ICES paper 1995

Load-Carrying in Reduced Gravities:
Operational Considerations

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Abstract: Extravehicular planetary explorers must wear protective suits and portable life support systems to provide them with a pressurized, breathable atmosphere. The mass of these systems has traditionally been quite large, and mass projections for some future regenerable systems are even higher. Yet very little is known about human load-carrying capabilities in reduced gravity levels. This work is a first attempt to investigate the biomechanics and energetics of human load-carrying in simulated reduced gravities to obtain load magnitude and placement data for spacesuit design and exploration mission planning purposes.

Introduction

Visionary leaders and agencies within the international aerospace community have the desire and resources available to explore this solar system. With such volition we will eventually return to the surface of the moon, and explore a planetary surfaces such as Mars and Phobos. In this country, several federally-appointed committees have recommended such ambitious endeavors: the Ride Commission Report of 199X and the Synthesis Group Report of 1991. Astronauts on a planetary surface must wear protective suits and portable life support systems (PLSSs) to provide them with a pressurized, breathable atmosphere. NASA has some experience in the design of planetary life support systems from the Apollo program, but the majority of human experience is in the zero-gravity environment of low earth orbit. The requirements for a zero-g life support system are different from a planetary life support system in many ways. Additionally, any future planetary system will likely be different from the former Apollo hardware. Restrictions on expendables and limitations on venting of contaminants such as water vapor and exhaust gases have forced engineers to use alternative designs in future extravehicular activity (EVA) systems. The new designs currently under consideration are much heavier. One study projects the mass of future spacesuit/PLSS designs to be very high, on the order of 400 lbm or more, compared to the Apollo spacesuit/PLSS weight of 190 lbm, and even the Shuttle EMU weight of 270 lbm. Clearly, a given earth mass creates only one-sixth of its earth weight when on the moon, but the crewperson’s body weight is reduced as well. Can humans carry 400 earth pounds—over 2 times their body mass—while in reduced gravity, and accomplish geologic exploration and scientific experimentation? Using our terrestrial experience base, we might think not. So how much extra mass can be carried? And is the traditional backpack configuration the best approach to load-carrying in reduced gravities? This study is our first attempt to investigate these questions.

Three initial hypotheses formed the framework for this study, but it was expected from the start that many of the most interesting results of this investigation might be unanticipated since no serious research has previously been conducted in the area of load-carrying by humans in partial gravity. The first hypothesis was that for levels of gravity less than one, it would prove advantageous to distribute loads as close as possible to the normal anthropometric center of gravity. Expected benefits included improved stability, energy conservation during walking, and decreased muscular and aerobic effort during tasks involving primarily the upper body. The second hypothesis was that a safe and reasonable load size for reduced gravity levels which produces a given workload measurement equivalent to a reasonable workload on earth (e.g., 30 percent load at 1.2 meters/second, and 15 percent load at 1.9 meters/second) will be greater than the one-g baseline, but significantly less than the product of the inverse g-level and the baseline load. And the third hypothesis was that a front load position may be advantageous, since higher speeds and thus longer stride lengths can be more easily attained in reduced gravity, thereby necessitating a forward shift of the body's center of gravity (normally achieved by a forward lean) to keep the line of gravity moving ahead of the pushoff foot.

Methods

Preliminary walking, lifting, kneeling, and positioning experiments were conducted aboard the NASA Johnson Space Center KC-135 Research Aircraft and the primary locomotion experiments were performed in the NASA Ames Research Center Neutral Buoyancy Test Facility. The 350 primary experiments were conducted at lunar (0.16-g), martian (0.38-g), and earth (1-g) gravity levels. An underwater treadmill, ballasting harness, and loading system were used to simulate reduced gravity locomotion while load-carrying. Loads carried emulated from zero to 45 percent (load factors from 1.0 to 1.45) of each test subject's body mass for the earth-g tests, from zero to 80 percent (load factors from 1.0 to 1.8) of body mass for the martian-g tests, and from zero to 270 percent (load factors from 1.0 to 3.7) of body mass for the lunar-g tests. The six test subjects (4 male, 2 female) walked and ran on the experiment treadmill at two primary speeds of 1.2 and 1.9 meters/second. Some additional tests were conducted at 2.4 and 3.0 meters/second. Heart rate, respiratory minute volume, and oxygen consumption rate, peak ground reaction forces, and strides per minute were measured for each test. In addition, each subject was asked to rate each test for comfort, difficulty, stability, and personal motivation. Each test subject completed between 48 and 72 tests, depending on schedule constraints, equipment problems, and individual capabilities.

Several problems stemming from real world constraints of time, budget, and gravity detracted from the quality of this research and should be pointed out here. These were firstly that the small number (six) of subjects tested was not large enough to cover the wide range of human responses to this type of exercise testing. However, the selection of this group of subjects was purposeful, in that all six met the current minimum qualifications of NASA astronauts. The second problem was that due to equipment failures and facility schedule conflicts, the test schedule to complete all 350 tests stretched out over 18 months, so that test subjects were vulnerable to physiological and psychological variations from test to test. The third problem was that, again due to schedule constraints, there was limited time for extensive training of subjects and performing numerous repetitions of tests to thoroughly validate data. And perhaps the most confounding problem was the imperfect reduced gravity simulation medium of water, which allows for realistic weight but not mass emulation, and which also requires additional energy expenditure (estimated at up to an additional 10 percent) to locomote in by the test subject.

