. The subject was "talked through" each task, and was given the opportunity to operate the weight-and-pulley machine for as long as desired for familiarization. On the test day the basal heart rate was measured while the subject sat relaxed in the test chair. Heart rate was monitored while a task from the random-sequence array shown in Table 3 was performed. The heart rate was recorded upon reaching a steady state, which normally required 3 to 4 minutes of task repetition. Approximately one minute of heart rate data was taken for later incremental analysis, to verify steady-state condition of heart rate. After the subject rested for 2 to 3 minutes, the same task was repeated and measured. After two repetitions of five tasks had been performed, a second basal heart rate was taken, after a rest period of approximately 5 minutes, in a sitting position. This process was

Appendix 1. Personal and Environmental Data Sheet

DATA SHEET

1. Subject control number: ____________________
2. Date/time of test: __________________________
3. Subject name: ____
4. Address: ____
5. Phone number: ______________________________
6. Height: ___________________
7. Weight: ___________________
8. Dominant hand: Right_______ Left_______
9. Self evaluation of physical stamina: Poor___Below Avg___Average___
   Above Avg___Superior___
10. Do you smoke? Yes___No___. Cigarettes/cigars per day:___.
    How long since last smoke before test? _______________
11. Do you drink alcoholic beverages? Yes___No___. How long since last
    drink before test? __________________
12. Height of adjusted chair seat: _____________
13. Height of top of shoulder joint when seated: _________________
14. List any unusual test conditions, such as excessive heat, noise,
    etc., which might tend to annoy you.

15. Start temperature: ____. Stop temperature: ____.
16. Start relative humidity: ____. Stop relative humidity: ____.

TABLE 2

Personal and Environmental Data for Subjects

Subject Number	Mean Basal Heart Rate, Beats/Minute	Age, Years	Weight, Pounds	Height, Feet	Temperature, °F			Relative Humidity, %		
					Start	Stop	Mean	Start	Stop	Mean
1	63	22.6	183	5.83	74	76	75	46	42	44
2	80	22.3	145	5.75	76	77	76.5	30	29	29.5
3	72	25.8	195	6.08	76	76	76	28	29	28.5
4	79	21.3	184	6.08	76	77	76.5	30	29	29.5
5	71	23.4	185	5.92	73	73	73	30	30	30
Means		23.1	178	5.93			74.5			32.3
Standard Deviations		1.6	17.3	0.13			1.3			5.9

Appendix 2. Standard Instruction Sheet

Instruction Sheet

This experiment will require you to pull hand grips and to push foot pedals while seated in front of a weight-and-pulley machine. Your heart rate will be recorded electronically, by means of sensors taped over your heart. You will be given an exercise task to perform for about 3 or 4 minutes, followed by a short rest period, after which the same task will be repeated. This sequence will be repeated until all the required exercise tasks have been performed. At the completion of each exercise, just prior to the rest period, the next exercise will be explained so that you can pick up the rhythm and procedure before the rest period. While performing the tasks, motions of the hands (or feet) should be performed alternately when both hands (or both feet) are involved in a particular exercise. When the hand and foot on the same side of the body are employed, the foot should be drawn upward toward the hip joint, as the extended arm is drawn back toward the shoulder, in a simultaneous motion. The same arm should be extended again as the foot on the same side of the body depresses the foot pedal. The metronome which has been placed on the weight-and-pulley machine should be followed carefully, to set the exercise pace. As you finish the first trial of each task, you will be asked to indicate your degree of fatigue by selecting one of the following phrases, in order of increasing severity, which best describes your physical condition: (1) Not fatigued, (2) Fatigue just noticeable, (3) Slightly fatigued, (4) Moderately fatigued, (5) Extremely fatigued. Try pulling the hand grips and pumping the pedals, to become familiar with the motion and

Appendix 2 Continued. Standard Instruction Sheet

effort required to operate the weight-and-pulley machine. Any questions concerning this experiment will be answered at this time.

TABLE 3

Random Task Sequence Performed by Subjects

Subject Number	Task Sequences, by Task Code																	
1	B*	4	8	12	9	2	B	10	1	11	13	3	B	6	7	5	14	15	B
2	B	14	10	1	12	3	B	13	8	15	4	9	B	2	5	6	11	7	B
3	B	2	13	8	12	14	B	9	15	6	7	4	B	10	11	1	5	3	B
4	B	10	14	5	7	15	B	8	6	4	9	12	B	3	1	13	11	2	B
5	B	2	10	9	8	1	B	13	15	11	6	5	B	7	12	4	3	14	B

*B - Basal heart rate.

repeated until the heart rates for all 15 repeated tasks and 4 basal heart rates had been recorded. The entire test lasted about 3½ hours for each subject.

Energy Expenditure Rate Measurement

Two E & M Instrument Company skin electrodes were attached to the skin of the subject with double-sided adhesive washers. The electrodes were placed on the left side of the chest, over the heart, with one above and one below the heart. The electrodes and other telemetry equipment are shown in Figure 3. The electrodes were attached to an E & M Instrument Company model FM-1100-E2 transmitter, which was carried in a plastic envelope attached to the subject's T-shirt. The radio signal generated by each heart beat was received by an E & M Instrument Company Model FM-1100-6 biotelemetry receiver, and routed through a Sanborn Company model 150-1500 low-level preamplifier to a Sanborn Company model 151 strip chart recorder and electronic timer. Each heart beat was recorded along with a one-second timing mark on a continuous strip of paper which moved at a speed of 5 millimeters per second. Beginning and end point of heart rate measurement was annotated on the paper strip, with the task code number and trial number. The number of heart beats recorded during a measured number of seconds provided the ratio used to compute the number of beats per minute.

The incremental heart rate induced by each task was the difference between basal heart rate and the steady-state heart rate measured for each task. The basal rate for a given series of two repetitions of each of five tasks was computed as the mean of the basal rates measured immediately prior to, and immediately following that series of

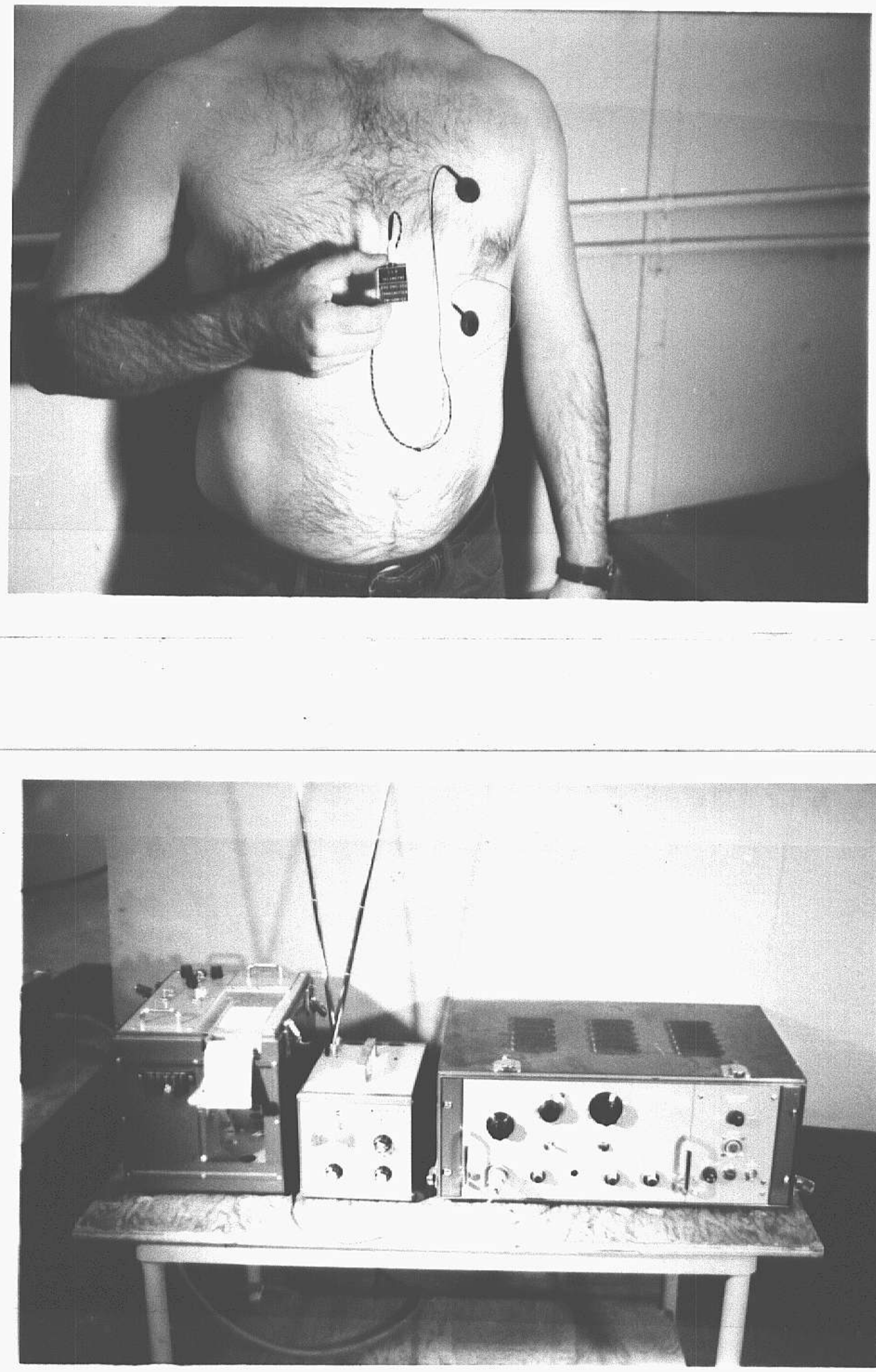

Figure 3. Telemetry apparatus for monitoring and recording heart rate.

measurements. The total heart rate (basal rate plus induced rate) was computed to be the mean of the heart rates of the two repetitions of a given task.

