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PREDICTION OF PHYSICAL WORKLOAD IN REDUCED GRAVITY ENVIRONMENTS

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ABSTRACT

This paper describes the background, development, and application of a methodology to predict human energy expenditure and physical workload in low gravity environments, such as a Lunar or Martian base. Based on a validated model to predict energy expenditures in Earth-based industrial jobs, the model relies on an elemental analysis of the proposed job. Because the job itself need not physically exist, many alternative job designs may be compared in their physical workload. The feasibility of using the model for prediction of low gravity work was evaluated by lowering body and load weights, while maintaining basal energy expenditure. Comparison of model results was made both with simulated low gravity energy expenditure studies and with reported Apollo 14 Lunar EVA expenditures. Prediction accuracy was very good for walking and for cart pulling on slopes less than 15°, but the model underpredicted the most difficult work conditions. This model was applied to example core sampling and facility construction jobs, as presently conceptualized for a Lunar or Martian base. Resultant energy expenditures and suggested work-rest cycles were well within the range of moderate work difficulty. Future model development requirements were also discussed.

1. INTRODUCTION

1.1. Need for Work Prediction Tools

The National Commission on Space (1986) has recently strongly recommended that the U.S. proceed in a research program to "support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars (p. 193)". If working in low gravity space environments is to become commonplace, the physical workload imposed by everyday tasks must be well understood. Based on extrapolations from previously developed models, we now have an opportunity to develop low gravity job design tools to insure that workloads imposed by tasks will not be beyond an average worker's capability. Although many aspects of work are becoming more cognitive and less physical in nature, the initial population of the Moon and other planets will require a great deal of physical work. Prediction of the physical workload of low gravity physical jobs will allow an estimation of the amount of rest required during a given job shift. In turn, the required amount of EVA surface time can be estimated. This paper presents a technique, extrapolated from Earth-based models of human energy expenditure, for predicting the physical workload imposed by a job in low gravity environments. Although many of the models likely will require significant modification for lower gravity work prediction, the elemental job analysis methodology is quite applicable.

1.2. Work Efficiency, Job Design, and Energy Expenditure

Humans are relatively inefficient when compared to working machines. Under the most optimal conditions, we can convert about 30% of input food energy to useful work, with the remaining 70% is wasted as heat (Sanders and McCormick, 1987). The design of a working task, nutrition, and other personal health factors dictate whether work is performed at a low or high efficiency. For example, shoveling in a stooped posture has an efficiency of about 3%, whereas shoveling in a more erect posture has about 6% energy efficiency (Grandjean, 1981). Webb (1973) reported that respiration is relatively inefficient at less than 5%, common tasks are 10-20% efficient, whereas bicycling and walking on an inclined treadmill may be upwards of 35% efficient in converting input energy to useful work. Careful design of jobs can insure that an individual is operating at the highest possible efficiency level, by lowering energy expenditure levels as much as possible.

Measurement of heat production provides a basis for estimating the efficiency of work. The rate of energy expenditure, in Kilocalories/minute (Kcal/min) can, in fact, provide a convenient measure of the difficulty of work. A resting individual expends about 1.5-2.5 Kcal/min, or about 1440-2400 Kcal per 16 hour waking day, just to perform the body's vital functions.[1] This basal expenditure is always present. On top of one's basal energy expenditure, additional energy is required to perform useful work, required when the body's limbs are moved through a distance. These additional task-based expenditures can exceed 10 Kcal/min for grueling work. The physical demands of a job or task may be defined through a consensus understanding of energy expenditure limits by the body. A well-accepted gradation of work demand was published by the American Industrial Hygiene Association (1971), and is shown in Table 1. The stated expenditures, for a healthy adult male, include both basal and task-based energy expenditures (E's), and vary from resting (1.5 Kcal/min) to Unduly Heavy Work (>12.5 Kcal/min). These E's may be physiologically measured, as described below. The example tasks, from Webb (1973), allow a more subjective understanding of the work difficulty. Writing while sitting at a table is essentially resting or basal E, whereas walking in loose snow can be unduly heavy work.

1.3. Objectives

This study has the objective of proving the feasibility of predicting physical workload in low gravity tasks by extrapolating from an Earth-based energy expenditure prediction model. After initial model development, an error analysis will add corrections to the model. As an example of model application, a sample task presently being designed for a Lunar or Martian base will then be subjected to workload and work-rest cycle analysis.

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[1]Nutritional intake must compensate for this energy expenditure. A common misconception is that calories, as opposed to kilocalories, are the basic common unit of food energy.

TABLE 1. WORK GRADE AND ENERGY EXPENDITURES, ADAPTED FROM AIHA (1971)

WORK GRADE	$\dot{E}$ (KCAL/MIN)	ENERGY/8 HR (KCAL/8 HR)	HEART RATE (BEATS/MIN)†	SAMPLE TASKS
Rest (sitting)	1.5	<720	60-70	Writing
Very Light Work	1.6-2.5	768-1200	65-75	Riding in Car/Typing
Light Work	2.5-5.0	1200-2400	75-100	Slow Walk/Lecturing
Moderate Work	5.0-7.5	2400-3600	100-125	Crawling/Tennis
Heavy Work	7.5-10.0	3600-4800	125-150	Chopping Wood/Stair Climb
Very Heavy Work	10.0-12.5	480-6000	150-180	Basketball/Cycling
Unduly Heavy Work	>12.5	>6000	>180	Wrestling/Walking in snow

†Note: These are typically observed heart rates; actual rates will vary highly
*Source: Webb (1973)

2. CURRENT JOB DESIGN TOOLS

2.1. Measurement of Energy Expenditure

The energy expended by a working individual may be inferred by measuring rate of O_2 consumption and/or CO_2 production while performing a task. The volume of expired air is measured during a specified time period, and the percentage of O_2 and/or CO_2 in this sample is taken. The difference in O_2/CO_2 percentage between inspired and expired air indicates percentage utilization/production. When multiplied by volume of expired air and divided by time, the rate of O_2 consumption/CO_2 production in volume/time is obtained. For a healthy, working adult, with normal nutrition and metabolism, about 4.9 Kcal of energy is generated for each liter of O_2 consumed/CO_2 produced (Ästrand and Rodahl, 1977). Other methods of physiological determination of energy expenditure also exist, such as direct measurement of heat generation, or inference from heart rate. Lunar EVA expenditures were generally determined from oxygen consumption, after correcting for suit leakage and other factors (see Johnston, et al., 1975).

