Locomotion While Load-Carrying in Reduced Gravities

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by

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Abstract

INTRODUCTION. The issues associated with determining a safe and reasonable load size and load location for astronauts performing activities on extra-terrestrial planetary surfaces have until now not been addressed. Extravehicular astronauts must wear protective suits and portable life support systems to provide them with a pressurized, breathable atmosphere. Supporting the mass of the suit and life support system represents a supplemental energy expenditure to the crewperson, in addition to his/her surface exploration duties. To design the extravehicular protective equipment for future planetary space missions, it is necessary to better understand human physical capabilities while load-carrying in reduced gravities. METHODS. An underwater treadmill and novel weighting system were used to simulate reduced-gravity locomotion while load-carrying. The test matrix included three gravity levels; six subjects; two locomotion speeds; and a range of loads, with a maximum load of 270 percent of each subject's body weight in the lunar simulation. RESULTS. With no additional loading, the average energy expenditure for walking at 1.2 mps was (in kcal/kg-min) 0.053, 0.060, and 0.069 for lunar, Martian and earth gravities, respectively. For the faster speed of 1.9 mps, the equivalent energy costs were found to be 0.062, 0.090, and 0.095. Energy expenditure increases as higher loads are carried, and the *rate* of increase is greater at higher gravities. The data indicate that an individual in average physical condition will be able to walk for eight hours on the moon carrying up to 170 percent of his or her body mass, and 50 percent of his or her body mass on Mars. The model of Whalen (1988) was used to calculate the daily planetary walking time required to maintain bone mass. CONCLUSIONS. Minimization of total mass should be a primary design driver of protective systems for Mars exploration if the system is to be carried. Additional exercise protocols will be necessary to maintain bone mass.

Introduction

Extensive research on the topic of terrestrial load-carrying by humans for the military and the outdoor sports industry suggests that a load of approximately 30 percent (for multipurpose activities) to 45 percent (for primarily walking) of body weight is reasonable for a human in one-g. However, the issues associated with determining a reasonable load size and load location for personnel performing activities on extra-terrestrial planetary surfaces have not been addressed. It may be reasonable to hypothesize that the load should be placed as close to the normal body center of gravity as possible, or that the load should be distributed in anthropometric ratios (with the same resultant c.g.). But because the human mass and muscle strength would ideally (with in-flight conditioning) stay fairly constant in going from one-g to planetary partial-g while the human weight is drastically altered, there is no credible method to determine what a reasonable load size is aside from performing reduced gravity human simulations.

The issues associated with the biomechanics of human movement in partial gravity (such as energy expenditure and heat production, balance, stance, force-imparting capability, load placement, and mobility) become increasingly important as we humans continue our exploration of the universe. The influence of load size and placement on work performance in altered gravity is specifically relevant to extravehicular spacesuit and portable life support system design and mass distribution, including the hardware elements associated with temperature and humidity control, oxygen supply and carbon dioxide removal, pressurization, communication, and power. Also of significance is the location and distribution of any additional loads the planetary extravehicular (EV) crew person may be required to carry (such as tools or sample packs).

This study seeks to address the effects of gravity level, speed of locomotion, and load size and placement on human metabolic work in reduced gravity simulations for the purpose of defining spacesuit design parameters and extraterrestrial mission operations guidelines. A primary objective was to identify a maximum safe load size (see also the discussions of optimum load) and corresponding c.g. placement for various gravity levels that can be carried by an astronaut for an eight-hour workday, and for which energy expenditure is measurably decreased and task performance is measurably enhanced relative to the range of projected load sizes and placements tested.

Methods

In this study, six subjects ran or walked underwater on an treadmill for six minutes per test while ballasted to one of two gravity levels: one-sixth g (lunar) and three-eighths g (Martian). Additional one-g tests were performed out of the water. The water immersion experiments were run in the Neutral Buoyancy Test Facility at NASA Ames. The treadmill was equipped with a force platform for measuring ground reaction forces. Subjects wore a commercial diving facemask with a demand regulator and communication system, and a ballasting harness. The ballasting harness was a custom-made skydiver-type vest with pockets in which packaged lead shot could be stored comfortably and close to the subject's torso.

The subjects traveled at two speeds: 1.2 meters per second and 1.9 meters per second. A personal computer based data acquisition system continuously monitored respiratory minute volume, heart rate, CO_2 and O_2 levels in the expired gas, strides per minute, and peak ground reaction forces.

Initial testing determined loading limitations for the subjects. At each gravity level and at each speed, the subjects were loaded with a "PLSS simulation" load about the torso, in addition to their planetary ballast. The PLSS load was increased from 10% of the subject's planetary body weight, up to a maximum of 45%. Subject comfort determined the maximum load for each gravity level: 270% of the subject's one-g body weight for the lunar tests, 80% for the Martian tests, and 45% in the one-g tests.

Later tests evaluated positioning of the PLSS load. Subjects carried a common load of 17.25 kg at each of several locations relative to the body centerline, using the Variable Load Positioning Backpack (VLPB) described below. The load positions used in this study were:

a) the torso position, in which we tried not to disturb the natural body center of gravity. In this configuration, lead weights were distributed as evenly as possible about the torso, immediately next to the body at the level of the pelvic girdle. This configuration was used to determine maximum allowable loads for each subject, as described above. The torso loads were carried with a commercial shoulder-strapped dive belt.
b) the high back position, in which the VLPB load was carried about 23 centimeters posterior to the frontal plane, at approximately the same level as the cervical curve of the neck.
c) the low back position, in which the VLPB load was carried about 23 centimeters posterior to the frontal plane, at approximately the height of ilium (the top of the pelvic girdle).
d) the low front position, in which the VLPB load was carried about 23 centimeters anterior to the frontal plane, at approximately the height of the ilium.