Subjects

The five subjects were healthy, untrained males who stated that they had no impairment to full use of arms and legs, and no history of heart malfunction. The mean age was 23.1 years. The mean weight was 178 pounds, and the mean height was 5.9 feet. Four subjects were right-handed and one was left-handed. Two were smokers, and three were non-smokers. Three occasionally consumed alcoholic beverages, and two were non-drinkers. Those who smoked or consumed alcoholic beverages had abstained for periods of time of at least sufficient length to make the effect on heart rate negligible. None of the subjects had previously served as the subject of a physiological experiment. Each was paid five dollars for participation in the test, of approximately 3½ hours duration. Personal and environmental measurements are shown in Table 2.

Environmental Conditions

The tests were conducted at about the same time each day for all subjects, beginning about 1:30 P.M. and ending about 5:00 P.M. The dry bulb temperature and relative humidity were measured at the beginning and end of the test series for each subject. The temperature ranged between 73° and 77° F, with a mean of 75.4° F. The relative humidity ranged between 28% and 46%, with a mean of 32.2%, but the maximum humidity range for any one subject was 4%. The noise in the test area was limited to a slight amount made by operation of the weight-and-pulley machine. Light intensity varied little since the primary source was from the same incandescent and florescent sources. Air flow was at a very low rate, since windows and heating duct grates were closed. The test clothing of all subjects consisted of denim pants, short-sleeved cotton T-shirt, cotton shorts, sweat socks and sneakers. No food or liquids were ingested during the test although water was available. The only adaptation to the test task was during a short familiarization period on a day prior to the test day, designed to reduce apprehensiveness, not to promote physical conditioning. The social interaction effects were stabilized by having no persons except the subject and the author within sight or hearing range during the test. Incentive was provided by paying subjects for participation, but no competition was designed into the task. The task activity level was designed to produce a substantial heart rate increase, but to avoid reaching the maximum ability of the subjects. The tasks were performed in a random sequence in order to minimize the effects of learning, apprehension, fatigue, and boredom. A simple task design was selected so that all subjects could perform the task adequately after an extremely short training period, thus minimizing the effects of skill and progressive learning. No feedback information was provided to the subject during the course of the test concerning the heart rate data generated and collected.

Statistical Design and Analysis

The order of performing tasks was randomized to minimize the sequential effects induced by performing the tasks. The heart rate data recorded for each task was divided into 10-second increments, so that the interval-by-interval heart rate could be compared. A relatively constant heart rate over the one minute measurement period verified that the heart had reached its steady state for a given task. Basal heart rates were established for each set of five tasks, for each subject, by calculating the mean of the basal heart rates measured immediately prior to, and immediately following each set of five tasks. The incremental heart rate increase for each task, by subject, was taken as the difference between the subject's mean basal rate for a given five-task set, and the mean total heart rate measured for each task in question. The incremental heart rates for each task, by subject, were used to calculate the mean incremental heart rate for each task, along with the standard deviation.

The Dixon criteria for rejection of outliers (Natrella, Mary G., 1963) was applied to the set of incremental heart rate data to check data apparently not consistent with other data taken under the same conditions. Suspected inconsistencies were checked by task, and by subject, for each work output level. The data apparently inconsistant by task proved to be consistent by subject, for the given level of work output, and vice versa. No heart rate data was rejected. A Spearman rank coefficient of correlation (Roscoe, 1969) was computed for individual and environmental factors, and for comparison of incremental heart rate induced by tasks with the resulting fatigue vote.

A null hypothesis was formulated that the summation of the means of the incremental heart rates of the incremental task equivalence is greater than the incremental heart rate of the same tasks performed simultaneously. For example, the summation of the means of the incremental heart rates for the left-arm task and the right-arm task was hypothesized to be greater than the mean incremental heart rate of the two-armed task. The null hypothesis was accepted if a t-test failed to reject it at the .05 risk level, using a one-tailed test. The underlying theory for this approach was that if there was no statistically significant difference between the mean incremental heart rates of a task and its hypothetical equivalence, constructed of sub-tasks, then the incremental heart rates of the fundamental motions could be summed to determine the incremental heart rate of a more complex task. If there was a statistically significant difference of the appropriate direction between the means, then performing two or more fundamental motions simultaneously created an interaction among the induced heart rates so that a multiplying factor exists for the induced heart rate of the combined motions. Hypothetical equivalence tasks, composed of summations of mean incremental heart rates of equivalent work output tasks, were compared to each other without regard to the direction of the difference between the means of the incremental heart rates. For this purpose a two-tailed t-test at the .05 level was used to test for statistically significant differences among the means.

Regression equations were calculated, using the mean incremental heart rates of measured tasks and the test work outputs. The equations were formulated to be used to predict maximum, mean, and minimum heart rate induced by a given work output, for the tasks used in this study.

For those tasks and corresponding incremental equivalence having a statistically significant difference between the means of the incremental heart rates, indicating that an interaction had occured, the multiplying factor was calculated. This combinatorial factor was calculated to be used with the summation of the fundamental sub-task heart rates to predict the combined-task incremental heart rate.

To determine which limb combination should be used to produce a given work output, an analysis was made of the incremental heart rates of equivalent tasks. Based on an evaluation of the number of tasks which were better, worse, and no different than the task in question, in terms of induced heart rate, a "preferred task" index and an "acceptable task" index were calculated. "Preferred task" index was defined as the ratio of the number of equivalent work output tasks inducing a greater incremental heart rate, to the total number of equivalent tasks. "Acceptable task" index was defined as the ratio of the number of equivalent work output tasks with a greater, or no different, induced incremental heart rate, to the total number of equivalent tasks. These indexes ranged between zero, for the least desirable task, to one, for the most desirable task, in terms of the incremental heart rate induced by performing the task.

RESULTS

Physical Cost for Various Limb Combinations

The heart rate for both repetitions of each task were recorded as shown in Table 4, from which the mean heart rate was calculated. The basal heart rates are shown in Table 5. This data was plotted on a graph for each task, in the order of performance, by subject, as shown in Figure 4 through Figure 8. The difference between the total heart rate and the basal heart rate is the mean incremental heart rate, as recorded in Table 6.

Table 7 shows the mean incremental heart rate induced by each task combination, by work output. The tasks for which heart rate was acutally measured appear in column 2 of Table 7. Each of the task sets appearing in the same row as a basic task in column 2 is an incremental equivalence, composed of the summation of the mean incremental heart rates of tasks giving the same total work output, involving the same limbs. For example, the task involving all four limbs could be performed nine different ways, using various combinations of simultaneously and sequentially performed tasks.

Comparison of Measured Tasks and Incremental Equivalent Tasks

The 15 tested tasks induced incremental heart rates which were summed in all possible combinations to produce sets of hypothetical incremental tasks with equivalent work output. The actual and theoretical incremental heart rates for a given work output were analyzed to test for statistically significant differences between the means of the incremental heart rates of the measured tasks and the equivalent hypothetical tasks. The results of the t-tests are shown in Tables 8 through 13.

TABLE 4

Total Heart Rate and Mean Total Heart Rate, Beats/Minute

Subject Number		Task Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Trial 1	76	76	80	84	81	89	92	94	94	90	102	94	103	101	113
	Trial 2	79	78	77	84	85	89	90	96	94	91	98	94	108	105	108
	$\overline{X}$	78	77	79	84	83	89	91	95	94	91	100	94	106	103	111
2	Trial 1	95	91	110	101	103	108	103	98	112	123	118	118	118	116	128
	Trial 2	96	94	108	98	109	99	112	102	106	115	110	116	115	116	130
	$\overline{X}$	95	92	109	100	106	104	108	100	109	119	114	107	117	116	129
3	Trial 1	87	89	81	86	91	89	94	93	93	96	90	104	100	103	103
	Trial 2	88	90	82	86	90	91	93	95	91	99	95	104	98	101	102
	$\overline{X}$	88	90	82	86	91	90	94	94	92	98	93	104	99	102	103
4	Trial 1	87	89	88	90	89	90	92	94	86	98	89	93	92	101	102
	Trial 2	84	89	90	86	87	92	94	92	82	97	90	92	91	98	102
	$\overline{X}$	86	89	89	88	88	91	93	93	84	98	90	93	92	100	102

TABLE 4 Continued

Total Heart Rate and Mean Total Heart Rate, Beats/Minute

Subject Number		Task Number														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
5	Trial 1	87	85	76	78	84	82	86	91	92	94	97	92	95	89	104
	Trial 2	86	87	76	75	88	84	89	90	88	93	95	94	98	91	108
	$\bar{X}$	87	86	76	77	86	83	88	91	90	94	96	93	97	90	106

TABLE 5

Basal* Heart Rates (Beats Per Minute)

Subject Number	Measurement Number 1	2	3	4	Basal Means 1-2	2-3	3-4
1	64	60	64	65	62	62	65
2	81	79	80	79	80	80	80
3	69	71	75	71	70	73	73
4	83	84	76	74	84	80	75
5	67	75	74	69	71	75	72

