THE ENERGY COST AND EFFICIENCY OF TREADMILL WALKING AT DIFFERENT RATES OF VERTICAL ASCENT AND GRADE

by

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ABSTRACT

Several investigators have shown that the physiological cost (defined as the energy expenditure) of a gross dynamic muscular work task is not only a function of the work rate (defined as the external work done by the body) but appears also to vary according to the particular combination of speed and tension used to achieve that work rate.

This study investigated the influence of the rate of vertical ascent (and hence work rate commensurate with body weight) and the inclination of slope on the energy cost, and hence efficiency, of grade walking. Three rates of vertical ascent were chosen (1300, 1800 and 2300 ft/hr) and four grades were used to achieve each of these rates (12, 16, 20 and 24%).

The energy cost was calculated from respiratory gas measurements. Energy cost was calculated for each of four phases, namely, standing, horizontal walking (at the same treadmill speed as for the subsequent grade walking), grade walking and recovery. Three trials (replications) were made at each combination of rate of vertical ascent and grade to ensure greater reliability of the data.

Three measures of efficiency were computed: (i) gross efficiency, (ii) net efficiency calculated using the difference between the energy cost of grade walking and standing (NES), (iii) net efficiency calculated using the difference between the energy cost of gradewalking and horizontal walking at the same treadmill speed (NEH). Each of these measures of efficiency was then submitted to a three factor analysis of variance (rate of vertical ascent, grade and trial replication).

The interaction between rate of vertical ascent and grade was significant for gross efficiency. The two highest rates of ascent showed a clear and significant trend in which the efficiency was linearly related to the reciprocal of the grade for the range of grade used in the study. Thus gross efficiency increased hyperbolically as the grade increased. At the lowest rate of vertical ascent the highest efficiency was at the 16% grade with no clearly defined pattern emerging. The main factor replication (repeated trials) was found to be significant but this was due to the accruing oxygen debt from one trial to the next.

The factors rate of vertical ascent and grade were significant for the analysis of variance of the net efficiency (NES). The influence of grade was as for gross efficiency, that is, increasing from 12% through 24%. The influence of rate of vertical ascent was the reverse of that for gross efficiency, that is, the efficiency decreased from the lowest rate to the highest rate. This indicated that the lower gross efficiency of the lowest rate of ascent was due to the disproportionately large contribution of standing metabolism to the total energy cost of grade walking.

Only the rate of vertical ascent was found to exert a significant influence on net efficiency (NEH). The net efficiency decreased linearly as the rate of ascent increased. The influence of grade was no longer significant and this supports the view that differences in gross efficiency and net efficiency (NES) were due to differences in the economy of the horizontal component of walking.

Pulmonary ventilation and, to a lesser extent, heart rate were confirmed as being useful predictors of the energy cost of walking in cases where the highest order of accuracy is not required. Also confirmed was the linear relationship between the energy cost of horizontal walking and the square of the speed. From this relationship the optimal velocity and energy cost of horizontal walking was calculated.

It was concluded from this study that the gross efficiency of grade walking is significantly influenced by factors such as rate of vertical ascent and grade. The influence of grade can be explained satisfactorily but that of rate of vertical ascent still requires some clarification.

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CHAPTER I

INTRODUCTION

This study investigates certain aspects of the energy cost and efficiency of horizontal and grade walking on a motor-driven treadmill. Studies (2,6,23) of horizontal walking and bicycle ergometry have shown that the physiological cost (as expressed by oxygen consumption or energy expenditure) of a given work rate (as measured by external work done by the body) varies according to the particular combination of speed and tension which was used to achieve that work rate.

HYPOTHESIS

The principal hypothesis of this study was that the physiological cost, and hence efficiency, of grade walking on a motor-driven treadmill is not constant for a given rate of external work but varies according to the combination of grade and speed used to achieve that rate of work. For the purpose of the study external work done in grade walking was defined as the product of gross body weight and rate of vertical ascent.

Furthermore, it was hypothesized that there will be, at any one rate of work, an optimal combination of speed and grade which produces maximum efficiency. This optimal combination of grade and speed may vary from individual to individual and from workrate to workrate. Such variations are to be examined.

PURPOSES

Specifically, the main purposes of the study were as follows:

1. To measure and compare the energy cost and efficiency of grade walking on a motor-driven treadmill at 12 different combinations of treadmill grade and vertical rate of ascent. These combinations included all pairings of three vertical rates of ascent (1300, 1800, and 2300 ft/hr) and four grades (12, 16, 20 and 24 per cent).
2. To examine the usefulness of three different measures of efficiency with respect to grade walking. These three measures are:
    - (a) Gross efficiency calculated with no deduction from the total cost of grade walking.
    - (b) Net efficiency calculated with a deduction for the energy cost of standing.
    - (c) Net efficiency calculated with a deduction for the energy cost of walking horizontally at the same velocity.
3. To elucidate any trends or relationships between the independent variables (grade and vertical rate of ascent) and the dependent variables (three measures of efficiency).
4. To investigate the relationships which have been reported between the energy expenditure of walking and variables such as body weight, body surface area, velocity of horizontal walking, heart rate and minute ventilation.

5. To establish some idea of the reliability and accuracy of the experimental procedures used in this study for the measurement of energy cost, and to compare the data obtained in this study with that obtained by previous investigators.

CONCEPT OF EFFICIENCY

The concept of efficiency is central to this study and it is important to look at some of the problems that beset the investigator who tries to come to grips with the concept. Consider from a thermodynamic point of view efficiency is defined as:

$$\text{Efficiency} = \frac{\text{Useful energy output}}{\text{Free energy made available}}$$

This ratio is normally expressed as a percentage. For the physiologist, working with complex living systems, the interpretation of this definition is not at all easy. The free energy made available is not difficult to measure; direct methods such as large scale calorimetry or indirect methods such as analysis of respiratory gases (and the equating of these to fuel combustion and energy production) have now reached a level of sophistication which enables reasonably precise measurements to be made. It is the problem of establishing what portion of this free energy can rightfully be thought of as contributing towards useful work which has created the most difficulties. It may well be that the problem is semantic and largely of our own making.

In measuring the efficiency of a given work task such as grade walking it is possible to measure directly (a) the external work done, i.e., useful energy output, and (b) the free energy made available, i.e., the total energy cost measured during the work. However, during a work task various bodily processes are continuing which operate, and require energy, independently of the work task. These processes would occur irrespective of the work task and it has been suggested by some (11,17) that the energy cost of these processes should be subtracted from the total cost of the work to establish the efficiency of the body for that work task. In this study the energy cost of standing has been deducted from the total cost of grade walking as one measure of net efficiency. Other investigators (3,10,25) have suggested that only that component of liberated energy directly associated with the upward displacement of the body should be considered. Thus a second measure of net efficiency, incorporating a deduction for the energy cost of walking horizontally at the same velocity was postulated. These two measures are essentially of academic interest only since the overall or gross efficiency of the body is the only measure likely to have practical significance.

CHAPTER II

REVIEW OF LITERATURE

The energy cost of a wide variety of physical activities has been reported and both the methods used and the results of these studies have been reviewed by Passmore and Durnin (21). Walking has been extensively investigated with grade walking rather less so. The earliest studies were made by Durig and Luntz (9,10) on men walking on the level and uphill at altitudes ranging from sea level to 14,000 feet in the years from 1900 to 1909. They concluded that the efficiency of mountain climbing was greatly influenced by the nature of the ground and the experience and state of training of the subject. Douglas et al., (8) confirmed the effect of the terrain on the efficiency of climbing and showed that the oxygen consumption for a given work rate of uphill walking was independent of altitude up to heights of 14,000 feet. Durnin (11) measured the oxygen consumption and energy cost of climbing with loads in natural outdoor conditions with subjects climbing at their natural pace. The efficiency of climbing (calculated using a deduction for resting metabolism) showed little variation with load and only slightly more with subject and grade. Durnin expressed surprise at these small variations in oxygen consumption, particularly in view of the marked subjective experiences which accompanied changes in the load carried. Pugh (22) made similar measurements on mountaineers during the approach marches on two Himalayan mountaineering expeditions and found that the nature of the ground contributed markedly to variations in climbing efficiency. He observed that mountaineers tend to choose a slow speed and steep grade, a combination that appeared to be more economical in terms of total energy expenditure.

All of the above studies were made in the field where a number of extraneous factors may have imposed unwanted variability. Despite the fact that treadmill walking is, in terms of biomechanics, somewhat different from normal walking, treadmill studies are useful in that it is possible to control or standardize this variability. In 1945 Erickson *et al.*, (13) studied the energy cost of treadmill walking with two young men at several possible combinations of speeds (2.5, 3.0, 3.5 and 4.0 mph) and grades (0, 5.0, 7.5 and 10.0 per cent). In addition the energy cost of walking at 3.5 mph and 10.0 per cent grade was measured in another 47 subjects. Their most important findings were as follows:

1. The inter-individual variability in gross oxygen consumption was 9.37 per cent of the mean value. Corrected for body-weight it was reduced to 3.99 per cent of the mean.
2. Training produced a slight increase in walking efficiency which in all cases was less than the replicate variability.
3. The increase in energy expenditure with speed on the four different grades were basically the same in the two subjects, being steeper at the higher grades.
4. Net climbing efficiency, calculated with a deduction for the energy cost of horizontal walking, showed maxima at medium speeds (3.0 and 3.5 mph) and low grade (5.0 per cent).

5. The inter-individual variability decreased with increasing rate of work.
6. A linear relationship (product moment correlation coefficient of 0.977) was found between excess oxygen consumption in recovery and the excess energy expenditure during work.

Erickson and his colleagues discussed the concept of net efficiency proposed by Zuntz and adopted by a number of other workers (3, 25), in which the caloric equivalent of the absolute amount of body lift (gross weight x vertical height gained) is divided by the difference in energy expenditure between grade and horizontal walking. Erickson and colleagues found that one subject displayed higher climbing efficiencies despite higher energy expenditures per unit body weight because of the fact that his horizontal walking had a higher energy cost. They interpreted this as a possible objection to this method of calculating net efficiency.

Orsini and Passmore (20) have suggested another method of calculating the net efficiency of grade walking. In order to take into account postural changes required to maintain balance in grade walking they recommend that the energy cost of downhill walking on the same grade be subtracted from the total cost. Lukin _et al._, (17) calculated net efficiencies (with a subtraction for the energy cost of standing) for a subject walking at 97.6 m/min on a 3^o (5.24 per cent) slope. When all the measured gravitational work was considered the efficiency was found to be 23.9 per cent but when only the gravitational work retained (i.e., that used in gaining height) was considered the efficiency dropped to 14.0 per cent. Whipp and Wasserman (28) have criticized the whole concept of mechanical efficiency as being inaccurate and misleading since both mechanical and biochemical processes determine the calculated efficiency. Illustrative of the inaccuracy of the concept they postulate the case of a person with severe airway obstruction. In this case because respiratory muscle work is increased such an individual would require extra oxygen to perform a given work task and thus the calculated "mechanical" efficiency is reduced despite the fact that there is no evidence to suggest that muscular efficiency is decreased. Whipp and Wasserman proposed the term work efficiency and recommended that its calculation should include only the oxygen consumed which is necessary to perform the measured work.

Because of the unnatural aspects of treadmill walking the possibility of an improvement in efficiency must be considered in any study in which efficiency is being examined. In this respect the evidence seems equivocal. Durig (9) found that his efficiency carrying a load of 18 kg on a 25 per cent grade increased with practice during the day. Durnin (11), on the other hand found no detectable differences due either to practice or fatigue. Knehr _et al._, (16) observed a progressive increase in efficiency when subjects were trained day after day while Erickson _et al._, (13) in the study previously reported found increases which were always less than the replicate variability. It seems reasonable to presume however, that the state of training and the general level of motor skill of the subjects will, together with the frequency of training, have some bearing upon the extent to which efficiency is increased.

The energy cost of walking has also been related to a number of mechanical variables. Cotes and Meade (6) found that the energy cost of walking at a natural step frequency on the horizontal treadmill was linearly related to:

(1) the vertical lift work, which is the product of lift per step, step frequency, and body weight.

(2) the square of the forward velocity.

Likewise they found that the energy cost of uphill walking could be described in terms of the vertical lift work provided allowance is made for the additional lift work involved in gaining height.

Studies of horizontal walking and bicycle ergometry have shown that these forms of locomotion have an optimal speed/tension combination with respect to energy expenditure relative to external work achieved (i.e., efficiency). In a study of horizontal walking Ralston (23) found that the curve relating energy expended per metre walked per kg of body weight was concave upward. When a subject was requested to walk at his natural speed he adopted a speed close to the minimum for this curve, the "natural" or optimal speed for the subject. Similar observations have been made in cycling. Banister and Jackson (2) studied the effect of speed and load changes on oxygen uptake for equivalent work loads during bicycle ergometry. They found that for each power output chosen there was an optimal combination of load and speed which required a minimal oxygen uptake, and that a shift of load and speed toward combinations of extreme speed and low load added considerably to the energy cost. For example, pedalling at 120 rpm at a power output of 360 kgm/min was physiologically equivalent (i.e., required the same oxygen intake) to a power output of 1,000 kgm/min at pedalling rates of 50 to 80 rpm.

The author recently carried out a study (26) which examined the effects of grade, rucksack load (carried on the back) and boot weight on the energy cost of uphill walking. Two young female subjects walked uphill on a treadmill at a rate of ascent of 1,000 ft/hr at all combinations of two levels of grade and speed (11.9 per cent at 1.6 mph and 19.3 per cent at 1.0 mph), rucksack weight (5 kg and 20 kg) and boot weight (1.25 kg and 3.75 kg). A factorial analysis of variance analysed the results of this 2^4 factorial design. Significant differences were found between:

(1) grades, for energy cost ($p < 0.01$) and efficiency ($p < 0.001$)

(2) boots, for energy cost ($p < 0.05$) and efficiency ($p < 0.001$)

(3) rucksacks, for energy cost ($p < 0.01$).

The extra cost of carrying the heavier rucksack was accounted for by the extra load, but the extra cost of wearing heavy boots or walking faster at a lower grade was due, at least in part, to reduced efficiency. As only two levels of grade and speed were considered it was not possible to establish any quantitative relationship between efficiency and grade. The elucidation of such a relationship, if it exists, is one of the objectives of the present study.

Other investigators have shown that up to a point, carrying a load on the back does not influence the efficiency of walking. Iampietro and Goldman (14) studied the energy cost of packboard carrying on a treadmill at various grades and speeds. Three standard weights of packboard were carried, namely ten, twenty and thirty kilograms. The energy cost per unit of weight for a given rate of progression and grade was essentially the same, regardless of the distribution of total weight between body weight and load for a "reasonably fit individual." Energy cost was shown to have a linear relationship with the weight of pack at the three weights used.

Brezina and Kolmer (4) studied the energy cost of walking at different speeds and with different loads. They showed that the maximal economic velocity was approximately 80 to 85 m/min. They also found that the cost was uninfluenced by loads of up to 21 kg, that is, that this amount of dead weight could be carried as economically as so much extra live weight. As their subject weighed 71 kg loads equivalent to approximately 30 per cent of the body weight might be regarded as equivalent to the same amount of body weight. Heavier loads brought about an absolute and a relative increase in the energy cost.

CHAPTER III

METHOD

The experiment described was carried out over a period of about five months in a laboratory situated at 1200 feet and maintained at a uniform temperature.

SUBJECTS AND GENERAL DESIGN

Six athletic subjects were studied whose physical data are given in Table 1. Weight was recorded on each day of testing and the

TABLE I

Physical Data of Subjects

Subject	Age	Weight, kg Mean ± S.D.	Height, cm	B.S.A. m^2 (DuBois)
AC	29	76.2 ± 0.5	178.0	1.96
RH	18	76.4 ± 1.5	172.5	1.91
JM	18	70.8 ± 0.5	183.7	1.92
GP	23	78.2 ± 0.6	186.5	2.03
AT	21	77.5 ± 0.5	179.2	1.94
MZ	19	96.6 ± 1.8	190.5	2.28

standard deviations reflect the variation in weight over the five month period. Subject MZ, a footballer, gained weight slowly over the period whereas the other subjects showed irregular fluctuations.

The experiment consisted of a pilot study followed by the major body of trials.

Pilot Study

An initial series of trials were conducted one per day for each subject over a period of about two weeks. A total of six trials of treadmill walking at one work rate of 2.9 mph at 18 per cent grade--a vertical rate of ascent of 2712 ft/hr was completed. Each trial consisted of the following consecutive phases:

(a) Five minutes of standing on the treadmill.

(b) Four minutes of horizontal treadmill walking at 2.9 mph with a measurement of energy cost (exercise $\dot{V}_{0_2}$) being made during the third and fourth minute.

(c) Ten minutes of grade treadmill walking at 2.9 mph and 18 per cent grade with two measurements of energy cost being made; during the fifth and sixth minutes and during the ninth and tenth minutes.

(d) Ten minutes of standing recovery with independent measurements of energy cost being made during the first and second five minute periods.

An analysis of the data was then made to determine the following:

1. Inter-individual variability.
   - (a) for gross measures of energy cost of grade walking.

   (b) for energy cost of grade walking corrected for body weight.

   (c) for energy cost of grade walking corrected for estimated body surface area (B.S.A. by method of DuBois).

2. Intra-individual variability over different days.
3. Intra-individual variability for estimates of energy expenditure made at different times within a trial. The validity of using the fifth and sixth minutes of grade walking as representative of a steady state of exercise was tested by comparing the data from this period with that taken in the ninth and tenth minutes.
4. The difference between using a five minute and a ten minute collecting period for measuring oxygen debt at the termination of walking.

Main Series of Trials

On the basis of the above analyses the six subjects undertook the main series of trials of walking at 12 different combinations of treadmill speeds and grades. The combinations used are given in Table II. They represent three levels of the rate of vertical ascent, each level being achieved by four different combinations of treadmill speed and grade. The three levels of rate of vertical ascent are denoted by V_1, V_2 and V_3 and the four levels of grade by G_1, G_2, G_3 and G_4.

Each combination of (e.g. V_1G_1) was tested in triplicate. Three trials at one combination were carried out in one testing session, and testing sessions for each individual were separated by at least one day. Each subject was assigned to work tasks in a random fashion (table of random numbers) to minimize any training effects which may have taken place. In fact the subjects were in a state of regular training and it is unlikely that the intensity of the treadmill walking was sufficient to cause any significant training effects.

TABLE II

Combinations of Treadmill Grade and Speed used in the Study

	Grade, per cent				Rate of vertical ascent	
	$12(G_1)$	$16(G_2)$	$20(G_3)$	$24(G_4)$	ft/hr	m/min
Speed mph	2.06	1.55	1.25	1.05	$1300(V_1)$	6.60
Speed mph	2.86	2.15	1.74	1.46	$1800(V_2)$	9.14
Speed mph	3.65	2.75	2.22	1.87	$2300(V_3)$	11.68

The subjects wore athletic shorts and track shoes at each testing session and were requested not to eat for at least two hours prior to the session. The difficulty of fitting a two-hour testing session into the subjects' regular daily programme, together with the limitations on the availability of laboratory time, meant that the pattern of eating and exercise activities which preceded each testing session were not as uniform as would have been desirable. This may explain the considerable variations in heart rate and respiratory exchange ratio for the standing phase. The period between trials within a test session was sufficient to carry out gas analysis of respired gas samples and to enable the metabolic rate to recover to normal so that there was no significant difference in this value at rest between trials.

Each trial consisted of the following consecutive phases.

(a) Five minutes of standing on the treadmill in order to achieve a baseline metabolic rate. One respired gas collection was made during this five minute period for analysis and three heart rates recorded, in the middle of the first, third and fifth minutes.

(b) Four minutes of horizontal walking in which one respired gas collection was made during the third and fourth minutes for later analysis and heart rates were recorded in the middle of each of these minutes. At the end of the fourth minute the treadmill was raised to the required grade.

(c) Six minutes of grade walking during which one respired gas collection was made and heart rates were recorded during the fifth and sixth minutes.

(d) Five minutes of standing recovery during which one gas collection was made and heart rates recorded in the middle of each minute.

INSTRUMENTATION

Room temperature and pressure were recorded at the beginning of each testing session. The subject was then weighed wearing recording instruments. Heart rates were recorded by radio telemetry (Parks Electronics, Beaverton, Oregon).

Pulmonary ventilation was measured by means of a Kofranyi-Michaelis (K-M) type meter (Max Planck Respiration Gas Meter) worn like a rucksack on the back. The subject inhaled air through a Colling triple J low-resistance valve and the exhaled gas passed through a pliable connecting tube of wide bore (id 1.5 inches) to the K-M meter. The mouthpiece and valve was suspended from above the treadmill by an adjustable cord so that this weight was not borne by the neck muscles of the subject during walking. The total weight of instrumentation and clothing carried by the subject was 5.0 kg. It has been shown by the author in a previous study that reasonably small loads carried on the back do not effect efficiency (26).

The K-M meter was calibrated over a range of flow rates encompassing those expected in the experiment. A known volume of air was passed from a Benedict spirometer through the meter in surges comparable to expiration. The K-M meter readings were consistently low and a regression equation of correction factor (CF) on recorded ventilation ($\dot{V}_E$, 1/min) was derived. This equation was $CF = 1.063 - 0.000294\ \dot{V}_E$, with a Standard error of estimate of ±0.0024 (product moment correlation coefficient of $r - 0.992$). The correction factor, together with the correction factor for temperature and pressure, were used to correct pulmonary ventilation to STPD. Analysis of respired gas was made from 0.6% aliquot samples of expired air collected in a rubber bladder corresponding to each period for which ventilation was measured. These samples were analysed at the end of or during each trial for O_2 and CO_2 content. Oxygen was analysed by means of a Westinghouse model 211 pulmonary function oxygen monitor and carbon dioxide by a Godart Capnograph. Percentage values of each gas were recorded on individual Philips rapid response recorders, Model PM 8100. These instruments were calibrated every trial with gases of known concentration from micro-Scholander analysis.

DATA ANALYSIS

A computer programme was used to process the raw data (Appendix I). The programme readout gave individual values of the parameters indicated below for each phase of each trial. The mean of each variable for each phase of the three trials at one combination of grade and speed was also calculated.

Recorded Variables

1. Heart rate, HR bpm.
2. Pulmonary minute ventilation, $\dot{V}_E$ STPD 1/min.
3. Per cent oxygen in expired air, O_{2_E} per cent
4. Per cent Carbon dioxide in expired air, CO_{2_E} per cent.
5. Respiratory gas exchange ratio, R.
6. Oxygen consumption, $\dot{V}_{O_2}$ 1/min.
7. Energy expenditure, E Kcal/min. This was calculated by the method of Weir (27). If O_E is the percentage of O_2 in expired air, then the energy value of one litre of expired air, E_L Kcal/min is given by $E_L = 1.046 - 0.05\ O_E$. The energy expenditure for any period is then given by $E = E_L . \dot{V}_E$, where

$\dot{V}_E$ is the volume of expired air for that period corrected to STPD. Weir claimed that this method has a maximum error of 1 in 500 if the amount of protein being metabolized by the subject is within the range 10 to 14 per cent.

8. Energy expenditure per 100 kg body weight, E_W Kcal/min/100 kg.
9. Energy expenditure per two square meters of body surface area, E_{BSA} Kcal/min/2m^2.

In addition the following parameters were calculated for each of the trials.

10. Three measures of efficiency of grade walking.
    (i) Gross efficiency, GE%, where no deduction from the energy cost of grade walking was made.
    (ii) Net efficiency, NES%, calculated using the difference between the energy cost of grade walking and energy cost of standing.
    (iii) Net efficiency, NEH%, calculated using the difference between the energy cost of grade walking and walking horizontally at the same speed.
11. Gross external work rate per minute in grade walking in both Kgm/min and Kcal/min. This was calculated as the product of body weight and vertical rate of ascent.

Various statistical analyses were made to determine significant differences between walking efficiency for the different combinations of grade and vertical rate of ascent. The principal treatment was an analysis of variance on all three measures of efficiency. A computer programme (Appendix 2) was used in this analysis. Since there were equal intervals between the levels of grade and vertical rate of ascent (4 per cent and 500 ft/hr respectively) it was also possible to perform a trend analysis using orthogonal polynomials. Further details of the statistical treatments are included in Chapters IV and V.