So the results of this study are not by any means perfect, but they do offer some worthwhile insights into the energetics of water simulated reduced gravity load-carrying by fit, well-educated, scuba-trained humans.

KC-135 Results

During the KC-135 tests, the Variable Load Positioning Backpack (VLPB) positioned a 21 kilogram load on the subjects at two extreme locations: high on the back, at shoulder height and 46 centimeters from the body's centerline; and low on the front torso, at hip height and 46 centimeters from the body's centerline. Subjects performed a variety of lifting, positioning, and walking tasks with the load in the two different locations. Since the parabolic arc flown by the KC-135 is relatively short (about 30 seconds for lunar-g and 40 seconds for martian-g), test time is insufficient to measure steady-state work or metabolic rates. Video footage was taken of all activities, and subjects completed questionnaires evaluating comfort, difficulty, stability and control for each task and load position. Analysis of the test footage and questionnaires indicate a preference for the low front load position over the high back position, although the low front load was sometimes awkward or interfered with the test subjects' performance of the lifting and positioning tasks. The preference for the low front position supports the hypotheses that the load should be located as close as possible to the normal body c.g., and that a front load position may be advantageous. The low front position preference is also in accord with the physical principle that a lower c.g. enhances stability.

Energy Results

As reported in the earlier discussion of primarily unloaded partial gravity locomotion studies, most of the results indicate that energy expenditure for locomotion decreases with decreasing gravity level, but the question as to exactly how much it decreases still remains. Estimates for lunar locomotion energy requirements range from about 20 percent to 134 percent of terrestrial energy requirements. For martian locomotion, energy requirements are estimated to be anywhere from about 40 percent to 134 percent of terrestrial locomotion requirements.

Figures 1 and 2 show the test data adjusted to account for roughly estimated water immersion effects. Ten percent was chosen because it is the high end of the range of estimated drag-induced energy expenditure for underwater locomotion (Newman, 1992), and while subjects may not have used the full 10 percent to overcome drag, it is suspected that the subjects generally expended some wasted nervous energy during the underwater tests. With these adjustments, unloaded lunar-g locomotion at 1.2 and 1.9 meters/second can be seen to require 76 and 67 percent, and unloaded martian-g locomotion at the same speed 88 and 93 percent, respectively, of the energy required for earth-g locomotion at the same speeds. Obviously, as the load factors increase, the energy differentials between the three gravity levels also increase, so significantly less energy is required to carry a load of a given percentage of body mass on the moon than on Mars, and on Mars than on the earth. These differences are accentuated as speed and load increase.

The position and slopes of the average torso regression lines for all six test subject's speed/gravity combinations indicate not only that energy expenditure increases with gravity level, but also that energy expenditure increases with load within gravity level more slowly at lunar gravity than at martian, and more slowly at martian than at earth gravity. In other words, a large amount of load can be added to the lunar astronaut with a relatively small increase in energy vis a vis his or her earthbound counterpart.

Figure 1: Average energy for Earth and simulated Mars and Lunar locomotion at

1.2 meters/second for all test subjects at a range of torso loads, adjusted for roughly estimated water immersion effects of 10 percent. Error bars show standard error for all points on each line within which 68 percent of all normally distributed values are expected to lie. Individual slopes for Earth torso regression lines range from 0.024 to 0.107 (average slope = 0.075) kcal/kg/min per load factor increase of one; for Mars from 0.020 to 0.070 (average slope = 0.032) kcal/kg/min per load factor increase of one; for Lunar from 0.009 to 0.032 kcal/kg/min (average slope = 0.017) per load factor increase of one.

Figure 2: Average energy for Earth and simulated Mars and Lunar locomotion at 1.9 meters/second for all test subjects at a range of torso loads, adjusted for roughly estimated water immersion effects of 10 percent. Error bars show standard error for all points on each line within which 68 percent of all normally distributed values are expected to lie. Individual slopes for Earth torso regression lines range from 0.126 to 0.328 (average slope = 0.173) kcal/kg/min per load factor increase of one; for Mars from 0.026 to 0.081 (average slope = 0.042) kcal/kg/min per load factor increase of one; for Lunar from 0.007 to 0.053 (average slope = 0.019) kcal/kg/min per load factor increase of one.