*Sitting, relaxed

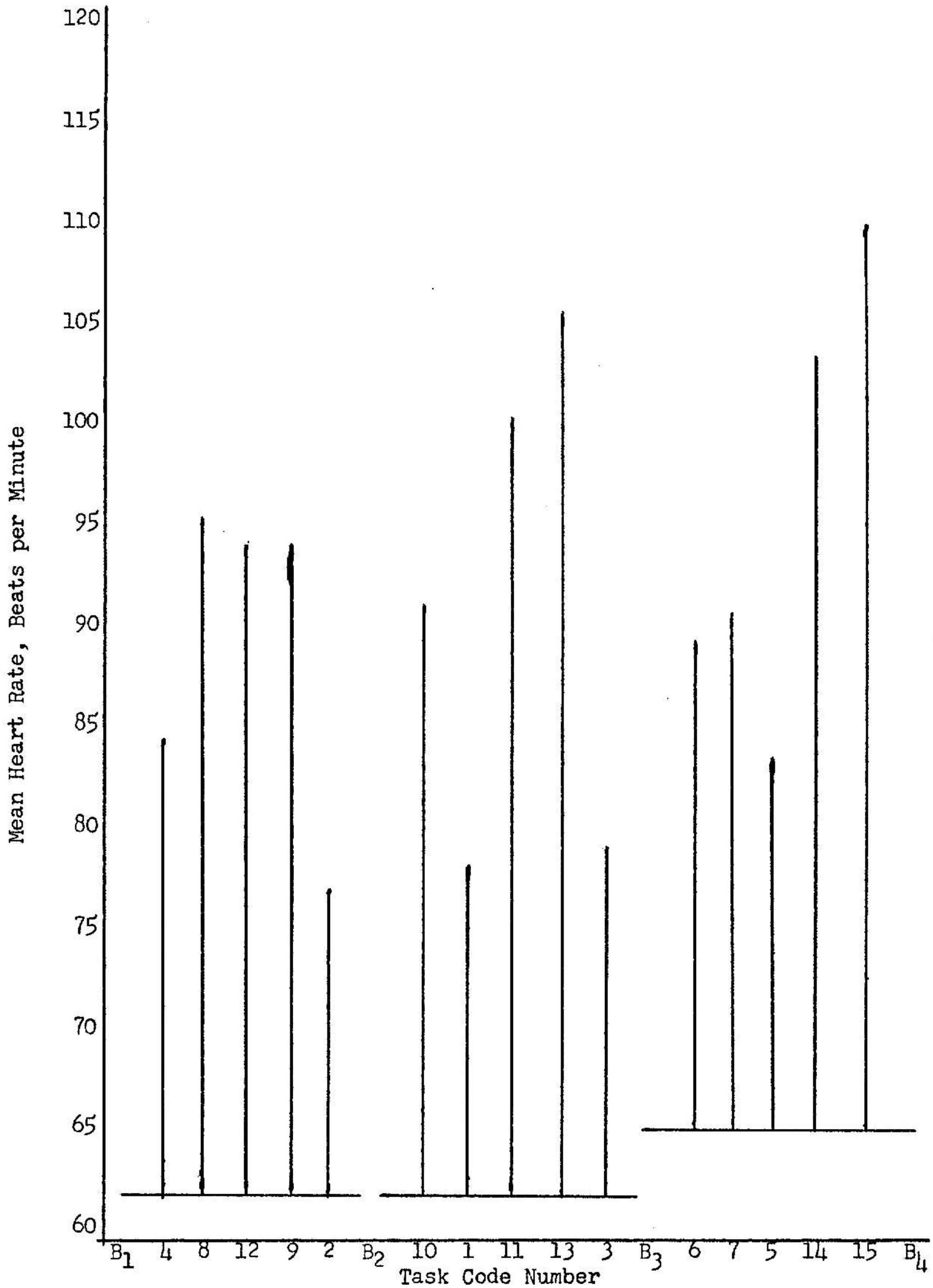

Figure 4. Mean Heart Rate for Tasks Performed by Subject Number 1.

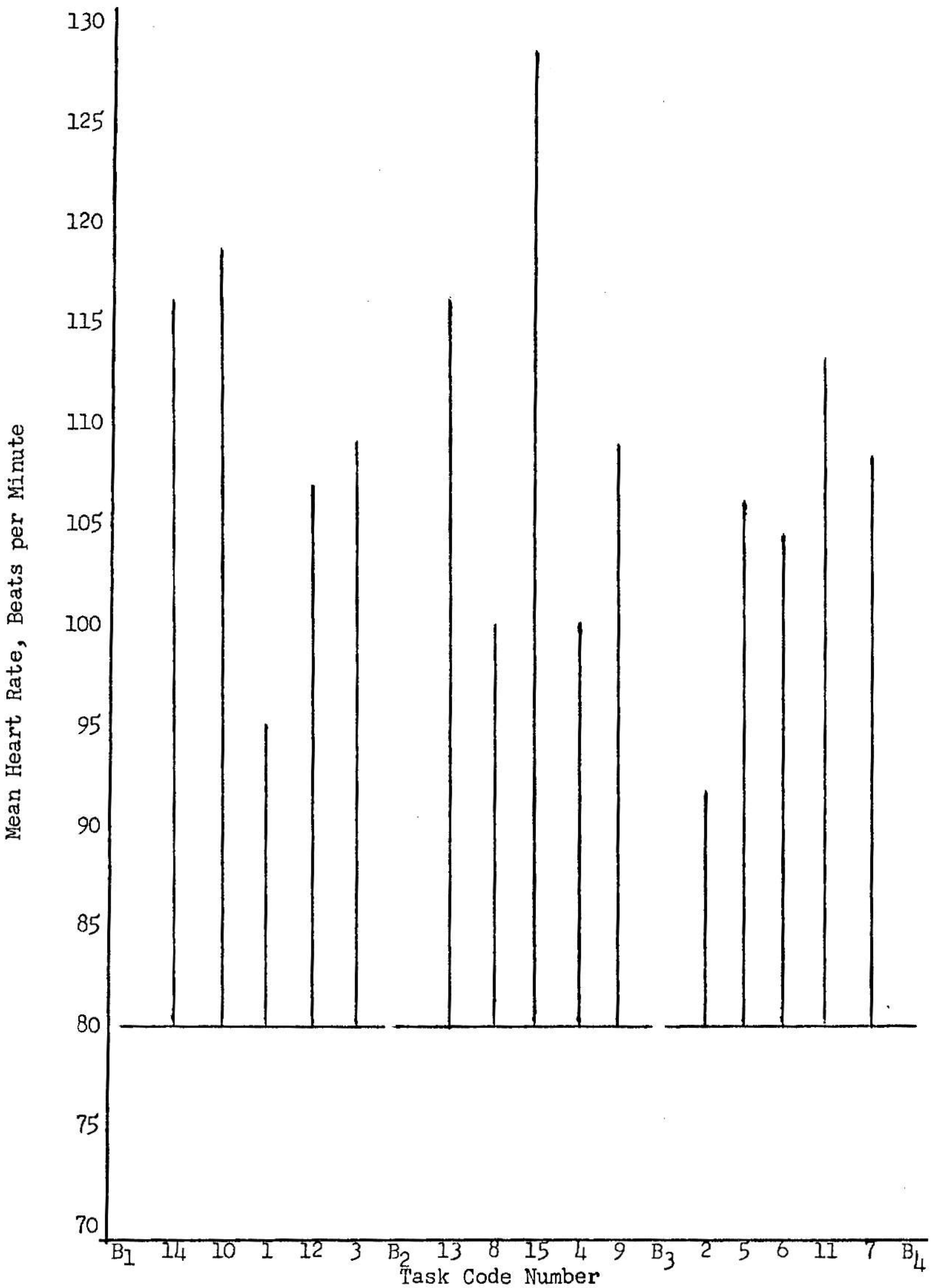

Figure 5. Mean Heart Rate for Tasks Performed by Subject Number 2.