ERROR

In scientific experimentation error is defined as the difference between a true value and an observed value. In the physical sciences this definition has some validity for in these disciplines it is normally possible to conceive of a true value, as for example the frequency of a sound wave. The error is then attributable to deficiencies in the instruments and techniques used to measure this true value. In the measurement of human attributes, whether physical or psychological, we are not so fortunate. It may be possible that some human attributes do have a true value but it is never possible to define it, or to achieve its measurement, since such attributes fluctuate with time and are often modified by the process of repeated measurement. The best that we can hope for is that a number of measurements of the attribute (the dependent variable) can be made under conditions which minimize the influence of all but those factors whose effects we are interested in observing (the independent variables).

In such measurements total variability of the dependent variable can be considered as arising from four independent sources.

1. Variability due to the effect of the independent variable(s). Ideally this should be as large as possible relative to the other three sources.
2. Variability due to uncontrolled factors which influence the dependent variable. In exercise physiology some such factors may be diet, exercise patterns, mental and physical fatigue, lack of motivation. Usually attempts will be made to control, or at least randomize these influences.
3. Random errors of experimentation due to the instruments, poor technique or limitations of human accuracy.
4. Systematic errors of experimentation due to similar factors.

Total error will be the sum of 2, 3, and 4.

There are two methods of approaching the problem of separating the variability in the dependent variable and assigning the amount appropriate to each source.

The Statistical Method

Whenever more than one measure is made of the dependent variable under the same conditions of independent variable(s) it is possible to apply statistical procedures to determine the variability due to sources other than systematic error. If only two sets of measurements are made then a reliability coefficient is calculated. One minus the square of the reliability coefficient gives the proportion of the obtained variance which is due to the error from sources 2 and 3. With more than two sets of measurements analysis of variance is the technique used.

TABLE III

The Energy Cost of Grade Walking in Kcal/min of Subject AC for the 12 Combinations of Rate of Vertical Ascent (V) and Grade (G), and Three Trials

	Treatment Level											
Trial	V_1G_1	V_1G_2	V_1G_3	V_1G_4	V_2G_1	V_2G_2	V_2G_3	V_2G_4	V_3G_1	V_3G_2	V_3G_3	V_3G_4
1	6.71	6.76	6.55	7.00	8.91	7.30	8.06	8.41	12.49	10.91	10.61	10.68
2	7.46	6.47	7.49	6.84	9.24	8.39	8.11	7.43	12.49	12.19	10.95	10.33
3	6.84	6.20	6.91	6.71	9.25	8.89	7.75	8.39	11.94	11.26	10.19	11.03

The Analytical Method

By carefully and methodically appraising the instruments and techniques used it is possible to define the probable outer limits of random experimental errors (and, if possible reduce them by improving instruments and techniques).

The likely errors of the present experiment will be examined in these ways.

Statistical

Table III shows the data collected on the energy cost of grade walking for subject AC. Three replications were made of this measure for each of 12 levels of the independent variable (i.e., combination of treadmill grade and rate of vertical ascent). If the trials are considered in pairs, correlation coefficients, in this case reliability coefficients, can be calculated. They are:

$$r_{12} = 0.947$$

$$r_{13} = 0.955$$

$$r_{23} = 0.955$$

The calculation $(1-r^2)100$ gives the per cent of the variability which is due to error. This is the random fluctuation, not due to changing the dependent variable, but rather to uncontrolled factors and random experimental errors. In these three cases the percentage of variability due to these sources are 10.3%, 8.8% and 8.8% respectively. However, this method makes use of only part of the data and thus loses some precision.

The results of a one-way analysis of variance of the same data are given in Table IV. The percentage of variability due to random sources has now been reduced to 7.14/160.54 x 100 = 4.45%, and the remaining 95.5% is due to the variability of the independent variables. Further trials would increase the precision of the experiment even more.

TABLE IV

One Way Analysis of Variance of the Energy Cost of Grade Walking for Subject AC

Nature of Effect	Sum of Squares	d.f.	Variance Estimate	F ratio
Combination of grade and load	153.40	11	13.95	46.9*
Replication	7.14	24	0.30	
Total	160.54	35		

* $p<0.001$

Analytical Assessment of Experimental Errors

Energy cost is calculated from the volume of expired air corrected to standard temperature and pressure dry, $\dot{V}_E$ STPD and the percentage of oxygen in this expired air, $O_E\%$. Each of these parameters in turn are calculated from several other measures. Errors in any of these measures will be propagated through the calculations and may be additive. It is possible to assess the maximum error likely to occur in any one measurement and then calculate what the final error could be were all the errors additive.

1. Volume of expired air.
   - (a) Reading the K-M meter. In this a reading error of ±0.2 l may occur. Since a volume measurement is the difference of two readings the maximum possible error is ±0.4 l.
   - (b) Calibration of the K-M meter. The regression equation for the correction factor on recorded flow rate had a standard error of estimate of 0.00235. Thus the 99% confidence limits for the correction factor were ±2.58 x 0.00235 = ±0.0061 (99% confidence limits for a normal distribution fall within ±2.58 SD). This assumes that the instrument against which the K-M meter was calibrated was accurate.
   - (c) The reading of gas temperature was accurate to ±1° c.
   - (d) The reading of room pressure was accurate to ±0.5 mm Hg.

For a recorded flow of 60 l/min and combining these errors in an additive fashion a percentage error (99% confidence limits) of ±1.3% was obtained.

2. Percentage of oxygen in expired air.
   - (a) The oxygen analyzer was calibrated from gases in cylinders which were measured by the method of Scholander. This method is accurate to ±0.01% if used correctly; from repeated measures of the calibration gases it would be reasonable to set the 99% confidence limits at ±0.05%. This would account, at least in part, for lack of

homogenity in the gas mixture in the cylinder but not for systematic errors in the use of the Scholander Method.

(b) The length of the recording on the oxygen analyzer could be read to ± 1/2 unit on a 100 unit scale. However, the possible error must be set somewhat wider, around ± 2 units, to allow for difficulty in assessing the base line reading which showed some instability. Other possible sources of error in using the analyzer might have been a non-linear response to the recorder and a shifting sensitivity. The latter problem was alleviated by calibrating the analyzer everytime gas analysis was made. The former problem was not investigated and it was assumed that the analyzer had a linear response over the range of oxygen values measured.

For a recorded oxygen content of 17 per cent in expired air and combining these errors in an additive fashion a percentage error (99% confidence limits) of 8.0 per cent was obtained. Thus, the analysis of the expired gas was a much greater source of error than the measurement of its volume.

Combining the two parameters to obtain the energy cost the maximum possible error was 10.5 per cent for an energy cost of 12 Kcal/min.

Comparison of Statistical and Analytical Assessments of Error

The energy cost for grade walking at 2.9 mph and 18 per cent grade in the pilot study for subject AC was 12.30 ±0.94 Kcal/min. Since there were 6 trials the standard error of the mean was $0.94/\sqrt{6} = \pm 0.38$ Kcal/min.

This means that the "true" value, has a 99 per cent change of being within 2.58 x 0.38 = 0.99 Kcal/min of the sample population mean of 12.30, i.e., in the range 11.31 to 13.29 Kcal/min.

Since the S.D. of the data was 0.94 Kcal/min, 99 per cent of the individual measures of the energy cost should lie within 2.58 x 0.94 = 2.42 Kcal/min of 12.30. This amounts to about 20 per cent of the mean. The analytical approach has assessed the 99 per cent confidence limits for random experimental error as about 10 per cent of the mean. Consequently, the maximum contribution of experimental error to the total random variability in the data is about one-half.

CHAPTER IV

RESULTS

PILOT STUDY

A summary of the results from the pilot study is given in Appendix 3. Each table in this Appendix shows the mean and standard deviation of all variables for all phases of six trials undertaken by one subject. Although the energy cost of grade walking in the ninth and tenth minutes of walking is generally greater than that for the fifth and sixth minutes of walking, an analysis of variance showed that the differences were not significant.[1] In fact, the variance of energy cost for grade walking within trials and between trials were not significantly different and thus these two sources of variability could be attributed to a common source. Consequently, the energy cost of grade walking was measured during the fifth and sixth minutes of exercise in the main series of trials.

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[1] For the purposes of this study the result of a statistical test is said to be:

(a) not significant when the probability of this result occurring by chance exceeds 0.05 ($p>0.05$).

(b) significant, when the probability of this result occurring by chance lies between 0.05 and 0.01 ($0.05>p>0.01$).

(c) very significant, when the probability of this result occurring by chance lies between 0.01 and 0.001 ($0.01>p>0.001$).

(d) highly significant, when the probability of this result occurring by chance is less than 0.001 ($p<0.001$).

MAIN SERIES OF TRIALS

An example of the computer write-out for one testing session of three trials for one subject is given in Appendix 4. The means and standard deviations for heart rate, pulmonary ventilation, respiratory exchange ratio, and energy cost for each phase and for each subject are given in Table V (standing phase), Table VI (horizontal walking phase), Table VII (grade walking phase), and Table VIII (recovery phase).

Heart Rate

Standing heart rate values showed considerable variation from trial to trial and from subject to subject. JM, a well-trained middle-distance runner had the lowest heart rates with a mean and standard deviation of 58.8 ± 7.5. Subjects GP and AT had much higher mean heart rates. GP was a graduate student with numerous commitments and twice he was tested after basketball practice and on both these occasions his heart rate was considerably higher than normal. AT, on the other hand showed an apprehensive tachycardia at the commencement of some testing sessions. On four occasions his heart rate decreased at the start of exercise.

In all subjects the increment in heart rate from the standing phase to walking horizontally was small, usually less than 10 bpm. The highest individual and mean heart rates attained were 164 and 162 respectively for MZ grade walking at 12 per cent grade and 3.65 mph (rate of vertical ascent 2300 ft/hr).

TABLE V

Heart Rate (HR), Pulmonary Ventilation ($\dot{V}_E$), Respiratory Exchange Ratio (R) and Energy Cost (E) for the Standing Phase of all Trials (N=36). The Upper Values are Means and the Lower Values Standard Deviations

Subject	HR	$\dot{V}_E$ ℓ/min	R	E Kcal/min
AC	74.0	11.1	0.79	1.58
	8.4	1.1	0.08	0.27
RH	79.2	10.5	0.81	1.42
	7.5	0.9	0.07	0.19
JM	58.8	11.5	0.80	1.63
	7.5	1.3	0.05	0.32
GP	80.0	11.2	0.88	1.42
	12.5	1.1	0.11	0.28
AT	84.3	10.8	0.77	1.43
	16.0	1.1	0.09	0.27
MZ	88.0	11.6	0.82	1.88
	8.6	1.3	0.08	0.27

TABLE VI

Heart Rate (HR), Pulmonary Ventilation ($\dot{V}_E$), Respiratory Exchange Ratio (R) and Energy Cost (E) for the Horizontal Walking Phase of all Trials (N=36). The Upper Values are Means and the Lower Values Standard Deviations

Subject	HR	$\dot{V}_E$ ℓ/min	R	E Kcal/min
AC	78.8	18.7	0.77	3.58
	8.5	4.4	0.08	1.05
RH	86.7	19.6	0.79	3.47
	7.1	2.7	0.11	0.77
JM	70.3	20.6	0.77	3.53
	8.2	3.4	0.06	0.84
GP	83.6	21.7	0.81	3.78
	10.2	3.9	0.09	0.83
AT	90.5	20.7	0.78	3.58
	9.3	3.3	0.09	0.88
MZ	93.1	21.1	0.79	4.37
	11.3	3.9	0.07	1.03

TABLE VII

Heart Rate (HR), Pulmonary Ventilation ($\dot{V}_E$), Respiratory Exchange Ratio (R) and Energy Cost (E) for the Grade Walking Phase of all Trials (N=36). The Upper Values are Means and the Lower Values Standard Deviations

Subject	HR	$\dot{V}_E$ ℓ/min	R	E Kcal/min
AC	111.1	40.1	0.79	8.83
	14.0	9.4	0.07	1.96
RH	128.8	42.0	0.85	8.81
	18.2	10.1	0.08	1.89
JM	109.4	40.0	0.76	8.30
	11.0	7.6	0.06	1.91
GP	116.9	42.9	0.86	9.09
	12.9	9.9	0.09	2.07
AT	133.3	45.3	0.80	8.97
	14.0	9.1	0.06	2.00
MZ	130.1	44.1	0.81	11.44
	15.2	10.7	0.06	3.12

TABLE VIII

Heart Rate (HR), Pulmonary Ventilation ($\dot{V}_E$), Respiratory Exchange Ratio (R) and Energy Cost (E) for the Recovery Phase of all Trials (N=36). The Upper Values are Means and the Lower Values Standard Deviations

Subject	HR	$\dot{V}_E$ ℓ/min	R	E Kcal/min
AC	80.3	16.7	0.89	2.97
		2.1	0.10	0.37
RH	90.7	15.4	0.89	2.78
		2.7	0.08	0.41
JM	68.3	15.6	0.81	2.68
		1.4	0.05	0.37
GP	86.7	16.6	0.92	2.74
		1.8	0.14	0.47
AT	105.8	16.4	0.86	2.79
		2.0	0.08	0.41
MZ	98.5	17.3	0.91	3.61
		2.7	0.08	0.75

Pulmonary Ventilation and Respiratory Exchange Ratio

Pulmonary ventilation was much more uniform from subject to subject than was heart rate. The highest individual and mean ventilations attained were 72.2 and 69.9 ℓ/min respectively for MZ at 12% grade and 3.65 mph.

Figures 1a to 1f show the changes in the respiratory exchange ratio (R) from phase to phase of the trials for each subject. Two basic patterns emerged:

1. The more common pattern (AC, RH, GP, MZ) was a drop in R at the start of exercise, followed by an increase throughout grade walking to reach a maximal, though not very high value, in recovery. JM showed a further decrease in R during grade walking but a return to higher values in recovery.
2. AT showed a slight but steady increase in R through all phases of the testing.

Two similar patterns were noted by the author in a previous study of grade walking with two women as subjects (26). It would probably be unwise to interpret too much from these patterns of R for, as Kleiber (15) has pointed out, R's measured over a period of a few minutes are unreliable indices of metabolism in man because of the influence of washout or retention of CO_2 and $)_2$ debt.

Oxygen Uptake and Energy Expenditure

Oxygen uptake and energy expenditure are often used synonymously to indicate the level of activity or metabolism. In the strictest sense the two are not interchangeable since the energy liberated by one volume

FIGURES 1a to 1f

Changes in the Respiratory Exchange ratio (R) from Phase to Phase of all Trials for each Subject. Phases were Standing (S), Horizontal Walking (H), Grade Walking (G) and Recovery (R). Means ± S.D.

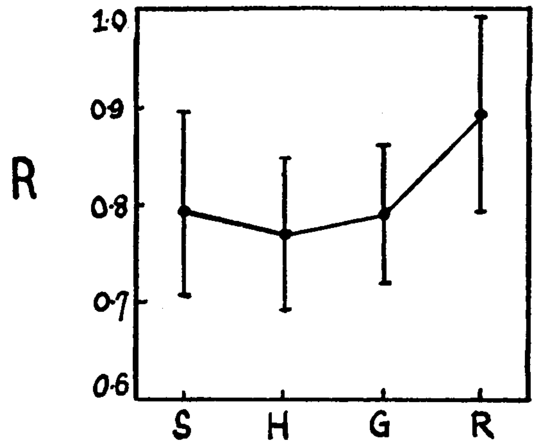


FIG. 1a SUBJECT AC

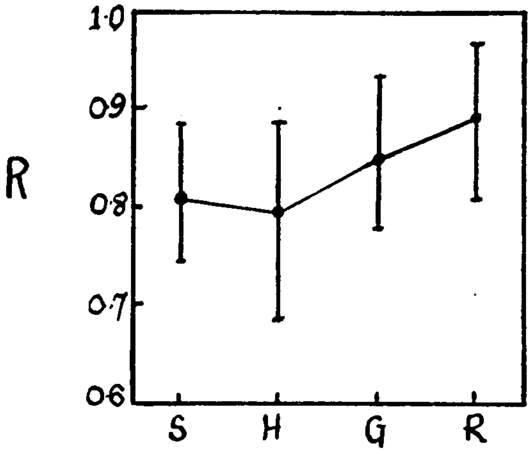


FIG. 1b SUBJECT RH

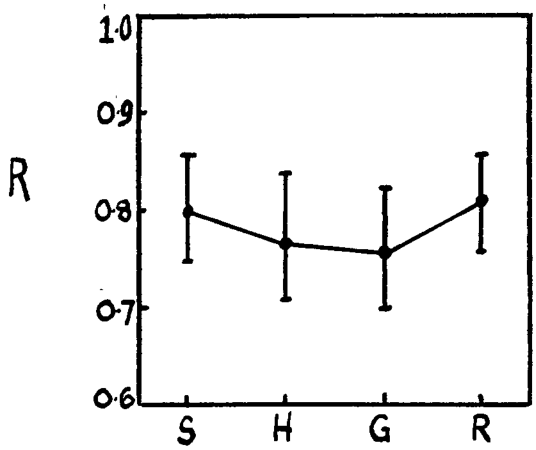


FIG. 1c SUBJECT JM

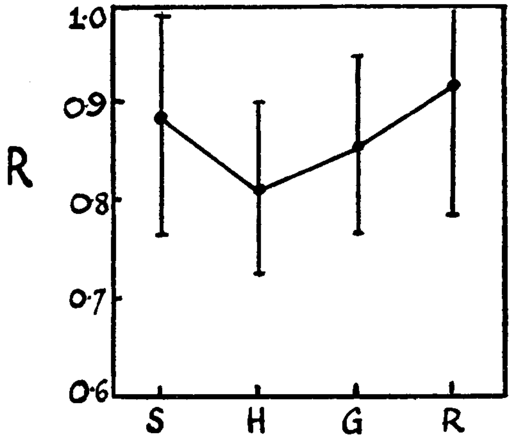


FIG. 1d SUBJECT GP

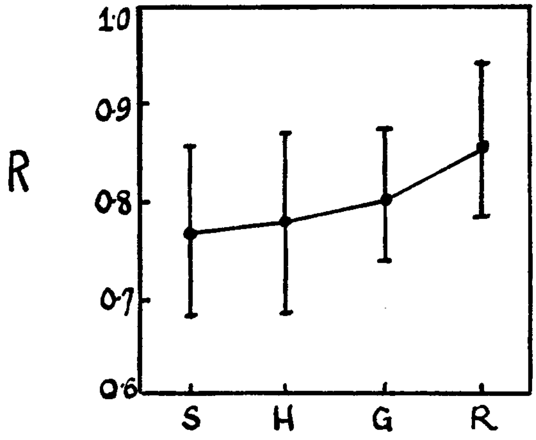


FIG. 1e SUBJECT AT

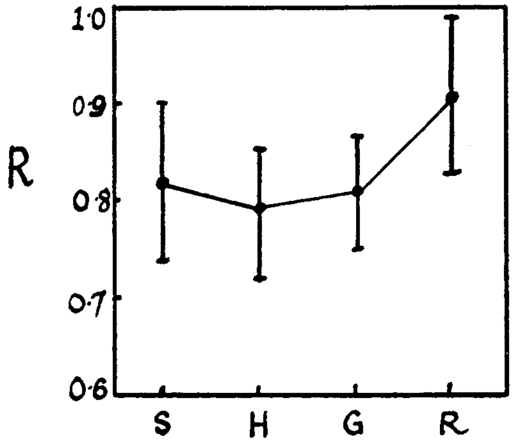


FIG. 1f SUBJECT MZ

of O_2 depends on the fuel being metabolised. For normal diets a frequently quoted energy equivalent for one litre of O_2 is 5 Kcal. In this investigation, using Weir's formula, the kilocaloric value of one litre of O_2 is not constant but varies around 4.8. Maximum energy is liberated by one litre of O_2 when the fuel substrate is carbohydrate. Maximum individual and mean oxygen uptakes ($\dot{V}_{O_2}$) were 4.16 and 4.07 ℓ/min respectively attained by MZ walking at 3.65 mph and 12% grade; these values were equivalent to energy costs of 20.02 and 19.51 Kcal/min (energy equivalents of 4.81 and 4.80 Kcal/l). Because of the high correlation between heart rate and oxygen uptake it was possible to make reasonable estimates of maximum oxygen uptake ($\dot{V}_{O_2}$ max) based on a maximum heart rate of 185 and assuming a completely linear relationship between heart rate and oxygen uptake (Table IX). The standard errors

TABLE IX

Maximum Oxygen Uptakes Estimated from the Linear Regression of Oxygen Uptake on Heart Rate, and Based on a Maximum Heart Rate of 185

Subject	Maximum Oxygen Uptake ℓ/min	 mℓ/kg/min
AC	3.85	50
RH	3.01	39
JM	4.39	62
GP	3.97	51
AT	3.17	41
MZ	4.64	48

of estimate for these regressions are 0.2 l/min. Apart from the validity of assuming a uniform maximal heart rate for all individuals these estimates probably err because, as shown by Maritz *et al.* (19) the relationship between heart rate and oxygen uptake is non-linear near maximal values.

Efficiency of Grade Walking

The complete data for three measures of efficiency are given in Appendix 5 (GE), Appendix 6 (NES) and Appendix 7 (NEH).

Gross Efficiency

The mean gross efficiency over all trials was 19.66 ± 1.92%. A summary of the analysis of variance of the gross efficiencies is given in Table X. The first order interaction between rate of vertical ascent and grade was found to be significant and this is shown graphically in Figure 2. Figures 3, 4, 5 and 6 show the effect of rate of vertical ascent, grade, replication and subject respectively on gross efficiency; the first two effects were highly significant, the replication effect very significant while the subject effect was not significant.

Net Efficiency (NES), Incorporating a Deduction for Standing Metabolism

The mean efficiency over all trials was 23.95 ± 2.65%. A summary of the analysis of variance of this measure of efficiency is given in Table XI. Two main factors were found to be significant; rate of vertical ascent at the 0.01 level and grade at the 0.001 level. These two effects are shown graphically in Figures 7 and 8.

TABLE X

Summary of the Analysis of Variance of Gross Efficiencies using an Additive Model with Pooling of Subject Interactions

Factors are rate of vertical ascent (V), grade (G), individual replications (R) and subject (S).

Nature of Effect	Source	Sum of Squares	Degree of Freedom	Variance Estimates	F Ratios
Main factors and subjects	V	67.50	2	33.75	17.14***
	G	284.94	3	94.98	48.24***
	R	22.06	2	11.03	5.60**
	S	8.00	5	1.60	-
Interactions between pairs of factors	VG	32.94	6	5.49	2.79*
	VR	9.00	4	2.25	1.14
	GR	11.69	6	1.95	-
Interaction of 3 factors	VGR	12.75	12	1.06	-
Residual		344.50	175	1.97	
Total		793.38	215	3.69	

* 0.05>p>0.01

** 0.01>p>0.001

*** p<0.001

FIGURE 2

Gross Efficiency by Rate of Vertical Ascent (V) and Grade (G). Means (±SD) are for all Replications and Subjects.