2.2. Prediction of Energy Expenditure

Energy expenditures in a task may be predicted via a methodology introduced by Garg (1976), and Garg, Chaffin, and Herrin (1978). Using extensive measurement of O_2 utilization by six young, healthy subjects performing controlled manual labor, these investigators derived equations expressing energy expenditure associated with specific job elements. Their regression equations express energy expended as a function of such personal parameters as body weight, weight of load, walking velocity, etc. The form of this prediction model is:

$$\bar{\dot{E}}_{job} = \frac{\sum_{i=1}^{n_{pos.}} \dot{E}_{posture_i} \times t_i + \sum_{i=1}^{n_{task}} \Delta E_{task_i}}{T} \qquad (1)$$

Where:

$\bar{\dot{E}}_{job}$	= Ave. job E (Kcal/min)	$n_{pos.}$	= Number of postures employed in job
$\dot{E}_{posture_i}$	= E due to maintenance of ith posture (Kcal/min)	n_{task}	= Number of tasks in job
		t_i	= Time duration of ith posture (Min)
ΔE_{task_i}	= E due to ith task during steady state work (Kcal)	T	= Time duration of job (min)

Equation 1 summates basal energy expenditure (left side of numerator) with energy expenditure due to specific tasks (right side of numerator). In the model, there are three basal postures: sitting, standing, and standing bent, as defined in Table 2. Body weight is simply multiplied by a constant for each of these postures, to achieve basal energy expenditures in the area of 1.5-2.5 Kcal/min. Each of the three basal E's are multiplied by the fraction of time spent in that posture (t_i/T) and summed to achieve the final basal E. Task energy expenditures are defined via regression equations for each job element. These are shown in Table 1, beneath the basal energy equations. Note that the task ΔE equations shown represent only a selected fraction of the equations in the model. Walking and Carrying yield Kcal spent in a duration of time, t. The Lifting and Lowering equations shown here describe energy expended per lift/lower, while keeping the legs essentially straight. The Pushing/Pulling equation describes energy expended during a movement of horizontal distance, X. Comparisons between alternative task arrangements made be made by altering the various input parameters, and noting overall impact on average task energy expenditure. In general, this model is extremely accurate and sensitive in predicting the energy expenditure of Earth-based industrial jobs (see Garg, Chaffing, and Herrin, 1978).

2.3. Work-Rest Allocation

Once the energy expenditure of a task has been defined, the next consideration is how much rest to include as part of a shift, to avoid excessive fatigue. An accepted technique in the industrial community relies on the concept of physical work capacity (PWC), the maximum work effort that an individual (or population) can exert over a shift, without any rest time, and without incurring any short or long term injury. As a rule of thumb, the energy expenditure rate at PWC ($\dot{E}_{PWC}$) should be 1/3 one's maximum aerobic capacity for 8 hour shifts, and 1/2 one's maximum aerobic capacity for 4 hour shifts (see Bink, 1962). For shorter shifts, higher E_{pwc}'s may usually be sustained without incurring any injury. By definition: $T_{job} E_{pwc} = T_{rest} E_{rest} + T_{work} E_{work}$, and $T_{job} = T_{rest} + T_{work}$, so after solving for rest time,

$$T_{rest} = T_{job} [E_{work} - E_{pwc}] / [E_{work} - E_{rest}] \quad (2)$$

Where: T_{rest} = rest time (min) E_{work} = working E (Kcal/min)
T_{job} = total shift time (min) E_{rest} = basal E (Kcal/min)
T_{work} = work time (min) E_{pwc} = pwc E (Kcal/min)

TABLE 2. SELECTED ENERGY PREDICTION MODEL ELEMENTS, FROM GARG (1978)

<u>BASAL ENERGY EXPENDITURES (KCAL/MIN)</u>
Sitting: E = .023 {BW} Standing: E = .024 {BW} Standing Bent: E = .028 {BW}

<u>WALKING AND CARRYING TASK ENERGY EXPENDITURES (KCAL)</u>
Walking: $\Delta E = .01 \{ 51 + 2.54 [BW \times V^2] + .379 [BW \times G \times V] \}t$
Carrying (at Waist):
$\Delta E = .01 \{ 68 + 2.54 [BW \times V^2] + 4.08 [L \times V^2] + 4.62 [L] + .379 [L+BW] [G \times V] \} t$

<u>LIFTING AND LOWERING ENERGY EXPENDITURES (KCAL/LIFT, LOWER)</u>
Stoop Lift: $\Delta E = .01\{.325 [BW] [.81-H1] + [1.41 (L) + .76 (S \times L)] [H2-H1]\}$
Stoop Lower: $\Delta E = .01\{.268 [BW] [.81-H1] + .675 (L) (H2-H1) + .522 (S)(.81-H1)]\}$

<u>PUSHING/PULLING AT .8 M HEIGHT (KCAL/PUSH)</u>
Pushing/Pulling: $\Delta E = .01 [X] \{.112 [BW] + 1.15 [F] + .505 [S \times F] \}$

Where: BW = Body Weight (Kg) L = Weight of Load (Kg)
F= Ave. Pushing/Pulling Force (Kg) S = Gender (Males = 1, Females = 0)
G = Grade of Surface (%) V = Speed of Walking (M/sec)
H1, H2 = Vertical Height from Floor (M) X = Horizontal Movement of Work (M)
(H2 is higher than H1) t = Element Time (Min.)

If T_{rest} is divided by T_{job}, the result is proportion rest time on job, and is independent of length of shift, given that E_{pwc} has already been assigned. Figure 1 plots the proportion of rest required as a function of E_{work} for two different PWC's. Note that the aerobic capacities of the average male and female, respectively, are 16 and 12 Kcal/min, so the chosen E_{pwc} will likely fall between the two ranges shown, for 4 to 8 hour shifts. It remains to be determined whether the E_{pwc} should remain the same in microgravity as in 1-G.