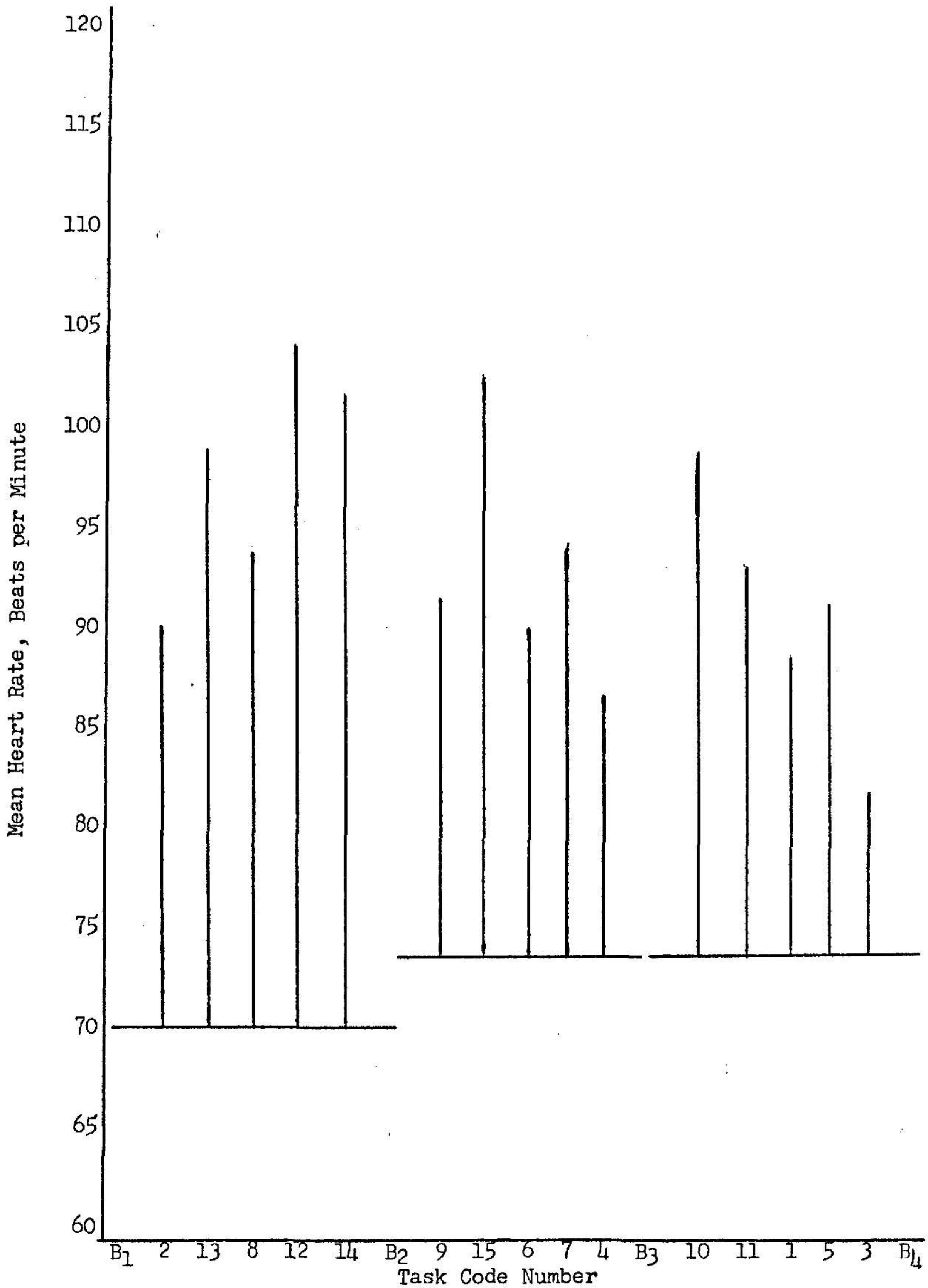

Figure 6. Mean Heart Rate for Tasks Performed by Subject Number 3.

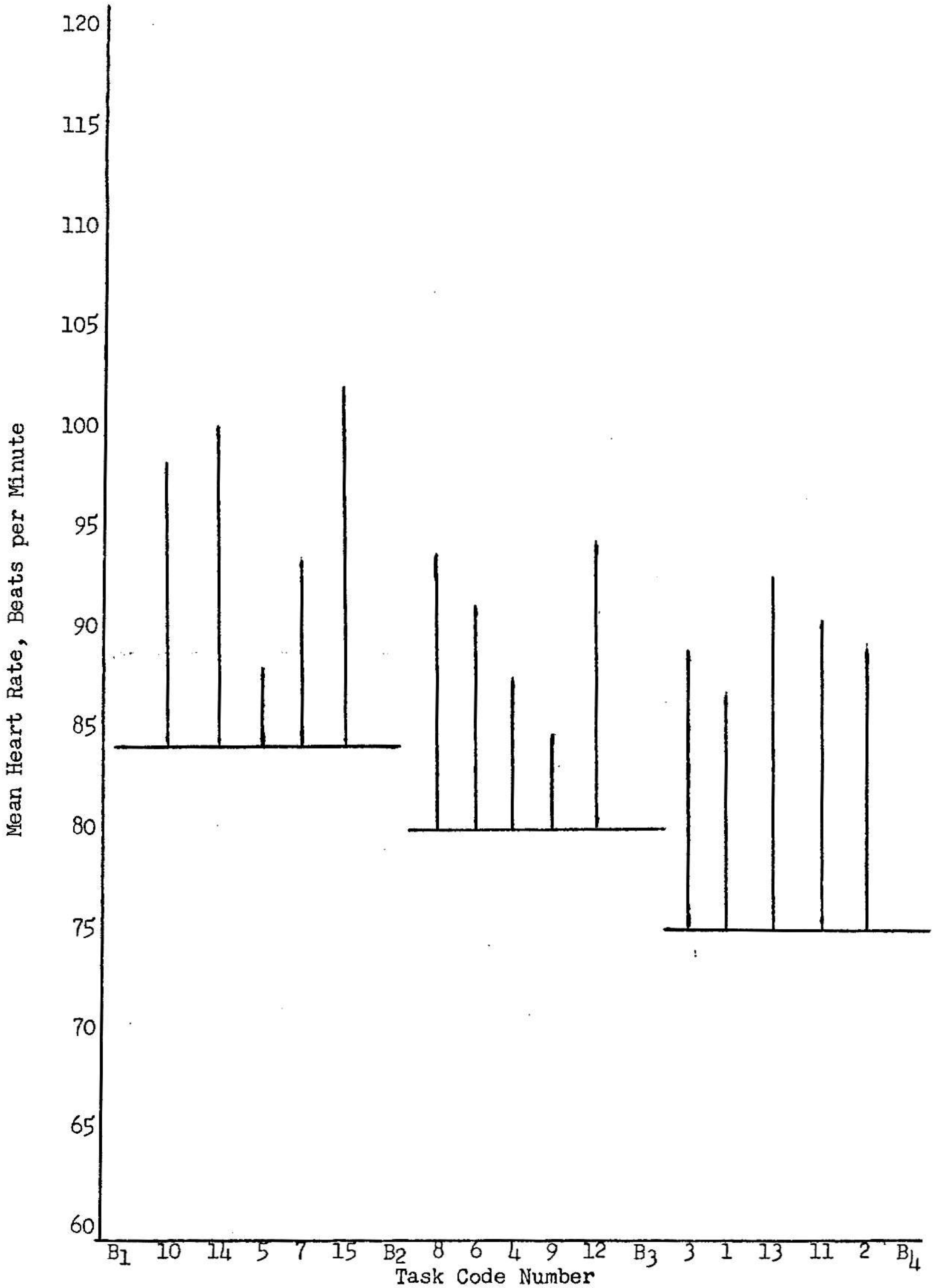

Figure 7. Mean Heart Rate for Tasks Performed by Subject Number 4.

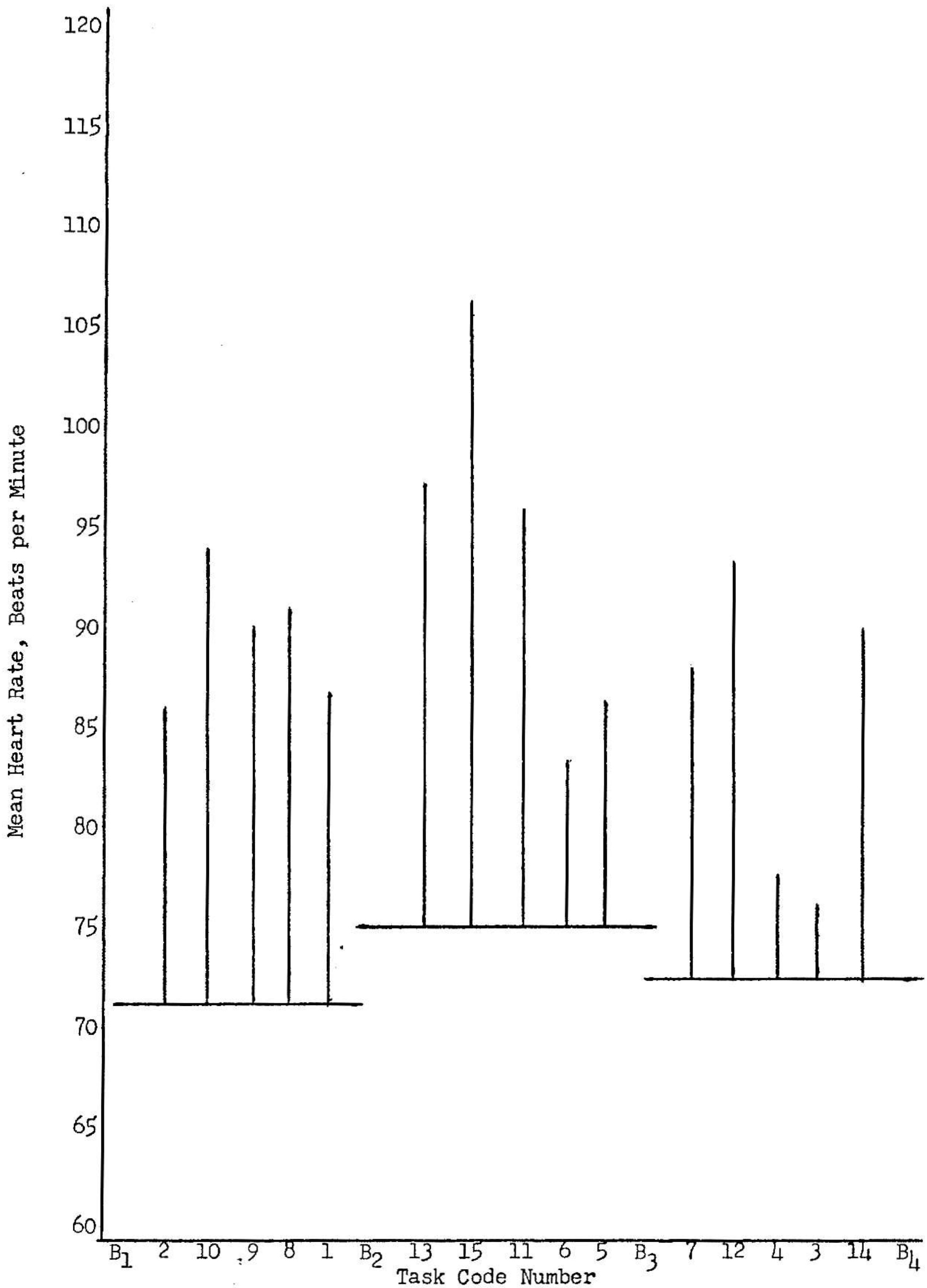

Figure 8. Mean Heart Rate for Tasks Performed by Subject Number 5.

