A new approach for estimating metabolic rates for manual materials handling jobs is presented. This approach was applied to 48 different jobs. The model validation showed a correlation coefficient of 0.95 between the measured and predicted metabolic rates. The coefficient of variation (standard error/sample mean) was 10.2 percent.

Prediction of metabolic rates for manual materials handling jobs*

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introduction

Assuring that job demands do not exceed workers' capabilities is the responsibility and goal of those in the field of ergonomics. If a person's capabilities are known, they may be used as a criterion for job design. In manual materials handling tasks a person must be capable of performing without excessive strain or fatigue. Biomechanical and physiological measurements provide an objective scale on which to compare different types of industrial jobs with respect to physical strain and fatigue. Metabolic energy expenditure rate and heart rate are the physiological measurements which have been suggested most often in the literature for determining the maximum task intensity that can be continuously performed without accumulating an excessive amount of physical fatigue.(1-9)

In activities such as repetitive lifting and load carying, large muscle groups perform submaximal, dynamic contractions. During this type of work a person's endurance is primarily limited by the capacity of the oxygen transporting and utilization systems (maximum aerobic power).(2) The methods for the determination of a person's maximum aerobic power will not be discussed in this paper, but excellent discussions are presented in the literature.(2,10-12) By relating the energy expended in a job to the aerobic power of the individuals for endurance effort, an objective assessment can be made of the work capacity of the worker for carrying out a particular job without undue fatigue.(3-8) The metabolic energy expenditure requirements of manual materials handling jobs can also be used to evaluate alternate work methods,(9) to determine wage and salary,(4,9,13) to establish duration and frequency of rest breaks,(1,8,13-14) and to determine the heat stress when temperature and/or humidity are in excess of a normal comfort range.(2)

Christensen(15) proposed that work could be performed at 50 percent of the maximum aerobic power for an eight-hour work day. Serious doubts were expressed by Astrand(10) that this was too high an expectation. Research by Brouha(16) supports the theory that a work capacity limit based on 50 percent of the maximum aerobic power of an individual was a fatigue-generating energy expenditure rate. Studies by Lehmann(17) (as stated by Bink,(3) Bink,(8) Snook and Irvine,(18) Andrews,(19) etc.) recommended 33 percent of the maximum aerobic power of a normal healthy person as the maximum energy expenditure rate that should be expended for an eight-hour work day. Generally, 16 Kcal/min is taken as the maximum aerobic power of a normal healthy young male for a highly dynamic job (walking, bicycling, etc.).(11) In fact, 80 percent of American men have a maximum aerobic power below 16 Kcal/min.(11) For an eight-hour continuous work period, a physical work capacity limit of 5.2 Kcal/min is recommended by Chaffin(11) (for a young healthy male). This physical work capacity is based on thirty-three percent of 16 Kcal/min taken as the maximum aerobic power of an average healthy young male. As stated by Moores,(13) the aforementioned 5.2 Kcal/min was also deemed an average

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acceptable level by Lehmann from studies undertaken throughout German industry. Indeed, older workers and female workers will require a much smaller physical work capacity limit.

The research reported in this paper will assume that physical capacity standard issue is resolvable and presents an approach to the next problem: predicting the metabolic requirements of a job based upon worker's characteristics and a description of the job.

present methods for estimating energy requirements

Many researchers have used the measurement of oxygen utilization rate to estimate the metabolic energy expenditure for various manual activities. Past studies have shown that a large range of metabolic requirements exist in common manual labor.(1,9,11,14,16,20) At present the three commonly used methods for determining metabolic rates are:

A. Measurement of oxygen consumption on the job.
B. Macro-studies (table values).
C. Micro-studies.

On the job measurement of oxygen utilization is the most straightforward for determining the metabolic requirements of an existing job. However, on the job measurement of oxygen utilization is sometimes difficult due to interference of measuring equipment with the normal work methods. Also, in manual handling jobs the methods, work operations, weight and size of working material and the particular worker are constantly changing.(21) Therefore, oxygen uptake measurements made today may not be valid sometime later in the future. Moreover, a single oxygen uptake measurement does not reflect how personal and task factors influence metabolic work load.

The "macro-studies", on the other hand, have a common objective of determining the metabolic energy expended by "average" people who are performing complex manual activities under different working conditions (such as unloading coal cars, handling boxes, stapling, loading corrugated cartons,(9) working in a hot environment, construction work,(5) etc.).

Table values provide only a very rough approximation of the metabolic load of any given job. Errors can be easily made due to the overly simplistic descriptions of jobs. For example, lifting 4.5 Kg of load from the floor to a 0.91 m high table is more than twice as expensive in net metabolic cost (net metabolic rate is defined as total metabolic rate minus resting standing/sitting metabolic rate for standing/sitting task) as lifting the same load from a 0.91 m high table to a 1.68 m high table.(14) Therefore, a single value for lifting, for example, would be in serious error. Metabolic energy expenditure estimates for more than 1000 different activities are available in the literature.(20) However, these are very specific to particular work situations employed at the time of measurement and do not for the most part reflect the effects of important personal and task parameters such as fequencies, weights, heights, etc. Further, lack of task descriptions makes it difficult to interpolate or extrapolate such values.