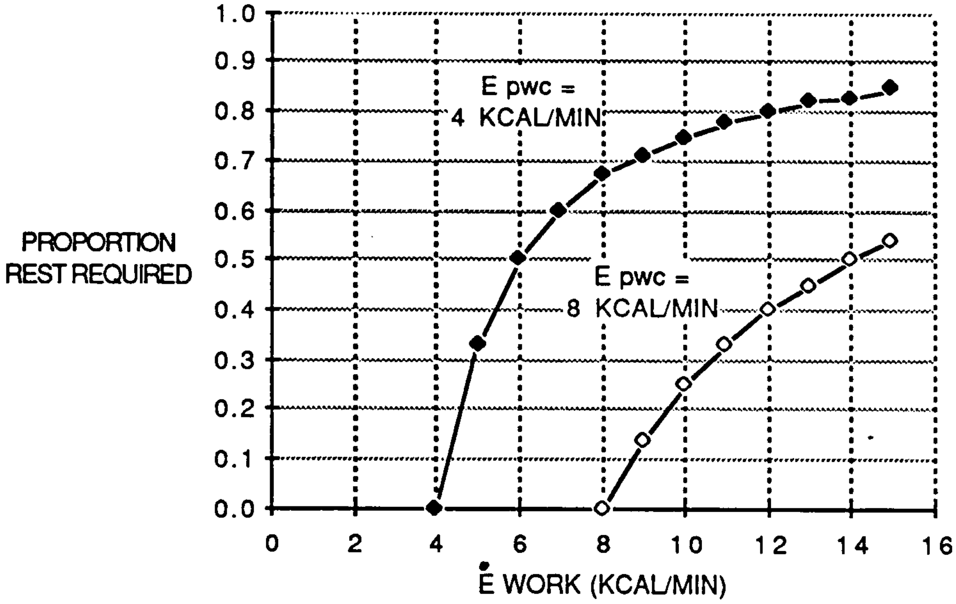

FIGURE 1. PROPORTION OF JOB SHIFT TIME SPENT RESTING AS A FUNCTION OF WORKING ENERGY EXPENDITURE. Plotted for two physical work capacities, based on Equation 2.

3. MODEL DEVELOPMENT: ENERGY EXPENDITURE PREDICTION IN REDUCED GRAVITY

When designing jobs for low gravity environments, it will be cumbersome to simulate every possible task on a low-gravity simulator, and physiologically measure oxygen consumption. Rather, empirical prediction equations are suggested as a way to ease this burden. While Garg's prediction model fits Earth-based industrial task data quite well, it is not known whether it can be used to predict lower gravity energy expenditures. A completely different set of relationships may indeed be in effect for walking, lifting, etc. On the other hand, weight reduction is likely the primary effect of lower gravity, as discussed by Wortz (1969), while mass acceleration characteristics will remain unchanged . By maintaining a constant basal metabolic rate, combined with decreased body weight and load weight in specific task energy contributions, estimates of workload may be made and compared with actual oxygen consumption data from low gravity simulations.[2] As a further simplifying assumption, the effect of a pressure suit and backpack may be estimated by adding their extra weight to an individual's body

[2]The assumption of a constant basal metabolic rate in lower gravity has been upheld by both Skylab and Apollo data (see Johnston and Dietlein, 1977; Johnston, et al.,1975).

weight in the task energy expenditure computations. The effects of pressure are not predicted by such model computations.

In the following sections, energy expenditures from specific tasks are reported, then predicted using Garg's (1976) model. For this analysis, work is divided into lower body work (walking), upper body work (stationary pushing and pulling), and whole body work (cart pushing and pulling). Table 3 provides an overview of the 8 studies in which sufficient task descriptions existed to allow use of the prediction model described above. Note that the relatively few subjects used in each study is not unusual for physiological studies. The average weight of these subjects varied from about 67 to 85 Kg, a fairly homogeneous group. All were healthy males, aged 20-40. Either inclined plane or vertical suspension systems were used to simulate low gravity (except, of course, in the Lunar EVA report), and some studies used pressure suits, pressurized to operational requirements. The lower-body work studies used walking speeds and walking slopes as independent variables. The upper-body work study measured torquing ability at a constant repetition rate. The whole-body work study measured ability to pull a small cart at varying velocities, weights, and slopes. Clearly, many other examples of whole-body tasks exist, but this was the only controlled study reported in the literature.

3.1. Lower Body Work

Studies of energy expenditure during 1/6 G walking were made during the latter 1960's, in preparation for the Apollo moon landings. Primary emphasis in these studies was placed upon differences in pressure suits, allowed walking speed, and task demand on the Lunar surface. One's E dramatically increases with speed of walking in either 1 G or 1/6 G environments. Wortz (1969) combined data from several sources to produce the observed relationship shown in Figure 2 (see Wortz et al. ,1971; Wortz and Prescott ,1966; Robertson and Wortz ,1968; and Passmore and Durnin ,1955). Observed E values, shown as a solid line, ranged between a resting 1.5 Kcal/min and a very difficult 11 Kcal/min for the treadmill study data. Observed E in 1/6 G was 1/4 to 1/2 that of E in 1 G, at all velocities. Using the mean body weight of 70 Kg from these studies, predicted E's were computed and plotted as a dashed line on the same figure. The computed values overpredicted observed 1 G data by 1 to 2 Kcal/min, but were much closer at the lower gravity level than at 1-G. This figure also displays 1/3 G predicted E's, as an estimate of walking energy expenditure on Mars.

The increased difficulty of walking with increasing velocity at 1/6 G was subjectively confirmed by Armstrong (1970). His impressions were that walking speed is limited to about 2 feet/sec (2.2 Km/hr) because "...The force at the foot necessary to maintain the speed will provide sufficient upward force to lift the person off the ground before the other foot comes down." This technique, called loping, is much like running in slow motion, in that both feet leave the ground at the same time. Steady state loping velocities were commonly 3-5 feet/sec (3.3-5.5 Km/sec) on the Lunar surface. During the 1/6 G simulations, subjects were forced to walk, rather than lope, and the data may reflect E values that are excessive. Decreasing observed E's would, of course, increase the prediction error of Garg's model.

TABLE 3. LOW-GRAVITY ENERGY EXPENDITURE STUDIES

REFERENCE	NO. SUBJS	AVE. WT. (KG, 1G)	SIM*	CLOTHING†	SIMULATED GRAVITY (G)	EXPERIMENTAL CONDITIONS
			LOWER-BODY WORK			
Robertson and Wortz (1968)	6	71.0	VS, IP	PS	1, 1/6	1, 2, 4 mph
Wortz and Prescott (1966)	9	80.7	VS	SS	1/4, 1/6, 1/8	2, 4 mph
Sanborn and Wortz (1967)	10	72.5	IP	SS	1/6	2, 4 mph
Wortz (1969)	1	75.0	VS	SS	1, 1/2, 1/4, 1/6	4 mph
Wortz, et al., (1969)	6	67.7	VS, IP	SS, PS	1/6	2, 4, 6, 8 kph 0, 7.5, 15, 30°
Waligora and Horrigan (1975)	2	78.0	LS	PS	1/6	0.7-5.7 kph -13.8 - 11.3°
			UPPER-BODY WORK			
Prescott and Wortz (1966)	7	84.9	VS	SS	1, 1/2, 1/6, 0	Push: 2/second Push/pull: 2/s
			WHOLE-BODY WORK			
Camacho, et al. (1971)	2	74.8	VS	PS	1/6	75,148 Kg carts, 1,2,3,4,5 kph -15, 0, 15° slopes