TABLE 6

Mean Incremental Heart Rate, Beats Per Minute

Subject Number	Task Code* 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Mean Basal Rate
1	15	15	17	22	19	25	27	33	32	29	38	32	44	38	47	63
2	15	13	29	21	27	25	29	21	30	34	35	27	38	36	49	80
3	15	19	9	13	18	17	21	24	19	25	20	34	29	32	30	72
4	11	14	14	8	5	11	10	13	4	15	15	13	17	17	19	79
5	16	15	5	6	12	9	17	20	19	23	22	22	23	19	31	71
Mean	14	15	15	14	16	17	21	22	21	25	26	26	30	28	35	73
Std. Dev.	1.79	2.05	8.22	6.55	7.37	6.76	6.58	6.50	10.0	6.34	8.93	7.57	9.78	8.75	11.3	6.17

*Task codes are shown in Table 1.

TABLE 6 Continued

Mean Incremental Heart Rate, Beats Per Minute

Subject Number	Task Code* 1+2	3+4	1+3	2+4	1+4	2+3	1+2+4	5+4	8+1	9+2	1+2+3	5+3	10+1	7+2	1+3+4
1	30	39	32	37	37	32	52	41	48	47	47	36	44	42	54
2	28	50	44	34	36	42	49	48	36	43	57	56	49	42	65
3	34	22	24	32	28	28	47	31	39	38	43	27	40	40	37
4	25	22	25	22	19	28	33	13	24	18	39	19	26	24	33
5	31	11	21	21	22	20	37	18	36	34	36	17	39	32	27
Mean	29	29	29	29	28	30	43	30	36	36	44	31	39	36	43

Subject Number	Task Code* 7+4	6+1	9+3	2+3+4	10+4	6+2	8+3	1+2+3+4	5+6	9+10	7+8	4+12	1+14	4+13	3+11
1	49	40	47	54	51	40	50	69	44	61	60	54	53	66	55
2	50	40	45	63	55	38	50	78	52	64	50	48	51	59	64
3	34	32	34	41	38	36	33	36	35	44	45	47	47	42	29
4	18	22	15	36	23	25	27	47	16	19	23	21	28	25	29
5	23	25	35	26	29	24	25	42	21	42	37	28	35	29	27
Mean	35	31	36	44	39	32	37	58	33	46	43	40	42	44	41

*Task codes are shown in Table 1.

TABLE 7

Sets of Measured Tasks and Hypothetical Incremental Equivalence, with Mean Incremental Heart Rates

Work Output, Kilocalories Per Minute	Measured Task Code* (Heart Rate)	Hypothetical Incremental Equivalence	Mean Incremental Heart Rate	Standard Deviation
0.2	1 (14)		14	
	2 (15)		15	
	3 (14)		15	
	4 (15)		14	
0.4	5 (16)	1+2 (29)	23	6.52
	6 (17)	3+4 (29)	23	6.0
	7 (21)	1+3 (29)	25	4.0

*Task codes listed in Table 1.

TABLE 7 Continued

Sets of Measured Tasks and Hypothetical Incremental Equivalence, with Mean Incremental Heart Rates

Work Output, Kilocalories Per Minute	Measured Task Code* (Heart Rate)	Hypothetical Incremental Equivalence				Mean Incremental Heart Rate	Standard Deviation
0.4	8 (22)	2+4 (29)				26	3.54
	9 (21)	1+4 (38)				25	3.54
	10 (25)	2+3 (30)				28	2.55
0.6	11 (26)	1+2+4 (43)	5+4 (30)	8+1 (36)	9+2 (36)	35	5.87
	12 (26)	1+2+3 (44)	5+3 (31)	10+1 (39)	7+2 (36)	35	6.25
	13 (30)	1+3+4 (43)	7+4 (35)	6+1 (31)	9+3 (36)	35	4.61
	14 (28)	2+3+4 (44)	10+4 (39)	6+2 (32)	8+3 (37)	36	5.55

*Task codes listed in Table 1.

TABLE 7 Continued

Sets of Measured Tasks and Hypothetical Incremental Equivalence, with Mean Incremental Heart Rate

Work Output, Kilocalories Per Minute	Measured Task Code* (Heart Rate)	Hypothetical Incremental Equivalence								Mean Incremental Heart Rate	Standard Deviation
0.8	15 (35)	1+2+3+4 (58)	5+6 (33)	9+10 (46)	7+8 (43)	4+12 (40)	1+14 (42)	4+13 (44)	3+11 (41)	42	6.76

NOTE: Number in parenthesis is mean incremental heart rate of the task code above it. Equivalent tasks are read horizontally, in terms of limb set involved.

*Task codes listed in Table 1.

TABLE 8

Reliability of the Differences Between the Means (t-ratios) for the Measured and Hypothetical Incremental Heart Rate Increases Induces by Two-Limb Tasks

Task	5	6	7	8	9	10	1+2	3+4	1+3	2+4	1+4	2+3
5	0	.60	4.47*	1.83	1.85	1.41	3.86*	2.71*	5.05*	5.93*	7.13*	5.29*
6		0	2.31*	1.82	1.71	4.19*	3.38*	3.63*	5.17*	11.8*	14.7*	5.51*
7			0	.52	0	6.47*	2.69*	1.51	3.69*	5.15*	8.75*	3.32*
8				0	.47	1.08	2.67*	1.03	1.51	3.37*	2.71*	1.59
9					0	1.97	1.90	1.18	1.94	2.76*	3.64*	2.17*
10						0	3.40*	2.21*	1.55	3.51*	2.19*	1.78

*P ≤ .05, one-tailed test.

TABLE 9

Reliability of the Differences Between the Means (t-ratios) for the Hypothetical Incremental Heart Rate Increases Induced by Two-Limb Tasks

Task	1+2	3+4	1+3	2+4	1+4	2+3
1+2	0	.11	.09	.13	.33	.19
3+4		0	.13	.08	.09	.33
1+3			0	0	.30	.66
2+4				0	.66	.29
1+4					0	.62
2+3						0

*$p \leq .05$, two-tailed test.

TABLE 10

Reliability of the Differences Between the Means (t-ratios) for the Measured and Hypothetical Incremental Heart Rate Increases Induced by Three-Limb Tasks

Task	11	12	13	14	1+2+4	5+4	8+1	9+2	1+2+3	5+3	10+1	7+2	1+3+4	7+4	6+1	9+3	2+3+4	10+4	6+2	8+3
11	0	.10	2.86*	.95	7.15*	1.24	3.56*	4.05*	6.28*	1.05	5.57*	3.69*	4.33*	3.52*	3.26*	3.72*	4.51*	5.13*	2.37*	5.17*
12		0	1.45	1.21	10.5*	.98	5.85*	4.15*	4.75*	.84	1.66	7.17*	2.76*	2.01	2.39*	2.65*	3.14*	3.09*	3.25*	2.51*
13			0	1.15	7.49*	.29	2.48*	3.12*	4.43*	.17	3.59*	2.56*	3.24*	3.33*	1.07	2.17*	3.26*	4.32*	1.07	3.66*
14				0	17.5*	.65	2.99*	3.37*	6.13*	.58	1.86	5.07*	4.75*	2.48*	3.18*	2.18*	4.32*	4.46*	3.74*	4.39*

*P ≤ .05, one-tailed test.

TABLE 11
Reliability of the Differences Between the Means (t-ratios) for the Hypothetical Incremental Heart Rate Increases Induced by Three-Limb Tasks

Task	1+2+4	5+4	3+1	9+2	1+2+3	5+3	10+1	7+2	1+3+4	7+4	6+1	9+3	2+3+4	10+4	6+2	8+3
1+2+4	0	3.85*	3.37*	3.65*	.30	2.49	1.92	6.78*	.08	3.09*	11.8*	2.81*	.09	1.45	12.7*	2.69
5+4		0	1.29	1.74	3.99*	.30	2.61	3.31*	3.94*	4.47*	.53	1.50	5.3*	10.6*	.64	3.00*
8+1			0	.29	1.79	.83	1.08	.29	.95	.40	1.82	.47	1.22	.59	1.50	.09
9+2				0	2.12	.93	1.89	0	1.37	.40	.61	.69	1.56	1.14	1.17	.29
1+2+3					0	3.86*	1.78	3.12*	.33	2.55	6.46*	2.11	.13	1.52	5.17*	2.71
5+3						0	1.83	.98	7.18*	1.15	.18	.81	5.92*	2.80*	.32	1.83
10+1							0	2.52	.73	1.32	4.20*	1.96	.91	.13	2.71	.05
7+2								0	2.15	.33	3.09*	.03	1.79	.98	2.31*	.30
1+3+4									0	3.09*	2.84*	1.56	.69	1.55	.03	2.71
7+4										0	1.06	.13	3.14*	3.00*	.44	1.24
6+1											0	1.17	3.39*	2.96*	.69	2.43
9+3												0	1.67	1.45	.68	.50
2+3+4													0	1.79	2.84*	.92
10+4														0	1.97	1.28
6+2															0	1.54
8+3																0

*$p \leq .05$, one-tailed test.