VLPB

The Variable Load Positioning Backpack (VLPB) was designed to secure a load at one of several positions relative to the body. It consists of a harness, a frame, interchangeable arms, and a series of cylindrical steel weights. The harness comprises a series of padded straps and buckles that serve to fix the frame to the subject's body. The 69 cm by 45 cm aluminum channel frame has removable pairs of upper and lower aluminum tee-section arms supporting cylindrical steel stock weights of various sizes. Only one set of arms is used at a time to support the weight in either upper rear, lower rear, or lower front positions. The horizontal distance from the body centerline to the weight was adjustable from 23 to 46 cm. The data presented here are for a configuration in which the weight was 23 cm from the frontal plane. The VLPB is donned in a manner similar to a hiking backpack, through the use of adjustable shoulder, chest, and waist straps sewn onto the frame. Figure 1 shows a subject wearing the VLPB underwater with the weight in the high back position.

Figure 1. Subject wearing the Variable Load Positioning Backpack, with weight in the high back position.

Results - Energetics

Pooled results.

Figures 2 and 3 show the average energy expended by the six subjects versus load factor. Load factor is defined as the simulated PLSS mass plus body mass, divided by body mass. Figure 2 represents the data for a 1.2 m/sec traveling speed; Figure 3 depicts the data for 1.9 m/sec. The y-intercept of each line represents the energy expended while traveling at that speed, carrying no additional load. These no-load expenditures for 1.2 m/sec are: 0.053, 0.060, and 0.069 kcal/kg-min for lunar, Martian, and earth gravities, respectively. The expenditures for a 1.9 m/sec traveling speed are 0.062, 0.090, and 0.095. Energy expenditure increases with load factor, as indicated by the positive slope of the lines. Furthermore, the energy cost of an additional increment of load increases with increasing gravity levels. This incremental cost is indicated by the consecutively increasing slopes of the lunar, Martian, and earth lines, which for the 1.2 m/sec data are respectively 0.017, 0.032, and 0.075 kcal/kg-min per load factor increase of one. The slopes of the lines for the 1.9 m/sec data are higher for each gravity level: 0.019, 0.042, and 0.173.

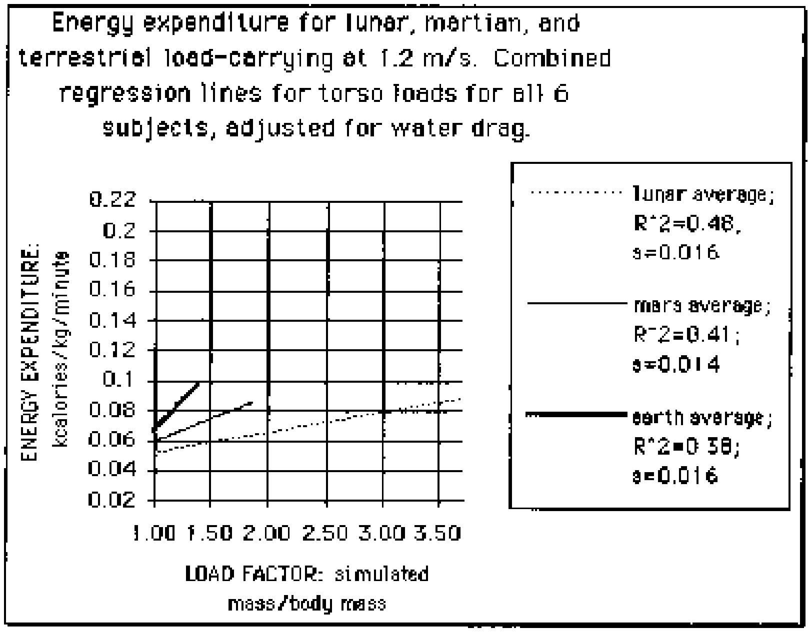


Figure 2. Average energy for Earth and simulated Mars and Lunar locomotion at 1.2 mps for all test subjects at a range of torso loads, adjusted for roughly estimated water immersion effects of 10 percent.

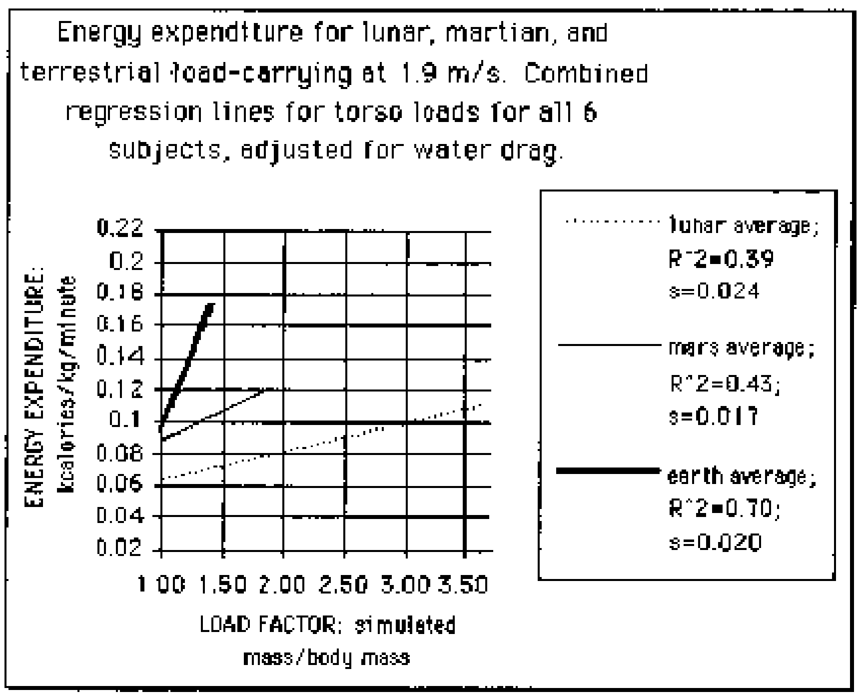


Figure 3. Average energy for Earth and simulated Mars and Lunar locomotion at 1.9 mps for all test subjects at a range of torso loads, adjusted for roughly estimated water immersion effects of 10 percent.