*Simulator Codes: IP=Inclined Plane, VS=Vertical Suspension, LS=Lunar Surface EVA
†Clothing Worn During Study: SS=Shirt Sleeve, PS=Pressure Suit

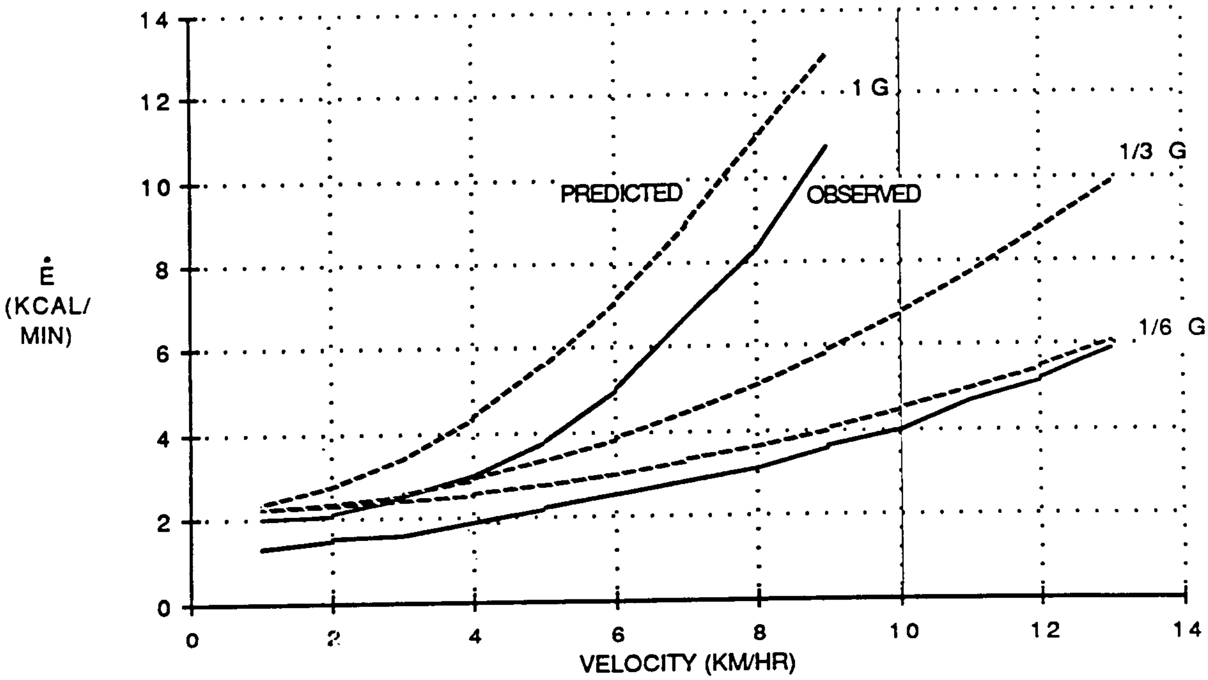

FIGURE 2. ENERGY EXPENDITURE AS A FUNCTION OF WALKING VELOCITY. Observed results (solid line) adapted from Wortz (1969), who summarized four treadmill studies. Predicted expenditures (dashed line) are from Garg's (1976) model.

Traction between a sole and the ground is linearly dependent on weight, so traction on the Moon is 1/6 that of an equivalent task on Earth. To successfully predict low gravity work, it is thus necessary to assess how much traction plays a part in increasing otherwise low walking energy expenditures in low gravity. This was done by Wortz (1969) by measuring the energy expended while maintaining a 1.79 Km/hr (4 Mi/hr) walk on a treadmill under gravity conditions between 1 and 1/6 G. Weight, and subsequent energy expenditure were reduced as simulated gravity decreased, shown in the lower curve of Figure 3.[3] The upper curve of this figure illustrates E values as weight was added to compensate for weight decreases due to simulated gravity. Thus, the traction and weight were the same at all tested gravity levels for the upper curve. The observed E only increased by about 1 Kcal/min between 1 and 1/6 G, even though the subjects were carrying an extra load of about 60 Kg. The observed rise in E was likely

[3]Percentage changes in E as shown by Wortz were converted to Kcal/min by using 7.0 Kcal/min as a baseline at a 1.79 Km/hr treadmill velocity, from Wortz and Prescott's (1966) analysis. The average 1-G body weights were within 5 Kg between these studies, so the estimated E is likely close to the actual E.

due to the effects of having to accelerate this extra mass with each step, as walking velocity is maintained. Indeed, weight seems to account for most of the decrease in E with decreasing gravity. Using the Walk element, with a constant E_{basal}, the solid data points in Figure 3 represent the predicted E values. At 1 G, predicted E was about 1.5 Kcal/min greater than actual, which could have been due to subjects of higher than average fitness level. Of course, the prediction model cannot adequately predict the increasing E at low G values due to increased load acceleration. The model very closely predicted the E declines at the three simulated gravity levels when no extra load was applied to the body.

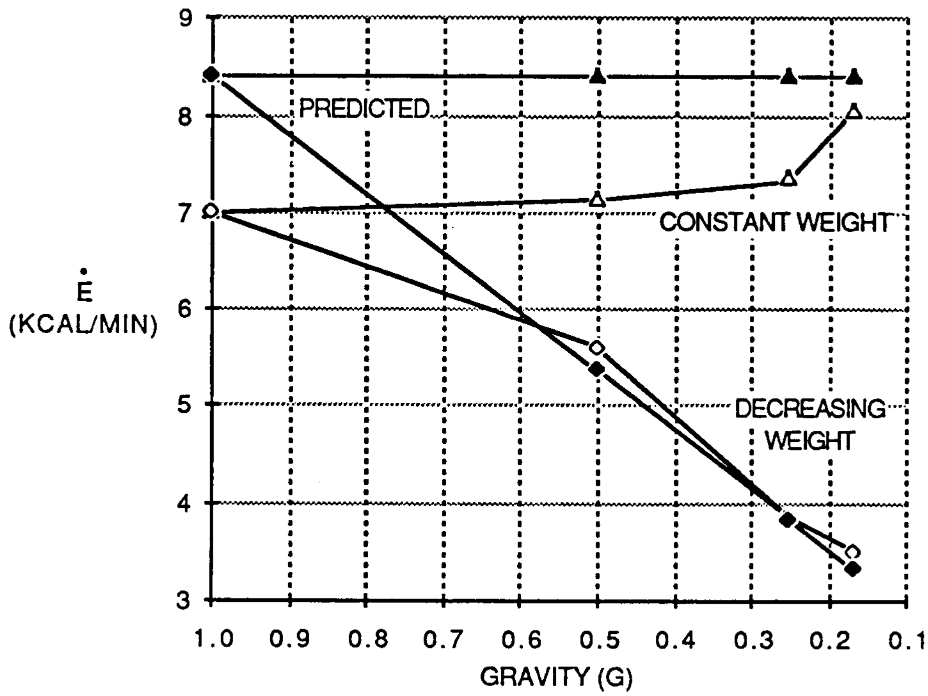

FIGURE 3. ENERGY EXPENDITURE AS A FUNCTION OF GRAVITY LEVEL. Adapted from Wortz (1969), by substituting 1-G expenditures from Wortz and Prescott (1966), as described in text. This data shown as light symbols, while predicted data are indicated by dark symbols.