A second group of studies (designated as "micro-studies") relates the magnitude of the metabolic energy expended by a person to the magnitude of various common physical measures of manual activity. The micro-study approach, primarily through regression and analysis of variance models, provides functional relationships between the metabolic energy expenditure rates and one or more of the physical parameters of the job.(11,14,21-32) A general conclusion is that relatively minor changes in the physical parameters that are commonly used to describe a person's manual activity result in significant changes in the metabolic energy expenditure rate. These micro-studies are primarily limited to the metabolic cost for walking, carrying and lifting; and do not include other manual materials handling activities such as lowering, pushing a load on the bench top, holding and different types of movement of arms which may comprise 50 percent of a manual materials handling job.

The need for better predictive models for metabolic energy expenditure rate has been pointed out from time to time by researchers in the past.(21,22,32,33) According to Hamilton:(22)

> "Perhaps the most noteworthy gap in the work physiology literature is the lack of information on job design parameters and physiological costs in a form useful for the design work. There is a need to develop models of general applicability to explain and predict the effcts of

changes in the different job design parameters on physiological cost. Such models should include the factors of work pace, load weight and horizontal and vertical movement."

In short, any physiological fatigue criteria (whether 5.2 Kcal/min or some other) cannot be used by the work analyst unless he can convert it into useful design parameters such as frequencies, weights, distances, etc. Consequently, the purpose of this study was to develop a method for estimating the metabolic energy expenditure rate based on physical descriptors of a job and the worker which would aid the job analyst/designer.

the model

The model is based on the assumption that a job can be divided into simple tasks, (activity elements) and that the average metabolic energy expenditure rate of the job can be predicted by knowing the energy expenditures of the simple tasks and the time duration of the job. By dividing the job into task elements and assigning a metabolic cost to each task based on measurable factors of force, distance, frequency, posture, technique, gender, body weight, and time within each task, an energy requirement to perform just that task can be determined. The average metabolic energy expenditure is simply equal to the sum of the energy demands of the task, and the maintenance of body posture, averaged over time. Mathematically:

$$\bar{\dot{E}}_{job} = \frac{\sum_{i=1}^{n_l} \dot{E}_{pos_i} x t_i + \sum_{i=1}^{n} \Delta E_{task_i}}{T} \qquad (1)$$

$\bar{\dot{E}}_{job}$ = Average energy expenditure rate of the job (Kcal/min)

$\dot{E}_{pos_i}$ = Metabolic energy expenditure rate due to maintenance of i^{th} posture (Kcal/min)

t_i = Time duration of i^{th} posture (min)

n_l = Total number of body postures employed in the job

ΔE_{task_i} = Net metabolic energy expenditure of the i^{th} task in steady state (Kcal)

n = Total number of tasks in the given job

T = Time duration of the job (min)

The metabolic energy expenditure rate of maintaining a body posture ($\dot{E}_{pos}$) is a function of gender, body weight and body posture. The net increase in metabolic energy expenditure of a task (ΔE_{task}) includes both static and dynamic work. The personal and task variables employed to account for their effects on net increase in metabolic energy expenditure of a task (ΔE_{task}) are gender, body weight, weight of the load or force applied by the hands, frequency of loading the body (pace), vertical height range of the task, forward and lateral movement of the arms in the horizontal plane, vertical movement of the body, grade and composition of the walking surface, speed of walking and carrying loads, body posture, technique employed to perform the task, and the time duration of the task.

These are also the important variables that have been shown to have significant effect on net metabolic energy expenditure of a task at submaximal levels.(11,14,21-32) Of course, age, training, physical fitness, size and awkwardness of load, speed of performing a task, handle design, temperature and humidity, all have a bearing on the metabolic energy expenditure rate of a task. However, in moderate to heavy manual materials handling tasks at submaximal levels under normal working conditions (wherein temperature, humidity and social environment are not in extreme), some of these factors play less important roles.(24) Further, some of these factors are difficult to measure. Based on past literature, it is assumed that the effects of these factors on the net metabolic energy expenditure rate at submaximal level is negligible compared to those included in the model (for a complete description, see Garg(24)). Also, most of the data needed for using this model can be obtained from existing motion and time study data or predetermined motion-time data systems which are widely used in industry today.

net metabolic cost of a task

An extensive investigation of the literature on metabolic energy expenditure rates of simple tasks revealed that most of the data were not

TABLE I
Subjects' Age, Body Weight, Stature, and Standing Metabolic Rates

	Females			Males		
Subject	1	2	3	4	5	6
Age (Yrs.)	18	22	19	21	20	22
Body Weight (Kg)	55.8	63.5	80.9	60.7	74.5	91.2
Height (m)	1.68	1.80	1.73	1.68	1.83	1.80
Standing n	11	5	9	9	11	9
Metabolic Rate $\bar{X}$	1.38	1.28	1.36	1.36	1.88	1.89
(Kcal/min) S	0.14	0.12	0.22	0.24	0.18	0.18

n = Number of observations
$\bar{X}$ = Sample mean
S = Sample standard deviation

suitable for this model primarily due to the lack of specific task descriptors. A systematic collection of metabolic energy expenditure rate data for 28 tasks was undertaken in the laboratory.(24) Over 540 oxygen uptake measurements were made. Different levels of weight of the load (or force) and frequency of loading the body (pace) were employed for each task. All experiments were designed so that main effects and some of their interactions accounting for most of the variation in energy expenditure rate could be analyzed.(24)

Six volunteers were selected. They were all judged to be healthy college students of 18 to 22 years of age. Table I summarizes the physical characteristics of each subject.