Stride Rate, Stride Length, and Load Cell Measurements

The range of strides per minute for each of the three gravity levels studied was as follows: for lunar gravity, from 28 to 53 strides per minute; for Martian gravity from 36 to 54 strides per minute; and for earth gravity from 44 to 90. These ranges cover all test conditions with varying speeds and loads, but they indicate a general trend toward increased stride rates with increasing gravity level. In accord with these results, the KC-135 reduced gravity parabolic flight test results compiled by Newman show the mean stride frequency for lunar locomotion at 2 mps (at the high end of the speeds tested for each gravity level) to be 48 strides per minute, and for Martian locomotion at the same speed the mean stride frequency was 58 strides per minute (Newman, 1992).

On this same topic, stride length, which is simply speed of locomotion in minutes divided by total combined right and left leg strides per minute, was shown to increase with the faster speed within each gravity level. In general, stride length is seen to be in the range of 0.6 to 1.2 times leg length for walking, regardless of gravity level. For the running speeds, stride length is seen to increase with speed within gravity level, and to increase with decreasing gravity for each speed.

These findings bring out a fundamental difference between walking, which is characterized by the subject having at least one foot on the ground at all times, and running, which is characterized by an airborne period. During walking, each footstep's ground reaction force is close to or slightly higher than the subject's body weight, since the legs are alternately supporting the body's weight, and the body is not being accelerated off the ground. During running, the ground reaction forces are substantially higher, since the ground reaction forces averaged over time (including the airborne periods) must still equal the weight of the subject's body, or the body would either go into orbit or sink through the running surface. The free flight or airborne time of each stride is governed by the planetary gravity acting on the body after it leaves the ground. Therefore, the air time for a given vertical velocity on the moon will be about six times that on earth, and on Mars will be just under three times that on the earth. This also explains why running stride lengths are longer in lower gravity environments.

Muscular force, which is defined as peak ground reaction force (PGRF) minus the subject's body weight, for walking speeds were found to be in similar ranges (0 to 260 N) regardless of gravity level. Similarly, for the running speeds, muscular forces for all three planets are in a higher range (180 to 640 N).

Several researchers (Cavagna and Margaria, 1964; Farley and McMahon, 1992) predicted that reduced gravity walking would be less efficient in reduced gravity, suggesting that the most efficient way to cover a given distance at reduced gravity levels may be running as opposed to walking, unlike on the earth. These theories are manifested in our study by the fact that at the earth walking speed of 1.9 mps, when the test subjects were weighted for lunar or Martian gravity, they ran instead of walking, commenting that it was easier to run than to walk. Even at the speed of 1.2 mps, the test subjects often ran when weighted for the lowest gravity level (lunar). These findings are in accord with the observations made of the Apollo astronauts perambulating on the surface of the moon. They had difficulty walking, as their bodies kept rising off the surface, so they tended to bound or skip. Certain aspects of this gait were a result of the pressurized spacesuits that were worn, which did not allow a great deal of hip mobility, thus restricting stride length.

Other researchers (Gazenko et al, 1981) suggested that an increased forward lean of the body and an increased forward component of the push-off force may help to compensate for the energy exchange shortfall by decreasing the deceleration of each footstep's touchdown, increasing the action of gravity in the body's forward acceleration, and increasing the muscular energy input. The test subjects in this study exhibited a forward lean which increased dramatically with decreasing gravity level. This can also be explained by the subject's lower weight which is conducive to long loping strides, coupled with his need to keep his center of mass in front of the supporting foot by a distance consistent with his speed and stepping rate.

Multi-gravity Energy Model

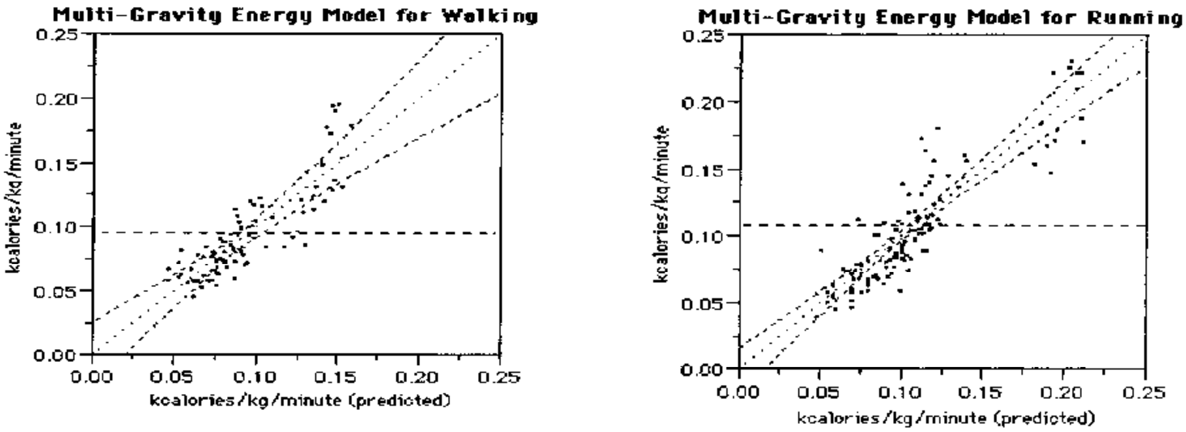
The data illustrate that energy expenditure increases with gravity level, locomotion speed, and load size carried. As explained above, since the biomechanics of running and walking are quite different, multiple regression analyses (MRAs) were performed for the walking data separately from the running data to quantify the combined linear effects of the variables. By including the additional variables of body mass and leg length, we are able to more accurately predict the expended energy for humans walking and running at variable gravity levels with the following two equations:

$$E_{walking} = 0.0788\ V + 0.0025\ G + 0.0569\ F - 0.0006\ B - 0.0100\ L - 0.0687 \quad (1)$$

$$E_{running} = 0.0309\ V + 0.0119\ G + 0.0177\ F - 0.0001\ B - 0.0976\ L + 0.0707 \quad (2)$$

where E is the energy in kcal/kg-min, V is the velocity in meters/sec, G is the gravity level in meters/sec^2, F is the load factor, B is the individual's body mass in kilograms, and L is the individual's leg length in meters.