Energy expenditures were obtained from the rate of oxygen consumption and heart rate during Lunar EVAs by Edwin Mitchell and Alan Shepard on Apollo 14. Relatively controlled observations of walking velocity, grade, and weight carried were used to predict E values. Two patterns emerged from this data, as shown in Figure 4. When climbing slopes steeper than 5%, E's climbed dramatically to the point where the workload was unduly heavy, when compared with slopes of less than 5%. When slopes were more reasonable, a relationship similar to that found in earlier simulations was obtained.[4] This EVA data was predicted by incorporating the appropriate slope, velocity, etc. information into Garg's model. In general, the model closely predicted the simulator data, which underpredicted the observed data more and more as velocity increased. This error will be discussed in the following section.

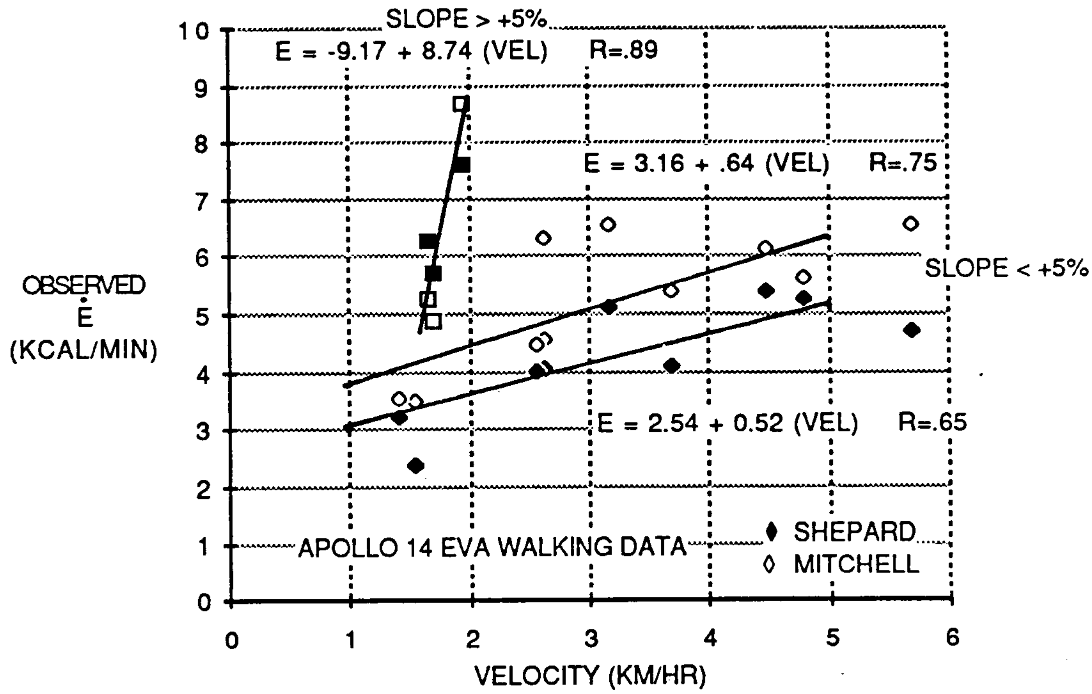

FIGURE 4. OBSERVED ENERGY EXPENDITURES DURING APOLLO 14 EVAS. Source: Waligora and Horrigan (1975). Shepard (dark data) and Mitchell (light) showed similar relationships between E and walking velocity.

3.2. Lower Body Prediction Error Analysis

An analysis of prediction error may be carried out by plotting observed versus predicted energy expenditures. Figure 5 shows this relationship for simulated gravity data. The data from Wortz, et al. (1969) agreed most closely with predicted values, with the model underpredicting observed data by an average of 15%. Note that this data was from subjects in shirt sleeves, and on horizontal ground. On the other hand, it was obtained by combining data from four studies. An extremely good prediction, accounting

[4]Though Lunar E's were 2.3 times higher than equivalent condition simulation E's, the simulated data was in fact highly predictive of the Lunar data. A linear regression between Lunar data from the average of Mitchell and Shepard's regression functions in Figure 4, and the simulated 1/6-G walking data from Figure 2 was: Lunar E = 2.13 + 1.55 (Simulated E). This relationship was quite linear (R=.98), and could be considered a 'real-world' correction factor, accounting for differences in the soil conditions, and the use of pressured suits.

for more than 95% of data variability, was obtained in these limited conditions. When predicting more isolated data, based on fewer subjects, the model may greatly underpredict energy expenditures, as shown by other data (squares)by Wortz and Prescott (1966). Wortz's (1969) 1/6-G observation was predicted very closely by the model.