The tote box used for the experiments was 0.3 m wide, 0.18 m high and 0.16 m deep. It was provided with cushioned handles both at the sides and at the top for two and one handed tasks, respectively. Lead shots were used to bring the tote box to a given level of load. The 'net metabolic rates' for standing and sitting body postures were calculated as follows:

$$\Delta\dot{E} = \dot{E} - \dot{E}_s$$

where:

$\Delta\dot{E}$ = Net metabolic rate (Kcal/min.)
$\dot{E}$ = Total steady state metabolic rate (Kcal/min.)
$\dot{E}_s$ = The resting, standing or sitting metabolic rate (as appropriate) (Kcal/min.)

All the experiments were performed for at least 10 minutes with a minimum of 20 minutes of rest between two successive experiments. The first five minutes was the warm-up period, or the time allowed to reach a steady state heart rate and oxygen uptake rate. During the last five minutes, ventilatory minute volume and the oxygen content of expired air were measured wth a dry gas meter (or Max plank respirometer for walking and carrying) and Beckman model C2 oxygen analyzer, respectively. Ventilatory minute volume was corrected for standard temperature, pressure and dry air. The rate of metabolic energy expenditure was determined by Weir(34) calorimetric equation which eliminates the R.Q. correction factor. Respired CO_2 concentrations were periodically checked and showed normative values for the R.Q. (about 0.8 to 0.9).

The experiments were conducted in an airconditioned laboratory. Barometric and psychometric measurements were taken periodically during the experiments. The dry-bulb temperature ranged between 21 and 25° C. and the relative humidity between 50 and 58 percent.

Prediction equations for the net metabolic cost (ΔE_{task}) for each task as a function of personal and task variables were developed via least squared error regression analysis. These equations and some data from the literature for estimating the net metabolic costs of various manual materials handling tasks are given in the Appendix.

For a detailed description of definitions of the above tasks, see Garg(24)(p. 88). It is worth mentioning that all the prediction equations for the net metabolic cost of different tasks, especially for lifting and lowering, are independent of the height of the worker even though the stature of the six subjects varied from

1.63 to 1.83 m. Heights of lift and lower are with reference to the floor level and are independent of worker's knee, waist, chest and overhead references. Speed of lift and lower was not controlled, though the subjects were instructed to maintain normal speed of operation. In equations 18 and 19, 'F' represents pushing/pulling force applied by the hands and, therefore, includes weight of the load as well as coefficient of friction of the surface. This can easily be measured by a hand dynamometer.

It is of importance to note that gender effects appear for certain tasks (lifting, lowering, pushing at bench height, lateral movement of arms of 90 degrees) but not for others (holding, walking, carrying, forward movement of arms, lateral movement of arms of 180 degrees, etc.). Indeed, gender effect was found statistically significant for all the tasks except walking and carrying. However, its contribution in explaining variance in net metabolic rate was of little importance. To maintain simplicity of equations for practical applications, gender effect was dropped from the prediction equations for these tasks and regression analysis was performed without gender and its interactions with other variables. This inconsistency about gender effect is in agreement with the controversial literature on effect of gender on metabolic rate at submaximal levels.(35-36) Any substantiative reason for the occasionally reported energy efficiency advantage of women at moderate work loads, even when divided by body weight, appears unclear at this time.

It is worth mentioning that the prediction equations are presented as net metabolic cost per performance (for example, Kcal/lift). Therefore, these equations can also be used to estimate the net metabolic cost of infrequently occurring tasks or the elements that appear in special cycles of a repetitive job. Thus, the model can be applied to both repetitive and semi-repetitive jobs.

The tasks listed in the Appendix (equations 5 to 26) certainly do not cover all industrial job activities. Jobs that require a significant amount of small hand or arm movements (such as cutting wire, cranking, etc.) are difficult to break down into task components. The following represents an assessment of hand and arm work load for these tasks:

Type of Work	Net Metabolic Rate* (Kcal/min.)
Hand work, light	0.2
Hand work, heavy	0.6
Work with one arm, light	0.7
Work with one arm, heavy	1.5
Work with both arms, light	1.2
Work with both arms, heavy	2.2

*Based on information from "Assessment of heat Stress and Strains," Engineering Series Bulletin No. 9-71, Industrial Health Foundation, Inc., Pittsburgh.

It is of importance to note that tasks listed above are to be treated just like any other task. For example, if in a given job a worker is performing heavy arm work with one arm for t_1 minutes, the metabolic component of this task in the model would be $1.5t_1$ Kcal.

summary of prediction equations and comparison with past studies

Results of the regression analysis on 28 different tasks studied were very encouraging. The correlation coefficients and coefficients of variations (ratio of standard error about the regression line to sample mean) were on the order of 0.98 and 0.08, respectively. Results showed that most of the variation (80 to 97%) in net metabolic cost of a task with a given technique could be explained by first order interactions of body weight and load with the frequency of loading the body. Similarly, interactions of body weight and load with the square of speed of walking explained 92 to 94 percent variation in net metabolic rate of walking and carrying loads. Main effects and other higher order interactions, although statistically significant, were found to be of little importance in explaining additonal variation about the mean value of the net metabolic cost.

Direct comparisons of metabolic costs for different tasks with the values given in the literature were limited etiher because of lack of data in the past literature or due to significant differences in experimental conditions.