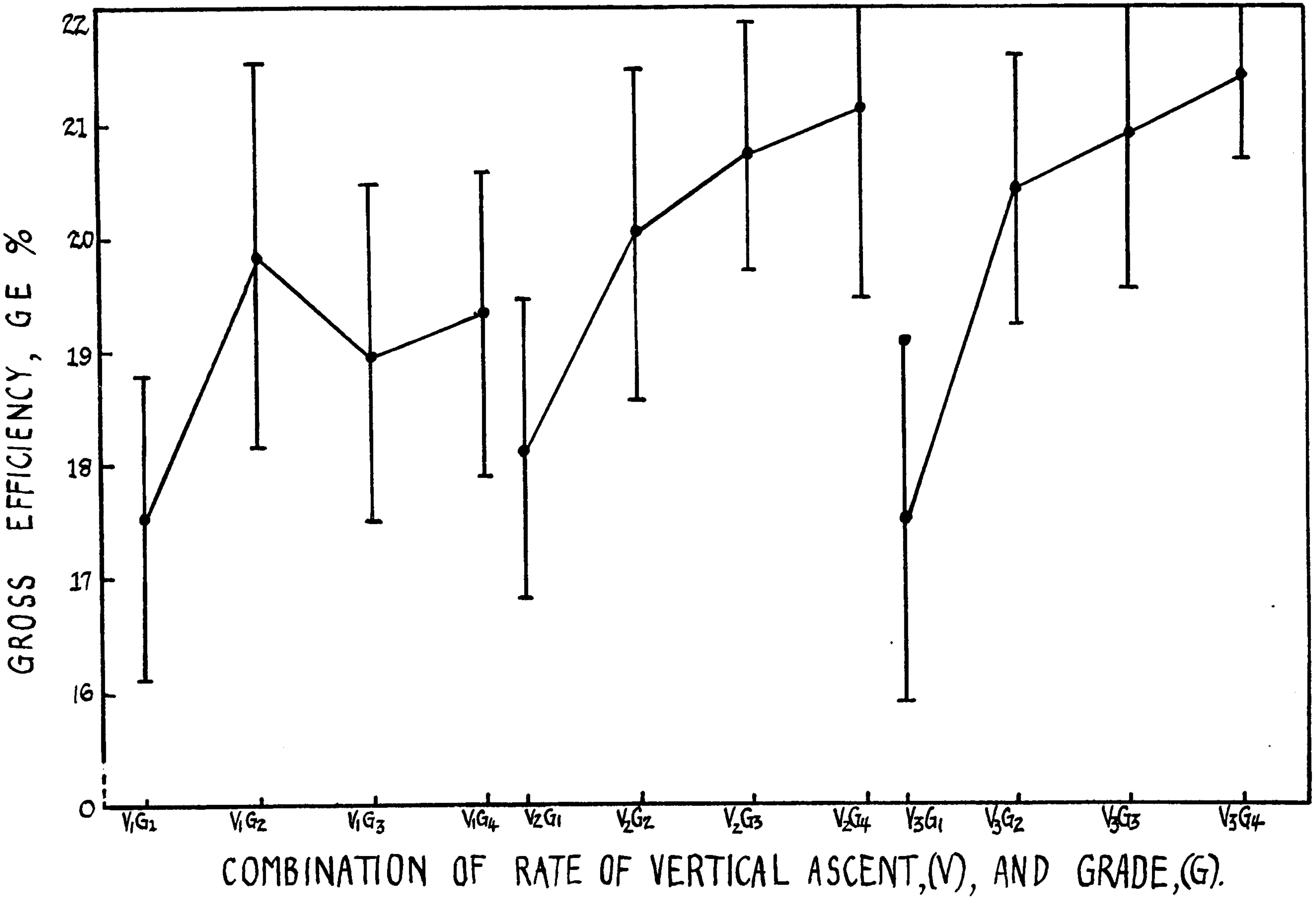

GROSS EFFICIENCY, GE %
22
21
20
19
18
17
16
0
V_1G_1
V_1G_2
V_1G_3
V_1G_4
V_2G_1
V_2G_2
V_2G_3
V_2G_4
V_3G_1
V_3G_2
V_3G_3
V_3G_4
COMBINATION OF RATE OF VERTICAL ASCENT,(V), AND GRADE,(G).

FIGURE 3

Gross Efficiency by Rate of Vertical Ascent (V). Means (±SD) are for all Grades, Replications and Subjects.

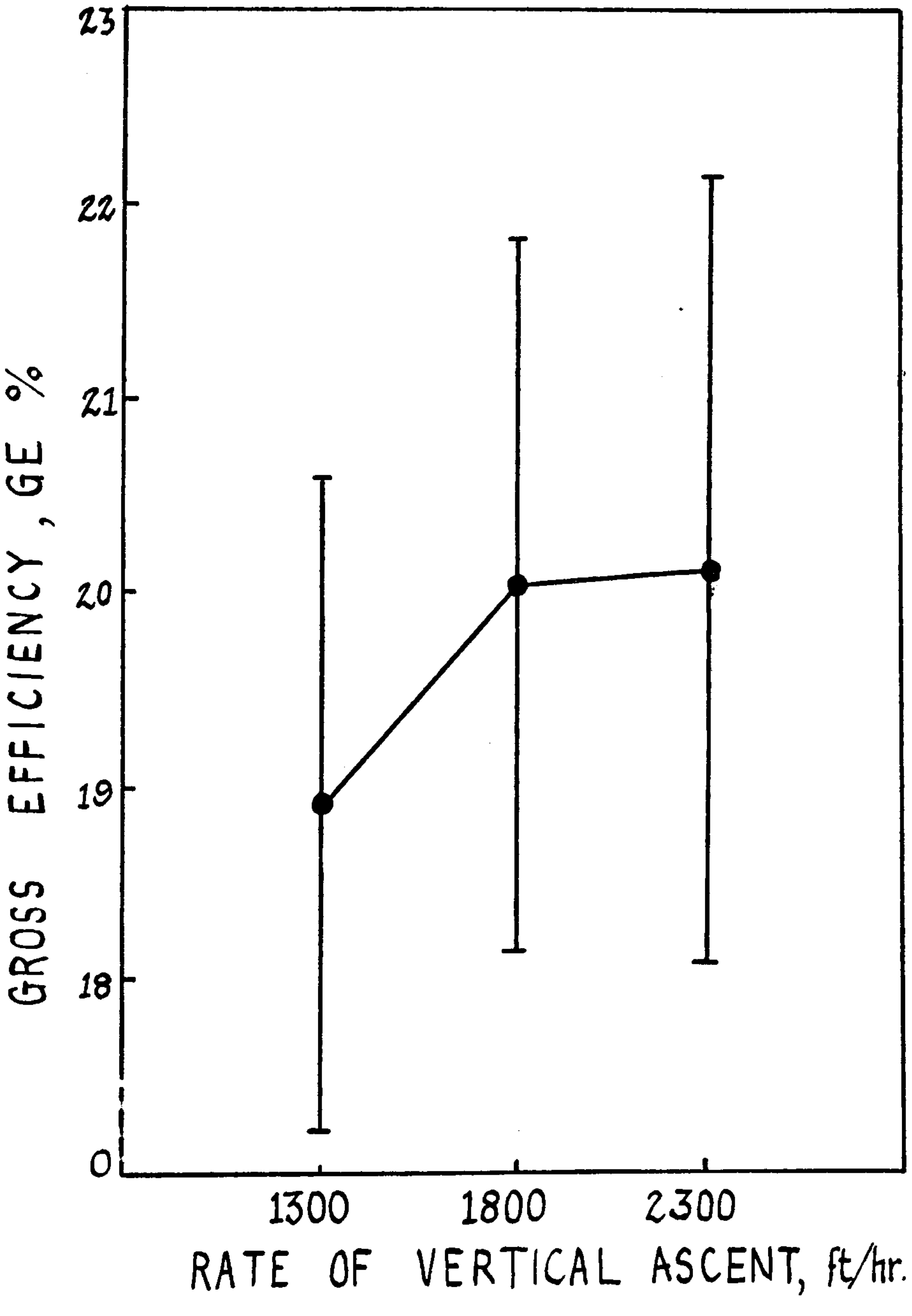

23
22
21
20
19
18
0
GROSS EFFICIENCY, GE %
1300
1800
2300
RATE OF VERTICAL ASCENT, ft/hr.

FIGURE 4

Gross Efficiency by Grade (G). Means (±SD) are for all Rates of Vertical Ascent, Replications and Subjects.

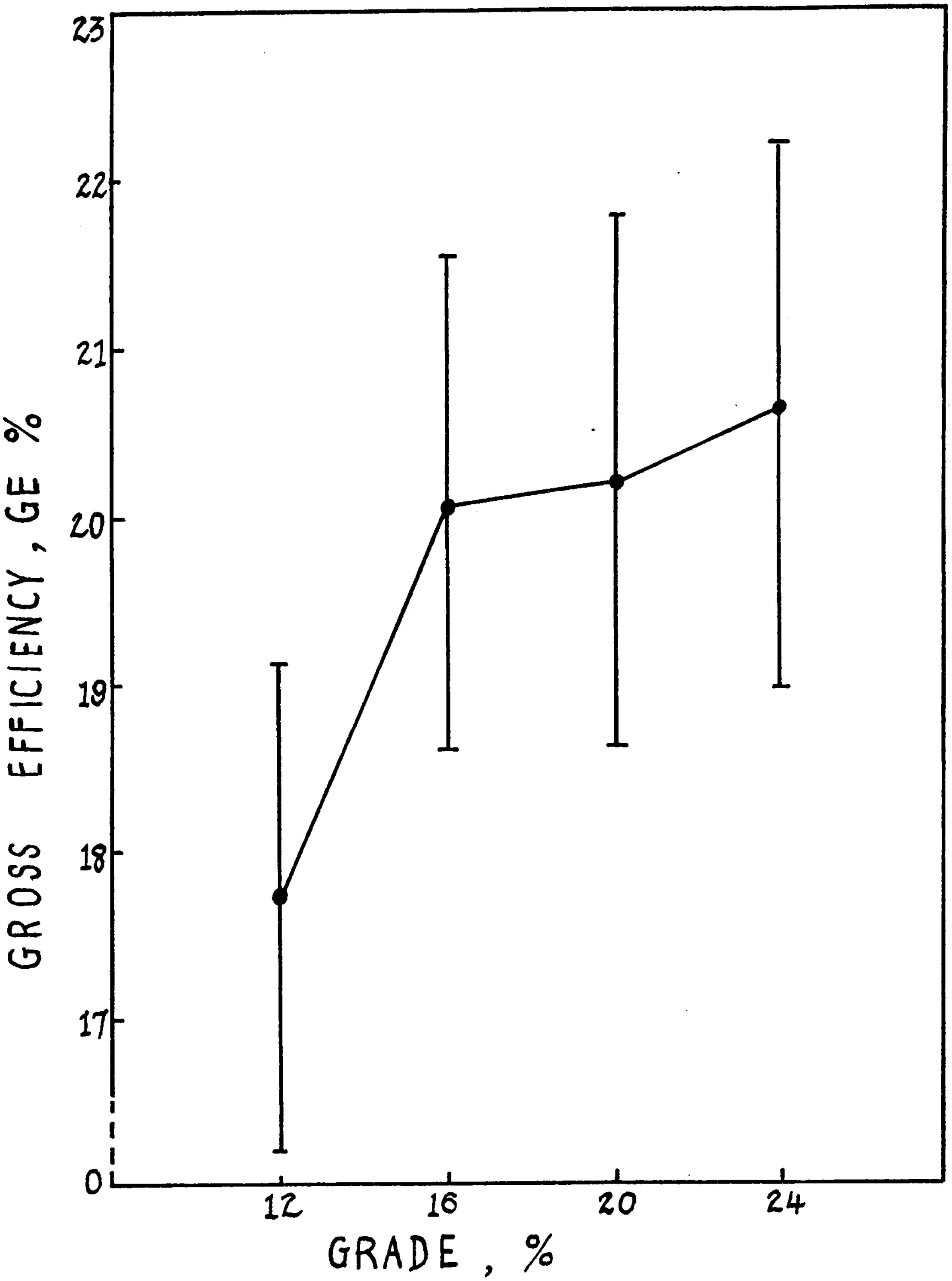

23
22
21
20
19
18
17
0
GROSS EFFICIENCY, GE %
12
16
20
24
GRADE, %

FIGURE 5

Gross Efficiency by Replication (R).
Means (±SD) are for all Rates of
Vertical Ascent, Grades and Subjects.

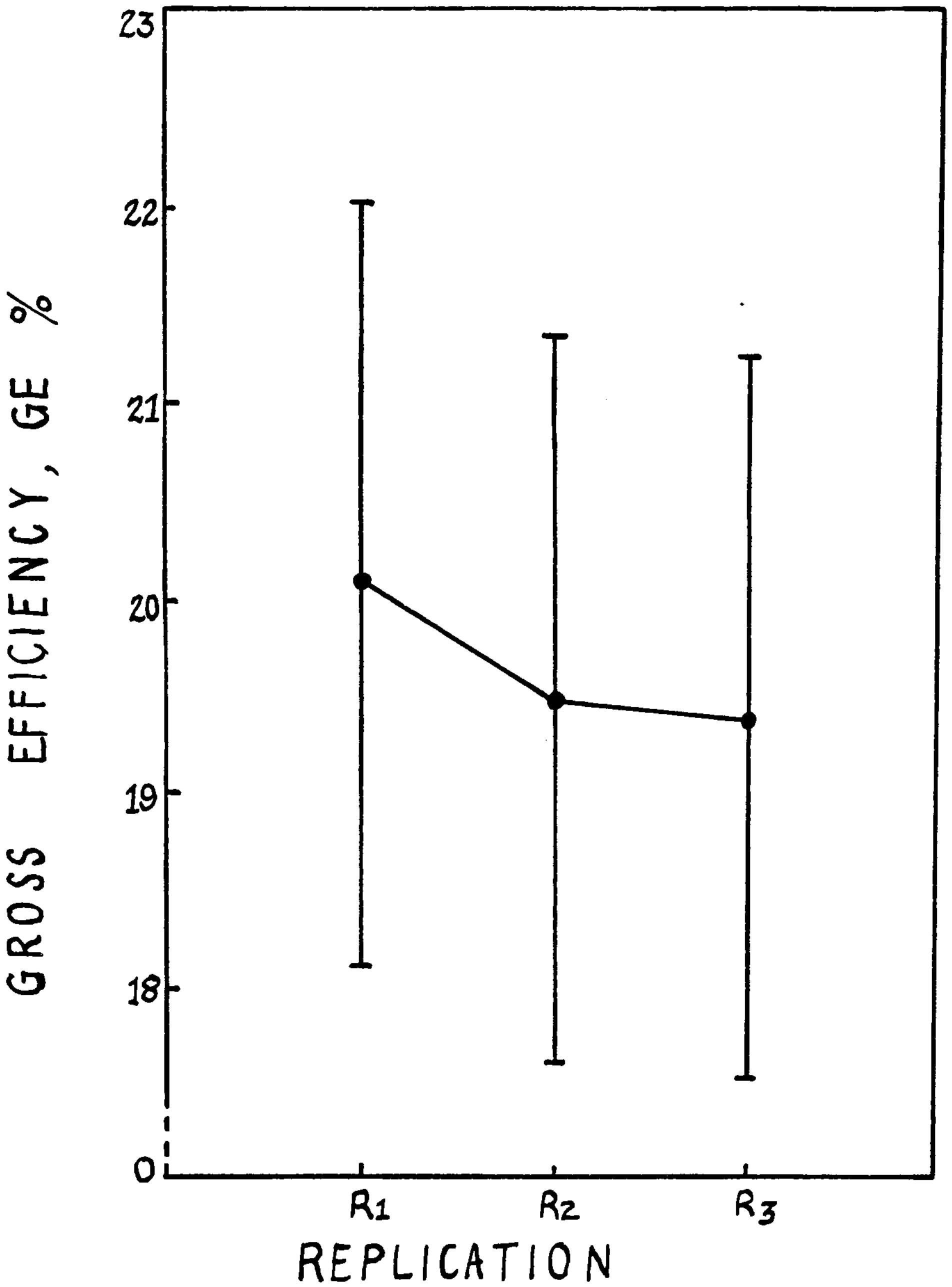

GROSS EFFICIENCY, GE %
23
22
21
20
19
18
0
R1
R2
R3
REPLICATION

FIGURE 6

Gross Efficiency by Subject. Means (±SD) are for all Rates of Vertical Ascent, Grades and Replications.

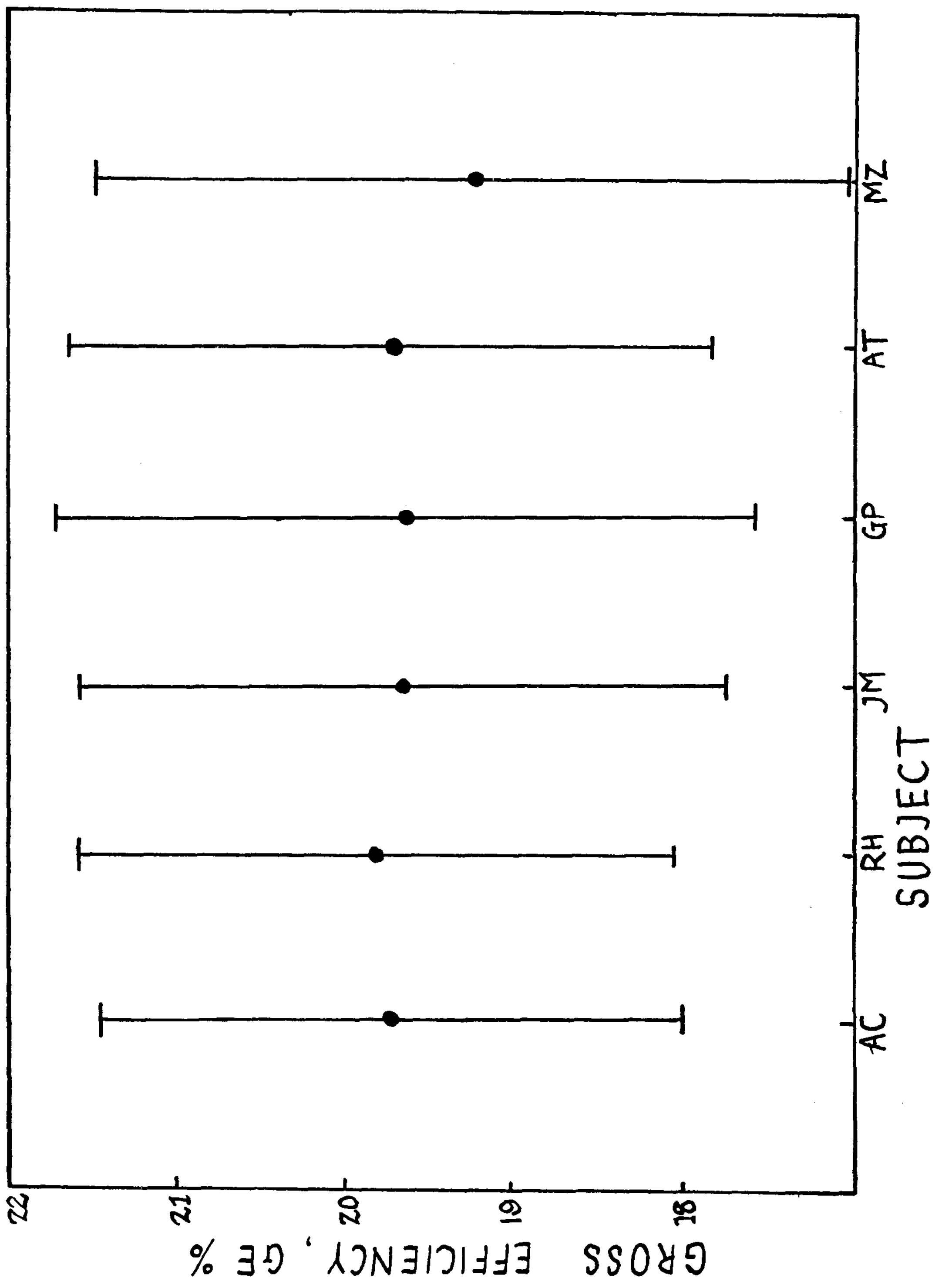

GROSS EFFICIENCY, GE %
22
21
20
19
18
SUBJECT
AC
RH
JM
GP
AT
MZ

TABLE XI

Summary of the Analysis of Variance of Net Efficiency, (NES), Incorporating a Deduction for the Metabolism of Standing, Using an Additive Model with Pooling of Subject Interactions

Factors are rate of vertical ascent (V), grade (G), individual replications (R) and subject (S).

Nature of Effect	Source	Sum of Squares	Degrees of Freedom	Variance Estimates	F Ratios
Main factors and	V	56.31	2	28.16	6.63**
subjects	G	556.38	3	185.46	43.68***
	R	8.50	2	4.25	-
	S	47.63	5	9.53	2.24
Interactions	VG	28.31	6	4.72	
between pairs	VR	14.81	4	3.70	
of factors	GR	23.75	6	3.96	
Interaction of 3 factors	VGR	30.63	12	2.55	
Residual		743.00	175	4.25	
Total		1509.31	215	7.02	

* $0.05>p>0.01$

** $0.01>p>0.001$

*** $p<0.001$

FIGURE 7

Net Efficiency (NES), Incorporating a Deduction for Standing Metabolism, Versus Rate of Vertical Ascent. Means (±SD) are for all Grades, Replications and Subjects.