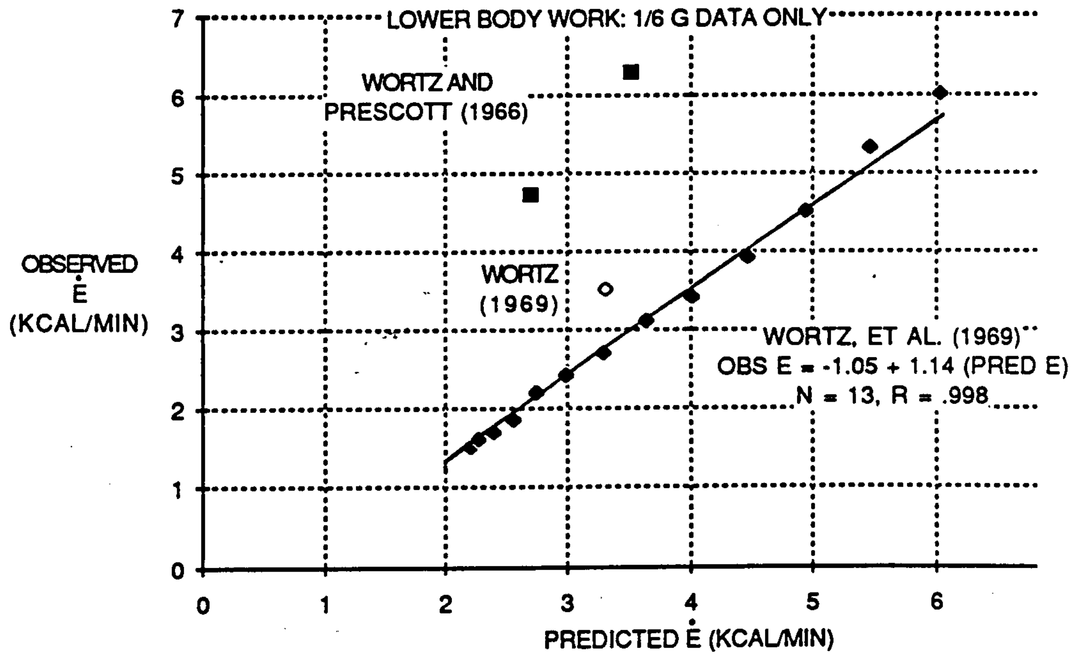

FIGURE 5. ENERGY EXPENDITURE PREDICTION ERROR FOR SIMULATED 1/6-G, TREADMILL DATA. Obtained by predicting E values for reported E's in given conditions.

Data from Lunar EVAs was also subjected to prediction error analysis, as shown in Figure 6. The Lunar data was obtained over many walking velocities, net slope changes, and surfaces which likely added to prediction error. A linear relationship between observed data and prediction model still existed (R=.65), but the mean observed energy expenditure value was underpredicted by about 30%.[5] The model so greatly underpredicted these values when slopes were greater than +5% that this data was not included in Figure 6. It also must be kept in mind that only two subjects were represented in the EVA data, clearly increasing prediction variability.

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[5]This underprediction, due to unaccounted factors, is in line with the previously reported simulator-real world difference of 30-50%. The close agreement between the prediction model and simulator data underscored the fact that a 'correction factor' of 2-4 Kcal/min should be added when attempting to predict actual pressure-suited, EVA energy expenditure on the Lunar surface.

3.3. Upper and Whole Body Work

Most work requires the use of the upper torso, in addition to mobility gained by use of the legs. Prediction of energy expenditures in these tasks requires other than just walking or carrying elements. Use of the hold and push/pull elements are examples of additional prediction equations that must be used. It is important to note that Garg's (1976) model was not developed for continuous pushing or pulling of heavy loads over extended distances. Thus, much of the analysis below represents extreme extrapolations.

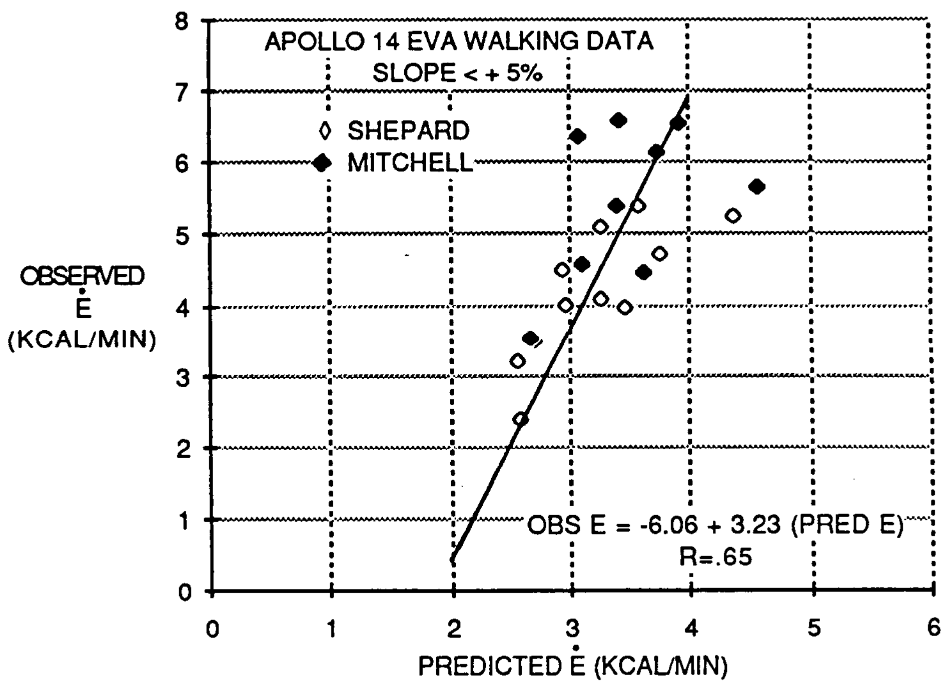

FIGURE 6. ENERGY EXPENDITURE PREDICTION ERROR FOR LUNAR EVA DATA. Lunar EVA data taken from Waligora and Horrigan (1975), using data only from net slopes of less than +5%. Prediction error from slopes greater than +5% was extremely large.

Prescott and Wortz (1966) predicted that loss of traction with lowered gravity levels should greatly decrease one's ability to torque bolts or perform other upper body work. They simulated a 9.2 M-Kg (800 in-lb.) torquing task, using simulated G levels of 1, 1/2, 1/6, and 0. Measured and predicted energy expenditures are shown in Figure 7. Two types of torquing tasks were used: a Push-only task where subjects torqued forward then returned to rest position, at a rate of 2/second. A Push/Pull task required torquing in both directions at the same rate. The two tasks produced essentially equivalent E values of 3-4 Kcal/min. As gravity was reduced, E's did not appreciably increase until weightlessness was achieved. Garg's model predicted E's nearly twice as great as the observed values, using the Push at element. Body weight did not enter into this equation, so constant E was predicted with lower gravity. Garg's model thus needs to take tractional changes into account with lowered gravity. The model also utilizes the same work element for pushing and pulling, so only one set of predicted data are plotted.