TABLE II

Comparison of Measured Metabolic Rates (Snook(28)) and Predicted Metabolic Rates for Lifting Tasks

Load (Kg)	Work Intensity (Kg–m/min.)	Measured Metabolic Rate(28) Mean (Kcal/min.)	Measured Metabolic Rate(28) Std. Dev.	Predicted Metabolic Rate (Kcal/min.)	Difference $\frac{B-A}{B}$ x 100
15.9	20	3.48	0.42	3.23	−7.7
15.9	40	5.17	0.69	4.65	−11.1
15.9	60	6.40	0.70	6.03	−6.1
15.9	80	7.51	0.80	7.40	−1.4
22.7	30	4.00	0.45	3.61	−10.8
22.7	40	4.58	0.48	4.19	−9.0
22.7	60	5.83	0.57	5.57	−1.0
22.7	80	7.01	0.56	7.05	+0.5
29.5	40	4.31	0.52	3.87	−11.3
29.5	60	5.31	0.53	4.93	−7.7
29.5	80	6.48	0.65	5.98	−8.3

However, for the comparisons that were possible, metabolic energy expenditures predicted from regression equations seem to be in general agreement with previous findings. The comparisons between the metabolic rates predicted from the regression equations presented in this paper and the past literature for holding, walking, carrying and lifting loads are summarized as follows:

Chaffin(32) developed a prediction model for the metabolic energy expended during arm activities. The model was primarily limited to weight holding activities in the sagittal plane. The net metabolic rates for holding 4.5, 13.6 and 22.7 Kg of load against the waist by a 75 Kg seated subject, based on one subject as reported by Chaffin,(32) are 0.22, 0.71 and 1.66 Kcal/min., respectively. The corresponding values for a standing worker from equation 16 are 0.28, 0.84 and 1.40 Kcal/min. In view of large inter-subject variability in net metabolic costs (300% between two subjects) as reported by Chaffin, it is reasonable to conclude that the values estimated from this research are comparable to the findings of Chaffin.

The relationship between the metabolic energy expenditure rate and speed of walking has been investigated by many researchers. The best agreement among the past studies is that the metabolic energy expenditure rate at the level walk is proportional to the body weight plus the product of body weight and the square of speed of walking for a limited range of walking speed. If 1.68 Kcal/min is taken as the resting standing metabolic rate of a 70 Kg person, the estimates of total metabolic rate for walking at 0.83 and 1.39 m/s (3 and 5 Km/hr) from the present and the past studies are as follows:

Author	Total Metabolic Rate for Level Walk (Kcal/min.) at walking speed 0.83 m/s	1.39m/s
Present study	3.39	5.51
Walt and Wyndham(29)	3.23	5.25
Grimby and Soderholm(10)	3.10	5.01
Cotes and Meade(11)	3.57	4.94
Kamon(17)	3.34	4.89
Givoni and Goldman(25)	2.89	4.51

Therefore, the metabolic rates for walking reported from this research are a little higher especially at higher speed of walking (4.7 to 18%). Some of these differences are due to differences in the experimental conditions and terrains employed in the past studies and this study. All the past studies reported above were carried on a level treadmill with the subjects wearing light clothing. In this study, subjects wore pants, shirts and heavy work shoes, walked on a finished concrete corridor. Walking on surfaces other than treadmill involves a higher metabolic rate as reported by Givoni and Goldman. Secondly, in this study, at 1.34 m/s the subjects walked back and forth on a 10 m path having a 90° turn. This involved a total of eight 180 degree turns every minute at both ends of the path. These particular settings resulted in frequent acceleration, deceleration and increased lateral movement of the hips. It is believed that the experimental settings of this

TABLE III
Partitioning of the Job Into Tasks and Estimated Net Metabolic Costs of the Tasks

Task No.	Task	Technique	Number of Times Performed	Load (Kg)	Task Description or Vertical Movement of Work Piece (m)		Time (min.)	Net Estimated Metabolic Cost (Kcal)
					from	to		
1	Lift	Stoop	14	30.7	0.25	1.17	–	10.74
2	Lift	Arm	4	30.7	1.17	1.52	–	1.29
3	Lift	Arm	2	30.7	1.17	1.78	–	1.03
4	Lift	Arm	1	30.7	1.17	2.03	–	0.71
5	Carry	In Front	14	30.7	7.5	steps	0.092	9.69
6	Lateral Movement of Arms of 90°	Standing, Both Hands	28	30.7	–	–	–	3.78
7	Lower	Stoop	1	30.7	1.17	0.51	–	0.29
8	Lower	Arm	4	30.7	1.17	0.81	–	0.54
9	Lower	Arm	1	30.7	1.52	1.17	–	0.18
10	Lower	Arm	2	30.7	1.78	1.17	–	0.58
11	Walk	–	14	0	7.5	steps	0.115	2.54

study are more comparable to the industrial work environment. Similar conclusions were drawn for carrying loads also.

Snook[28] studied the metablic energy expenditure rates for lifting tote boxes (0.48 x 0.34 x 0.14 m) through a 0.51 m lift from floor level to knuckle height. The means and standard deviations of measured metabolic rates on 30 workers and the corresponding predicted metabolic rates from equations 3 and 6, assuming 77 Kg as average body weight, are summarized in Table II.