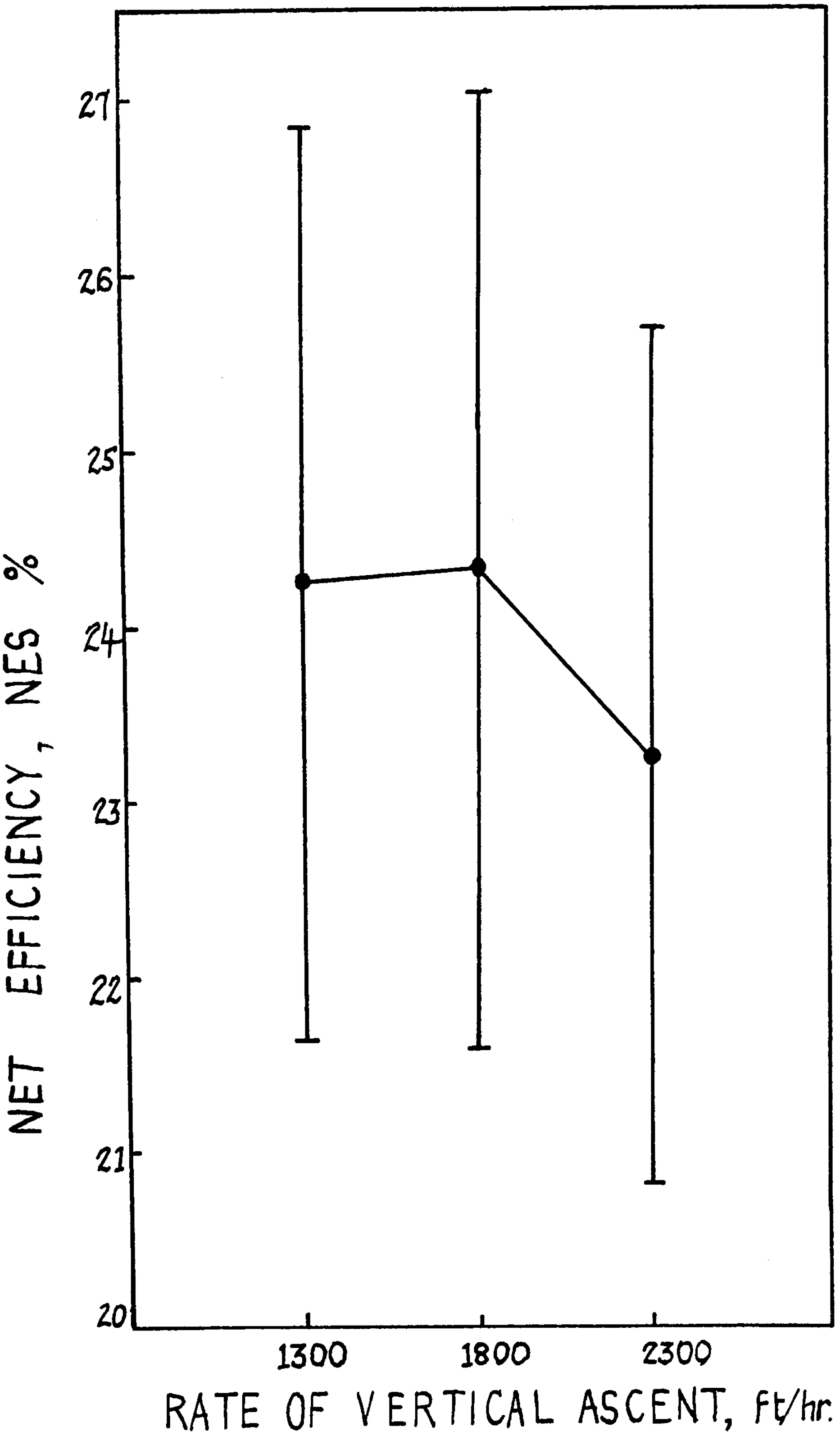
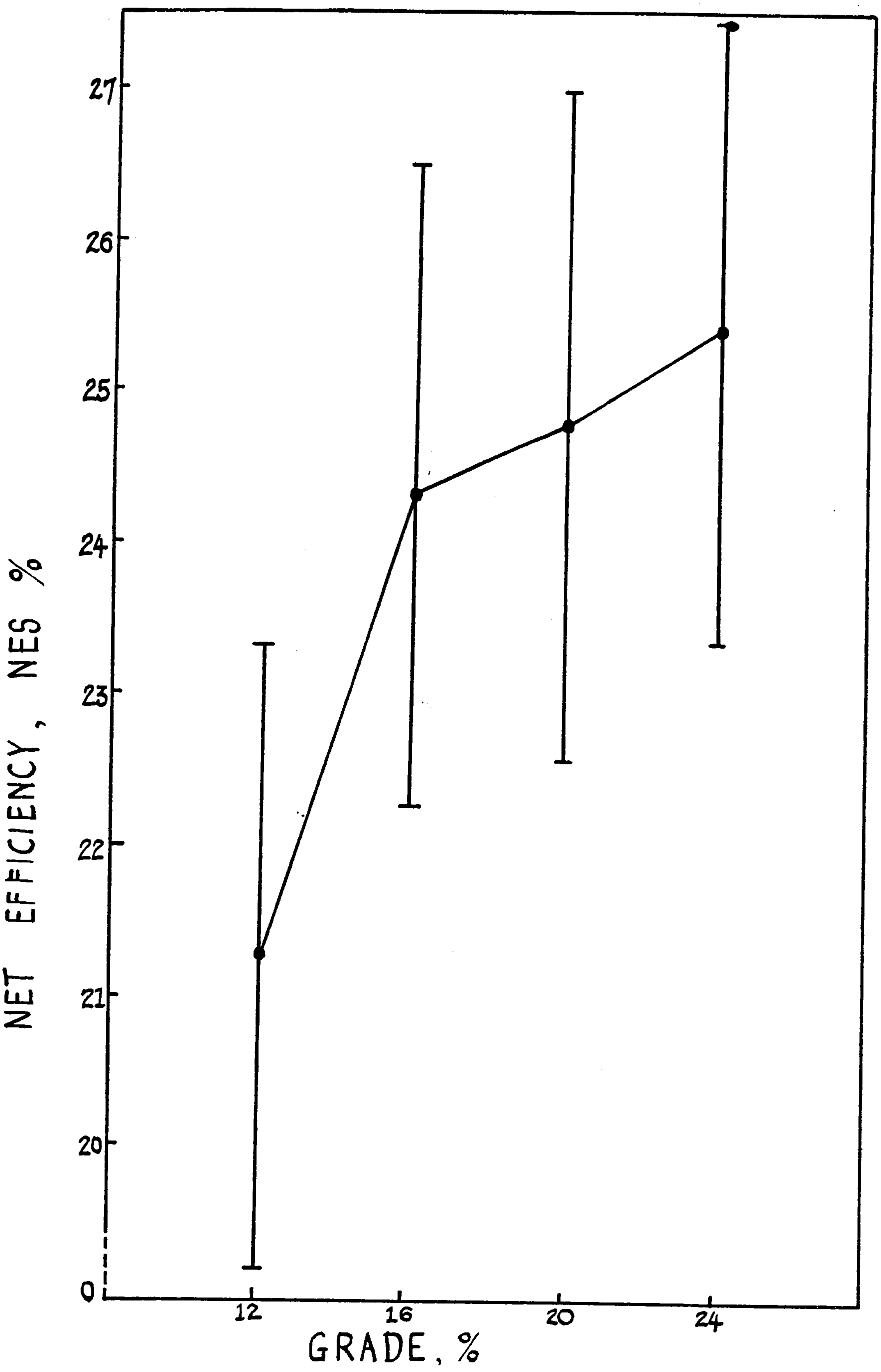

27
26
25
24
23
22
21
20
NET EFFICIENCY, NES %
1300
1800
2300
RATE OF VERTICAL ASCENT, Ft/hr.

FIGURE 8

Net Efficiency (NES), Incorporating a Deduction for Standing Metabolism, Versus Grade. Means (±SD) are for all Rates of Vertical Ascent, Replications and Subjects.


NET EFFICIENCY, NES %
27
26
25
24
23
22
21
20
0
12
16
20
24
GRADE, %

Net Efficiency (NEH), Incorporating a Deduction for the Energy cost of Horizontal Walking

The mean efficiency over all trials was 33.73 ± 4.87%. A summary of the analysis of variance of this measure of efficiency is given in Table XII. The only factor found to be significant was the rate of vertical ascent (at the 1.01 level) and this effect is shown in Figure 9.

It will be noted that the standard deviations of the three measures of efficiency increase markedly in the order GE, NES, NEH. This increased variability reflects the increased relative uncertainty introduced whenever the difference of two variables is involved. When one variable, z, in a computation is calculated as the difference of two other variables x and y, the error in z, δz, is given by,

$$\delta z = \delta x + \delta y$$

and the relative uncertainty z/Z by,

$$\frac{\delta z}{Z} = \frac{\delta x + \delta y}{x - y}$$

where δx and δy are the errors in x and y. Thus it can be seen that the closer the values of x and y (as with the energy cost of grade walking and horizontal walking) the greater is the relative uncertainty—and hence the greater the variability of the data.

TABLE XII

Summary of the Analysis of Variance of Net Efficiency, (NEH), Incorporating a Deduction for the Energy Cost of Horizontal Walking, Using an Additive Model with Pooling of Subject Interactions

Factors are rate of vertical ascent (V), grade (G), individual replications (R) and subject (S).

Nature of Effect	Source	Sum of Squares	Degrees of Freedom	Variance Estimates	F Ratios
Main factors and	V	392.06	2	196.03	9.23**
subjects	G	121.06	3	40.35	1.90
	R	48.25	2	24.13	1.14
	S	210.00	5	42.00	1.98
Interactions	VG	186.13	6	31.02	1.46
between pairs	VR	132.25	4	33.06	1.56
of factors	GR	175.63	6	29.27	1.38
Interaction of 3 factors	VGR	126.69	12	10.56	
Residual		3716.88	175	21.24	
Total		5108.94	215	23.76	

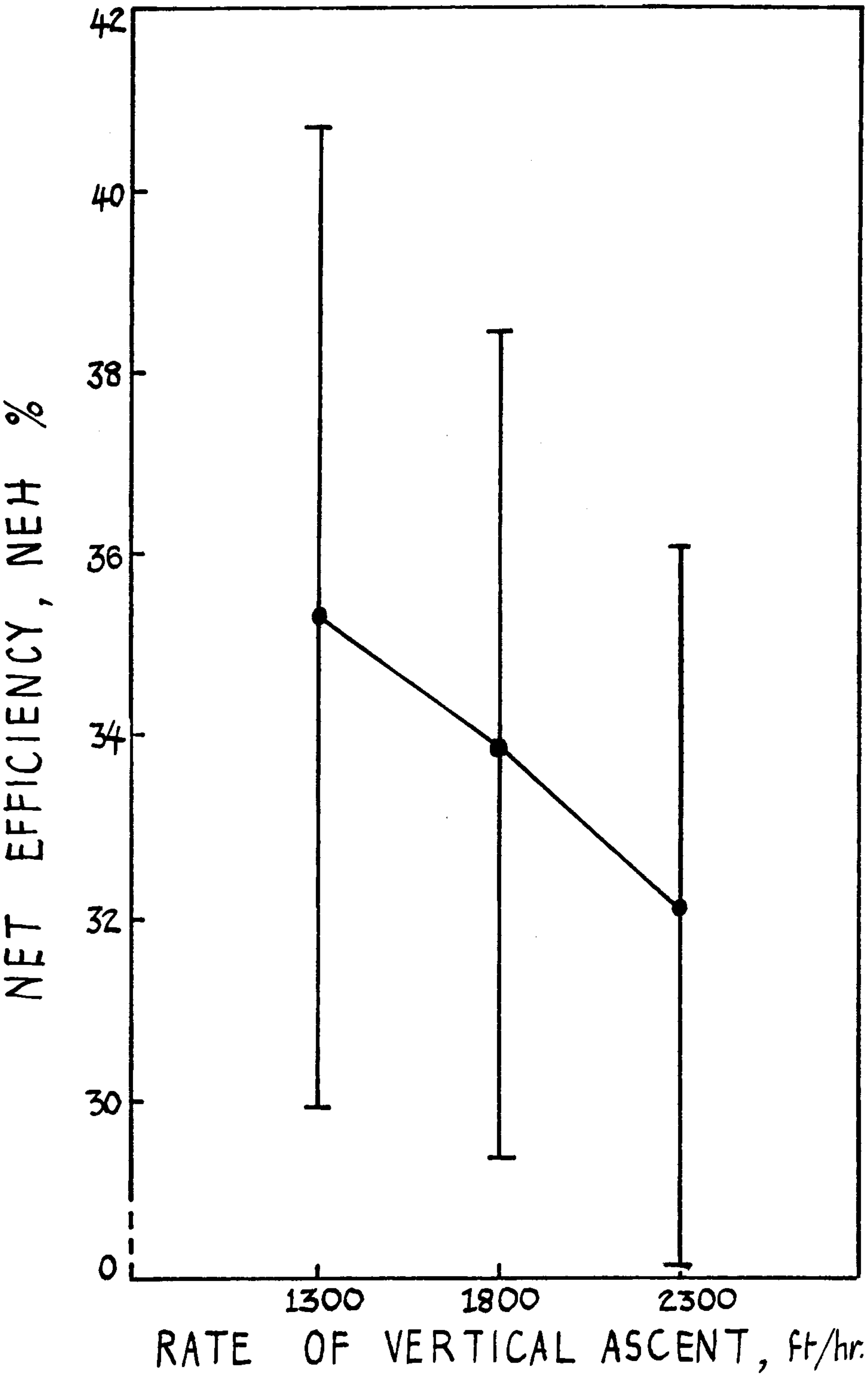
* 0.05>p>0.01

** 0.01>p>0.001

*** p<0.001

FIGURE 9

Net Efficiency (NEH), Incorporating a Deduction for Horizontal Walking, Versus Rate of Vertical Ascent. Means (±SD) are for all Grades, Replications and Subjects.


NET EFFICIENCY, NEH %
42
40
38
36
34
32
30
0
1300
1800
2300
RATE OF VERTICAL ASCENT, ft/hr.

CHAPTER V

INTERPRETATIONS OF RESULTS AND DISCUSSION

HEART RATE AND PULMONARY VENTILATION AS PREDICTORS OF ENERGY COST AND PHYSICAL WORK CAPACITY

Heart Rate and Physical Work Capacity

Heart rate correlated well with work rate for individual subjects and regression equations were calculated to enable estimates of the physical work capacity at a heart rate of 170 (PWC_{170}) to be made (Table XIII).

TABLE XIII

The Correlation Coefficient (r), Regression Equation (W_R = a HR + b) and estimated PWC_{170} (±SD) for the Regression of Work Rate (WR) in kgm/min on Heart Rate (HR)

Subject	r*	Regression Equation	PWC_{170} kgm/min
AC	0.990	$W_R = 13.31\ HR - 74.0$	1518 ± 29
RH	0.998	$W_R = 10.30\ HR - 581.2$	1170 ± 10
JM	0.991	$W_R = 14.64\ HR - 917.0$	1572 ± 22
GP	0.991	$W_R = 14.91\ HR - 983.9$	1551 ± 24
AT	0.9995	$W_R = 12.37\ HR - 887.5$	1216 ± 5
MZ	0.9996	$W_R = 15.48\ HR - 1094.4$	1537 ± 6

* $p<0.01$

Heart Rate as a Predictor of Energy Cost

Absolute heart rate and incremental heart rate (working heart rate--resting heart rate) both proved to be relatively poor predictors of the energy cost of horizontal walking. This could be attributed to

(a) the relative instability of resting heart rate from one testing session to the next

(b) the small increment in heart rate when proceeding from rest to horizontal walking.

In the case of grade walking correlations between absolute heart rate and energy cost and incremental heart rate and energy cost were much higher and the predictive properties of the relationships considerably improved. This was due to the much larger increments in heart rate when proceeding from the resting phase to the grade walking phase. Absolute heart rate was the better predictor of energy cost of the two parameters and the correlation coefficients, regression equations and standard errors of estimate for the regression of energy cost of grade walking on the mean heart rate for each trial are given in Table XIV. The data, given for each individual and for the group, indicates that group treatment leads to some loss of predictive precision.

Andrews (1) and Datta and Ramanathan (7) have used several different work tasks to investigate the value of these relationships for energy expenditures. Andrews found that substituting linear regression equations, individually computed for each subject, for respiratory calorimetry increased the average standard deviation of individual assessments by about 50 per cent, from 0.37 to 0.55 Kcal/min. In this

TABLE XIV

The Correlation Coefficient (r), Regression Equation (E_G = aHR + b) and Standard Error of Estimate (S) for the Regression of Energy Cost of Grade Walking (E_G) in Kcal/min on Mean Heart Rate (HR) for each Subject and for the Group

Subject	r*	Regression Equation	S Kcal/min
AC	0.90	$E_G = 0.125\ HR - 5.11$	0.85
RH	0.91	$E_G = 0.095\ HR - 3.38$	0.78
JM	0.94	$E_G = 0.164\ HR - 9.58$	0.64
GP	0.87	$E_G = 0.140\ HR - 7.30$	1.01
AT	0.81	$E_G = 0.115\ HR - 6.34$	1.17
MZ	0.92	$E_G = 0.189\ HR - 13.18$	1.20
All Subjects	0.80	$E_G = 0.111\ HR - 4.31$	1.44

* $p<0.001$

investigation the increase was more in the order of 70 per cent, from 0.55 to 0.94 Kcal/min. For regression equations based on grouped subjects but homogenous tasks the variation was about twice the inherent variation of individual assessments made under laboratory conditions with respiratory calorimetry. Andrews concluded that the regression method appears most suitable for field studies in which the rate of energy expenditure of large numbers of workers are to be estimated.

Pulamonary Ventilation as a Predictor of Energy Cost

Pulmonary ventilation correlated highly with the energy cost of both horizontal and grade walking and the regression data for both individual subjects and grouped subjects is given in Table XV. A typical regression line for one subject is shown in Figure 10. It will be noted:

(a) that the correlations were higher for grade walking than for horizontal walking.

(b) that some predictive precision is lost when regression equations are calculated for grouped subjects.

(c) that the correlations are higher and the standard errors of estimate lower than for the corresponding regressions between energy cost and heart rate.

(d) that there is no significant pattern to the difference between regression lines for the horizontal and grade walking. For the grouped subjects the slopes of the lines are almost identical (Figure 11), though the intercept on the ordinate is less for horizontal walking, leading to slightly lower estimates of energy cost for horizontal walking at all levels of ventilation observed in this study.

Datta and Ramanthan also investigated the predictive properties of pulmonary ventilation. They obtained an average correlation coefficient of 0.90 for energy cost of stair climbing and pulmonary ventilation and a simple relation, $E = 0.210\ \dot{V}_E$, which they claimed fitted data from

TABLE XV

The Correlation Coefficient (r), Regression Equation ($E = a\,\dot{V}_E + b$) and Standard Error of Estimate (S) for the Regression of (a) Energy Cost of Horizontal Walking (E_H) in Kcal/min and (b) Energy Cost of Grade Walking (E_G) in Kcal/min on Pulmonary Ventilation ($\dot{V}_E$) in l/min for Each Subject and for the Group

Subject	r*	Regression Equation	S Kcal/min
AC	0.94	$E_H = 0.221\ \dot{V}_E - 0.55$	0.37
	0.96	$E_G = 0.198\ \dot{V}_E + 0.88$	0.54
RH	0.89	$E_H = 0.254\ \dot{V}_E - 1.52$	0.35
	0.91	$E_G = 0.171\ \dot{V}_E + 1.65$	0.77
JM	0.93	$E_H = 0.227\ \dot{V}_E - 1.16$	0.31
	0.96	$E_G = 0.243\ \dot{V}_E - 1.42$	0.53
GP	0.85	$E_H = 0.194\ \dot{V}_E - 0.44$	0.47
	0.96	$E_G = 0.200\ \dot{V}_E + 0.49$	0.61
AT	0.89	$E_H = 0.228\ \dot{V}_E - 1.16$	0.39
	0.96	$E_G = 0.210\ \dot{V}_E - 0.55$	0.59
MZ	0.92	$E_H = 0.241\ \dot{V}_E - 0.73$	0.41
	0.98	$E_G = 0.287\ \dot{V}_E - 1.22$	0.65
All Subjects	0.90	$E_H = 0.219\ \dot{V}_E - 0.77$	0.39
	0.90	$E_G = 0.215\ \dot{V}_E - 0.12$	1.04

* $p<0.001$

FIGURE 10

The Regression Lines for Energy Cost of (1) Grade Walking (Unbroken Line) and (2) Horizontal Walking (Dot-Dash Line) on Ventilation for One Subject (JM). The Individual Values (Dots) and Standard Error of Estimate (Broken Lines) are for the Grade Walking-Ventilation Relationship.

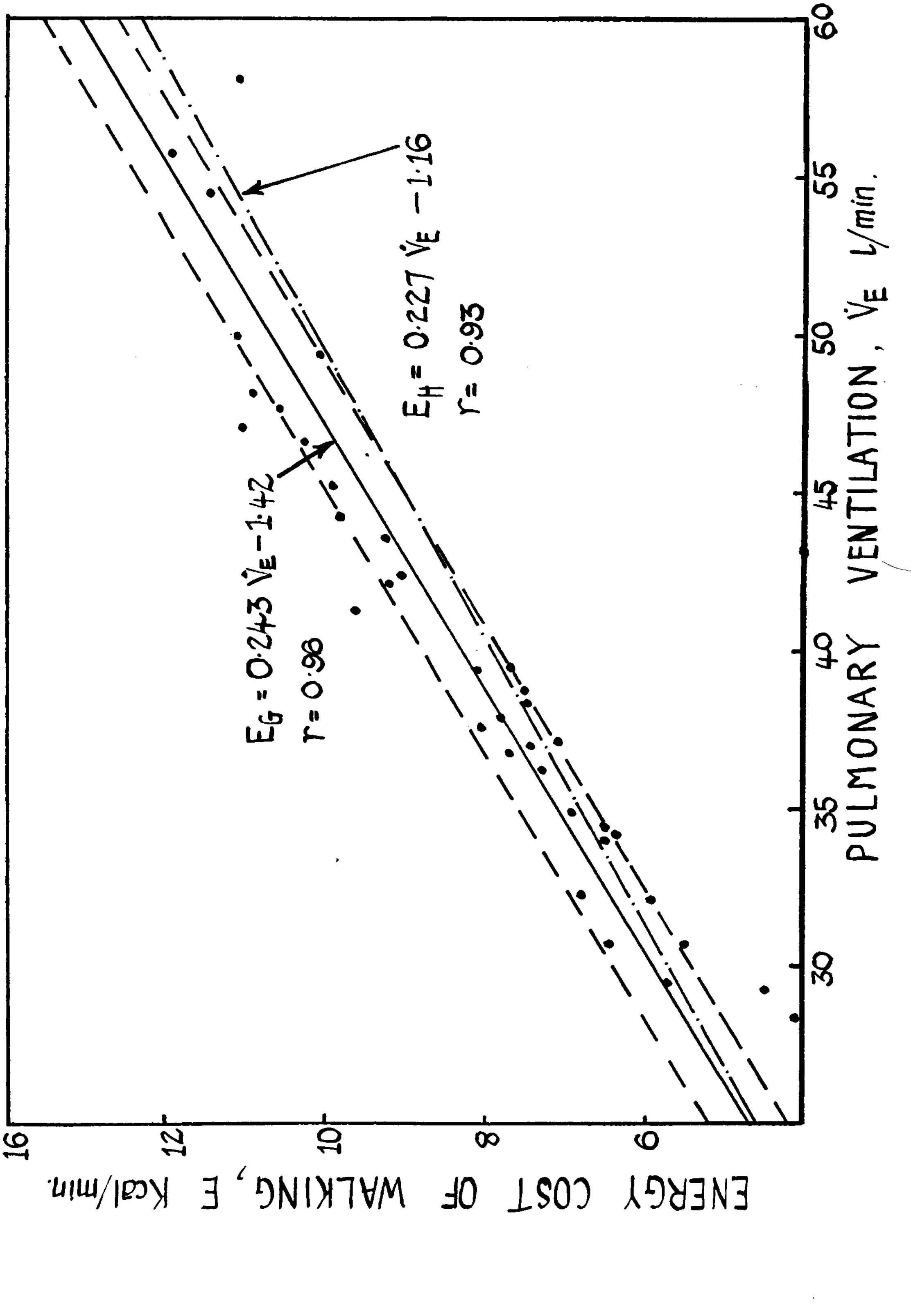
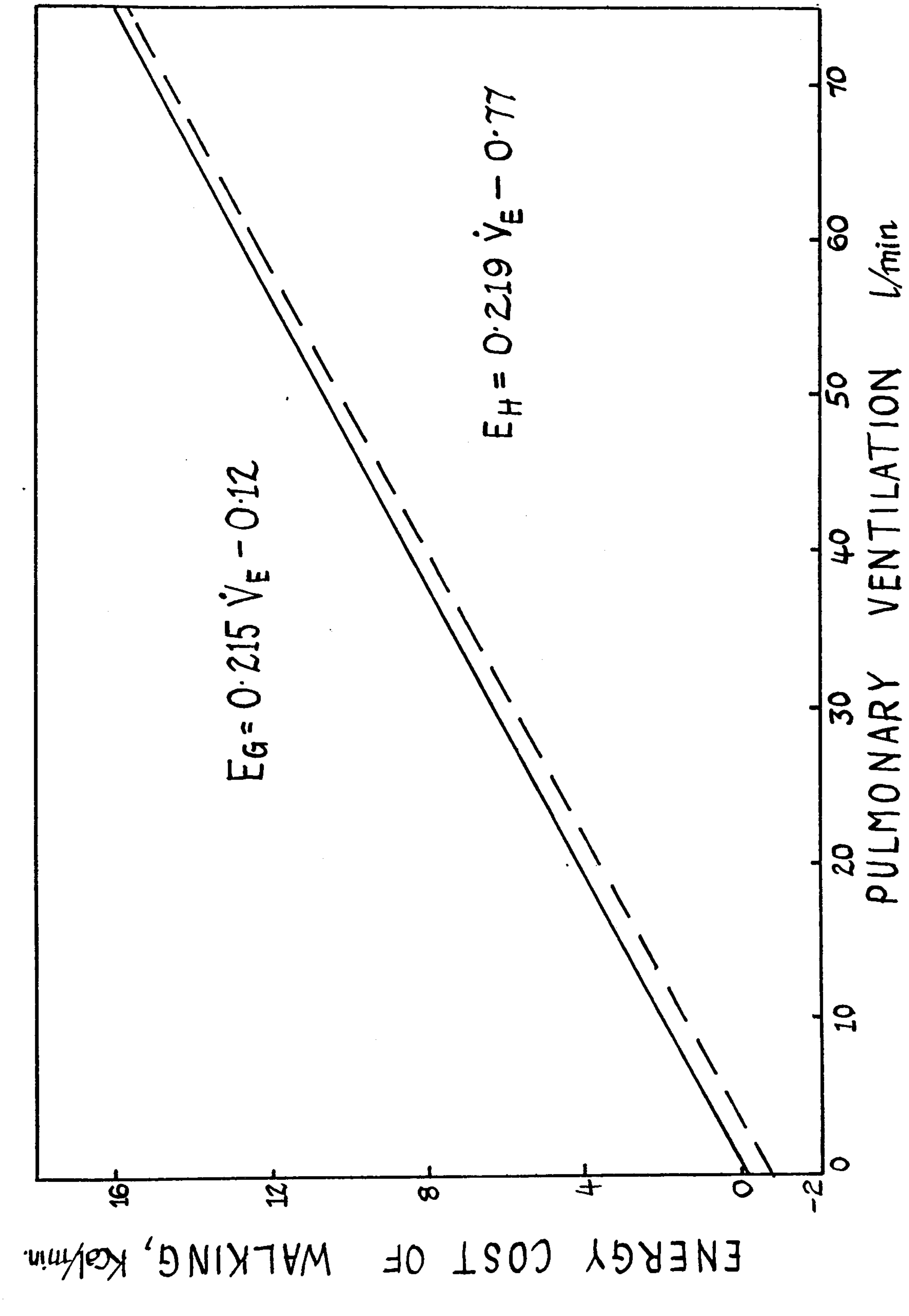

ENERGY COST OF WALKING, E Kcal/min.
16
12
10
8
6
30
35
40
45
50
55
60
PULMONARY VENTILATION, $\dot{V}_E$ L/min.
$E_G = 0{\cdot}243\ \dot{V}_E - 1{\cdot}42$
$r = 0{\cdot}98$
$E_H = 0{\cdot}227\ \dot{V}_E - 1{\cdot}16$
$r = 0{\cdot}93$

FIGURE 11

The Regression Lines for Energy Cost of (1) Grade Walking (E_G) and (2) Horizontal Walking (E_H) on Pulmonary Ventilation for All Subjects.