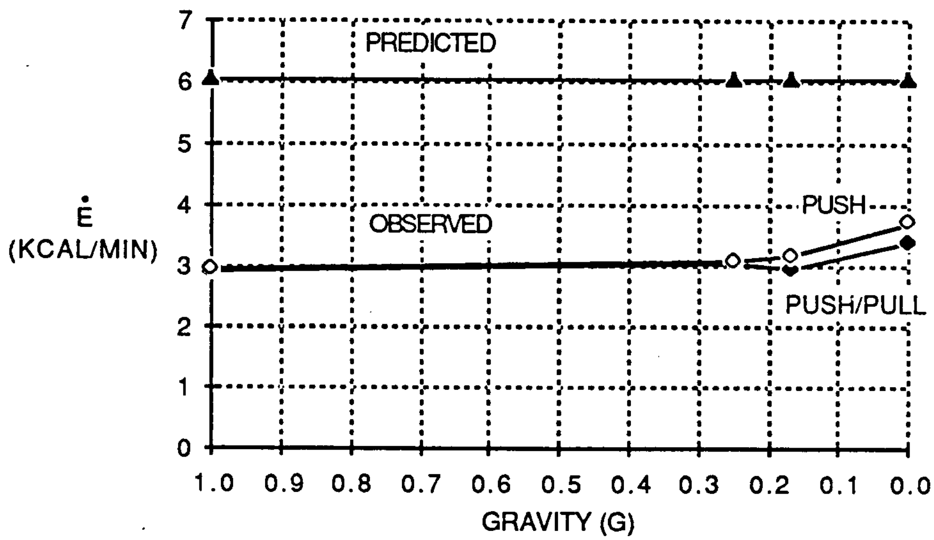

FIGURE 7. ENERGY EXPENDITURE DURING UPPER BODY TORQUING. Source: Prescott and Wortz (1966). Predicted E values (triangles) are from Garg's (1976) model. Both Push and Push/Pull tasks were performed at 2/second, and in shirt sleeves.

An analysis of whole body energy expenditure was provided by the cart pulling studies of Camacho, et al. (1971). In preparation for using a small cart on the Lunar surface, two cart weights (75, 148 Kg), five pulling velocities (1-5 Km/hr), and 3 walking grades (-15, 0, 15°) served as independent variables. Figure 8 provides observed and predicted E's for the conditions tested. For very steep, 15° slopes, observed E's were greater than 8 Kcal/min, and increased by 4 Kcal/min between 1 and 2 Km/hr. The prediction model does not specifically cover cart pulling, so the hand push/pull element was utilized, by inserting the equivalent hand force (as reported by Camacho, et al., 1971) exerted over a distance of 1 meter. This energy expenditure was then converted to a rate by correcting for velocity of movement. The model underpredicted the steep, 15° slope E's, but was fairly accurate on 0° and -15° slopes. On the steep downhill, energy expenditures were quite a bit smaller than on the other slopes, and this was very closely predicted. Cart pulling on level ground increased with velocity, and the model overpredicted the light cart E's by only 1 Kcal/min. The heavy cart E's were also overpredicted, but by 1-4 Kcal/min, with error increasing as velocity increased. At 2-4 Km/hr, the heavy cart only produced 1-2 Kcal/min greater expenditure than the light cart.

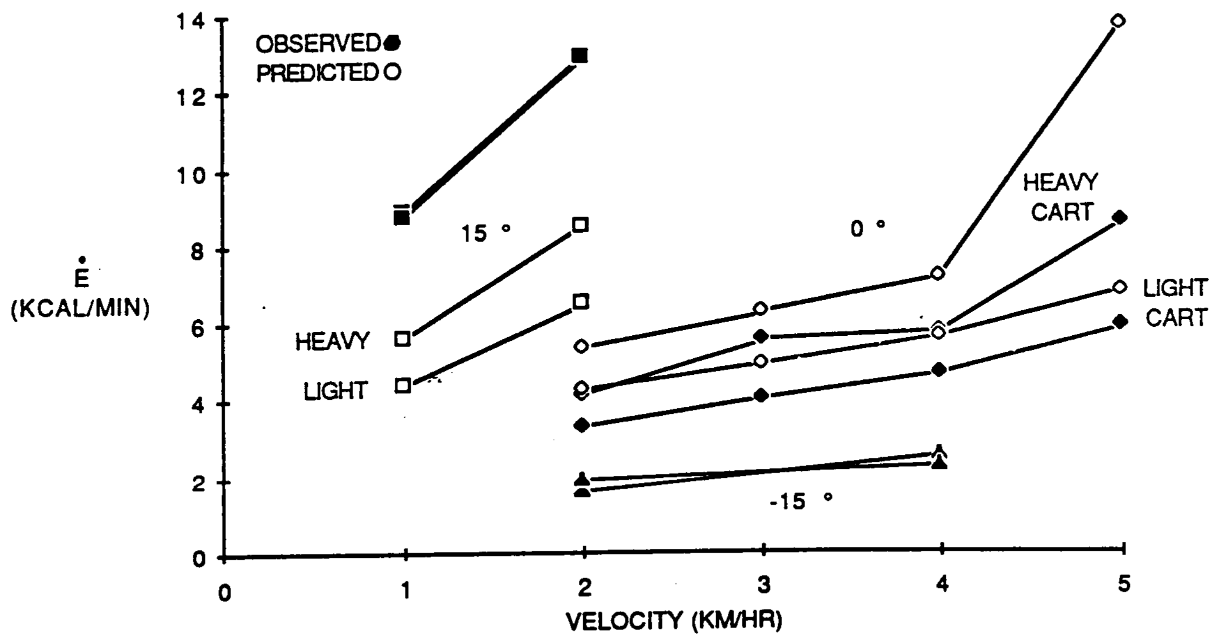

FIGURE 8. ENERGY EXPENDITURE DURING CART PULLING. Source: Camacho, et al. (1971). Predicted E values, from Garg's (1976) model are indicated by light data points.

3.4. Whole Body Prediction Error Analysis

The torquing data by Prescott and Wortz (1966) was overpredicted by 3 Kcal/min at nearly all tested gravity levels, and did not account for increasing E due to decreasing foot traction. The reason for the large overprediction is likely due to the fact that the tested subjects were of much higher fitness level than the average, healthy male adult working population. The torquing task, repeated twice per second, should have been more fatiguing. The investigators did not find any change in basal energy expenditure as gravity level was reduced, so the greatest difference in prediction was due to the task energy expenditure.

The cart-pulling studies provided more hope for prediction of whole-body energy expenditures. Observed versus predicted data from all conditions is shown in Figure 9. The excessively high E values for 15° slopes had a qualitatively different observed versus predicted relationship than the horizontal or downward slopes. A linear regression fit to the latter data clearly showed that cart pulling data can be well predicted (R=.97) by Garg's (1976) model. Conditions were very realistic in this study, in that pressure suits were worn, and pulling took place on a Lunar soil simulant. Thus, it appears that the model can account for pressure suits and simulator conditions, but has a difficult time with steep upward slopes. A rough indication of 15° slope E values could be obtained by adding 4-6 Kcal/min onto predicted values.