TABLE 12

Reliability of the Differences Between the Means (t-ratios) for the Measured Hypothetical Incremental Heart Rate Increases Induced by Four-Limb Tasks

Task	15	1+2+3+4	5+6	9+10	7+8	4+12	1+14	4+13	3+11
15	0	8.85*	-1.77	3.74*	5.43*	7.47*	15.6*	3.88*	2.40*

*$p \leq .05$, one-tailed test.

TABLE 13

Reliability of the Differences Between the Means (t-ratios) for the Hypothetical Incremental Heart Rate Increases Induced by Four-Limb Tasks

Task	1+2+3+4	5+6	9+10	7+8	4+12	1+14	4+13	3+11
1+2+3+4	0	13.3*	.16	3.44*	4.76*	4.33*	4.37*	7.18*
5+6		0	3.97*	2.81*	2.17*	3.42*	3.68*	2.05
9+10			0	.97	1.40	.78	.52	1.10
7+8				0	1.80	.10	.13	.58
4+12					0	1.89	1.45	.21
1+14						0	.37	.38
4+13							0	.91
3+11								0

*$P \leq .05$, two-tailed test.

It was concluded that those tasks having no statistically significant differences between the means of the incremental heart rates were essentially equivalent, i.e. incremental heart rates of sub-tasks could be summed to predict the incremental heart rate of a more complex task having an equivalent work output. Tables 14, 15, and 16 show those tasks having a statistically significant difference, and indicates which one task of two tasks is superior, in terms of lower mean incremental heart rate.

The 45 measured tasks and hypothetical tasks were organized by work output and induced mean incremental heart rate, in increments of five beats/minute, as shown in Table 17. The organization was made without regard to statistically significant differences between the means of the heart rates induced by each task. The purpose of this table was to enable the observer to compare tasks which would produce a given work output, within a narrow range of induced mean incremental heart rates. For example, task 15 should be chosen for a work output of 0.8 kilocalories per minute, for the least cost, in terms of heart rate, of 31-35 beats per minute. If 36-40 beats per minute were acceptable, two other task combinations may be used to give the same work output. This approach allows consideration of physical cost and work output in task design selection, so that a given work output may be obtained at minimal physical cost.

Regression equations were computed to show the relationship between work output and maximum, mean, and minimum mean incremental heart rate for the measured tasks. The calculations are shown in Appendix 3, and a graph of work output verses mean incremental heart rate is shown in Figure 9. The minimum and maximum heart rate

TABLE 14

Identification of Two-Limb Tasks Having Statistically Significant Differences Between Means of Incremental Heart Rates

Task	5	6	7	8	9	10	1+2	3+4	1+3	2+4	1+4	2+3
5			*				*	*	*	*	*	*
6			*			*	*	*	*	*	*	*
7						*	*		*	*	*	*
8							*			*	*	
9										*	*	*
10							*	*		*	*	
1+2												
3+4												
1+3												
2+4												
1+4												
2+3												

*Indicates statistically significant differences between means, with task listed on left superior, in terms of lesser mean incremental heart rate, to task listed at top.

TABLE 15
Identification of Three-Limb Tasks Having Statistically Significant Differences Between Means of Incremental Heart Rates

Tasks	11	12	13	14	1+2+4	5+4	8+1	9+2	1+2+3	5+3	10+1	7+2	1+3+4	7+4	6+1	9+3	2+3+4	10+4	6+2	8+3
11			*		*		*	*	*		*	*	*	*	*	*	*	*	*	*
12					*		*	*	*			*	*		*	*	*	*	*	*
13					*		*	*	*		*	*	*	*		*	*	*		*
14					*		*	*	*			*	*	*	*	*	*	*	*	*
1+2+4						#	#	#				#		#	#	#			#	
5+4									*			*	*	*			*	*		*
8+1																				
9+2																				
1+2+3										#		#			#				#	
5+3													*				*	*		
10+1															#					
7+2															#				#	
1+3+4														#	#					
7+4																	*	*		
6+1																	*	*		
9+3																				
2+3+4																			#	
10+4																				
6+2																				
8+3																				

*Statistically significant difference between means, with task listed on the left superior, in terms of lesser mean incremental heart rate, to task listed at the top.

#Indicates task listed at the top is superior, in terms of lesser mean incremental heart rate, to task listed at the left.

TABLE 16

Identification of Four-Limb Tasks Having Statistically Significant Differences Between Means of Incremental Heart Rates

Tasks	15	1+2+3+4	5+6	9+10	7+8	4+12	1+14	4+13	3+11
15		*		*	*	*	*	*	*
1+2+3+4			#		#	#	#	#	#
5+6				*	*		*	*	
9+10									
7+8									
4+12									
1+14									
4+13									
3+11									

*Statistically significant difference between means, with task listed on the left superior, in terms of lesser mean incremental heart rate, to task listed at the top.

#Indicates task listed at the top is superior, in terms of lesser mean incremental heart rate, to task listed at the left.

TABLE 17

Selection of Task Design by Work Output and Induced Mean Incremental Heart Rate

Mean Incremental Heart Rate, Beats Per Minute	0.2 Kilocalories Per Minute (1 Limb)	0.4 Kilocalories Per Minute (2 Limb)	0.6 Kilocalories Per Minute (3 Limb)	0.8 Kilocalories Per Minute (4 Limb)
11-15	1, 2, 3, 4			
16-20		5, 6		
21-25		7, 8, 9, 10		
26-30		1+2, 3+4, 1+3 2+4, 1+4, 2+3	11, 12, 13, 14, 5+4	
31-35			5+3, 7+4, 6+1, 6+2	15
36-40			8+1, 9+2, 7+2, 10+1, 9+3, 10+4, 8+3	5+6, 4+12
41-45			1+2+4, 1+2+3, 1+3+4 2+3+4	7+8, 1+14, 4+13, 3+11
46-50				9+10
51-55				
56-60				1+2+3+4

Appendix 3. Calculation of Regression Equations

x = work output, kilocalories per minute

y = mean incremental heart rate, beats per minute

Slope = b = $\sum (x_i-\bar{x})\ (y-\bar{y})\ /\ (x_i-\bar{x})^2$

Intercept = a = $\bar{y}$-b $\bar{x}$

y = a+b x

Task	x_i	$\lvert x_i-\bar{x}\rvert$	$\lvert x_i-\bar{x}\rvert^2$	Minimum Heart Rate y_i	$\lvert y_i-\bar{y}\rvert$	$(x_i-\bar{x})\ (y_i-\bar{y})$	Mean Heart Rate y_i	$\lvert y_i-\bar{y}\rvert$	$(x_i-\bar{x})\ (y_i-\bar{y})$	Maximum Heart Rate y_i	$\lvert y_i-\bar{y}\rvert$	$(x_i-\bar{x})\ (y_i-\bar{y})$
1	0.2	.23	.053	11	.47	.11	14	7.67	1.76	16	15.27	3.51
2	0.2	.23	.053	13	1.53	.35	15	6.67	1.53	19	12.27	2.82
3	0.2	.23	.053	5	6.47	1.49	15	6.67	1.53	29	2.27	.52
4	0.2	.23	.053	6	5.47	1.26	14	7.67	1.76	22	9.27	2.13
5	0.4	.03	.00	5	6.47	.19	16	5.67	.17	27	4.27	.13
6	0.4	.03	.00	9	2.47	.07	17	4.67	.14	25	6.27	.19
7	0.4	.03	.00	10	1.47	.04	21	.67	.02	29	2.27	.07
8	0.4	.03	.00	13	1.53	.05	22	.33	.01	33	1.73	.05
9	0.4	.03	.00	4	7.47	.22	21	.67	.02	32	.73	.02
10	0.4	.03	.00	15	3.53	.11	25	3.33	.09	34	2.73	.08

Appendix 3 Continued. Calculation of Regression Equations

Task	x_i	$\lvert x_i-\bar{x}\rvert$	$\lvert x_i-\bar{x}\rvert^2$	Minimum Heart Rate y_i	$\lvert y_i-\bar{y}\rvert$	$(x_i-\bar{x})(y_i-\bar{y})$	Mean Heart Rate y_i	$\lvert y_i-\bar{y}\rvert$	$(x_i-\bar{x})(y_i-\bar{y})$	Maximum Heart Rate y_i	$\lvert y_i-\bar{y}\rvert$	$(x_i-\bar{x})(y_i-\bar{y})$
11	0.6	.17	.029	15	3.53	.60	26	4.33	.74	38	6.73	1.15
12	0.6	.17	.029	13	1.53	.26	26	4.33	.74	34	2.73	.46
13	0.6	.17	.029	17	5.53	.94	30	8.33	1.42	44	12.73	2.16
14	0.6	.17	.029	17	5.53	.94	28	6.33	1.08	38	6.73	1.15
15	0.8	.37	.137	19	7.53	2.79	35	13.33	4.92	49	17.73	6.55
	6.4		.465	172		9.42	325		15.93	469		20.99