It is concluded from Table II that the total metabolic rates predicted from equations 3 and 6 are comparable to the means of the measured metabolic rates and certainly fall within one standard deviation of the measured metabolic rates. The difference between the predicted and the means of the measured metabolic rates ranged from +0.5 to −11.3 percent. The average of the absolute percent differences was 6.8 percent, which was found to be on the same order as the intra-subject variability reported by Wyndham, *et al.*[38]

The predicted metabolic rates for lifting were consistently lower than the means of the measured metabolic rates with one exception. One possible explanation for the underprediction is that the workers employed in manual materials handling tend to be heavier than the 50 percentile U.S. population because of the nature of the job. If the average body weight of the 30 workers was assumed to be 91 Kg, the predicted metabolic rates were found to be consistently higher than the means of the measured metabolic rates. In this case, the average of the percent differences between the predicted and the measured metabolic rates was 3.3 percent. This further illustrates that both the personal and the task variables play an important role in estimating the metabolic requirements of a given task. Any inaccuracy in the description of the work will significantly affect the estimate of metabolic rate for the job.

an example of model application

A film of steel workers handling steel frames was analyzed on a motion and time study projector for a total of 5.27 minutes (work time + 15% rest allowance). The job consisted of primarily lifting an iron frame, carrying it to the cart, stacking it on the cart and walking back to the machine. The actual breakdown of the job into tasks and the net metabolic costs of each task are given in Table III. The job was performed by two male workers who weighed approximately 91 Kg. The weight of the iron frame was 61.4 Kg and it was assumed that this weight was equally distributed between the two workers. It was not possible to measure the distance of walking or carrying loads. Therefore, the number of steps walked or carried were counted to estimate the distances.

In Table III, the first task is lifting the 30.7 Kg of load from a vertical height of 0.25 m to 1.2 m from the floor. This height range is broken down into two vertical height ranges, namely 0.25 to 0.8 m and 0.8m to 1.2 m. The net metabolic cost of this task is estimated using equations 5 and 8. Similarly, net metabolic costs of tasks 2 to 4 are estimated from equation 8. From the film, it was observed that the workers on the average, took 7.5 steps in 0.092 minutes while carrying the load.

In the laboratory three subjects were asked to carry 15 Kg of load at 0.89 and 1.34 m/s walking speeds. The average steps taken at the two walking speeds were 88 and 112 per minute. It was estimated that 7.5 steps in 0.092 minute would approximately correspond to a walking speed of 0.83 m/sec. (3 Km/hr.) Of course, stride length may vary with the weight of the load and leg length; particularly when the men are locked together carrying a load between them. This will certainly affect the speed of walking and the estimated speed of walking of 0.83 m/s may be a gross approximation to the actual speed of walking.

Using this 0.83 m/s for speed of walking, the net metabolic cost for carrying the load is estimated from equation 14. Similarly, the net metabolic cost for task 11, i.e., walking, is estimated from equation 12. The task 6 is lateral movement of arms of 90 degrees in the standing posture. The net metabolic cost of this task is estimated from equation 22. The next four tasks are lowering the load. The vertical range of lowering for task 7 is divided into two parts; one from 1.2 m to 0.8 m and the other from 0.8 m to 0.51 m. The net metabolic cost for this task is estimated form equations 9 and 11. Similarly, net metabolic costs for tasks 8 to 10 are estimated from equation 11.

The estimates of net metabolic costs for the eleven tasks are given in the last column in Table III. These net metabolic costs sum to a total of 31.37 Kcal. Since the workers maintained standing posture during the entire period of analysis (5.27 min.), the postural component of metabolic cost is 2.18 Kcal/min. as estimated from equation 3. Therefore, the average metabolic rate of the job from equation 1 is as follows:

$$\bar{E}_{job} = \frac{2.18 \times 5.27 + 31.37}{5.27}$$

$$= 8.13 \text{ Kcal/min.}$$

This is a fairly high metabolic rate and a person cannot be expected to last for eight hours on this job without adequate rest periods. It is also evident from Table III that the two major components leading to this high metabolic rate are lifting (task I) and carrying (task 5). One of the possible solutions to reduce this high metabolic rate may be to put the cart near the lifting operation; thus, avoiding the carrying and walking metabolic costs.

The mean of the measured metabolic rates of these workers was 7.5 Kcal/min. Thus, the model predicted value differs form the mean of the measured values by +0.63 Kcal/min. or 7.7 percent. It is of importance to note that the film was not shot at the same time when the metabolic measurements on workers were made. Therefore, a difference between the pace (work rate) in the film and the pace when the metabolic measurements were made will lead to an error in prediction. Extrapolations were needed to estimate the metabolic cost of lifting 30.7 Kg of load since 25 Kg was the maximum load employed for lifting in this study. Similarly, the metabolic cost of walking at 0.66 m/s was extrapolated as 0.89 m/s which was the minimum walking speed employed in this study.

model validation

The model predicted metabolic rates were compared with the measured metabolic rates on a wide variety of jobs. These included steel workers, refuse collection, twister operations and various carton handling jobs reported in the literature.(14,22) All of these were complex manual materials handling jobs involving many simple tasks. Subjects used for the model validation were traditional male workers employed in their respective jobs. Therefore, this was an independent model validation and the subjects employed for the validation were not the same as those employed in the laboratory for developing the prediction equations 5 to 26. Further, the oxygen uptake measurements were made by people other than the present authors for all the jobs employed for the model validation with the exception of refuse collection. The following is a brief summary of the model validation:

Aquilano(14) studied the effects of load, pace and vertical height range on the metabolic cost of jobs involving lifting and moving loads with the arms. A total of 20 jobs were studied using different levels of weight of the load, work pace and height of the lift. Six male workers

TABLE IV

Comparison of the Model Predicted and the Measured Metabolic Rates from Aquilano[11]