Figures 4 and 5 plot the actual energy expenditures vs. the model-predicted values for these two analyses, with 95% confidence intervals. The R^2 correlation coefficient for the walking model is 67%, meaning that 67 percent of the variation in the actual y values is accounted for by the regression equation. The R^2 correlation coefficient for the running model is 82%.



(a) (b)

Figure 4. Multiple gravity level energy model for walking (a) and running (b). Actual collected test data are plotted by the y-axis, and model predicted values are plotted by the x-axis. The dashed horizontal line represents the mean y value. The dotted diagonal line represents simply x=y, and dashed confidence curves represent the range within which 95 percent of the data are expected to lie, assuming a normal distribution. (a) The R^2 correlation coefficient for the walking model is 67 percent. (b) The R^2 correlation for this model is 82 percent.

Effects of individual fitness level on maximum load carrying capability

Several researchers have suggested that an acceptable exercise intensity for an eight-hour work day which will prevent undue fatigue is in the range of 35 to 50 percent of the individual's maximum oxygen uptake capacity (Astrand, 1967, and Saha, 1979, Astrand, 1956, Patton, 1990). It is believed that this level of exercise intensity is not high enough to produce any significant depletion of muscle glycogen or increase in blood lactate levels, both of which are contributing factors to decreased muscular strength and fatigue (Patton, 1990).

If we believe this assertion, then we can speculate on the level of physical conditioning that would be required for an eight hour day of locomotion at a given speed, while carrying a load. Figures 6, 7, and 8 present the energy data for each gravity level and speed combination as percentages of each individual's maximum oxygen uptake capacity. The percentages are plotted versus load factor. The dashed horizontal lines at 35 percent and 50 percent of VO_2 max indicate levels at which personnel in average or excellent condition, respectively, can exercise for 8 hours without becoming overly tired. The density ellipses are confidence curves showing where 90 percent of the data are expected to lie, assuming a bivariate normal distribution.

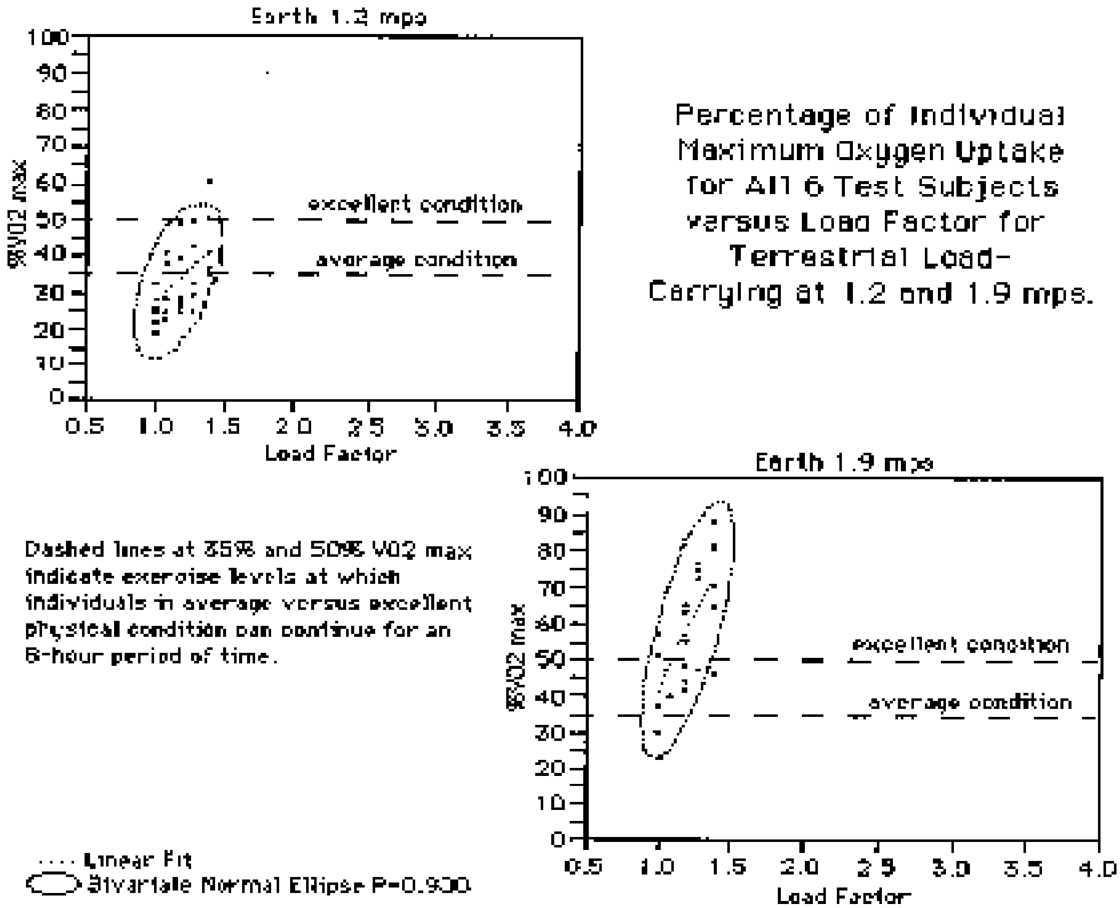


Figure 5. Percentage of individual maximum oxygen uptake versus load factor for terrestrial load-carrying at two speeds. "Excellent" and "average" lines give indications of reasonable exercise levels for highly conditioned and average individuals.