$E_G = 0{\cdot}215\ \dot{V}_E - 0{\cdot}12$
$E_H = 0{\cdot}219\ \dot{V}_E - 0{\cdot}77$
PULMONARY VENTILATION L/min
0
10
20
30
40
50
60
70
ENERGY COST OF WALKING, Kcal/min.
-2
0
4
8
12
16

different sources satisfactorily within allowable limits. In fact, this relation compares very closely to the regression equation

$$E = 0.215\ \dot{V}_E - 0.12$$

computed for the six subjects in this study grade walking on a treadmill. Pulmonary ventilation of 50 l/min gives an estimated energy cost of 10.50 Kcal/min from the equation of Datta and Ramanathan and 10.63 Kcal/min from the equation obtained in this study. This is a very good agreement when one considers that the nine subjects in Datta and Ramanathan's study were sedentary office workers of mean weight 52 kg, compared to the six athletic subjects of mean weight 79 kg used in this study.

Comparison of Heart Rate and Pulmonary Ventilation as Predictors of Energy Cost

Datta and Ramanthan concluded that pulmonary ventilation was a much better predictor of energy cost than heart rate although the correlation coefficients were comparable. They based this conclusion on the superior agreement of observed and predicted values when the regression equations were applied to groups of subjects other than that from which the regression equation had originally been obtained.

By applying Hotelling's formula[1] for testing the difference between correlated correlation coefficients it was shown that the difference

---

[1] $$t = \frac{(r_{12} - r_{13} \sqrt{(N-3)\ (1+r_{23}}}{\sqrt{2(1 - r_{23}^2 - r_{12}^2 - r_{13}^2 + 2r_{12}\ r_{13}\ r_{23}}}$$

between the correlation coefficient for energy cost and pulmonary ventilation (grouped subjects) and that for energy cost and heart rate (grouped subjects) was very significant. This seems to support the claim by Datta and Ramanathan.

The correlation between heart rate and pulmonary ventilation was 0.94 and thus little was to be gained in predictive power by computing a multiple correlation coefficient (R). The R in fact was 0.961, barely greater than the 0.960 for pulmonary ventilation. Simply from a practical point of view the superiority of measuring pulmonary ventilation as opposed to heart rate in a field situation is evident. Although the advent of radio telemetry has considerably simplified the task of measuring heart rate continuously, such apparatus is costly and not as adaptable to the field situation. The author's personal experience in field situations with small battery operated tape recorders to record heart rate indicates that this method is unreliable. On the other hand, the development of small lightweight masks, valves and portable respirometers has made the measurement of pulmonary ventilation relatively straightforward and precise (provided the respiromater is accurately calibrated).

Thus the use of pulmonary ventilation for estimating the energy cost of work tasks has much to recommend it when the highest levels of precision are not required. A necessary condition, however, is that a representative sample of the group to be measured are tested on the particular task in order to obtain a working regression equation of E on $\dot{V}_E$. It would be unwise to assume that regression equations such as that obtained in this study could be applied indiscriminately to all populations and work tasks.

INTER-INDIVIDUAL AND INTRA-INDIVIDUAL VARIABILITY OF ENERGY COST

The six trials conducted during the pilot study at one combination of treadmill grade and speed afforded an opportunity to examine the inter-individual and intra-individual variability.

Intra-individual variability may be considered as the normal variation in energy cost, from trial to trial, for a given subject performing the same task under identical conditions. This variation is often given as the coefficient of variation, i.e., 100 x SD/Mean. The coefficients of variation for the six subjects over the six trials were 7.65%, 3.44%, 2.29%, 2.13%, 9.69% and 6.56% respectively giving an average of 5.38%. This compares favourably with an average value of 10.2% for 20 subjects tested by Durnin and Namyslowski (12). The subjects in this study were measured for lying, sitting, walking and climbing, each measured on four different occasions. Erickson et al., (13) obtained much lower coefficients of variation, namely 1.83%, 1.50% and 2.59% on three subjects tested six times at a treadmill speed and grade of 2.5 mph and 10%. However these subjects were living under the supervision of the experimenters and their regimen of sleep, diet and activity was closely supervised.

Inter-individual variability for the energy cost of the six grade walks was 17.1%. This reduced to 6.7% when corrected for body weight. Durnin and Namyslowski obtained a value of 16.7% for their 20 subjects while grade walking, while Erickson et al., obtained 9.37%, which reduced to 3.99% when corrected for body weight.

Inter-individual Variability and Body Dimensions

A considerable proportion of the inter-individual variability of energy cost is due to the variations in body size of the subjects. Two measures of body size are frequently quoted with respect to the influence of this variable on energy metabolism; these are body weight and body surface area. The influence of these measures on the energy expenditure of standing, horizontal and grade walking, and recovery is shown in Table XVI. The largest reduction in inter-individual variation of the energy cost of standing was produced by an adjustment for body surface area. This is in agreement with the generally accepted view that resting or basal metabolism is a function of body surface area. In the case of the exercise phases of testing and recovery, the greatest

TABLE XVI

Inter-individual Coefficients of Variation (%) of Three Measures of Energy Expenditure for all Phases of All Trials

	Standing	Horizontal Walking	Grade Walking	Recovery
Gross energy cost	11.6	9.0	12.0	11.9
Energy cost per unit body weight	9.3	3.8	0.9	3.8
Energy cost per unit BSA	7.5	8.5	5.8	5.8

reduction in inter-individual variability occurred when energy cost was corrected for body weight. The reduction for grade walking was very marked; about 93% of the inter-individual variability was removed when the variations in body weight of the six subjects was taken into account. It would appear that where gross movements of the whole body are involved as in grade walking the principal cause of inter-individual variability is variation in body weight.

Intra-individual Variability and Reliability

Erickson *et al.*, (13) have indicated that the changes produced by controlled independent variables (in this instance rate of vertical ascent and grade) must be much greater than the random variations produced by uncontrolled factors if the results of an experiment are to be considered reliable. In this investigation random variations amount to 5 per cent, (Table IV, p. 24), a very small proportion of the changes induced by changing the rate of vertical ascent or grade.

ENERGY COST OF STANDING

The average energy cost of standing for all trials and all subjects was 1.560 Kcal/min. Andrews (1) obtained average cost of 1.46 Kcal/min for relaxed standing with six subjects whose mean weight was 75 kg. Correcting this value to the mean weight of the subjects in this study (there is no data on their B.S.A.) produces a highly comparable value of 1.54 Kcal/min. The subjects of the former study also had a very similar average heart rate to that of those in this study, 79.0 and 77.4 respectively.

ENERGY COST OF HORIZONTAL WALKING

Cotes and Meade (6) obtained a highly significant linear relationship between the energy cost of horizontal walking and the square of the speed.[1] A similar relationship was noted in this study and regression data is given in Table XVII. For the grouped subjects the

TABLE XVII

The Correlation Coefficient (r), Regression Equation ($E_H = a\ v_H^2 + b$) and Standard Error of Estimate (S) for the Regression of Energy Cost of Horizontal Walking (E_H) in Kcal/min on the Square of the Horizontal Speed (v_H) in mph for Each Subject

Subject	r*	Regression Equation	S Kcal/min
AC	0.87	$E_H = 0.272\ v_H^2 + 2.29$	0.52
RH	0.88	$E_H = 0.202\ v_H^2 + 2.52$	0.37
JM	0.83	$E_H = 0.210\ v_H^2 + 2.54$	0.47
GP	0.78	$E_H = 0.193\ v_H^2 + 2.87$	0.52
AT	0.90	$E_H = 0.230\ v_H^2 + 2.48$	0.38
MZ	0.93	$E_H = 0.284\ v_H^2 + 3.03$	0.39

* $p<0.001$

---

[1] For the purposes of this study the speed of the treadmill at any inclination will be denoted by v_G mph. The component of this speed in the vertical plane will be denoted by v_V mph (= V/5280 ft/hr). The component in the horizontal plane will be denoted by v_H mph. When the grade is zero $v_G = v_H$ and the latter symbol will always be used in this context.

regression equation was $E_H = 0.232\ v_H^2 + 2.62$ with $r = 0.86$ and the standard error of estimate = 0.46 Kcal/min. This equation is similar to that derived by Cotes and Meade for 10 subjects of lighter build,

$$E_H = 0.187\ v_H^2 + 2.38$$

Body weight also influenced the energy cost of horizontal walking and adjusting the energy cost to a common body weight led to an increased correlation between energy cost and velocity squared. This reduced the coefficient of variation of the estimated energy cost from 9.8% to 7.6%. This relationship of energy cost to the square of treadmill speed is to be expected since energy expenditure should, according to Ralston (23), be a function of kinetic energy. Ralston obtained similar relationships between energy expenditure and horizontal speed in a study of 12 men and 7 women. He found no significant differences due to sex and showed that one equation adequately predicted the energy cost per unit body weight for speeds up to 100 m/min (close to 4 mph). Above that speed Ralston observed that there was some loss of linearity which, he claimed, was to be expected at higher levels of metabolic activity.

The Optimal Velocity of Horizontal Walking

If the energy cost of horizontal walking is denoted by E_H Kcal/min body weight by W kg, and the horizontal speed by v_H mph then the general equation relating R_H and v_H is given by:

$$E_H = a + b\ v_H^2 \qquad (1)$$

where a and b are constants (2.62 and 0.232 respectively for the equation obtained in this study). Multiplying both sides of equation (1) by $60/W.v_H$ equation (2) is obtained.

$$\frac{60\ E_H}{W.v_H} = \frac{a\ 60}{W.v_H} + \frac{b60\ v_H^2}{W.v_H} \tag{2}$$

Simplifying this equation we obtain:

$$E = \frac{a'}{v_H} + b'\ v_H \tag{3}$$

where E Kcal/mile/kg is the energy cost of horizontal walking in Kcal per mile per kilogram body weight and a' and b' are new constants. This equation represents a hyperbolic curve concave upwards. As v_H approaches zero or indefinately large value E becomes indefinately large. E has a minimum value which can be determined by differentiation with respect to v_H and equating to zero. When Ralston (23) applied this procedure to his data on the energy cost of horizontal walking he obtained a hyperbola with a minimum value for E of 0.78 Kcal/Km/kg when the velocity was 74 m/min (2.76 mph). This curve was based on average values and was almost flat between approximately $v_H = 65$ and $v_H = 85$ m/min (2.42 to 3.17 mph). Ralston observed that when a subject was told to walk at a "natural" or "comfortable" speed he adopted a speed at or close to the minimum for the curve.

From the study by Cotes and Meade (6) it would appear that the optimal speed is that at which the amount of lift work (defined as the product of lift per step, step frequency and body weight) done is a minimum. At speeds below or above the optimal value the step frequency and lift per step change to values which increase the amount of lift work per unit distance covered. Cotes and Meade obtained minimal energy expenditure at an optimal speed of 3.5 mph for 10 young male subjects. Both Ralston and Cotes and Meade found that the energy cost of quiet standing was less than the value predicted by the regression lines for $v_H = 0$. Ralston observed that the predicted energy cost when $v_H = 0$ was close to the energy cost of the slowest speed compatible with normal balance. In this investigation the value of E_H when $v_H = 0$ was 2.62 Kcal/min, well in excess of the standing value of 1.56 Kcal/min.

When the same computations were made on the linear regression equation obtained in this investigation for grouped subjects the curve $E = 0.76v_H + 1.99/v_H$ was derived (Figure 12). This had a minimum value of 1.84 Kcal/mile/kg (0.74 Kcal/Km/kg) at a velocity of 3.36 mph (90 m/min). Thus the minimal value was very close to that found by Ralston but at a somewhat higher velocity. The optimal velocity was close to that determined by Cotes and Meade. It would be of interest to elucidate those factors which determine the optimal speed for an individual. Table XVIII gives the indices (energy cost and speed) for the minimum point on the individual curves computed for each subject from the regression lines of energy cost on the square of speed. A superficial examination reveals no relationship between either the optimal speed or minimum energy cost and body dimensions such as height and weight. There does appear to be a slight tendency for a low efficiency (i.e., high energy cost per unit distance per unit body weight) to be associated with a low optimal speed. However, the correlation

FIGURE 12

The Energy Cost of Horizontal Walking Per Unit Distance Per Unit Body Weight Versus Speed. Derived from the Linear Regression of Energy Cost on Speed.

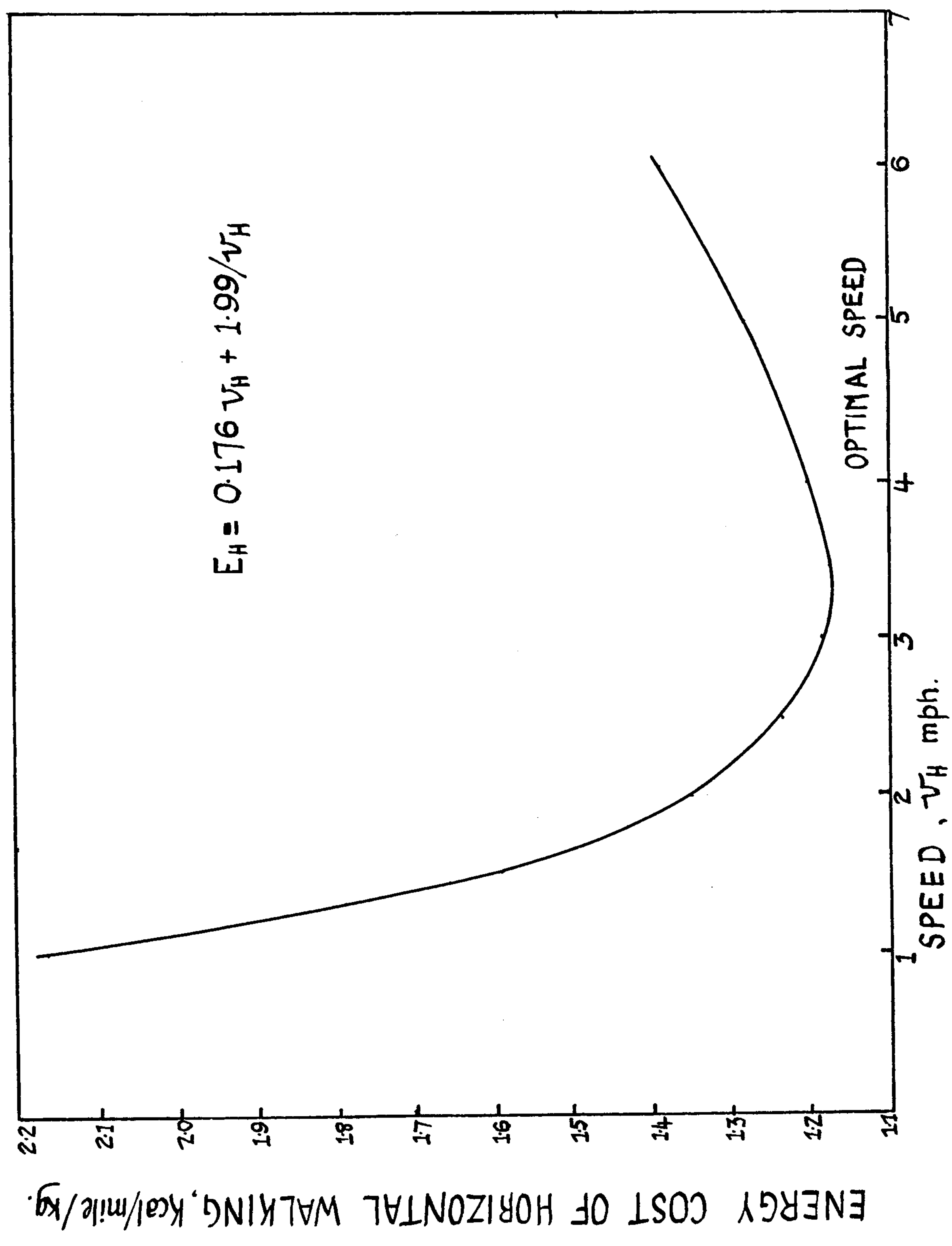

$E_H = 0.176\,v_H + 1.99/v_H$
OPTIMAL SPEED
SPEED , v_H mph.
ENERGY COST OF HORIZONTAL WALKING, Kcal/mile/kg.
1
2
3
4
5
6
7
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2

TABLE XVIII

The Minimum Energy Cost of Horizontal Walking for Each Subject and the Speed at which the Minimum is Attained (Optimal Speed). Grouped Data Shown for Comparison

Subject	Optimal Speed mph	Minimum Energy Cost of Walking	
		Kcal/mile	Kcal/mile/kg
AC	2.90	94.7	1.243
RH	3.53	85.7	1.121
JM	3.48	87.7	1.239
GP	3.86	89.9	1.150
AT	3.28	90.6	1.169
MZ	3.27	111.4	1.153
Group	3.36	93.5	1.184

coefficient of -0.54 is not significant. Further investigation of this aspect of energy expenditure would be of interest.

ENERGY COST OF GRADE WALKING

The energy cost of grade walking showed a range from 5.09 Kcal/min for JM at 1.55 mph and 16% to 20.02 for MZ at 3.65 mph and 12%. Pugh (22) developed a regression equation for oxygen uptake on the external work done in climbing a hill with an average grade of 20%. Table XIX gives a comparison of the observed energy costs for one subject walking at three different speeds at 20% grade and the values predicted by Pugh's equation. The agreement is quite close.

TABLE XIX

A Comparison of Predicted and Observed $\dot{V}_{O_2}$ in l/min for Subject AC Grade Walking at 20%. Predicted Values Calculated from the Regression Equation of Pugh (22): $\dot{V}_{O_2} = 0.509 + 0.00166\ W$, Where W is External Work Rate in Kgm/min.

Speed mph	Work Rate Kgm/min	Predicted $\dot{V}_{O_2}$, l/min	Observed $\dot{V}_{O_2}$ l/min
1.25	543	1.41	1.49
1.74	743	1.74	1.66
2.22	956	2.10	2.20

EFFICIENCY OF GRADE WALKING

The values obtained in this study for the three measures of efficiency are of the same order as those obtained by other investigators (Table XX). A comparison of the gross efficiencies obtained by the author in two different studies are of some interest since the methods used for measuring energy cost were basically the same. The efficiencies obtained on the two female subjects were significantly higher than those for the six male subjects used in the present study, despite their wearing heavy boots in half the trials (this was shown to reduce efficiency). Boogens and Keatings (5) observed the same phenomena and suggested that women expend less energy than men because they take shorter strides relative to the length of their legs and thus do less lift work for a given distance covered. Ralston (23), however found no significant difference between his male and female subjects.

TABLE XX

A Comparison of Some Efficiencies of Grade Walking
Obtained by Various Investigators.
The Values Given are Either
Means (±SD) or Ranges

Source	Range of Grades %	Range of Speeds mph	Efficiency, %		
			GE	NES	NEH
Present Study	12 -24	1.05-3.65	19.7± 1.9	24.0± 2.7	33.7± 4.9
Erickson _et_ _al_. (13)	5 -10	2.5 -4.0			24.8-35.2
Durnin* (11)	17.5-21.3	1.8 -2.1		19 -23	28 -32
Pugh* (22)	20	?	16 -23	28	
Taylor† (26)	12 -19	1 -1.6	18.3-27.7 mean 22.6		

* Field studies with some light load carrying.

† Female subjects with some load carrying and wearing of heavy boots which reduced efficiency (significant).

The Influence of Rate of Vertical Ascent and Grade on Efficiency

Gross Efficiency

The interaction of the two factors rate of vertical ascent and grade was significant (Table X, p. 38, Figure 2, p. 39). To determine between which levels of these factors the differences were significant the Duncan Test was applied, and the results of this are shown in Table XXI. At a rate of ascent of 1300 ft/hr (which corresponded to

TABLE XXI

Results of the Duncan Test to Determine the Levels of Grade (G) Between which Differences of Gross Efficiency are Significant. The Test was made for Each Rate of Vertical Ascent (V).

Rate of Vertical Ascent		Grade		
		G_2	G_3	G_4
V_1	G_1	**	**	**
	G_2		NS	NS
	G_3			NS
V_2	G_1	**	**	**
	G_2		NS	*
	G_3			NS
V_3	G_1	**	**	**
	G_2		NS	*
	G_3			NS

NS not significant * $0.05>p>0.01$ ** $0.01>p>0.001$

an average work load of about 520 Kgm/min for the subjects) only those differences between a grade of 12% and the others were significant. At the higher rates of ascent (equivalent to about 720 and 920 Kgm/min of work) the grade differential had to be 8% or more in order for there to be a significant difference in efficiency--with the exception in all cases of the 12 to 16% interval. The way in which efficiency changed with grade was rather similar in the case of the two highest rates of ascent. Tests for linear, quadratic and cubic trends were all non-significant. The way in which the efficiency appeared to approach an asymptotic level suggested a hyperbola of the form y=a/x+b. This was confirmed by the high negative correlations obtained between efficiency and the reciprocal of the grade (Table XXII). An analysis of linear trend (using unequal interval adjustments) was highly significant. The asymptotic levels are those obtained as $G \to \infty$, that is 24.74%

TABLE XXII

Correlation Coefficients (r), Regression Equations and Standard Errors of Estimate (S) for the Regression of Gross Efficiency (GE) on the Reciprocal of Grade (G) for the Two Highest Rates of Vertical Ascent

Rate of Vertical Ascent ft/hr	r*	Regression Equation	S %
1800	-0.997	$GE = 24.74 - \frac{79.09}{G}$	0.10
2300	-0.971	$GE = 25.73 - \frac{95.18}{G}$	0.37

* 0.01>p>0.001

and 25.73% respectively for rates of ascent of 1800 ft/hr and 2300 ft/hr. Very similar curves were obtained for both gross efficiency and net efficiency (NES) when efficiency versus grade was compared over all rates of ascent (Figure 4 p. 41, Figure 8 p. 46). Margaria (18) has observed that when walking up increasing inclines the net efficiency (NES) tends to 25%, a value which is maintained constant for inclines from 20% to 40%. This is in agreement with the trend shown by the curve in Figure 8, p. 46. Margaria credits this increased efficiency at higher grades to two factors:

1. at higher grades the centre of gravity no longer oscillates vertically but moves in one direction only. Thus, no lift work is wasted.
2. at higher grades the work resulting from speed changes at every step are negligible because of the slower speeds involved.