Job No.	Model Predicted Metabolic Rate (Kcal/min.) A	Mean* of Measured Metabolic Rate (Kcal/min.) B	Range** of Measured Metabolic Rates (Kcal/min.)	Difference	
				Net A − B	% $\frac{A-B}{B} \times 100$
1	5.16	4.62	3.97 - 5.25	+0.54	11.7
2	7.24	6.47	5.20 - 7.79	+0.77	11.9
3	9.14	8.28	6.70 - 9.82	+0.86	9.2
4	4.37	4.0	3.59 - 4.91	+0.37	9.2
5	7.59	6.72	6.19 - 7.93	+0.87	12.9
6	10.71	9.77	8.66 - 11.21	+0.94	9.6
7	5.33	4.84	3.99 - 5.86	+0.49	10.1
8	7.61	6.72	5.69 - 8.35	+0.89	13.2
9	10.21	9.16	7.81 - 10.80	+1.05	11.4
10	4.75	4.38	3.39 - 4.97	+0.37	8.4
11	9.35	8.09	6.63 - 9.63	+1.26	15.5
12	13.19	11.95	10.37 - 14.04	+1.24	10.3
13	4.39	3.73	2.89 - 4.10	+0.66	17.6
14	4.29	4.28	3.69 - 4.98	+1.01	23.5
15	6.27	5.07	4.10 - 6.03	+1.20	23.6
16	4.16	3.79	3.29 - 4.46	+0.37	9.7
17	6.59	6.09	4.97 - 6.77	+0.50	8.2
18	8.34	8.10	6.70 - 9.72	+0.24	2.9
19	6.92	5.17	4.17 - 5.53	+1.75	33.8
20	7.04	5.70	5.40 - 5.96	+1.34	23.5

*Mean of six subjects with two trials per subject.

**Range on six subjects.

performed each job twice. For a detailed description of the breakdown of the jobs into tasks see Garg.(24) The model predicted and means and ranges of the measured metabolic rates on six male workers are given in Table IV. It is of importance to note from Table IV that for all the twenty jobs, the model overpredicted. the mean of the differences between the model predicted and the measured metabolic rates is 0.84 Kcal/min. or 13.2 percent. Fifteen out of

TABLE V

Comparison of the Model Predicted and the Measured Metabolic Rates from Hamilton and Chase[22]

Job No.	Model Predicted Metabolic Rate (Kcal/min.) A	Mean* of Measured Metabolic Rate (Kcal/min.) B	Range** of Measured Metabolic Rates (Kcal/min.)	Difference	
				Net A − B	% $\frac{A-B}{B} \times 100$
1	3.32	3.20	2.85 - 3.40	+0.12	3.7
2	3.68	3.62	3.08 - 3.96	+0.06	1.7
3	4.06	3.94	3.56 - 4.35	+0.12	3.0
4	4.43	4.52	3.78 - 5.07	−0.09	1.9
5	4.13	3.89	3.77 - 4.36	+0.24	6.2
6	4.70	4.63	4.46 - 4.99	+0.07	1.5
7	5.26	5.20	4.55 - 5.81	+0.06	1.1
8	5.80	5.85	5.36 - 6.76	−0.05	0.8
9	4.96	4.62	4.09 - 5.15	+0.34	7.4
10	5.70	5.58	4.84 - 6.20	+0.12	2.1
11	6.44	6.50	5.77 - 7.13	−0.06	0.9
12	7.18	7.43	6.47 - 7.91	−0.25	3.4
13	5.77	5.76	4.95 - 6.39	+0.01	0.2
14	6.69	6.88	6.25 - 7.98	−0.19	2.8
15	7.63	8.18	6.56 - 9.42	−0.55	6.7
16	8.55	9.65	7.89 - 12.09	−1.10	11.4

TABLE VI
Comparison of the Model Predicted and the Measured Metabolic Rates for Twister Operations

Job No.	Model Predicted Metabolic Rate (Kcal/min.) A	Measured Metabolic Rate (Kcal/min.) B	Difference Net $A - B$	Difference Percent $\frac{A-B}{B} \times 100$
1	5.12	5.5	−0.38	6.9
2	5.57	6.4	−0.83	12.9
3	4.44	4.4	+0.04	0.9
4	4.33	4.2	+0.13	3.1
5	4.63	4.5	+0.13	2.8
6	4.62	4.8	−0.18	3.7
7	5.28	6.3	+1.02	16.2
8	3.97	3.8	+0.17	4.5

twenty predicted metabolic rates are well within the range of the measured values. It is worth mentioning that mean of inter-subject variability (coefficient of variation) on six young male subjects as estimated from Aquilano's data was on the order of 13.6 percent.

Hamilton and chase(22) studied the metabolic rates for carton handling. Six young male workers (19-26 years of age) performed all 16 combinations of load weight (4.5, 6.8, 9.1 and 11.4 Kg) and work pace (6, 9, 12, and 15 cartons per minute).

From Table V, the mean of measured metabolic rates for the six workers varies from 3.20 to 9.65 Kcal/min. The corresponding model predicted metabolic rates vary from 3.32 to 8.55 Kcal/min. Thus, the model responds reasonably well to the changes in the physical work load.

The difference between the model predicted and the measured metabolic rates varies from 0.2 to 11.4 percent. The mean of absolute differences for the sixteen jobs is 0.21 Kcal/min. or 3.8 percent. This mean difference is well within the intra-subject variability of up to 8% reported by Wyndham.(38) For nine out of sixteen jobs, the model overpredicted and for the remaining seven jobs it underpredicted. It is of importance to note that the model predicted metabolic rates for all the sixteen jobs well within the corresponding range of measured metabolic rates.