From Figure 5, we can see that in earth gravity conditions, an individual in average condition could walk at a speed of 1.2 m/sec for eight hours and carry twenty percent of their body mass (load factor 1.2). Individuals in excellent condition would have little trouble carrying up to 45 percent of their body mass. And indeed, military subjects are expected to be able to carry 35%-45% of their body mass during training and strategic maneuvers. At the higher speed of 1.9 m/sec, most individuals would have to be in above average to excellent condition to continue for eight hours even without a load.

In Martian gravity (Figure 6), an individual in average condition can walk at 1.2 m/sec for eight hours carrying an average of up to 50 percent of his or her body mass. If in excellent condition, almost all of the test subjects could carry the entire range of tested loads for eight hours. At the higher speed of 1.9 m/sec, as in earth gravity, most individuals would have to be in above average to excellent condition to continue for eight hours even without a load.

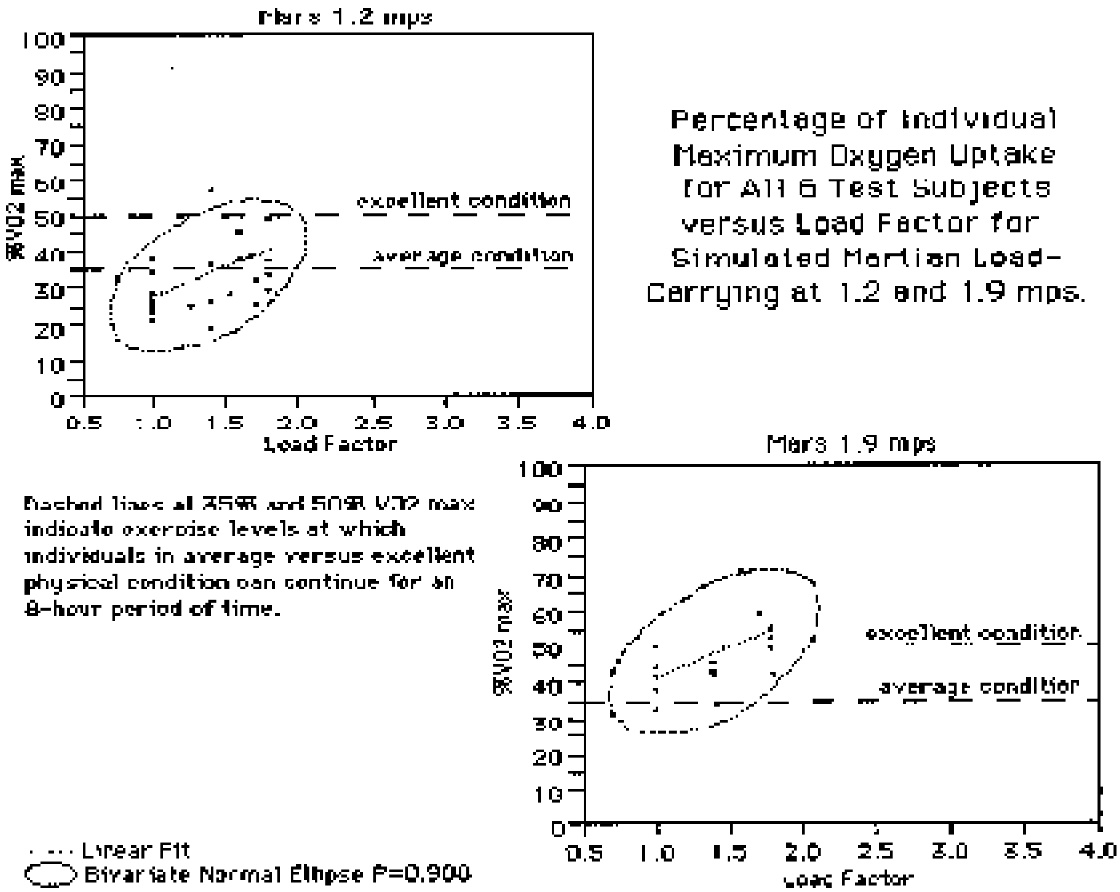


Figure 6. Percentage of individual maximum oxygen uptake versus load factor for Martian load-carrying at two speeds. "Excellent" and "average" lines give indications of reasonable exercise levels for highly conditioned and average individuals.

The slopes on the lunar graphs (Figure 7) are much flatter; therefore there is a large difference in load size that can be carried by an individual in average physical condition, versus one in excellent physical condition. In lunar gravity, an individual in average condition can walk at 1.2 m/sec for eight hours carrying an average of 170 percent of their body mass. If in excellent condition almost all of the test subjects could carry the entire range of tested loads, up to 270 percent of body mass, for that duration. At the higher speed of 1.9 m/sec, a test subject in average condition can walk for eight hours carrying an average of up to 60% of his or her body mass. If in excellent condition, one could carry up to 250 percent of their body mass for an eight hour duration.