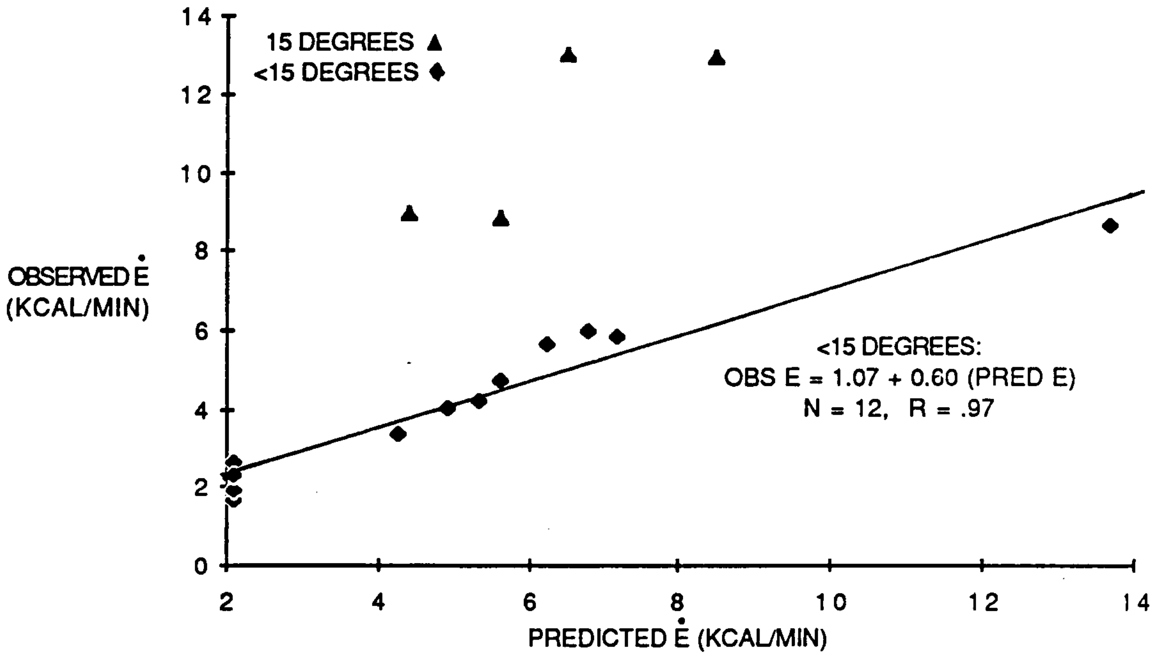

FIGURE 9. ENERGY EXPENDITURE PREDICTION ERROR FOR LUNAR CART PULLING. Relationship for 15° slope (triangles) was qualitatively different from - 15° and 0° slopes (diamonds).

4. MODEL APPLICATION: WORKLOAD ANALYSIS OF CORE SAMPLING IN LOW GRAVITY

Blacic, Rowley, and Cort (1985) provided a conceptualization of rock drilling on Mars or the Moon. A portable jack-hammer drill will be connected, via high-pressure tubing, to a compressed CO_2 tank, on skids. The drill will have a depth capability of 2-3 meters, drilling a 50 mm diameter hole, into hard rock, in 30 minutes. The CO_2 will provide oscillatory motion to the drill bit, and will clear out the hole as drilling continues. The 1-G weight of the drill and skid, scaled from present equipment, were estimated to be 90 Kg.

To estimate the physical workload of a drilling outing, a number of assumptions must be made. A 70 Kg male, wearing a 20 Kg suit and 30 Kg life-support pack, will perform the drilling. An average surface grade of 5% will be negotiated; this parameter will compensate for small surface irregularities. The drill is driven to a core site via a rover, where the unit is riding .80 M off the ground. Upon arriving at the site, the worker grabs the drill and skid and carries them to the site of the first hole, where they are lowered. All walking and carrying is carried out at .56 M/sec (2Km/hr), and successive core samples are collected 200 meters apart. Drilling is carried out by holding the operating drill for 30 minutes. The CO_2 unit is lifted and carried to the next drilling site, and the next hole is drilled. Five cores are drilled in this manner, by travelling around the rover. After all samples are collected, the worker will return to the rover for driving back to base. The physical work aspect of the shift, from leaving the rover to returning to the rover, requires 186 minutes. Analysis of this activity provided the data shown in Table 4. From Table 1, this task would be considered moderate work in 1-G, Light work in 1/3-G, and Very light to Light work in 1/6-G. The greatest energy expenditure in this job, besides basal, was due to carrying the drill 200 meters in between core samples. Due to the low frequency of task repetition, lifting and lowering accounted for a small percentage of overall energy expenditures. The contribution of lifted load to overall E is relatively small in lower gravity environments. Subsequent analysis has shown that, for a 50 Kg load increase (to 140 Kg), the associated increases in E for this job are 37%, 20%, and 10%, for 1-G, 1/3-G, and 1/6-G, respectively. A physical work capacity of 4 Kcal/min could be presumed if this task were carried out for 8 hours. If this were the case, 4 hours of rest would be required on Earth, and no additional rest on Mars or on the Moon. It is likely that the PWC is greater than this, however, due to the 3 hour work shift. Thus, no additional rest need be added to this core sampling job.

TABLE 4. PREDICTED ENERGY EXPENDITURES FROM CORE SAMPLING JOB

	PREDICTED ENERGY EXPENDITURES PER 186 MINUTE SHIFT					
LOCATION	BASAL	CARRY	LOWER	HOLD	LIFT	TOTAL
Earth (1-G)	2.00	2.96	0.02	1.13	0.05	6.16
Mars (1/3-G)	2.00	1.07	0.01	0.38	0.02	3.48
Moon (1/6-G)	2.00	0.60	0.01	0.19	0.01	2.80

5. CONCLUSIONS AND RESEARCH NEEDS

This paper has outlined a methodology for predicting energy expenditures for physical work in low gravity environments. It must be emphasized again that the form of these models may change quite a bit for lower gravity levels, and only empirical study can elicit these differences. Nevertheless, some E values from studies were surprisingly well-predicted, while others were not. The single element of walking was well predicted both in simulators and on the Lunar surface, so long as slopes were relatively small. The lunar data also required an additional 2-4 Kcal, due to pressure suits and other real factors. Upper-body torquing was overpredicted by 3 Kcal/min at nearly all gravity levels, while cart pulling was accurately predicted at horizontal and downhill slopes. The latter was promising, as Garg did not include cart pulling in his prediction equations.

To obtain accurate predictive low gravity energy expenditure models, extensive simulation under highly controlled conditions is required. This paper has demonstrated the feasibility and use of such equations, but much is left to be done. More predictive equations are required for tasks such as pushing and pulling objects up and down grades, loping, digging, etc. The definition of shift rest time is completely dependent on Earth-based concepts of physical work capacity. It is highly likely that one's PWC increases at lower gravity levels, but this must be shown.

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