Minimum Incremental Heart Rate

$y = 172/15 = 11.47$

$b = 9.42/.465 = 20.26$

$\bar{x} = 6.4/15 = 0.43$

$a = 11.47 - 20.26(0.43) = 2.76$

$y = 2.76 + 20.26\,x$

Mean Incremental Heart Rate

$\bar{y} = 325/15 = 21.67$

$b = 15.93/.465 = 34.26$

Appendix 3 Continued. Calculation of Regression Equations

$a = 21.67 - 34.26(0.43) = 6.94$

$y = 6.94 + 34.26\ x$

Maximum Incremental Heart Rate

$\bar{y} = 469/15 = 31.27$

$b = 20.99/.465 = 45.14$

$a = 31.27 - 45.14(.43) = 11.86$

$y = 11.86 + 45.14\ x$

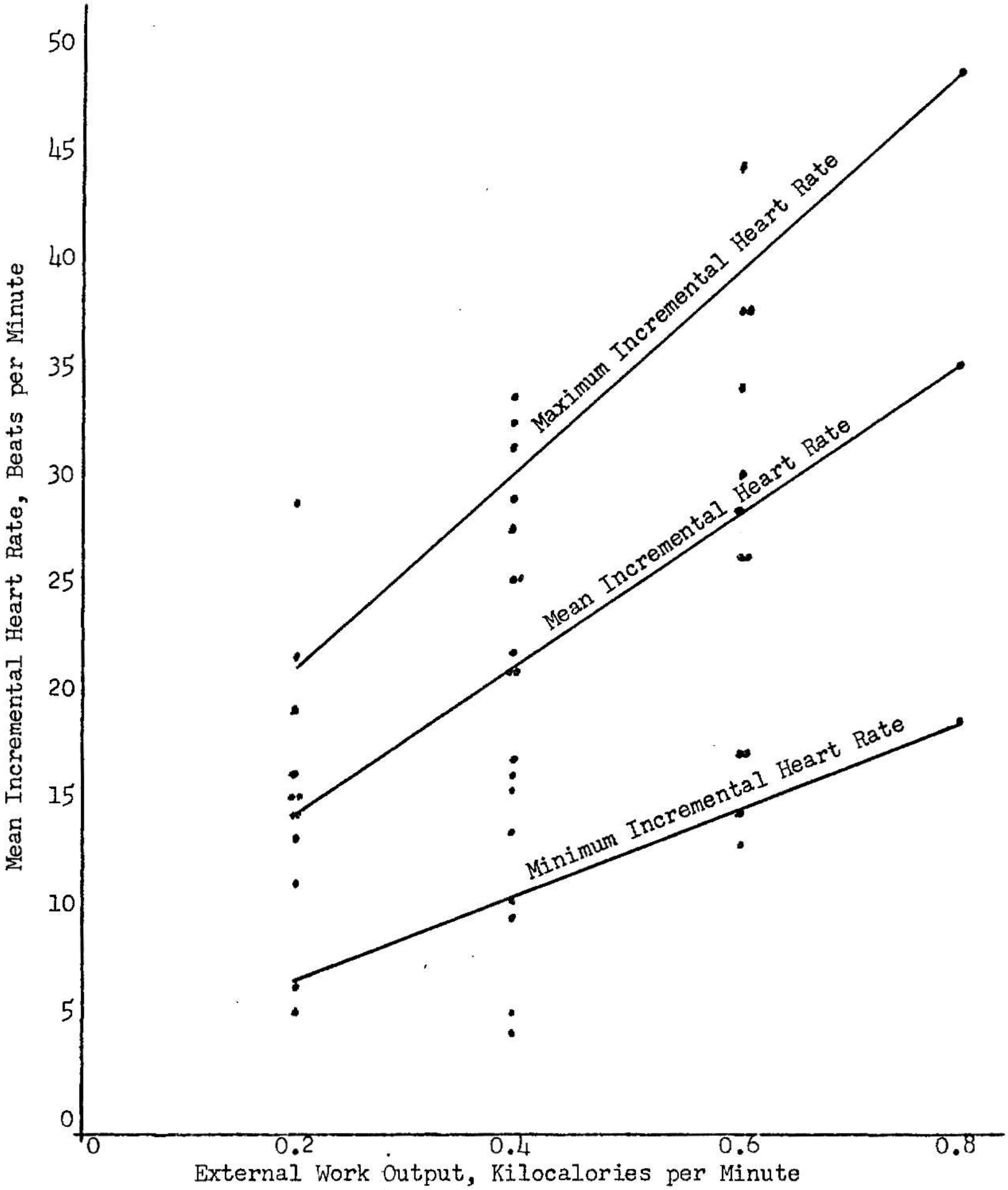

Figure 9. Repression Equations for Relationship Between Work Output and Mean Incremental Heart Rate

regression equations were computed from data representing the minimum or maximum incremental heart rate induced in any subject, for a given task. The equations were formulated to make possible the prediction of minimum, mean and maximum mean incremental heart rate to be expected from a given work output.

Interaction Combinatorial Coefficients

The statistical analysis performed indicated that the mean incremental heart rate induced by some of the tasks tested could be predicted by summation of the mean incremental heart rates of the increments of the tasks in question. The t-values not marked with an asterisk in Tables 8 through 13 indicate those tasks for which no statistically significant difference exists between the means of the incremental heart rates. The incremental heart rates of some of the sequentially performed tasks can be summed to predict the incremental heart rate of the same tasks performed simultaneously. When the mean incremental heart rates of the increments of other tasks were summed, they generally over-estimated the actual measured mean incremental heart rates, by varying factors. The combinatorial factors were calculated for the various limb combinations, so that the mean incremental heart rates of sub-tasks could be summed and multiplied by a factor to predict the mean incremental heart rate of a multi-limb task. The combinatorial factor for the various limb combinations are found in Table 18. No simple relationship exists whereby one combinatorial factor can be used with the mean incremental heart rate induced by the involvement of a given set of limbs to predict the mean incremental heart rate which will be induced by production of a given work output. The

TABLE 18

Combinatorial Factors for Prediction of Mean Incremental Heart Rate Induced by a Complex Task, Through Summation of Mean Incremental Heart Rates of Incremental Tasks

Number Lines Involved (Work Output)	Complex Task Code	Incremental Task Codes (Combinatorial Factor)
1 (0.2 kilocalories per minute)	1	
	2	
	3	
	4	
2 (0.4 kilocalories per minute)	5	1+2** (.55)
	6	3+4 (.59)
	7	1+3 (.73)
	8	2+4 (.76)
	9	1+4 (.75)

TABLE 18 Continued

Combinatorial Factors for Prediction of Mean Incremental Heart Rate Induced by a Complex Task, Through Summation of Mean Incremental Heart Rates of Incremental Tasks

Number Lines Involved (Work Output)	Complex Task Code	Incremental Task Codes (Combinatorial Factor)							
	10	2+3 (.83)*							
3 (0.6 kilocalories per minute)	11	1+2+4 (.60)	5+4 (.87)*	8+1 (.72)	9+2 (.72)				
	12	1+2+3 (.59)	5+3 (.84)*	10+1 (.67)*	7+2 (.72)				
	13	1+3+4 (.70)	7+4 (.86)	6+1 (.97)*	9+3 (.83)				
	14	2+3+4 (.64)	10+4 (.72)	6+2 (.88)	8+3 (.76)				
4 (0.8 kilocalories per minute)	15	1+2+3+4 (.60)	5+6 (1.06)*	9+10 (.76)	7+8 (.81)	4+12 (.88)	1+14 (.83)	4+13 (.80)	3+11 (.85)

*No statistically significant difference in means of incremental heart rates at .05 level, one-tailed test.

NOTE: Combinatorial factors valid only for comparison within same row.

** $.55\ (\overline{HR}_1 + \overline{HR}_2) = HR_5$

interactions involved in use of various limb combinations result in a complex relationship among combinatorial heart rate factors.

Selection of Optimal Limb Combinations

Selection of the optimal limb combination to produce a given work output was difficult, based on mean incremental heart rate above, because of the statistical differences among the means. Partially ordered data existed, whereby for a given work output task A was significantly different from task B, task B was significantly different from task C, but task A was not significantly different from task C. To further complicate the selection process, many tasks were statistically no more costly than their work output equivalence. An evaluation was made, for each task, of the numbers of equivalent tasks which were statistically "worse," "no different," and "better." The results are shown in Table 19, along with the "preferred task" and "acceptable task" indexes. These indexes permitted a numerical evaluation of tasks, based on relative superiority.

Upon completion of each task the subject was asked to vote on his degree of fatigue, on a five-point scale ranging between "not fatigued" and "extremely fatigued." The results of this test are listed in Table 20.

Spearman rank coefficient of correlation comparisons are listed in Table 21. The comparisons were made for individual and environmental factors, and for fatigue sensation votes, to determine correlation with the mean incremental heart rate of subjects. No significant correlations were found, except between the mean incremental heart rate of subject number 2, and his fatigue votes for the second group of five tasks.