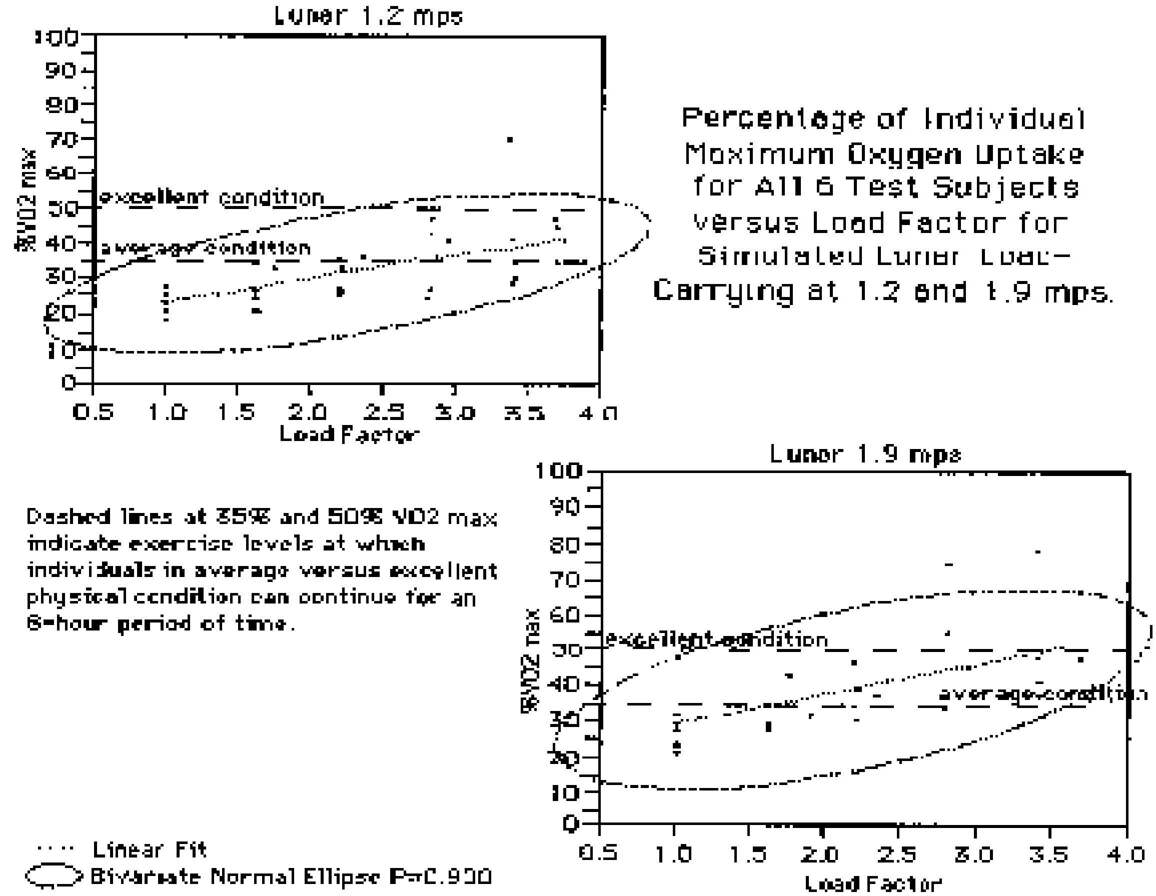


Figure 7. Percentage of individual maximum oxygen uptake versus load factor for lunar load-carrying at two speeds. “Excellent” and “average” lines give indications of reasonable exercise levels for highly conditioned and average individuals.

<u>Implications for bone maintenance</u>

Researchers at Stanford University developed a model to predict bone density based on levels and patterns of loading, believing that all daily load cycles are involved in the maintenance of bone structure (Whalen, 1988). When applied to the maintenance of bone during spaceflight through the use of treadmill walking, their equation takes the following form:

$$T = t(w/W)^4 \tag{3}$$

where T is the required space treadmill walking time, t is the corresponding walking time on earth for a given level of bone maintenance, w is the weight on the subject’s foot on earth, and W is the weight on the subject’s foot in space. The model assumes moderate walking speeds. The crux of Whalen’s theory is that high bone stresses are more effective in building or maintaining bone mass than simply increasing the number of daily loading cycles, therefore a small increase in the magnitude of the load pays off in greatly decreased exercise time.

Using an earth walking time (t) of 4 hours to represent the earth walking time of a moderately active individual, we can apply Whalen's equation to determine the equivalent planetary walking time under different loading factors. In one-g the four hour bone maintenance walking requirement can be reduced to 1 hour if a 40% load is carried. Figures 8, 9, and 10 show space walking time (equivalent to 4 hours on earth, unloaded) for earth, Martian and lunar gravities. The equivalent walking times for Martian and lunar gravities are unattainably high: 18 and 26 hours daily, at even the highest load factors.

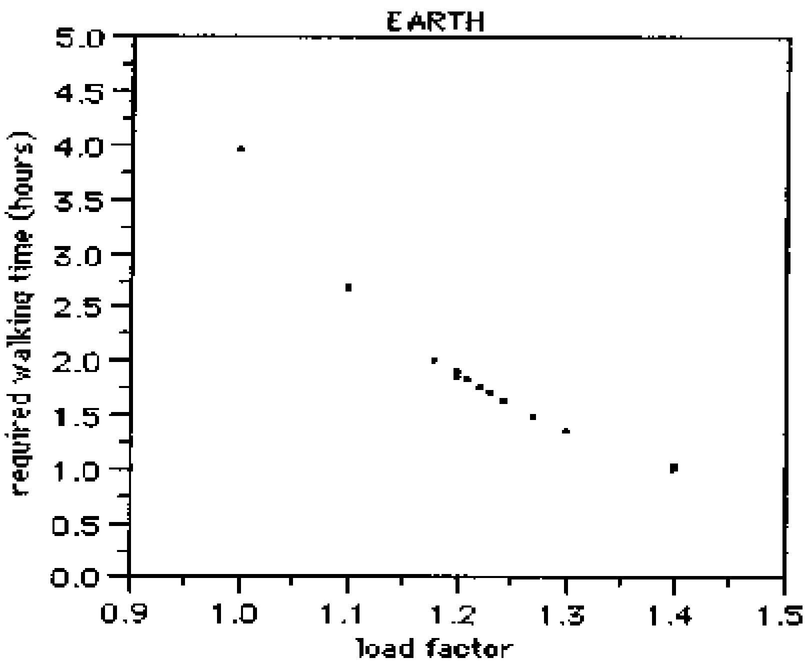


Figure 8. Required walking time on Earth with various load factors to maintain bone mass at the level of a moderately active individual on earth. Enlarged section shows walking times under 100 hours.