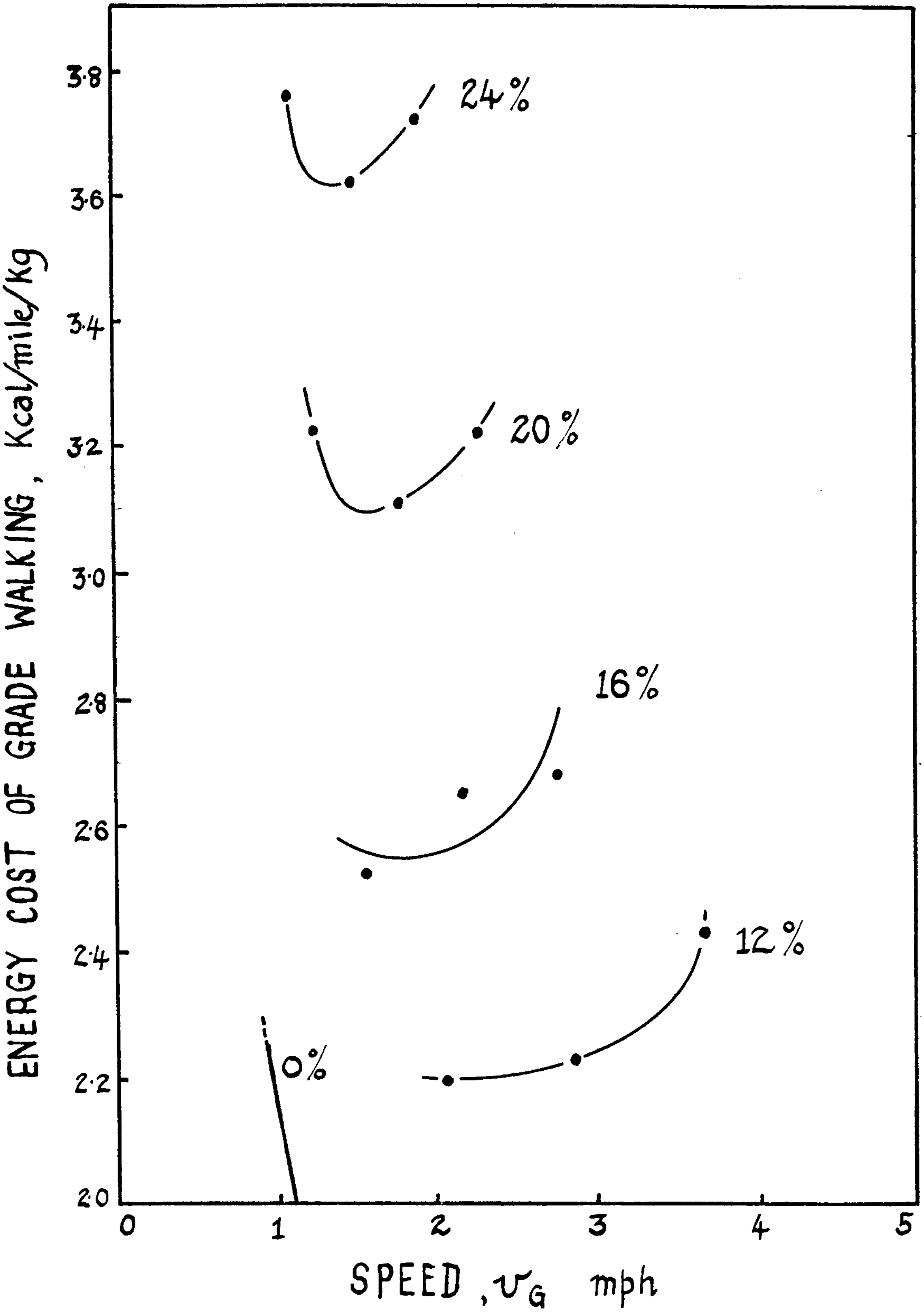
The asymptotic values quoted for this study must be interpreted with caution since it is unwise to predict beyond the range covered by the original observations unless there is a logical reason, based on other knowledge, to believe that the linear relation would hold true beyond the observed range.

The different curve obtained at a rate of ascent of 1300 ft/hr remains to be explained. Tests for linear, quadratic and cubic trends were all significant and the result therefore ambiguous. At this low rate of vertical ascent the speeds necessary to attain this rate were very slow. As has already been noted, the energy cost of walking horizontally at these slow speeds was elevated above the optimal value and this would tend to counteract the inherent advantage of a high incline. At 1300 ft/hr the gross efficiency over all grades was lower than for the highest rates of ascent. This was due to a much higher proportion of the energy cost of the grade walking being contributed by the resting metabolism at a low work rate as compared to higher intensities of work. This is shown by the fact that the net efficiency (NES) at this lowest rate was not less than for the highest rates of vertical ascent. In order to elucidate this further we may consider a hypothetical case in which there are three different rates of vertical ascent which produce work loads of 1, 2 and 3 Kcal/min respectively. If we assume that the net efficiency (NES) is 25% in all cases then the difference in energy cost between grade walking and standing will be 4 x 1 = 4, 4 x 2 = 8, and 4 x 3 = 12 Kcal/min respectively. If the standing metabolism is in all cases 1.5 Kcal/min then the total metabolism of grade walking will be 5.5, 9.5 and 13.5 Kcal/min respectively. Gross efficiencies will thus be 1/5.5 x 100 = 18.2%, 2/9.5 x 100 = 21.1% and 3/13.5 x 100 = 22.2% respectively. Thus although all three work tasks have the same net efficiency the gross efficiencies differ because of the uneven contribution of standing metabolism to the total cost.

The general trend of efficiency due to the influence of speed and grade are well illustrated by the curves in Figure 13. The curves have been drawn freehand and follows the general form shown by Margaria (18). The net energy expenditure (difference between that for grade walking and standing) per unit body weight per unit distance covered is

FIGURE 13

The Net Energy Cost of Grade Walking (Deduction for Standing Metabolism) Per Unit Distance Per Unit Body Weight as a Function of Speed and Grade (%).


ENERGY COST OF GRADE WALKING, Kcal/mile/kg
SPEED, v_G mph
3·8
3·6
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
0
1
2
3
4
5
24%
20%
16%
12%
0%

a function of both speed and grade. As the grade increases so the turning point becomes sharper and the optimal velocity increases. Presumably, the optimal velocity approaches the value for horizontal walking as $G \to 0$.

The replication factor was found to be very significant indicating a progressive decrease in efficiency from trial one through to trial three. This conflicts with the evidence of Durig (9) who found small increases in efficiency during the course of a day, and with Durnin (11) who found no detectable differences due to either practice or fatigue. It is possible that differences in the intensity of the exercise and the frequency and duration of rest pauses could account for the different observations. This is supported by the fact that the replication factor was not significant in the analysis of variance of the net efficiency (NES), suggesting that the greater energy cost of walking in the second and third trials was due to continuing repayment of the oxygen debt from the previous trial.

Net Efficiency

There were fewer instances and a lesser degree of significance between the levels of factors than for gross efficiency. This may have been due, at least in part, to the greater variability of the data, itself a reflection of the manner in which net efficiency was calculated.

Net Efficiency, NES.

The main factors, rate of vertical ascent and grade, were still very significant. The general influence of grade was as in the computation of gross efficiency, although the calculated efficiencies were a few percent higher. In the case of rate of vertical ascent, however, the influence was reversed (Figure 3, p. 40, Figure 7, p. 45), the highest rate of vertical ascent being associated with the lowest efficiency. This has already been explained in part by the non-uniform contribution of standing metabolism to the total cost of walking. Nevertheless this observation does not explain why the net efficiency of the highest rate of vertical ascent is significantly lower than for the other two rates.

Net Efficiency, NEH.

The severity of grade seemed to have no significant influence on NEH. This supports the view that it is differences in the economy of the horizontal component of grade walking which largely contribute to the highly significant differences between the gross efficiency of walking up varying inclines. The only significant difference found in the analysis of variance of NEH was between the levels of the rate of vertical ascent. The decrease in efficiency was almost linear from 1300 ft/hr to 2300 ft/hr (Figure 9, p. 49). It is difficult to find any plausible explanation for this trend.

From the results of this investigation it is obvious that the analysis of three measures of efficiency has led to some insight into the energetics of grade walking which could not have been obtained from a simple consideration of gross efficiency. Evidence from this study suggests that the net efficiency invorporating a deduction for the energy cost of resting is the best single measure of efficiency, but that for practical applications such as the design of ramps and trails to minimize or maximize effort gross efficiency is of more use.

CHAPTER VI

SUMMARY

The technique of measuring energy expenditure by open-circuit respirometry using a portable respirometer to collect a sample and to measure the volume of expired gas was found to have acceptable levels of precision and reliability. Some reservations have been made on the use of breath by breath gas analysers to analyse the samples of expired air because of

(i) the problem of establishing an accurate baseline

(ii) the problem of shifting sensitivity

(iii) the relatively large number of possible sources of error in the calibration of the analyser.

Prediction of energy cost of a gross dynamic muscular work task from the pulmonary ventilation and, to a lesser extent, heart rate was found to have practical usefulness in circumstances where the highest order of accuracy is not required. However, the regression relationship to be used must be calculated by testing a representative sample of the population to be measured on the particular work task involved.

The influence of body size on energy metabolism was examined and it was found that of the two measures of body size considered in this investigation body surface area was more closely related to metabolism at rest, while body weight was more closely related to metabolism during exercise and recovery.

The linear relationship between the energy cost of horizontal walking and the square of its velocity was confirmed and from computed regression lines minimal energy expenditure and optimal velocity values were calculated for each subject. These showed considerable inter-individual variation for which there was no satisfactory explanation.

The gross efficiency of grade walking was found to be greatly influenced by the rate of vertical ascent and grade, and by the interaction of these two factors. Gross efficiency increased as the rate of vertical ascent increased. This was partly due to the decreasing proportional contribution of standing metabolism to the total metabolism as the intensity of the work task increased. Gross efficiency increased with increasing grade and this was found to be due to differences in the economy of the horizontal component of walking. The factor replication of trials was also found to be significant but it was deduced that this was due to the accruing oxygen debt from one trial to the nest as these trials were all performed on the same day. When the net efficiency (NES), calculated using a deduction for standing metabolism, was considered replication was no longer significant.

NES increased with increase in grade, parallelling the trend observed in the gross efficiency. It decreased, however, with an increase in the rate of vertical ascent, a reversal of the order observed in the gross efficiency. This could partly, but not entirely, be explained as due to the decreasing proportional contribution of standing metabolism to the total metabolism as the intensity of the work task increased.

The net efficiency (NEH) calculated using a deduction for the metabolism of horizontal walking was found to be significantly influenced only by the rate of vertical ascent. The linear decrease in NEH with increase in the rate of vertical ascent remains to be explained.

It was concluded that gross efficiency is the only measure of efficiency which has practical applications but that a consideration of NES and NEH produces some interesting insights into the nature of treadmill walking.

REFERENCES

1. Andrews, R.B. Estimation of values of energy expenditure rate from observed values of heart rate. HUMAN FACTORS 9 (6) 581-86, 1967.

2. Banister, E.W. and R.C. Jackson. The effect of speed and load changes on oxygen intake for equivalent power outputs during bicycle ergometry. INT. Z. ANGEW PHYSIOL 24: 284-90, 1967.

3. Benedict, F.G. and H. Murschhauser. CARNEGIE PUB. No. 231, 1915.

4. Brezina, E. and W. Kolmer. Uber den energieverbrauch bei der geharbeit unter dem einfluss verschiedener geschwindigkeiten und verschiedener belastungen. BIOCHEMISCHE ZEITSCHRIFT 38: 129-53, 1912.

5. Boogens, J. and W. R. Keatings. The expenditure of energy by men and women walking. J. PHYSIOL. 138:165, 1957.

6. Cotes, J.E. and F. Meade. The energy expenditure and mechanical energy demand in walking. ERGONOMICS 3: 97-119, 1960.

7. Datta, S.R. and N. L. Ramanathan. Energy expenditure in work predicted from heart rate and pulmonary ventilation. J. APPL. PHYSIOL. 26: 297-302, 1969.

8. Douglas, C. G., J. S. Haldane, Y. Henderson and E. C. Schneider. Physiological observations made on Pike's Peak, Colorado, with special reference to adaptation to low barometric pressures. PHIL. TRANS. B, 203: 185-318, 1913.

9. Durig, A. Beitrage sur physiologie des menschen im hochgebirge. PFLUG ARCH. GES. PHYSIOL 113: 213-316, 1906.

10. Durig, A. and N. Zuntz. Beitrage sur physiologie des menschen im hochgebirge. ARCH. ANAT PHYSIOL., LPZ., suppl. 417-56, 1904.

11. Durnin, J. V. G. A. The oxygen consumption, energy expenditure, and efficiency of climbing with loads at low altitudes. J. PHYSIOL 128 L 294-30, 1955.

12. Durnin, J. V. G. A. and L. Namyslowski. Individual variations in the energy expenditure of standardized activities. J. PHYSIOL. 143: 573-78, 1958.

13. Erickson, L., E. Simonson, H. L. Taylor, H. Alexander and A. Keys. The energy cost of horizontal and grade walking on the motor-driven treadmill. AM. J. PHYSIOL 145: 391-401, 1946.

14. Iampietro, P. F. and R. F. Goldman. Prediction of energy cost of treadmill work. Civil Aeronautical Research Institute, Federal Aviation Agency, Oklahoma. December, 1961.

15. Kleiber, M. "The Fire of Life." New York, John Wiley & Sons, Inc., 1961, pp. 86-7.

16. Knehr, C. A., D. B. Dill and W. Neufeld. Training and its effects on man at rest and at work. AM. J. PHYSIOL 136: 148-56, 1942.

17. Lukin, L., M. J. Polissar and H. J. Ralston. Methods for studying energy costs and energy flow during human locomotion. HUMAN FACTORS 9(6) : 603-8, 1967.

18. Margaria, R. Current concepts of walking and running. In "Frontiers of Fitness." R. J. Shephard (Ed.), Springfield, Illinois, Charles C. Thomas, 1971, pp. 201-3.

19. Maritz, J. S., J. F. Morrison, J. Peter, N. B. Strydom and C. H. Wyndham. A practical method of estimating an individual's maximal oxygen intake. ERGONOMICS 4 : 97, 1961.

20. Orsini, D. and R. Passmore. The energy expended carrying loads up and down stairs : Experiments using the Kofranyi-Michaelis calorimeter. J. PHYSIOL 115: 95-100, 1951.

21. Passmore, R. and J. V. G. A. Durnin. Human energy expenditure. PHYSIOL. REV. 35: 801-40, 1955.

22. Pugh, L. G. C. E. Muscular exercise on Mount Everest. J. PHYSIOL. 141: 233-61, 1958.

23. Ralston, H. J. Energy-speed relation and optimal speed during level walking. INT. Z. ANGEW. PHYSIOL. Bd. 17,S: 277-83, 1958.

24. Scholander, P. Analyser for accurate estimation of respiratory gases in one-half cubic centimetre samples. J. BIOL. CHEM. 167: 235-50, 1947.

25. Smith, H. M. CARNEGIE PUB. No. 309, 1922.

26. Taylor, R. G. The effects of grade, rucksack weight and boot weight on the energy expenditure of uphill walking. Submitted for publication, 1970.

27. Weir, J. B. de V. New methods for calculating metabolic rate with special reference to protein metabolism. _J_. _PHYSIOL_. 109: 1-9, 1949.

28. Whipp, B. J. and K. Wasserman. Efficiency of muscular work. _J_. _APPL_. _PHYSIOL_. 26(5): 644-8, 1969.

APPENDIX 1

COMPUTER PROGRAMME FOR CALCULATING VARIOUS PARAMETERS INVOLVED IN UPHILL WALKING

```
C       PROGRAM TO CALCULATE VARIOUS DARAMETERS INVOLVED IN UPHILL WALKING
C       NAMELY:HR, E(S D).O2%,CO2%,VO2,R,E,EW,EBSA,KGM/MIN,KCAL/MIN,EFF.
C       THESE PARAMETERS ARE EXPLAINED FURTHER IN PROGRAM
        INTEGER BP,RA,TMS,GRADE,TEMP,HRA,HRB,HRC,HRD,HRE,HRM,HRMM
        DIMENSION  NAME(20),BWS(100),BWA(100),BP(100),RA(100)
        DIMENSION  TMS(100),GRADE(100),VOL(1000),TEMP(1000)
        DIMENSION  HRA(1000),HRB(1000),HRC(1000),HRD(1000),HRE(1000)
        DIMENSION  OO(1000),COO(1000),VE(1000),VOO(1000),R(1000)
        DIMENSION  E(1000),EW(1000),EBSA(1000),HRM(1000),HRMM(250)
        DIMENSION  VM(250),OOM(250),COOM(250),RM(250),VOOM(250)
        DIMENSION  EM(250),EWM(250),EBSAM(250),PGM(250),PCAL(250)
        DIMENSION  EF(250),EFF(250),EFM(250),TABLE(41,18),BSA(100)
        DO 992 M=1,41
        READ(5,993) (TABLE(M,J),J=1,18)
  993   FORMAT(16F5.3/2F5.3)
  992   CONTINUE
C       NL=NUMBER OF SUBJECTS
        NL=6
        DO 990 NM=1,NL
        WRITE(6,88)
   88   FORMAT('1',T15,'THE ENERGY COST AND EFFICIENCY OF UPHILL WALKS')
        READ(5,100) NAME
  100   FORMAT(20A4)
        WRITE(6,99) NAME
   99   FORMAT(' ',T20,20A4)
        READ(5,101) BWS(NM),BWA(NM),BSA(NM),BP(NM),RA(NM),TMS(NM)
       1,GRADE(NM)
  101   FORMAT(2F10.2,F5.2,2I5,F5.2,I5)
C       BWS=BODY WEIGHT STRIPPED,BWA=BODY WEIGHT WITH APPARATUS
C       BSA=BODY SURFACE AREA,BP=BAROMETRIC PRESSURE,RA=RATE OF ASCENT
C       TMS=TREADMILL SPEED,GRADE=GRADE %
        WRITE(6,98) BWS(NM),BWA(NM),BSA(NM),BP(NM),RA(NM),TMS(NM),
       1GRADE(NM)
   98   FORMAT(17X,'BODY WEIGHT STRIPPED=',F10.2,/8X,'BODY WEIGHT WITH
       1 APPARATUS=',F10.2, 20X,'BODY SURFACE AREA=',F5.2,/15X,'BAROMETRIC
       2 PRESSURE=',I5,/23X,'RATE OF ASCENT=',I5,/22X,'TREADMILL SPEED=',
       3 F5.3,/30X,'GRADE=',I5)
C       SET UP VARIABLES NUMBER OF TRIALS =ITRIALS
        ITRIAL=3
        I=4*ITRIAL
        WRITE(6,999)
  999   FORMAT(/7X,'PHASE',T15,'TRIAL',T22,'HEART RATE',T33,'VOL(L/MIN)',
       1T45,'O2%',T50,'CO2%',T58,'R',T61,'VO2(L/MIN)',T73,'E(KCAL/MIN)',
       2T85,'EW(KCAL/MIN/100KG)',T105,'EBSA(KCAL/MIN/2M*M)')
        DO 1000 J=1,I
C       READ DATA CARDS
        READ(5,102) VOL(J),TEMP(J),HRA(J),HRB(J),HRC(J),HRD(J),HRE(J),
       1OO(J),COO(J)
  102   FORMAT(F5.1,6I5,2F5.2)
 1000   CONTINUE
C       ESTABLISH WHAT TRIAL PROGRAM IS WORKING ON.
        K=ITRIAL+1
```

```
0035             L=K+ITRIAL
0036             M=L+ITRIAL
0037             N=M+ITRIAL
0038             II=ITRIAL
0039             IJ=2*II
0040             IK=3*II
0041             IL=4*II
0042             DO 1001 IM=1,I
0043             IF(IM.LE.K)GO TO 200
0044             IF(IM.GT.II.AND.IM.LT.L)GO TO 201
0045             IF(IM.GT.I[illegible].AND.IM.LT.M)GO TO 202
0046             IF(IM.GT.IK.AND.IM.LT.N)GO TO 203
0047        200  J=5
0048             GO TO 300
0049        201  J=2
0050             GO TO 300
0051        202  J=2
0052             GO TO 300
0053        203  J=5
0054             GO TO 300
            C    CALCULATIONS BEGIN HERE
            C    CALCULATION OF VO EXPIRED CORRECTED FOR TEMP,BP,FLOW.
            C    CF=CORRECTION FACTOR.
0055        300  CF=1.063-(.000[illegible]4*(VOL(IM)/J)     )
            C    VE= CORRECTED  VO
0056             T=TEMP(IM)
0057             B=BP(IM)
0058             VE(IM)=[illegible] E(([illegible]-0[illegible]8)/2,IN-14)*((VOL(IM)*CF)/J)
            C    CALCULATE  USING  R= (VCO2/VO2)
0059             FENN= 100-(OO(IM)+COO(IM))
0060             VCOO=(COO(IM)-(FENN*.0003795))*(VE(IM)*.01)
0061             VOO(IM)=((FENN*.2648)-OO(IM))*(VE(IM)*.01)
0062             R(IM)=VCOO/VOO(IM)
            C    CALCULATION OF E,EW,EBSA,KGM,KCAL,EF,
            C    E=ENERGY COST IN KCAL/MIN,ENERGY COST IN KCAL/MIN/100KG= EW
            C    EBSA=ENERGY COST IN KCAL/MIN/2M*M,KGM=KILOGRM*METRFS UP /MIN
            C    KCAL=KCAL DONE IN KCAL/MIN,EF=GROSS EFFICIENCY.,
0063             AK=1.040-(.05*R(IM))
0064             E(IM)=VOO(IM)*AK
0065             EW(IM)=(E(IM)*100)/BWS(NM)
0066             EBSA(IM)=(E(IM)*2)/BSA(NM)
            C    CALCULATING  MEAN HR
0067             IF(IM.LE.K GO TO 400
0068             GO TO 401
0069        400  J=3
0070        401  HRM(IM)=(HRA(IM)+HRB(IM)+HRC(IM)+HRD(IM)+HRE(IM))/J
0071             WRITE(6,500)HRM(IM),VE(IM),OO(IM),COO(IM),R(IM),VOO(IM),
                1E(IM),EW(IM),EBSA(IM)
0072        500  FORMAT(T25,I3,T35,F5.1,T43,F5.2,T49,F5.2,T55,F5.3,T63,F5.3,
                1T75,F5.2,T90,F5.2,T110,F5.2)
0073             SA=0
0074             SB=0
```

```
             SC=0
             SD=0
             SE=0
             SF=0
             SG=0
             SH=0
             SI=0
C            CALCULATE MEAN OF ALL VALUES FOR EACH PHASE OF TRIALS
             IF(IM.EQ.ITRIAL) GO TO 501
             IF(IM.EQ.I[illegible])GO TO 502
             IF(IM.EQ.I[illegible])GO TO 503
             IF(IM.EQ.I[illegible])GO TO 504
             GO TO 1001
        501  II=0
             GO TO 1009
        502  II=II
             GO TO 1009
        503  II=IJ
             GO TO 1009
        504  II=IK
             GO TO 1009
       1009  DO 1002 LL=1,II
             JL=LL+LI
             SA=VE(JL)+SA
             SB=HRH(JL)+SB
             SC=OD(JL)+SC
             SD=COD(JL)+SD
             SE=R(JL)+SE
             SF=VOD(JL)+SF
             SG=E(JL)+SG
             SH=EW(JL)+SH
             SI=EBSA(JL)+SI
       1002  CONTINUE
             V[illegible](IM)=SA/II
             HRHM(IM)=SB/II
             ODM(IM)=SC/II
             CODM(IM)=SD/II
             RM(IM)=SE/II
             VODM(IM)=SF/II
             EM(IM)=SG/II
             EWM(IM)=SH/II
             EBSAM(IM)=SI/II
             IF(IM.EQ.ITRIAL)GO TO 505
             IF(IM.EQ.I[illegible])GO TO 506
             IF(IM.EQ.I[illegible])GO TO 507
             IF(IM.EQ.I[illegible])GO TO 508
        505  WRITE(6,701)
        701  FORMAT(/7X,'STANDING',T17,'MEAN')
             GO TO 509
        506  WRITE(6,702)
        702  FORMAT(/5X,'HORIZONTAL',T17,'MEAN')
             GO TO 509
```

```
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 0126            507 WRITE(6,703)
 0127            703 FORMAT(/7X,'GRADE',T17,'MEAN')
 0128                GO TO 509
 0129            508 WRITE(6,704)
 0130            704 FORMAT(/7X,'RECOVERY',T17,'MEAN')
 0131            509 WRITE(6,700)HRMM(IM),VM(IM),DOM(IM),CDOM(IM),RM(IM),VOOM(IM) ,
                    1 EM(IM),EW (IM),EBSAM(IM)
 0132            700 FORMAT('+',T25,I3,T35,F5.1,T43,F5.2,T49,F5.2,T55,F5.3,T63,F5.3,
                    1T75,F5.2,T90,F5.2,T110,F5.2)
 0133           1001 CONTINUE
 0134                WRITE(6,996)
 0135            996 FORMAT(/7X,'KGM/MIN',T30,'KCAL/MIN',T50,'GROSS EFFICIENCY %',
                    1T80,'NET EFFICIENCY %A',T110,'NET EFFICIENCY %B' )
               C     EXTERNAL WORK DONE IN GRADE WALKINGIN KGM/MIN=PGM
               C     EXTERNAL WORK DONE IN GRADE WALKINGIN KCAL/MIN=PCAL
               C     GROSS EFFICIENCY =EF
               C     NET EFFICIENCY WITH STANDING DEDUCTED =EFF
               C     NET EFFICIENCY WITH HORIZONTAL WALKING=EFN
 0136                DO 1004 JM=1,I1
 0137                PGM(NM)=(R (NM)*BW (NM))/(60*3.2808)
 0138                PCAL(NM)=PGM(NM)*.0023427
 0139                JN=JM+IJ
 0140                EF(NM)=(PCAL(NM)*100)/E(JN)
 0141                EFF(NM)=(PCAL(NM)*100)/(E(JN)-E(JM))
 0142                KI=JM+I1
 0143                EFN(NM)=(PCAL(NM)*100)/(E(JN)-E(KI)       )
 0144                WRITE(6,997)PGM(NM),PCAL(NM),EF(NM),EFF(NM),EFN(NM)
 0145            997 FORMAT (/7X,F6.1,T22,F6.3,T55,F5.2,T85,F5.2,T115,F5.2)
 0146           1004 CONTINUE
 0147            990 CONTINUE
 0148                END
```