Oxygen uptake measurements were made on three male workers, employed by the City of Ann Arbor, while each one was collecting refuse in a different residential area. At the same time, films were shot to record all their body movements. All the refuse bags and containers were also weighed. The average weights of the refuse bags in the three areas studied were 7.3, 7.7 and 10.9 Kg. The model predicted and the measured metabolic rates for the three jobs are as follows:

See table at bottom of page.

Job No.	Predicted Metabolic Rate (Kcal/min.)	Measured Metabolic Rate (Kcal/min.)	Difference Absolute $A - B$	Difference % $\frac{A-B}{B} \times 100$
1	6.50	6.96	-0.46	6.6
2	7.15	7.57	-0.42	5.5
3	7.65	7.48	+0.17	2.3

The mean of absolute difference for the three jobs is 0.35 Kcal/min or 4.8 percent. The differences between the model predicted and the measured metabolic rates are of the same order as the intra-subject variability. The breakdown of the refuse collection into the tasks, also showed that in refuse collection, walking, carrying , and climbing in and out of the truck consumed as much metabolic energy as lifting and lowering the refuse containers.(24)

Eight jobs (known as twister operations) from a cable manufacturing company available on video tapes were analyzed for predicting metabolic rates. These jobs consisted of changing supply and takeup reels weighing 10.5 to 35.9 Kg; cutting, pulling, brazing and disposing wires; tagging and freeing tension arm, etc. The mean of the absolute differences between the model predicted and the measured metabolic rates is 0.36 Kcal/min or 7.5 percent (Table VI). For five out of eight jobs, the model overpredicted and for the remaining three jobs it underpredicted.

summary of model validation

The model predicted metabolic rates for complex jobs were compared with the measured metabolic rates by dividing each complex job into simple tasks and estimating the metabolic cost for each task. A total of 48 comparisons were made. The measured metabolic rates varied from 3.2 to 11.95 Kcal/minute. The absolute difference between the model predicted and the measured metabolic rates varied from 0.2 ot 33 percent. For 34 out of 48 cases the model overpredicted and for the remaining 14 cases the model underpredicted. It was felt that this overprediction was primarily due to the use of untrained subjects employed for laboratory experiments. The measured and the model predicted metabolic rates for the 48 cases compared are plotted in Figure 1. The regression analysis between the measured and the predicted metabolic rates, resulted in the following equation:

$$\dot{E}_p = 1.043\ \dot{E}_m$$

where:

$\dot{E}_p$ = The model predicted metabolic rate (Kcal/min.)

$\dot{E}_m$ = The measured metabolic rate (Kcal/min.)

The correlation coefficient and the standard coefficient and the standard error were 0.95 and 0.61, respectively. The predictions from the model accounted for 90.8 percent of the variation in the measured metabolic rates. The coefficient of variation (standard deviation/sample mean) was 10.2 percent, which is very reasonable when compared to intra-individual coefficient of variation of 3.5 to 7.2 percent.(38)

conclusions

This research shows that the metabolic rate prediction model can be used to estimate the metabolic rates of a wide variety of manual materials handling jobs. The predictions from the model are very reasonable and acceptable for most practical applications. The partitioning of a job into task factors also shows which particular components are most stress producing in terms of metabolic energy expenditure, thereby being useful for job design. Furthermore, the prediction model gives a structure to all the factors, except training and environment, which have been shown by the past researchers to affect a person's metabolic energy expenditure rate.

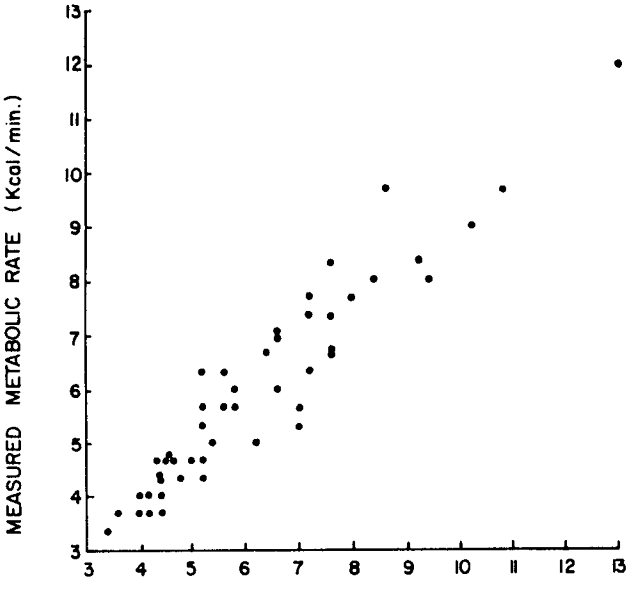

Figure 1 — The measured versus the model predicted metabolic rates.

It is hoped that the model may be used in the future as a criteria for designing manual materials handling jobs that a person is capable of performing without excessive strain or physical fatigue. An examination of the relationships between energy expenditure, as estimated by the prediction model, and the work study engineer's assessment of the job is facilitated with such a model. This will lead to exchange of information between exponents of the two disciplines and could lead to improvements in the application of work measurement and production standards. Predetermined motion time data systems may develop a new set of motion time values which would consider physiological stresses. This research combined with existing static strength prediction models makes it possible to form a computer assisted work place – methods design system which can be used to predict more comprehensively the total human performance capability.

appendix

maintenance of body postures:*

Sitting $\dot{E} = 0.023\ BW$ (2)

Standing $\dot{E} = 0.024\ BW$ (3)