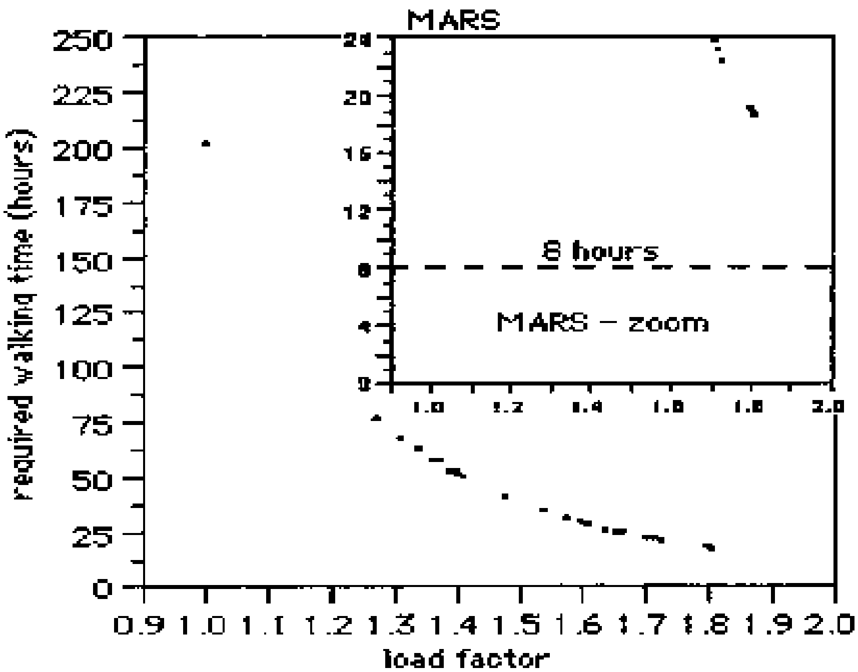


Figure 9. Required walking time on Mars with various load factors to maintain bone mass at the level of a moderately active individual on earth. Enlarged section shows walking times under 24 hours.

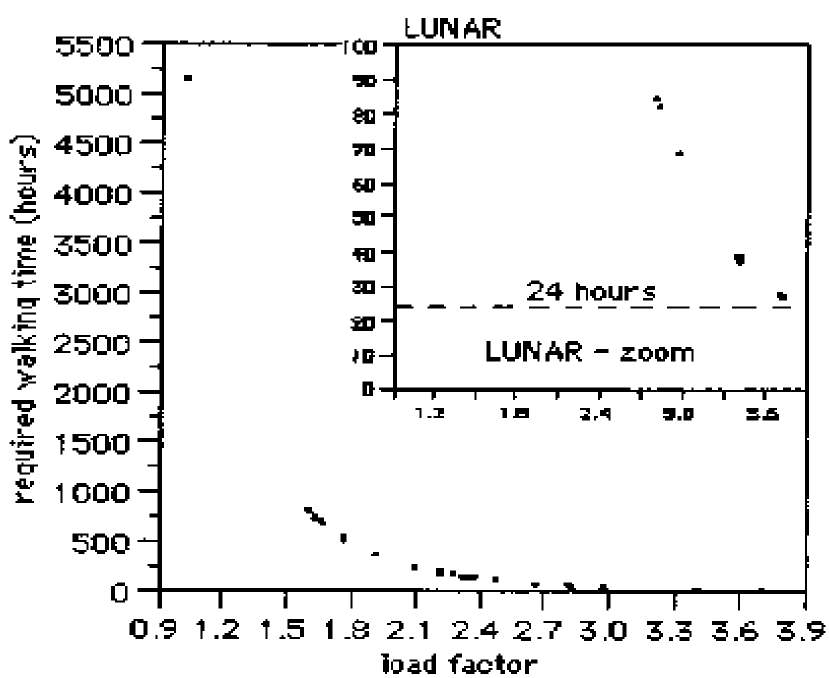


Figure 10. Required walking time on the moon with various load factors to maintain bone mass at the level of a moderately active individual on earth. Enlarged section shows times under 100 hours.

However, subjects in this study, like the Apollo astronauts, tended to run in reduced gravity, thus experiencing higher ground reaction forces. If we modify Whalen's equation by substituting peak ground reaction force (PGRF) for W,

$$T = t(w/PGRF)^4 \tag{4}$$

The data are plotted now as equivalent planetary locomotion time for bone maintenance vs. load factor using the modified equation (4) in Figures 11 through 14. In examining these figures, we discover that in Mars gravity at 1.2 m/sec, the required locomotion times are lower than eight hours only at load factors greater than 1.6. From the preceding section, only individuals in excellent condition would be able to maintain this locomotion speed for 8 hours with this load. The equivalent locomotion times necessarily are lower at the higher speed, but we have already concluded that only extremely fit individuals would be able to maintain that speed for eight hours, even unloaded.

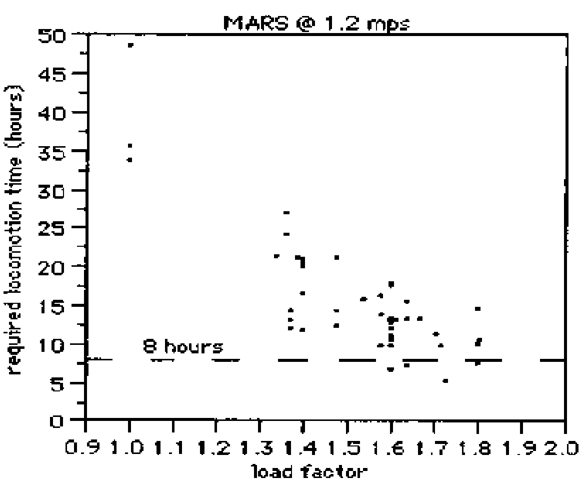


Figure 11. Predicted locomotion time required for Mars at 1.2 mps with various load factors to maintain bone mass at the level of a moderately active individual on earth, using equation (4).