APPENDIX 2

COMPUTER PROGRAMME FOR THREE FACTOR ANALYSIS OF VARIANCE

```
      C**  THREE FACTOR WITHIN SUBJECTS DESIGN ANOVA
      C**  PROGRAM WRITTEN BY [illegible] MONTGOMERY
            DIMENSION FORM(20),TITLE(20),FACTA(20),FACTB(20),FACTC(20),Y(20,10
           1,10,10),ABC(10,10,10),ABCSQ(10,10,10),ABCVAR(10,10,10),ABCSD(10,10
           2,10),ABS(20,10,10),ACS(20,10,10),BCS(20,10,10),AB(10,10),ABSQ(10,1
           30),ABM(10,10),ABVAR(10,10),ABSD(10,10),AC(10,10),ACSQ(10,10),ACM(1
           40,10),ACVAR(10,10),ACSD(10,10),BC(10,10),BCSQ(10,10),BCM(10,10),BC
           5VAR(10,10),BCSD(10,10),A(10),ASQ(10),AM(10),AVAR(10),ASD(10),B(10)
           6,BSQ(10),BM(10),BVAR(10),BSD(10),C(10),CSQ(10),CM(10),CVAR(10),CSD
           7(10),ABCM(10,10,10),AS(20,10),BS(20,10),CS(20,10) ,S(20)
            READ(5,34)NANAL
            NDEX=0
        999 NDEX=NDEX+1
            READ(5,35)(FORM(I),I=1,20)
            READ(5,1)NA,NB,NC,NS,(TITLE(I),I=1,16)
            READ(5,35)(FACTA(I),I=1,20)
            READ(5,35)(FACTB(I),I=1,20)
            READ(5,35)(FACTC(I),I=1,20)
            WRITE(6,4)(TITLE(I),I=1,16)
            WRITE(6,36)(FACTA(I),I=1,20)
            WRITE(6,36)(FACTB(I),I=1,20)
            WRITE(6,36)(FACTC(I),I=1,20)
            DO 1000 I=1,NS
            DO 1000J=1,NA
            DO 1000 K=1,NB
       1000 READ(5,FORM)(Y(I,J,K,L),L=1,NC)
      C***
      C***  SUM AND SUM OF SQUARES TOTAL
            SUM =0.0
            SUMSQ=0.0
      C***
      C***  ABC SUMMARY MATRIX
            DO 1030 J=1,NA
            DO 1030 K=1,NB
            DO 1030 L=1,NC
            ABCSQ(J,K,L)=0.0
            ABC(J,K,L)=0.0
            DO 1020 I=1,NS
            ABC(J,K,L)=ABC(J,K,L) + Y(I,J,K,L)
            ABCSQ(J,K,L)=ABCSQ(J,K,L)+Y(I,J,K,L)**2
            SUM =SUM + Y(I,J,K,L)
            SUMSQ=SUMSQ + Y(I,J,K,L)**2
       1020 CONTINUE
            ABCM(J,K,L)=ABC(J,K,L)/NS
            ABCVAR(J,K,L)=ABCSQ(J,K,L)/NS-ABCM(J,K,L)**2
            ABCSD(J,K,L)=SQRT(ABCVAR(J,K,L))
       1030 CONTINUE
            WRITE(6,37)
            WRITE(6,20)
            WRITE(6,38)
            WRITE(6,21)
            DO 1021 J=1,NA
```

```
0040             WRITE(6,40)
0041             DO 1021 K=1,NB
0042        1021 WRITE(6,6)(ABC(J,K,L),L=1,NC)
0043             WRITE(6,22)
0044             DO 1022 J=1,NA
0045             DO 1022 K=1,NB
0046        1022 WRITE(6,6)(ABCS( J,K,L),L=1,NC)
0047             WRITE(6,23)
0048             DO 1023 J=1,NA
0049             DO 1023 K=1,NB
0050        1023 WRITE(6,6)(ABCN(J,K,L),L=1,NC)
0051             WRITE(6,24
0052             DO 1024 J=1,NA
0053             DO 1024 K=1,NB
0054        1024 WRITE(6,6)(ABCBAR(J,K,L),L=1,NC)
0055             WRITE(6,25)
0056             DO 1025 J=1,NA
0057             DO 1025 K=1,NB
0058        1025 WRITE(6,6)(ABCS( J,K,L),L=1,NC)
0059             WRITE(6,39)
           C***
           C***  ABS SUMMARY MATRIX
0060             DO 1050 I=1,NS
0061             DO 1050 J=1,NA
0062             DO 1050 K=1,NB
0063             ABS(I,J,K)=0.0
0064             DO 1040 L=1,NC
0065             ABS(I,J,K)=ABS(I J,K) + Y(I,J,K,L)
0066        1040 CONTINUE
0067        1050 CONTINUE
           C***
           C***  ACS SUMMARY MATRIX
0068             DO 1070 I=1,NS
0069             DO 1070 J=1,NA
0070             DO 1070 L=1,NC
0071             ACS(I,J,L)=0.0
0072             DO 1060 K=1,NB
0073             ACS(I,J,L)=ACS(I J,L) + Y(I,J,K,L)
0074        1060 CONTINUE
0075        1070 CONTINUE
           C***
           C***  BCS SUMMARY MATRIX
0076             DO 1090 I=1,NS
0077             DO 1090 K=1,NB
0078             DO 1090 L=1,NC
0079             BCS(I,K,L)=0.0
0080             DO 1080  J=1,NA
0081             BCS(I,K,L)=BCS(I K,L) + Y(I,J,K,L)
0082        1080 CONTINUE
0083        1090 CONTINUE
           C***
           C***  AB SUMMARY MATRIX
```

```
      DO 1110 I=1,NA
      DO 1110 J=1,NB
      AB(I,J)=0.0
      ABSQ(I,J)=0.
      DO 1100 K=1,NC
      AB(I,J)=AB(I,J)+ABC(I,J,K)
      ABSQ(I,J)=ABSQ(I,J)+ABCSQ(I,J,K)
 1100 CONTINUE
      ABM(I,J)=AB(I,J)/(NC*NS)
      ABVAR(I,J)=ABSQ(I,J)/(NC*NS)-ABM(I,J)**2
      ABSD(I,J)=SQRT(ABVAR(I,J))
 1110 CONTINUE
      WRITE(6,37)
      WRITE(6,26)
      WRITE(6,38)
      WRITE(6,21)
      DO 1101 I=1,NA
 1101 WRITE(6,6)(AB(I,J),J=1,NB)
      WRITE(6,22)
      DO 1102 I=1,NA
 1102 WRITE(6,6)(ABSQ(I,J),J=1,NB)
      WRITE(6,23)
      DO 1103 I=1,NA
 1103 WRITE(6,6)(ABM(I,J),J=1,NB)
      WRITE(6,24)
      DO 1104 I=1,NA
 1104 WRITE(6,6)(ABVAR(I,J),J=1,NB)
      WRITE(6,25)
      DO 1105 I=1,NA
 1105 WRITE(6,6)(ABSD(I,J),J=1,NB)
      WRITE(6,40)
C***
C***  AC SUMMARY MATRIX
      DO 1130 I=1,NA
      DO 1130 K=1,NC
      AC(I,K)=0.0
      ACSQ(I,K)=0.
      DO 1120 J=1,NB
      AC(I,K)=AC(I,K)+ABC(I,J,K)
      ACSQ(I,K)=ACSQ(I,K)+ABCSQ(I,J,K)
 1120 CONTINUE
      ACM(I,K)=AC(I,K)/(NB*NS)
      ACVAR(I,K)=ACSQ(I,K)/(NB*NS)-ACM(I,K)**2
      ACSD(I,K)=SQRT(ACVAR(I,K))
 1130 CONTINUE
      WRITE(6,37)
      WRITE(6,27)
      WRITE(6,39)
      WRITE(6,21)
      DO 1121 I=1,NA
 1121 WRITE(6,6)(AC(I,K),K=1,NC)
      WRITE(6,22)
```

```
0134              DO 1122 I=1,NA
0135        1122 WRITE(6,6)(ACSQ(I,K),K=1,NC)
0136              WRITE(6,23)
0137              DO 1123 I=1,NA
0138        1123 WRITE(6,6)(ACM(I,K),K=1,NC)
0139              WRITE(6,24)
0140              DO 1124 I=1,NA
0141        1124 WRITE(6,6)(ACVAR(I,K),K=1,NC)
0142              WRITE(6,25)
0143              DO 1125 I=1,NA
0144        1125 WRITE(6,6)(ACSD(I,K),K=1,NC)
0145              WRITE(6,39)
            C***
            C***  BC SUMMARY MATRIX
0146              DO 1150 J=1,NB
0147              DO 1150 K=1,NC
0148              BC(J,K)=0.0
0149              BCSQ(J,K)=0.
0150              DO 1140 I=1,NA
0151              BC(J,K)=BC(J,K)+ABC(I,J,K)
0152              BCSQ(J,K)=BCSQ(J,K)+ABCSQ(I,J,K)
0153        1140 CONTINUE
0154              BCM(J,K)=BC(J,K)/(NA*NS)
0155              BCVAR(J,K)=BCSQ(J,K)/(NA*NS)-BCM(J,K)**2
0156              BCSD(J,K)=SQRT(BCVAR(J,K))
0157        1150 CONTINUE
0158              WRITE(6,37)
0159              WRITE(6,23)
0160              WRITE(6,38)
0161              WRITE(6,21)
0162              DO 1141 J=1,NB
0163        1141 WRITE(6,6)(BC(J,K),K=1,NC)
0164              WRITE(6,22)
0165              DO 1142 J=1,NB
0166        1142 WRITE(6,5)(BCSQ(J,K),K=1,NC)
0167              WRITE(6,23)
0168              DO 1143 J=1,NB
0169        1143 WRITE(6,5)(BCM(J,K),K=1,NC)
0170              WRITE(6,24)
0171              DO 1144 J=1,NB
0172        1144 WRITE(6,6)(BCVAR(J,K),K=1,NC)
0173              WRITE(6,25)
0174              DO 1145 J=1,NB
0175        1145 WRITE(6,6)(BCSD(J,K),K=1,NC)
0176              WRITE(6,39)
            C***
            C***  AS SUMMARY MATRIX
0177              DO 1170 I=1,NS
0178              DO 1170 J=1,NA
0179              AS(I,J)=0.0
0180              DO 1160 K=1,NB
0181              DO 1160 L=1,NC
```

```
      AS(I,J)=AS(I,J)+ Y(I,J,K,L)
 1160 CONTINUE
 1170 CONTINUE
C***
C*** BS SUMMARY MATRIX
      DO 1190 I=1,NS
      DO 1190 K=1,NB
      BS(I,K)=0.0
      DO 1180 J=1,NA
      DO 1180 L=1,NC
      BS(I,K)=BS(I,K)+Y(I,J,K,L)
 1180 CONTINUE
 1190 CONTINUE
C***
C***  CS SUMMARY MATRIX
      DO 2210 I=1,NS
      DO 2210 L=1,NC
      CS(I,L)=0.0
      DO 2200 J=1,NA
      DO 2200 K=1,NB
      CS(I,L)=CS(I,L)+Y(I,J,K,L)
 2200 CONTINUE
 2210 CONTINUE
C***
C***  SUMS OF SQ ARES FOR MAIN-EFFECTS  UNCORRECTED
      DO 2230 I=1,NA
      A(I)=0.0
      ASQ(I)=0.
      DO 2220 J=1,NB
      A(I)=A(I)+AB(I,J)
      ASQ(I)=ASQ(I)+ABSQ(I,J)
 2220 CONTINUE
      AM(I)=A(I)/(NB*NC*NS)
      AVAR(I)=ASQ(I)/(NB*NC*NS)-AM(I)**2
      ASD(I)=SQRT(AVAR(I))
 2230 CONTINUE
      WRITE(6,37)
      WRITE(6,29)
      WRITE(6,38)
      WRITE(6,21)
      WRITE(6,5)(A(I),I=1,NA)
      WRITE(6,22)
      WRITE(6,5)(ASQ(I),I=1,NA)
      WRITE(6,23)
      WRITE(6,5)(AM(I),I=1,NA)
      WRITE(6,24)
      WRITE(6,5)(AVAR(I),I=1,NA)
      WRITE(6,25)
      WRITE(6,6)(ASD(I),I=1,NA)
      WRITE(6,39)
      SSA=0.0
      DO 2240 I=1,NA
```

```
      SSA=SSA+A(I)**2/(NB*NC*NS)
 2240 CONTINUE
      DO 2260 J=1,NB
      B(J)=0.0
      BSQ(J)=0.
      DO 2250 I=1,NA
      B(J)=B(J)+AB(I,J)
      BSQ(J)=BSQ(J)+ABSQ(I,J)
 2250 CONTINUE
      BM(J)=B(J)/(NA*NC*NS)
      BVAR(J)=BSQ(J)/(NA*NC*NS)-BM(J)**2
      BSD(J)=SQRT(BVAR(J))
 2260 CONTINUE
      WRITE(6,37)
      WRITE(6,30)
      WRITE(6,30)
      WRITE(6,21)
      WRITE(6,6)(B(J),J=1,NB)
      WRITE(6,22)
      WRITE(6,6)(BSQ(J),J=1,NB)
      WRITE(6,23)
       WRITE(6,6)(BM(J),J=1,NB)
      WRITE(6,24)
       WRITE(6,6)(BVAR(J),J=1,NB)
      WRITE(6,25)
      WRITE(6,6)(BSD(J),J=1,NB)
      WRITE(6,39)
      SSB=0.0
      DO 2270 I=1,NB
      SSB=SSB+B(I)**2/(NA*NC*NS)
 2270 CONTINUE
       DO 2290 J=1,NC
      C(J)=0.0
      CSQ(J)=0.
      DO 2280 I=1,NA
      C(J)=C(J)+AC(I,J)
      CSQ(J)=CSQ(J)+ACSQ(I,J)
 2280 CONTINUE
      CM(J)=C(J)/(NA*NB*NS)
      CVAR(J)=CSQ(J)/(NA*NB*NS)-CM(J)**2
      CSD(J)=SQRT(CVAR(J))
 2290 CONTINUE
      WRITE(6,37)
       WRITE(6,31)
      WRITE(6,30)
      WRITE(6,21)
      WRITE(6,6)(C(J),J=1,NC)
      WRITE(6,22)
      WRITE(6,6)(CSQ(J),J=1,NC)
      WRITE(6,23)
      WRITE(6,6)(CM(J),J=1,NC)
      WRITE(6,24)
```

```
       WRITE(6,6)(CVAR(J),J=1,NC)
       WRITE(6,25)
       WRITE(6,6)(CSD(J),J=1,NC)
      WRITE(6,39)
      SSC=0.0
      DO 2300 I=1,NC
      SSC=SSC+C(I)**2/(NA*NB*NS)
 2300 CONTINUE
      DO 2320 I=1,NS
      S(I)=0.0
      DO 2310 J=1,NA
      DO 2310 K=1,NB
      S(I)=S(I)+ABS(I,J,K)
 2310 CONTINUE
 2320 CONTINUE
      SSS=3
       SSS=0.0
      DO 2330 I=1,NS
      SSS=SSS+S(I)**2/(NA*NB*NC)
 2330 CONTINUE
C***
C***  SUMS OF SQUARES-FIRST ORDER INTERACTIONS-UNCORRECTED
      SSAB=0.0
      DO 2340 I=1,NA
      DO 2340 J=1,NB
      SSAB=SSAB+AB(I,J)**2/(NC*NS)
 2340 CONTINUE
      SSAC=0.0
      DO 2350 I=1,NA
      DO 2350 J=1,NC
      SSAC=SSAC+AC(I,J)**2/(NB*NS)
 2350 CONTINUE
      SSBC=0.0
      DO 2360 I=1,NB
      DO 2360 J=1,NC
      SSBC=SSBC+BC(I,J)**2/(NA*NS)
 2360 CONTINUE
      SSAS=0.0
      DO 2370 I=1,NS
      DO 2370 J=1,NA
      SSAS=SSAS+AS(I,J)**2/(NB*NC)
 2370 CONTINUE
      SSBS=0.0
      DO 2380 I=1,NS
      DO 2380 J=1,NB
      SSBS=SSBS+BS(I,J)**2/(NA*NC)
 2380 CONTINUE
      SSCS=0.0
      DO 2390 I=1,NS
      DO 2390 J=1,NC
      SSCS=SSCS+CS(I,J)**2/(NA*NB)
 2390 CONTINUE
```

```
      C***
      C*** SUMS OF SQUARES OF HIGHER ORDER INTERACTIONS-UNCORRECTED
            SSABC=0.0
            DO 2400 I=1,NA
            DO 2400 J=1,NB
            DO 2400 K=1,NC
            SSABC=SSABC+ABC(I,J,K)**2/NS
       2400 CONTINUE
            WRITE(6,*)SABC
            SSABS=0.0
            DO 2410 I=1,NS
            DO 2410 J=1,NA
            DO 2410 K=1,NB
            SSABS=SSABS+ABS(I,J,K)**2/NC
       2410 CONTINUE
            SSACS=0.0
            DO 2420 I=1,NS
            DO 2420 J=1,NA
            DO 2420 K=1,NC
            SSACS=SSACS+ACS(I,J,K)**2/NB
       2420 CONTINUE
            SSBCS=0.0
            DO 2430 I=1,NS
            DO 2430 J=1,NB
            DO 2430 K=1,NC
            SSBCS=SSBCS+BCS(I,J,K)**2/NA
       2430 CONTINUE
      C***
      C***  CORRECTION FACTOR AND CORRECTED SUMS OF SQUARES
            X=SUM**2/(NA*NB*NC*NS)
            SST=SUMSQ-X
            SSA=SSA-X
            SSB=SSB-X
            SSC=SSC-X
            SSS=SSS-X
            SSAB=SSAB-X-SSA-SSB
            SSAC=SSAC-X-SSA-SSC
            SSBC=SSBC-X-SSB-SSC
            SSAS=SSAS-X-SSA-SSS
            SSBS=SSBS-X-SSB-SSS
             SSCS=SSCS-X-SSC-SSS
            SSABC=SSABC-X-SSA-SSB-SSC-SSAB-SSAC-SSBC
            SSABS=SSABS-X-SSA-SSB-SSS-SSAB-SSAS-SSBS
            SSACS=SSACS-X-SSA-SSC-SSS-SSAC-SSAS-SSCS
            SSBCS=SSBCS-X-SSB-SSC-SSS-SSBC-SSBS-SSCS
            SSABCS=SST      -SSA-SSB-SSC-SSS-SSAB-SSAC-SSBC-SSAS-SSBS-SSCS
           1-SSABC-SSABS-SSACS-SSBCS
            SSRES=SSAS+SSBS+SSCS+SSABS+SSACS+SSBCS+SSABCS
      C***
      C***  DEGREES OF FREEDOM
            NDFA=NA-1
            NDFB=NB-1
```

```
      NDFC=NC-1
      NDFS=NS-1
      NDFAB=NDFA*NDFB
      NDFAC=NDFA*NDFC
      NDFAS=NDFA*NDFS
      NDFBC=NDFB*NDFC
      NDFBS=NDFB*NDFS
      NDFCS=NDFC*NDFS
      NDFABC=NDFA*NDFB*NDFC
      NDFABS=NDFA*NDFB*NDFS
      NDFACS=NDFA*NDFC*NDFS
      NDFBCS=NDFB*NDFC*NDFS
      NDFABCS=NDFA*NDFB*NDFC*NDFS
      NDFRES=NS*(NA*NB*NC-1)
C***
C**** MEAN SQUARES
      AMS=SSA/NDFA
      BMS=SSB/NDFB
      CMS=SSC/NDFC
      SMS=SSS/NDFS
      ABMS=SSAB/NDFAB
      ACMS=SSAC/NDFAC
      BCMS=SSBC/NDFBC
      ASMS=SSAS/NDFAS
      BSMS=SSBS/NDFBS
      CSMS=SSCS/NDFCS
      ABCMS=SSABC/NDFABC
      ABSMS=SSABS/NDFABS
      ACSMS=SSACS/NDFACS
      BCSMS=SSBCS/NDFBCS
      ABCSMS=SSABCS/NDFABCS
      RESMS=SSRES/NDFRES
C***
C*** F RATIOS
      FA=AMS/ASMS
      FB=BMS/BSMS
      FC=CMS/CSMS
      FAB=ABMS/ABSMS
      FAC=ACMS/ACSMS
      FBC=BCMS/BCSMS
      FABC=ABCMS/ABCSMS
      FAR=AMS/RESMS
      FBR=BMS/RESMS
      FCR=CMS/RESMS
      FABR=ABMS/RESMS
      FACR=ACMS/RESMS
      FBCR=BCMS/RESMS
       FABCR=ABCMS/RESMS
      WRITE(6,8)
      WRITE(6,9)SSA,NDFA,AMS,FA,SSB,NDFB,BMS,FB,SSC,
     1NDFC,CMS,FC,SSS,NDFS,SMS
      WRITE(6,10)SSAS,NDFAS,ASMS,SSBS,NDFBS,BSMS,SSCS,
```

```
                 1NDFCS,CSMS
0422              WRITE(6,11)SSAB,NDFAB,ABMS,FAB,SSAC,NDFAC,ACMS,FAC,
                 1SSBC,NDFBC,BCMS,FBC
0423              WRITE(6,12)SSABS,NDFABS,ABSMS,SSACS,NDFACS,ACSMS,
                 1SSBCS,NDFBCS,BCSMS
0424              WRITE(6,13)SSABC,NDFABC,ABCMS,FABC,SSABCS,NFABCS,ABCSMS
0425              WRITE(6,14)SST
0426              WRITE(6,32)
0427              WRITE(6,33)SSA,NDFA,AMS,FAR,SSB,NDFB,BMS,FBR,SSC,NDFC,CMS,FCR,SSS,
                 1NDFS,SMS,SSAB,NDFAB,ABMS,FABR,SSAC,NDFAC,ACMS,FACR,SSBC,NDFBC,BCMS
                 2,FBCR,SSABC,NDFABC,ABCMS,FABCR,SSRES,NDFRES,RESMS,SST
0428              IF(NCEFF.EQ.ANYL)GO TO 999
0429            1 FORMAT(4I4,16A4)
0430            2 FORMAT(7X,F4.2)
0431            3 FORMAT(T10,6F12.2)
0432            4 FORMAT('1',T20,20A4)
0433            5 FORMAT(T5,'CELL MEANS')
0434            6 FORMAT('0',T5,F12.2)
0435            7 FORMAT('1',T5,'CELL STANDARD DEVIATIONS')
0436            8 FORMAT('1',T50,'SUMMARY OF ANALYSIS OF VARIANCE',//,T34,'NON-ADDIT
                 1IVE MODEL - TESTS USING FACTOR BY SUBJECT INTERACTIONS',///,T5,'SO
                 2URCE',T20,'SUMS OF SQUARES',T40,'DEGREES FREEDOM',T60,'MEAN SQUARE
                 3S',T80,'F-RATIOS')
0437            9 FORMAT('0',T5,'A',T20,F12.2,T40,I10,T60,F12.2,
                 1T80,F12.3,//,T5,'B',T20,F12.2,T40,I10,T60,F12.2,
                 2T80,F12.3,//,T5,'C',T20,F12.2,T40,I10,T60,F12.2,
                 3T80,F12.3,//,T5,'SUBJECTS',T20,F12.2,T40,I10,T60,F12.2)
0438           10 FORMAT('0',T5,'A X SUBJ',T20,F12.2,T40,I10,T60,F12.2,
                 1//,T5,'B X SUBJ',T20,F12.2,T40,I10,T60,F12.2,
                 2//,T5,'C X SUBJ',T20,F12.2,T40,I10,T60,F12.2)
0439           11 FORMAT('0',T5,'A X B',T20,F12.2,T40,I10,T60,F12.2,
                 1T80,F12.3,//,T5,'A X C',T20,F12.2,T40,I10,T60,F12.2,
                 2T80,F12.3,//,T5,'B X C',T20,F12.2,T40,I10,T60,F12.2,
                 3T80,F12.3)
0440           12 FORMAT('0',T5,'AB X SUBJ',T20,F12.2,T40,I10,T60,F12.2,
                 1//,T5,'AC X SUBJ',T20,F12.2,T40,I10,T60,F12.2,
                 2//,T5,'BC X SUBJ',T20,F12.2,T40,I10,T60,F12.2)
0441           13 FORMAT('0',T5,'A X B X C',T20,F12.2,T40,I10,T60,F12.2,
                 1T80,F12.3,//,T5,'ABC X SUBJ',T20,F12.2,T40,I10,T60,F12.2)
0442           14 FORMAT('0',T3,'TOTAL',T20,F12.2)
0443           20 FORMAT('0',T40,'STATISTICS FOR ABC MATRIX - CULLAPSED ACROSS SUBJE
                 1CTS')
0444           21 FORMAT('0','******************************************************
                 1****************************',//,T5,'SUMS',//,T5,'****************
                 2****************************************************************')
0445           22 FORMAT('0',T5,'***************************************************
                 1*****************************',//,T5,'SUMS OF SQUARES',//,T5,'****
                 2******************************************************************
                 3**********')
0446           23 FORMAT('0',T5,'***************************************************
                 1****************************',//,T5,'MEANS',//,T5,'***************
                 2******************************************************************
```