TABLE 19
Preferred Task and Acceptable Task Indexes

Work Output, Kilocalories Per Minute	Task	Number of Tasks: Worse	No Different	Better	Total	Preferred Task Index	Acceptable Task Index
0.2	1	0	3	0	3	0	1.0
	2	0	3	0	3	0	1.0
	3	0	3	0	3	0	1.0
	4	0	3	0	3	0	1.0
0.4	5	7	4	0	11	.64	1.0
	6	8	3	0	11	.73	1.0
	7	6	3	2	11	.55	.82
	8	3	8	0	11	.27	1.0
	9	3	8	0	11	.27	1.0
	10	4	5	2	11	.36	.82
	1+2	0	6	5	11	0	.55
	3+4	0	8	3	11	0	.73
	1+3	0	8	3	11	0	.73
	2+4	0	5	6	11	0	.45
	1+4	0	5	6	11	0	.45
	2+3	0	7	4	11	0	.64
0.6	11	15	4	0	19	.79	1.0
	12	12	7	0	19	.63	1.0
	13	12	6	1	19	.63	.95
	14	13	6	0	19	.68	1.0
Continued							
0.6	6+2	5	11	3	19	.26	.84
	8+3	3	10	6	19	.16	.68
	1+2+4	0	5	14	19	0	.26
	5+4	9	10	0	19	.47	1.0
	8+1	1	14	4	19	.05	.79
	9+2	1	14	4	19	.05	.79
	1+2+3	0	8	11	19	0	.42
	5+3	5	14	0	19	.26	1.0
	10+1	0	13	6	19	0	.68
	7+2	4	8	7	19	.21	.63
	1+3+4	0	9	10	19	0	.47
	7+4	5	10	4	19	.26	.79
	6+1	8	8	3	19	.42	.84
	9+3	1	14	4	19	.05	.79
	2+3+4	0	10	9	19	0	.53
	10+4	0	11	8	19	0	.58
0.8	15	7	1	0	8	.88	1.0
	1+2+3+4	0	1	7	8	0	.13
	5+6	6	2	0	8	.75	1.0
	9+10	0	6	2	8	0	.75
	7+8	1	5	2	8	.13	.75
	4+12	2	5	1	8	.25	.88
	1+14	1	5	2	8	.13	.75
	4+13	1	5	2	8	.13	.75
	3+11	1	6	1	8	.13	.88

TABLE 20

Fatigue Vote* After Performing Tasks

Subject Number	Task Code Number B**	1	2	3	4	5	B	6	7	8	9	10	B	11	12	13	14	15	B
1	1	2	3	3	2	2	1	2	2	3	3	2	1	2	3	3	3	3	2
2	1	2	2	2	2	3	1	3	2	3	2	3	1	2	3	2	2	3	1
3	1	2	3	2	3	2	1	2	3	2	2	2	1	2	2	2	2	2	1
4	1	2	2	3	2	2	1	2	3	2	3	2	1	2	1	2	3	2	1
5	1	1	1	1	1	1	1	2	2	2	1	2	1	2	1	1	1	2	1

*Fatigue vote code:

1 - Not fatigued.

2 - Just noticeable fatigue.

3 - Slightly fatigued.

4 - Moderately fatigued.

5 - Extremely fatigued.

**B - Basal heart rate

TABLE 21
Spearman Rank Coefficient of Correlation Comparisons

Factors Compared		r_s
Mean Basal Heart Rates, By Subject	Age	-.500
	Weight	-.300
	Height	-.025
	Temperature	.875
	Relative Humidity	-.625
Mean Incremental Heart Rate, Subject 1	Fatigue Vote	.775
	Fatigue Vote	.875
	Fatigue Vote	.500
Mean Incremental Heart Rate, Subject 2	Fatigue Vote	.250
	Fatigue Vote	.900*
	Fatigue Vote	.175
Mean Incremental Heart Rate, Subject 3	Fatigue Vote	.625
	Fatigue Vote	.750
	Fatigue Vote	.500
Mean Incremental Heart Rate, Subject 4	Fatigue Vote	-.250
	Fatigue Vote	-.350
	Fatigue Vote	.725
Mean Incremental Heart Rate, Subject 5	Fatigue Vote	.500
	Fatigue Vote	.875
	Fatigue Vote	.375

*Statistically significant at the .05 level. For n=5, a=.05, r_s must equal or exceed .900 to achieve statistical significance.

DISCUSSION

Static and Dynamic Limb Loading

Results of the tasks performed for this study showed that higher incremental heart rates are associated with higher work output. The work output chosen for each limb for this study was not particularly fatiguing, which resulted in relatively small incremental heart rates. The building-block principle was used to provide as few differences as possible among the fundamental sub-tasks involved in the test.

During most of the tests not all limbs were dynamically involved in performing tasks. For example, when one arm was used to pull a weight, the other arm was held in a position ready to pull a weight, while the legs were in a position such that both feet were flat on the platform, next to the depressed-pedal position. While the other three limbs were not dynamically involved, static loading could not be ruled out. Some bracing and balancing were involved in the muscular actions of the non-tested limbs. The various combinations of limbs involved in tests resulted in other combinations of static loading in muscles.

Some task combinations caused an extremely unbalanced muscle-load condition in the subject, such as during use of the arm and the leg on the same side of the body. Not only was static loading present in muscles for counter balancing, but certain motions were also induced in the body. For the loading described, a noticeable rotation of the body occured about an axis parallel to the spine of the subject. Other off-balance loading also produced reactive motions in the body. These motions caused some tensing and relaxing of muscles, which assisted in pumping blood. This assistance probably in some measure counteracted the deleterious effect of muscle static loading.

Andrews (1967(a)) states, in a summary of work by other researchers, that the dynamic use of the legs returns blood to central circulation which has been pooled in the legs. The muscles act as a venous pump, to assist in returning the blood to the heart. Since the leg muscles are larger than the arm muscles, a proportionately greater pumping action occurs when the legs are involved. A lower heart rate is induced because of the pumping assistance of the leg muscles, if other test conditions remain the same. The effect of the pumping assistance was seen in some, but not all, of the test results.

Interactions Resulting From Task Design

In general, lower mean incremental heart rates were induced, for a given work output, by a set of limbs simultaneously involved in performing a task, as opposed to the summation of mean incremental heart rates of those limbs performing sub-tasks sequentially. Higher mean incremental heart rates were also associated with higher levels of work output. For the tasks for which heart rate was measured, a given work output induced mean incremental heart rates which varied, depending on the particular limbs involved. For example, 0.2 kilocalories/minute of work output involved one limb at a time, and induced 14 to 15 beats/minute of mean incremental heart rate. Two limbs produced 0.4 kilocalories/minute and cost 16-26 beats/minute. Three limbs produced 0.6 kilocalories/minute and cost 26-28 beats/minute, while four limbs produced 0.8 kilocalories/minute at a cost of 35 beats/minute. These physical costs noted do not include the summations of mean incremental heart rates of hypothetical sequentially-performed tasks created for statistical analysis.

Many interactions of static and dynamic loading, balanced and unbalanced loading, and arm muscles versus leg muscles were evident in the test results for a given work output. For example, the measured mean incremental heart rate for the left arm, right arm, and right leg was 26 beats per minute. The sum of the incremental heart rates of the left and right arms individually was 29 beats per minute, and the right leg alone added 14 beats per minute, for a total of 43 beats per minute. Taken another way, use of the arms simultaneously resulted in 16 beats per minute, to which the right leg added 14 beats per minute, for a total of 30 beats per minute. The same task, performed three ways, produced mean incremental heart rates of 29, 43, and 30 beats per minute.

Interactions may also be noted by comparing the measured mean incremental heart rates induced by the various work output levels. For example, the 0.8 kilocalorie per minute work output cost of 35 beats per minute was not twice the cost of 0.4 kilocalorie per minute work output, which was 26-30 beats per minute. A smaller increase in heart rate cost is required for each increase step in work output.

The effects of some interactions were so small as to be not statistically significant. A possibility exists that compensating interactions were at work in some task combinations, whereby a heart rate increase from one factor was offset by a heart rate decrease from another factor. Where an arm on one side of the body operated simultaneously with a leg from the opposite side of the body, the unbalanced loading may have been compensated for by the venous pumping action of the leg.

Use of the devised indexes indicated that any single limb was equivalent to any other single limb, in terms of induced incremental heart rate. Where two limbs were involved, the simultaneous use of the two legs was the superior limb combination. The left hand, right hand, and right foot combined in simultaneous operation to make the optimum three-limb combination. The optimum four-limb combination involved the simultaneous use of all four limbs.

The complexity of the interactions found in the study reported herein was also reported by Andrews (1966) in an investigation of the additivity of values of energy expenditure of simultaneously performed simple muscular tasks. Andrews found that the sum of the net energy expenditure rates of the tasks exceeded the net energy expenditure rate in seven of the eight cases tested, by 20 per cent or more in four cases. It was concluded that a system of standard metabolic data would be extremely complex, if at all feasible. This conclusion is born out by the results of the study which serves as a starting point for this thesis. A system of standard data of energy cost of simple physical motions would be complex, and possibly not feasible.

CONCLUSIONS

A simple system of codifying human physical tasks according to the energy expenditure of the basic motion components is highly desirable, so that tasks can be designed and tested mathematically, rather than by "guess-and-test." The feasibility, based on the results of this study and the comments of Andrews (1966), seems remote. It was concluded that a complex system of interactions exists between muscle sets used to perform physical tasks, such that no simple method of predicting energy cost of a task is possible, from summation of the component task energy expenditure rates. A system of standard motion-cost data would be complex, if at all feasible. The extensive testing required would result in voluminous tables, but the process would permit theoretical evaluation of task design before performing live evaluation. This study pointed out some of the advantages of simultaneous, rather than sequential performance of sub-tasks which make up a more complex task. These advantages frequently include reduced mean incremental heart rate, which is often augmented by balanced loading and the use of the legs in performing the task.

Further research is needed to determine methods of bringing together optimal environmental factors and optimal work design factors into integrated systems of task design which will provide overall maximal physical work output with minimal energy expenditure. The concept of codifying fundamental motions by physical cost for given work output could lend itself to operations research techniques to find the optimal sequence, for some tasks.

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INTERACTIONS OF A MULTI-LIMB PUSH-PULL TASK

by

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Each of 5 male subjects performed 15 tasks consisting of pulling hand grips and pushing foot pedals on a weight-and-pulley machine, at work output loads of 0.2 kilocalories per minute for each limb. Physiological cost to the subjects was measured in terms of induced mean incremental heart rate. Tests were devised to determine the relative superiority of task organizations, by work output level. Combinatorial factors and relative value indexes were calculated for tasks, to permit selection of the optimal limb combination for a given work output. It was concluded that a complex system of interactions exists between muscle sets used to perform physical tasks, such that no simple method of predicting energy cost of a task is possible, from summation of the component task energy expenditure rates. A system of standard data of energy cost of simple physical motions would be complex, if at all feasible.