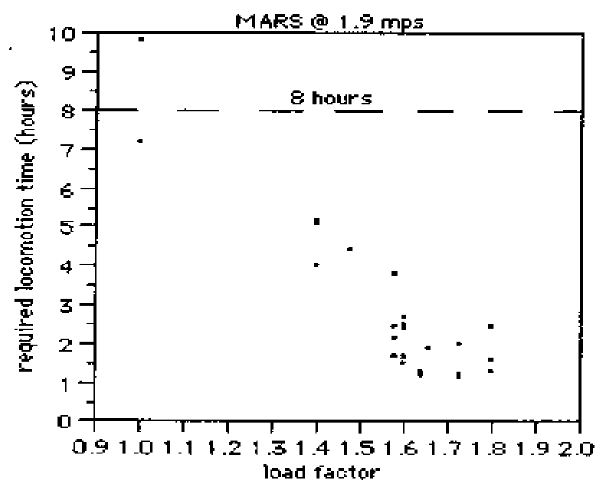


Figure 12. Predicted locomotion time required for Mars at 1.9 mps with various load factors to maintain bone mass at the level of a moderately active individual on earth, using equation (4).

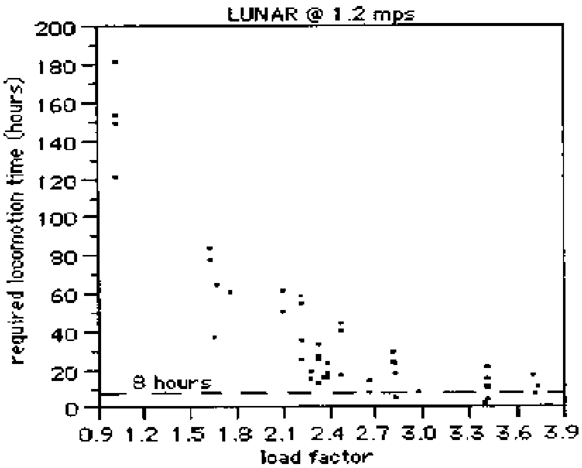


Figure 13. Predicted locomotion time required on the moon at 1.2 mps with various load factors to maintain bone mass at the level of a moderately active individual on earth, using equation (4).

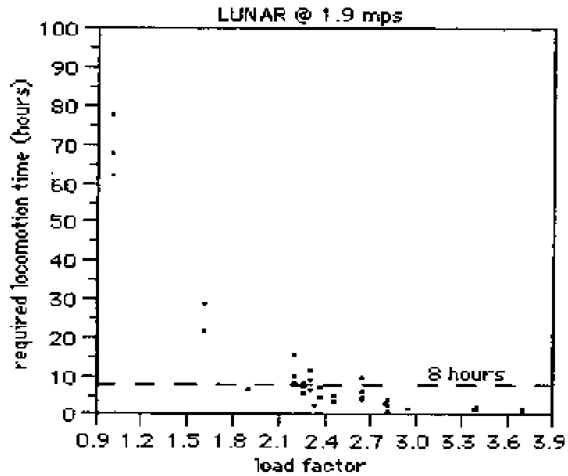


Figure 14. Predicted locomotion time required on the moon at 1.9 mps with various load factors to maintain bone mass at the level of a moderately active individual on earth, using equation (4).

At 1.2 m/sec on the moon, the bone maintenance locomotion times decrease to *near* 8 hours at high load factors -- 3.0 and higher. However, at 1.9 m/sec, a good deal of data points are below eight hours at load factors of 2.4 and above. This means that individuals carrying 140% of their body weight and traveling at 1.9 m/sec for 8 hours could maintain their bone mass, assuming the applied modification of Whalen's model to hold true. This individual would have to be in above average to excellent condition, however, from the above discussion.

Conclusions

Preliminary data on the energy cost of walking in reduced gravities while load-carrying has been presented. The energy cost increases with gravity level, with speed, and with increasing mass of the carried load. The energy cost of a supplemental increment of load increases with gravity level. That is, the energetic cost of backpacks of higher mass is more critical to a mars mission than a lunar mission. In fact, it may be mission-limiting.

A linear, multi-gravity energy model for walking and running while load carrying has been developed. The energy cost (kcal/kg-min) is a function of the locomotion speed, the gravity level, the load carried, the individual's body mass, and the individual's leg length.

Some discussion has been devoted to daily locomotion protocols with respect to their effectiveness in bone maintenance. The modification of Whalen's theory is a bit simplistic, and the foregoing discussion is meant to serve only as a launching pad for additional research. The view proposed here, however simplistic, *does* give some insight into the interaction of carry-able load size, fitness level, and bone maintenance via planetary locomotion. In lower gravities, some combination of longer walking times and higher load factors will be required to maintain bone mass. The theory is crude but indicates that the required locomotion times for bone maintenance might be unattainably high, for the tested load factors and locomotion speeds. Supplemental bone maintenance measures will likely need to be implemented.

Higher locomotion speeds are amenable to the maintenance of bone tissue within attainable time schedules. Yet, if the locomotion is to be done while load-carrying, as it has been in the past, individuals must be in above average to excellent physical condition to maintain the locomotion speed for an 8-hour work day. Whether humans can maintain excellent physical conditioning for long periods in the low gravity environment or in the zero-gravity transit leg of a mission remains to be seen.

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