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                 5')
 0447            24 FORMAT('0',T5,'****************************************************
                   1*****************************',//,T5,'VARIANCES',//,T5,'**********
                   2******************************************************************
                   3****')
 0448            25 FORMAT('0',T5,'****************************************************
                   1*****************************',//,T5,'STANDARD DEVIATIONS',//,T5,'
                   2******************************************************************
                   3**************')
 0449            26 FORMAT('0',T22,'STATISTICS FOR AB MATRIX - COLLAPSED ACROSS SUBJEC
                   1TS AND FACTOR C')
 0450            27 FORMAT('0',T22,'STATISTICS FOR AC MATRIX - COLLAPSED ACROSS SUBJEC
                   1CTS AND FACTOR B')
 0451            28 FORMAT('0',T22,'STATISTICS FOR BC MATRIX - COLLAPSED ACROSS SUBJEC
                   1TS AND FACTOR A')
 0452            29 FORMAT('0',T50,'STATISTICS FOR LEVELS OF FACTOR A')
 0453            30 FORMAT('0',T50,'STATISTICS FOR LEVELS OF FACTOR B')
 0454            31 FORMAT('0',T50,'STATISTICS FOR LEVELS OF FACTOR C')
 0455            32 FORMAT('1',T50,'SUMMARY OF ANALYSIS OF VARIANCE',//,T40,'ADDITIVE
                   1 MODEL - NO POOLING OF SUBJECT INTERACTIONS',///,T5,'SOURCE',T20,'SUMS
                   2 OF SQUARES',T40,'DEGREES FREEDOM',T60,'MEAN SQUARES',T80,'F-RATIO
                   3S')
 0456            33 FORMAT('0',T5,'A',T20,F12.3,T40,I10,T60,F12.3,T80,F12.4,//,T5,'B',
                   1T20,F12.3,T40,I10,T60,F12.3,T80,F12.4,//,T5,'C',T20,F12.3,T40,I10,
                   2T60,F12.3,T80,F12.4,//,T5,'SUBJECTS',T20,F12.3,T40,I10,T60,F12.3,/
                   3/,T5,'A X B',T20,F12.3,T40,I10,T60,F12.3,T80,F12.4,//,T5,'A X C',T
                   420,F12.3,T40,I10,T60,F12.3,T80,F12.4,//,T5,'B X C',T20,F12.3,T40,I
                   510,T60,F12.3,T80,F12.4,//,T5,'A X B X C',T20,F12.3,T40,I10,T60,F12
                   6.3,T80,F12.4,//,T5,'RESIDUAL',T20,F12.3,T40,I10,T60,F12.3,//,T3,'T
                   7OTAL',T20,F12.2)
 0457            34 FORMAT(I4)
 0458            35 FORMAT(20A4)
 0459            36 FORMAT('0',T10,20A4)
 0460            37 FORMAT('1',T3,'====================================================
                   1===============================================')
 0461            38 FORMAT('0',T3,'====================================================
                   1===============================================')
 0462            39 FORMAT('0',//T3,'END*END*END*END*END*END*END*END*END*END*END*END*E
                   1ND*END*END*END*END*END*END*END*END*END*END*END*END*END')
 0463            40 FORMAT('0',T5,'----------------------------------------------------
                   1-----------------------------------------------')
 0464            50 FORMAT(F2.0)
 0465               STOP
 0466               END
```

APPENDIX 3

HEART RATE, RESPIRATORY GASES, AND ENERGY COST FOR THE SIX PILOT STUDY TRIALS AT A TREADMILL SPEED OF 2.9 MPH AND GRADE OF 18%. EACH TABLE SHOWS THE DATA FOR ONE SUBJECT: UPPER VALUES ARE MEANS, LOWER VALUES ARE STANDARD DEVIATIONS

MEANS AND STANDARD DEVIATIONS

SUBJECT: AC

Phase of Trial	HR	$\dot{V}_E$ l/min	O_{2_E} %	CO_{2_E} %	R	$\dot{V}_{O_2}$ l/min	E Kcal/min
Standing	73 5	11.5 1.5	18.11 0.24	2.16 0.28	0.72 0.06	0.35 0.07	1.62 0.30
Horizontal Walking	84 5	20.5 1.0	17.16 0.48	2.68 0.34	0.66 0.05	0.83 0.09	3.83 0.38
Grade Walking, 5th & 6th min.	140 5	56.0 1.8	16.51 0.33	3.72 0.23	0.80 0.04	2.59 0.23	12.30 0.94
Grade Walking 9th & 10th min.	146 6	59.0 3.1	16.41 0.24	3.79 0.26	0.79 0.02	2.80 0.19	13.20 0.87
Recovery, first 5 min.	114, 91, 86, 84, 83	21.9 1.8	17.36 0.18	3.19 0.12	0.86 0.05	0.80 0.10	3.89 0.47
Recovery, second 5 min.	83, 84 81, 82 78	12.9 1.1	18.00 0.49	2.41 0.52	0.78 0.10	0.40 0.08	1.89 0.36

MEANS AND STANDARD DEVIATIONS

SUBJECT: RH

Phase of Trial	HR	$\dot{V}_E$ l/min	O_{2_E} %	CO_{2_E} %	R	$\dot{V}_{O_2}$ l/min	E Kcal/min
Standing	80 9	11.0 1.1	18.48 0.28	2.24 0.37	0.93 0.09	0.28 0.04	1.31 0.18
Horizontal Walking	96 3	23.9 2.3	17.75 0.17	2.77 0.13	0.83 0.04	0.79 0.09	3.78 0.42
Grade Walking, 5th & 6th min.	163 6	62.6 2.6	17.18 0.14	3.55 0.26	0.92 0.08	2.39 0.13	11.68 0.46
Grade Walking 9th & 10th min.	172 4	65.5 2.3	17.35 0.26	3.42 0.19	0.94 0.07	2.37 0.18	11.66 0.75
Recovery, first 5 min.	149, 115 106, 104 105	25.4 1.3	17.36 0.30	3.71 0.30	1.04 0.03	0.90 0.07	4.51 0.35
Recovery, second 5 min.	101, 98 99, 97 99	12.3 1.6	18.22 0.28	2.35 0.22	0.86 0.07	0.37 0.09	1.64 0.26

MEANS AND STANDARD DEVIATIONS

SUBJECT: JM

Phase of Trial	HR	$\dot{V}_E$ 1/min	O_{2_E} %	CO_{2_E} %	R	$\dot{V}_{O_2}$ 1/min	E Kcal/ min
Standing	53 8	10.7 0.9	18.41 0.44	2.17 0.23	0.85 0.13	0.29 0.08	1.40 0.33
Horizontal Walking	75 7	21.5 1.7	17.65 0.09	2.63 0.11	0.76 0.55	0.74 0.06	3.51 0.28
Grade Walking, 5th and 6th min.	130 3	48.7 0.8	16.79 0.10	3.56 0.20	0.82 0.04	2.10 0.06	10.04 0.23
Grade Walking, 9th and 10th min.	132 2	50.7 1.8	16.90 0.11	3.62 0.20	0.86 0.05	2.10 0.12	10.16 0.50
Recovery, first 5 min.	99, 85, 79, 78, 76	19.1 0.9	17.28 0.18	3.36 0.24	0.89 0.08	0.68 0.11	3.47 0.20
Recovery, second 5 min.	75, 76, 73, 75, 76	12.1 1.2	18.50 0.11	2.35 0.03	0.93 0.06	0.30 0.04	1.47 0.19

MEANS AND STANDARD DEVIATIONS

SUBJECT: GP

Phase of Trial	HR	$\dot{V}_E$ l/min	O_2 $\%_E$	CO_2 $\%_E$	R	$\dot{V}_{O_2}$ l/min	E Kcal/min
Standing	80 9	11.2 1.1	18.69 0.25	1.80 0.23	0.78 0.08	0.26 0.04	1.24 0.16
Horizontal Walking	86 5	23.2 1.9	17.71 0.07	2.55 0.27	0.75 0.09	0.79 0.07	3.73 0.32
Grade Walking, 5th & 6th min.	138 9	60.0 2.5	17.15 0.11	3.52 0.23	0.87 0.06	2.32 0.06	11.29 0.24
Grade Walking, 9th & 10th min.	143 6	61.7 2.9	17.09 0.13	3.44 0.18	0.86 0.07	2.44 0.15	11.88 0.61
Recovery, first 5 min.	118, 108, 100, 100, 97	24.8 1.2	17.75 0.41	2.99 0.15	0.93 0.10	0.80 0.12	4.01 0.46
Recovery, second 5 min.	98, 95, 91, 96, 95	14.2 0.9	18.60 0.14	1.89 0.11	0.78 0.09	0.37 0.08	1.65 0.18

MEANS AND STANDARD DEVIATIONS

SUBJECT: AT

Phase of Trial	HR	$\dot{V}_E$ 1/min	O_{2_E} %	CO_{2_E} %	R	$\dot{V}_{O_2}$ 1/min	E Kcal/min
Standing	83 10	11.6 1.4	18.41 0.61	2.00 0.49	0.77 0.11	0.32 0.10	1.47 0.45
Horizontal Walking	97 3	25.5 1.8	17.43 0.40	2.69 0.22	0.73 0.07	0.94 0.13	4.43 0.56
Grade Walking 5th & 6th min.	156 3	64.6 2.4	16.98 0.37	3.42 0.18	0.83 0.08	2.64 0.28	12.69 1.23
Grade Walking 9th & 10th min.	160 3	67.7 1.9	17.01 0.28	3.34 0.14	0.82 0.06	2.77 0.28	13.24 1.20
Recovery, first 5 min.	144, 123 110, 103 105	24.3 1.3	17.34 0.25	3.15 0.21	0.84 0.08	0.90 0.008	4.34 0.36
Recovery, second 5 min.	101, 99 99, 97 102	15.2 1.5	18.16 0.35	2.31 0.30	0.80 0.07	0.45 0.09	2.15 0.42

MEANS AND STANDARD DEVIATIONS

SUBJECT: MZ

Phase of Trial	HR	$\dot{V}_E$ 1/min	O_{2_E} %	CO_{2_E} %	R	$\dot{V}_{O_2}$ 1/min	E Kcal/ min
Standing	79 4	10.9 1.8	18.09 0.51	2.23 0.41	0.74 0.05	0.33 0.07	1.53 0.33
Horizontal Walking	98 4	24.6 2.3	16.34 0.31	3.34 0.24	0.67 0.03	1.19 0.10	5.53 0.43
Grade Walking 5th & 6th min.	156 4	66.7 1.8	16.02 0.35	4.20 0.19	0.82 0.05	3.40 0.25	16.29 1.07
Grade Walking 9th & 10th min.	166 4	72.3 2.7	16.06 0.30	4.15 0.23	0.81 0.03	3.66 0.16	17.52 0.75
Recovery, first 5 min.	141, 116 112, 108 107	26.8 1.1	16.32 0.45	4.05 0.27	0.84 0.04	1.28 0.14	6.16 0.64
Recovery, second 5 min.	105, 105 107, 107 105	14.0 0.8	17.67 0.29	2.70 0.25	0.79 0.01	0.48 0.06	2.28 0.30

APPENDIX 4

EXAMPLE OF THE COMPUTER WRITE-OUT FOR ONE TESTING SESSION OF THREE TRIALS FOR ONE SUBJECT

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          THE ENERGY COST AND EFFICIENCY OF UPHILL WALKS
              A  H.R    CHAPMAN   A  2                   26  1 71
            BODY WEIGHT STRIPPED=      76.10
      BODY WEIGHT WITH    APPARATUS=      81.10
               BODY SURFACE AREA = 1.96
          BAROMETRIC  PRESSURE=  740
                   RATE OF ASCENT= 1[illegible]00
                  TREADMILL SPEED=1.550
                         GRADE=   16

PHASE   TRIAL  HEART RATE VOL(L/MIN)  O2%  CO2%    R  VO2(L/MIN)  E(KCAL/MIN) EW(KCAL/MIN/100KG)  EBSA(KCAL/MIN/2M*M)

                      89         11.1   18.09  2.22 0.727   0.334        1.57          2.06             1.60

                      80         12.1   18.58  2.03 0.819   0.296        1.42          1.86             1.45

                      76         11.7   17.95  2.35 0.735   0.370        1.74          2.29             1.78

STANDING MEAN         81         11.6   18.21  2.20 0.760   0.333        1.58          2.07             1.61

                      86         16.9   16.81  3.41 0.783   0.731        3.48          4.58             3.55

                      80         17.6   17.41  2.96 0.797   0.649        3.10          4.07             3.16

                      81         16.4   17.15  3.07 0.765   0.650        3.08          4.05             3.15

HORIZONTAL MEAN       82         17.0   17.12  3.15 0.782   0.677        3.22          4.23             3.29

                     106         31.2   16.58  3.68 0.805   1.413        6.76          8.88             6.90

                     105         32.1   16.89  3.40 0.799   1.354        6.47          8.50             6.60

                     102         32.1   17.06  3.55 0.888   1.272        6.20          8.14             6.32

GRADE    MEAN        104         31.8   16.84  3.54 0.831   1.346        6.48          8.51             6.61

                      90         15.7   17.71  3.27 1.008   0.505        2.52          3.32             2.57

                      81         15.9   17.29  3.49 0.938   0.587        2.89          3.80             2.95

                      84         15.9   17.46  3.13 0.869   0.568        2.75          3.62             2.81

RECOVERY MEAN         85         15.9   17.49  3.30 0.938   0.554        2.72          3.58             2.78

KGM/MIN             KCAL/MIN          GROSS EFFICIENCY %          NET EFFICIENCY %A           NET EFFICIENCY %B

 535.6               1.255                 18.56                      24.17                       38.27

 535.6               1.255                 19.40                      24.83                       37.20

 535.6               1.255                 20.25                      28.17                       40.31
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APPENDIX 5

GROSS EFFICIENCY (GE) OF GRADE WALKING BY SUBJECT, RATE OF VERTICAL ASCENT (V) AND GRADE (G)

Subject	Vertical Rate of Ascent, ft/hr											
	1300 Grade %				1800 Grade %				2300 Grade %			
	12	16	20	24	12	16	20	24	12	16	20	24
AC	18.73	18.56	19.41	17.97	19.39	23.80	21.58	20.53	17.62	20.29	21.10	20.89
	16.84	19.40	16.98	18.40	18.71	20.71	21.45	23.22	17.62	18.17	20.45	21.60
	18.37	20.25	18.40	18.76	18.69	19.55	22.45	20.59	18.43	19.66	21.98	20.23
RH	16.36	23.74	17.18	20.08	20.05	21.37	20.78	22.84	19.97	19.49	20.01	21.92
	17.10	19.57	19.44	18.52	19.27	17.44	20.00	19.40	19.72	21.42	19.64	21.34
	17.78	17.53	17.92	21.06	17.53	20.27	19.62	23.54	19.85	19.15	20.53	21.94
JM	19.57	22.95	20.38	18.25	16.81	20.55	22.25	23.09	18.85	19.58	20.09	22.45
	17.63	21.06	17.18	18.46	17.53	20.93	20.42	21.71	18.08	20.84	18.86	20.79
	15.61	21.26	17.92	16.89	17.83	19.77	21.22	21.65	17.33	20.63	18.90	21.00
GP	17.66	19.59	20.26	21.80	16.12	19.02	19.89	21.51	17.04	21.94	21.27	20.62
	17.23	18.74	16.93	19.34	17.95	19.57	21.15	24.41	17.04	20.94	21.04	22.79
	16.35	17.93	18.39	21.33	21.37	19.02	19.37	20.43	16.89	19.00	22.21	22.41
AT	20.68	19.75	20.76	21.40	19.15	21.27	19.55	19.85	17.80	20.91	23.28	20.81
	15.96	19.26	19.32	19.30	17.33	21.55	22.32	17.52	17.25	23.04	20.30	22.68
	16.34	18.12	19.49	19.91	16.14	19.23	18.89	20.25	18.03	20.46	21.54	21.70
MZ	16.67	21.72	20.76	19.26	17.62	19.12	22.20	19.84	14.29	20.06	24.19	20.48
	19.36	19.00	18.94	18.44	17.44	19.25	19.57	20.23	14.78	21.95	20.31	21.00
	15.80	18.17	21.98	17.69	17.49	18.33	20.95	19.97	14.92	19.75	21.05	21.44

APPENDIX 6

NET EFFICIENCY (NES) WITH A DEDUCTION FOR STANDING METABOLISM, BY SUBJECT, RATE OF VERTICAL ASCENT (V) AND GRADE (G)

Subject	Vertical Rate of Ascent, ft/hr											
	1300 Grade %				1800 Grade %				2300 Grade %			
	12	16	20	24	12	16	20	24	12	16	20	24
AC	20.20	24.17	26.39	24.68	22.01	28.63	25.95	25.97	21.37	23.63	24.25	23.97
	20.36	24.83	21.67	24.29	22.68	24.87	27.16	31.31	21.02	20.73	23.69	24.22
	24.57	28.17	23.95	23.68	21.89	22.82	27.78	25.97	22.43	22.78	26.65	24.12
RH	20.39	29.25	20.58	26.58	24.73	24.91	25.45	27.66	22.63	22.32	22.51	24.40
	22.33	24.38	25.79	24.65	23.28	20.48	23.64	23.23	22.31	24.65	22.57	24.48
	22.52	21.32	23.15	28.66	20.33	25.07	24.22	29.08	22.71	21.46	23.06	25.65
JM	24.53	29.80	27.30	22.74	19.71	24.68	26.43	27.59	22.49	23.21	23.07	26.26
	23.43	27.47	24.56	26.33	22.48	25.32	26.65	28.95	21.30	26.05	22.28	25.05
	21.62	26.24	24.97	23.39	22.70	23.28	27.23	29.72	20.51	25.26	22.53	25.87
GP	21.44	25.00	24.94	25.76	18.00	22.04	24.53	25.43	18.40	25.02	24.29	22.48
	22.38	23.60	20.36	22.97	21.47	23.42	27.14	28.79	19.33	24.43	24.77	26.01
	20.75	23.83	22.53	27.36	26.05	24.15	23.46	23.71	19.25	22.21	26.51	25.54
AT	23.70	24.98	24.32	28.30	22.51	24.68	22.34	23.44	20.19	23.78	26.85	24.47
	19.47	25.34	23.41	24.78	20.83	27.59	28.81	20.11	19.87	27.42	23.00	26.86
	20.30	22.64	22.39	26.36	19.00	24.36	23.27	24.88	20.48	22.82	25.54	25.02
MZ	19.78	28.50	29.69	25.19	20.62	23.13	26.71	24.18	16.03	22.19	28.13	23.38
	25.26	24.55	25.23	24.42	20.38	22.77	22.86	25.92	16.92	24.95	23.30	24.82
	19.50	21.81	31.10	23.60	20.66	21.94	25.11	24.09	16.91	23.05	24.23	25.17

APPENDIX 7

NET EFFICIENCY (NEH) WITH A DEDUCTION FOR THE ENERGY LOST OF HORIZONTAL WALKING BY SUBJECT

RATE OF VERTICAL ASCENT (V)

AND GRADE (G)

Subject	Vertical Rate of Ascent, ft/hr											
	1300 Grade %				1800 Grade %				2300 Grade %			
	12	16	20	24	12	16	20	24	12	16	20	24
AC	41.88	38.27	33.92	29.81	36.52	44.73	38.77	35.45	35.61	30.97	28.37	29.59
	29.97	37.20	29.51	29.29	33.45	32.22	35.62	42.07	39.14	25.84	28.17	32.87
	37.77	40.31	32.43	32.86	31.50	29.73	36.25	31.82	46.80	27.41	34.08	29.33
RH	29.08	49.01	27.12	38.70	35.59	34.88	35.34	40.00	36.20	30.24	29.04	29.23
	33.07	35.81	35.80	29.68	33.67	24.83	32.76	27.47	35.81	41.93	29.32	31.18
	32.74	27.65	30.57	36.11	30.11	38.10	31.81	37.08	33.32	31.46	30.75	34.46
JM	36.67	43.98	33.56	31.30	31.22	38.60	35.93	38.43	31.90	29.86	28.78	35.25
	37.38	37.38	29.60	35.52	31.98	41.69	34.36	37.50	38.10	35.29	30.10	33.94
	30.16	38.30	37.34	30.58	34.75	30.41	34.18	47.66	33.18	32.30	29.65	34.57
GP	40.08	45.02	41.89	40.44	26.90	32.32	32.31	33.46	25.63	37.54	32.67	30.00
	42.75	34.42	28.30	30.28	34.27	31.79	35.72	41.80	28.07	36.27	29.35	33.04
	50.77	33.45	32.83	37.48	40.02	34.81	39.58	30.38	30.23	30.46	35.31	33.67
AT	33.92	37.18	35.52	37.55	37.58	38.10	29.91	27.88	33.02	33.39	35.62	29.63
	30.86	42.29	36.15	33.32	31.84	36.88	40.35	23.19	29.23	34.95	33.22	36.38
	27.79	34.84	31.87	34.65	27.00	31.72	29.37	29.44	31.46	32.03	35.87	33.45
MZ	38.38	43.77	42.26	33.84	31.80	30.36	33.85	28.73	21.20	29.48	36.29	28.49
	43.62	35.88	32.74	28.67	32.68	31.75	29.34	32.39	24.83	33.66	30.51	29.87
	27.03	36.60	45.26	27.97	29.86	29.26	35.21	31.46	23.91	30.62	30.96	32.88