Standing, bent position $\dot{E} = 0.028\ BW$ (4)

net metabolic cost of tasks:

stoop lift (Kcal/lift)

$$\Delta E = 10^{-2}[0.325\ BW\ (0.81 - h_1) + (1.41L + 0.76\ S \times L)\ (h_2 - h_1)] \text{ for } h_1 < h_2 \leqslant 0.81 \qquad (5)$$

squat lift (kcal/lift)

$$\Delta E = 10^{-2}[0.514\ BW\ (0.81 - h_1) + (2.19L + 0.62\ S \times L)\ (h_2 - h_1)] \text{ for } h_1 < h_2 \leqslant 0.81 \qquad (6)$$

one hand lift (Kcal/lift)

$$\Delta E = 10^{-2}[0.352\ BW\ (0.81 - h_1) + 3.03L\ (h_2 - h_1)] \text{ for } h_1 < h_2 \leqslant 0.81 \qquad (7)$$

arm lift (Kcal/lift)

$$\Delta E = 10^{-2}[0.062\ BW\ (h_2 - 0.81) + (3.19L - 0.52\ S \times L)(h_2 - h_1)] \text{ for } 0.81 < h_1 < h_2 \qquad (8)$$

stoop lower (Kcal/lower)

$$\Delta E = 10^{-2}[0.268\ BW\ (0.81 - h_1) + 0.675L\ (h_2 - h_1) + 5.22\ S\ (0.81 - h_1)] \text{ for } h_1 < h_2 < 0.81 \qquad (9)$$

squat lower (Kcal/lower)

$$\Delta E = 10^{-2}[0.511\ BW\ (0.81 - h_1) + 0.701L\ (h_2 - h_1)] \text{ for } h_1 < h_2 \leqslant 0.81 \qquad (10)$$

arm lower (Kcal/lower)

$$\Delta E = 10^{-2}[0.093\ BW\ (h_2 - 0.81) + (1.02L + 0.37\ S \times L)\ (h_2 - h_1)] \text{ for } 0.81 < h_1 < h_2 \qquad (11)$$

walking (Kcal)

$$\Delta E = 10^{-2}(51 + 2.54\ BW \times V^2 + 0.379\ BW \times G \times V)\ t \qquad (12)$$

carrying, loads held at arms length at sides (in one or both hands) (Kcal)

$$\Delta E = 10^{-2}[80 + 2.43\ BW \times V^2 + 4.63L \times V^2 + 4.62L + 0.379\ (L + BW)\ G \times V]\ t \qquad (13)$$

carrying, loads held against thighs or against waist (Kcal)

$$\Delta E = 10^{-2}[68 + 2.54\ BW \times V^2 + 4.08L \times V^2 + 11.4L + 0.379\ (L + BW)\ G \times V]\ t \qquad (14)$$

holding, at arms length, against thighs or at sides (both hands) (Kcal)

$$\Delta E = 0.037\ L \times t \qquad (15)$$

holding, against waist (Kcal)

$$\Delta E = 0.062\ L \times t \qquad (16)$$

holding, at arms length in one hand (Kcal)

$$\Delta E = 0.088\ L \times t \qquad (17)$$

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*For definition see Aberg, *et.al.* 21

pushing/pulling, at bench height (0.8 meter) (Kcal/push)

$$\Delta E = 10^{-2}X(0.112\ BW + 1.15F + 0.505\ S \times F) \quad (18)$$

pushing/pulling, at 1.5 meter height (Kcal/push)

$$\Delta E = X\ (0.086 + 0.036F) \quad (19)$$

lateral movement of arms of 180 degrees, both hands (Kcal/lateral movement of arms)

$$\Delta E = 10^{-2}\ (0.11\ BW + 0.726L) \quad (20)$$

lateral movement of arm of 180 degrees, one hand (Kcal/lateral movement of arm)

$$\Delta E = 10^{-2}\ (0.097\ BW + 0.946L) \quad (21)$$

lateral movement of arms of 90 degrees, standing, one or both hands (Kcal/lateral movement of arms.)

$$\Delta E = 10^{-2}\ (3.31 + 0.629L + 0.143\ S \times L) \quad (22)$$

lateral movement of arms of 90 degrees, sitting, both hands (Kcal/lateral movement of arms)

$$\Delta E = 10^{-2}\ (3.5 + 0.682L + 0.321\ S \times L) \quad (23)$$

lateral movement of arm of 90 degrees, sitting, one hand (Kcal/lateral movement of arm)

$$\Delta E = 10^{-2}\ (2.54 + 1.1L + 0.248\ S \times L) \quad (24)$$

forward movement of arms, standing, one or both hands (Kcal/movement of arms)

$$\Delta E = 10^{-2}\ X\ (3.57 + 1.23L) \quad (25)$$

forward movement of arms, sitting, one or both hands (Kcal/movement of arms)

$$\Delta E = 10^{-2}\ X\ (6.3 + 2.71L) \quad (26)$$

Where:

$\dot{E}$ = Metabolic rate (Kcal/min.)
ΔE = Kcal for walking, carrying and holding. For all other tasks, units are Kcal/performance.
BW = Body weight (Kg)
F = Average pushing/pulling force applied by hands (Kg).
G = Grade of the walking surface (%).
h_1 = Vertical height from floor (m); starting point for lift and end point for lower.
h_2 = Vertical height from floor (m); end point for lift and starting point for lower.
L = Weight of the load (Kg)
S = Gender; 1 for males; 0 for females
V = Speed of walking (m/s)
X = Horizontal movement of work piece (m)
t = Time (minutes)

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