Load Placement Recommendations for Planetary Spacesuit Design

Torso loads worked quite well for all gravity levels investigated, requiring the least energy expenditure in 20 of the 36 test cases. In every speed/gravity combination except 1.2 meters/second/lunar, the torso energy average was lowest. The low back position did not appear to be a particularly good choice for any of the three gravity levels, being the position with the most high energy cases overall (18 out of 36). Overall average energy for the low back position was worst or tied for worst for each gravity level. Conversely, the high back position did not seem to be a bad choice for any of the gravity levels, ranked second lowest across the board in average energy for each speed/gravity combination. The low front load position tested better energy-wise than the low back position at the lower speed and worse at the higher speed for every gravity level. This may be due to the problem mentioned earlier with the low front position weight mounting hardware sometimes interfering with the test subjects' stride length, especially at the higher locomotion speeds.

In this study, torso load-carrying generally required the least amount of energy for all gravity levels, followed by high back load-carrying, and low back load-carrying required the highest amount of energy. As pointed out by physiologists Daniels, Vanderbie, and Bonmarito of the US Army Quartermaster Climatic Research Laboratory (1953), an increase in forward lean is found when the load carried is moved from torso to high back, and from high back to low back. Thus, it would appear that there may be a relationship between the angle of forward lean and the energy expenditure required to locomote with a load, at least for the back and torso loads. This theory may be related to the fact that vital lung capacity is altered by postural changes, so any load-carrying system which results in the wearer's altered posture (such as forward lean) could reduce vital capacity. Furthermore, Bedale's work points out the physiological inefficiency of load-carrying systems which effect significant postural deviation from the vertical (Bedale, 1924). The sternum strap and hip belt of the VLPB are not believed to have restricted the wearers' breathing in any way.

To summarize the results for earth load placement, the torso load seems best for the cases studied, with the high back as a good alternative. Low front and low back loads do not appear to be the best choices for earth, possibly because it is easier to balance a load placed high on the back (by bending slightly forward at the waist) than one on either the front or the low back.

For Mars, like earth, the torso load again seems the best, and again the high back position appears to be a decent alternative. The low front position seems to be the only consistently bad choice for Mars. The low back position made its best showing for martian gravity, where it balanced its four highest energy cases with four lowest energy cases.

For lunar gravity, the torso distribution again appears desirable, but its margin over any other positions was much narrower at this gravity level than either of the others as it led the low front position by five lowest energy cases to four. The low front and torso load positions may have tested well for lunar because the lower c.g. gives increased stability which is highly useful in this very low-gravity environment. As hypothesized at the outset, a front load position may be beneficial since longer stride lengths can be more easily attained (and as we have seen are indeed the norm) in reduced gravity, thereby necessitating a forward shift of the body's center of gravity (normally achieved by a forward lean) to keep the line of gravity moving ahead of the pushoff foot. If this can be achieved by load placement, the astronaut can maintain a more upright posture, which may allow him/her to take longer strides more efficiently.

As mentioned previously, an artifact of the test hardware is that the low front position weight mounting hardware sometimes limited the test subjects' stride length, especially at the higher locomotion speeds. This should be acknowledged when examining the results, especially in cases such as the lunar tests where the results for energy expenditure for the low front position tested well for the slow speed but not as well for the higher speed, and where the subjective ratings of the low front load position were favorable.

Figure 3 summarizes average energy for each of the four load placement positions at the two primary speeds in the three gravity levels tested.

Figure 3: Summary of average energy for each of four load placement positions in three gravity levels. Load carried was approximately 20 percent of each test subject's one-g body weight.

Just as the pooled torso energy data for the simulated reduced gravity tests was adjusted lower by 10 percent to account for roughly estimated water immersion effects, so the Mars and lunar energy data for the various load placement positions could also be adjusted. This would probably improve the accuracy of inter-gravity level comparisons.

Efficiency and Optimum Load Considerations

It was noted that in some of the reduced gravity test cases, energy expenditure appeared to increase more slowly for the intermediate load factors, in fact, many of the sets of data points appeared to describe a second degree polynomial better than a straight line. This led to an examination of the concepts of efficiency and load optimization. Thus, the collected energy measurements of kcalories per minute were converted into kcalories per kilogram of total load (total load equals test subject mass plus external load mass) per meter traveled to allow for discussion of efficiency in carrying each increment of total load each increment of distance. This calculation of efficiency means that lower kcal/total kg/meter values reflect higher efficiency.

In considering definitions of optimum load, the lowest energy per kilogram per meter load factors for each gravity level are the most obvious choices, assuming a mission objective is to transport as much mass as possible as far as possible in as short a time as possible. Other factors which should also be considered are places in the energy cost curves which show little increase in energy expenditure for substantial increases in load (such as the high end of virtually all of the lunar efficiency curves), and rapid rises in the energy cost curves which show significant increases in energy for a minor increase in load (such as most of the earth 1.9 meters/second efficiency curves). In addition, exercise level and duration requirements must be taken into account.

While the data collected in this study are not extensive enough to determine elaborate equations for polynomial efficiency curves for each gravity level, as seen in Figures 4 and 5, there are low points in the individual lunar curves at a range of load factors from 2.4 to 3.7 (and an aggregate low point of 3.2), with very little increase in energy cost at the high load factors for any test subject at either speed. On the moon it appears to be more efficient to travel at 1.9 meters/second than at 1.2 meters/second with or without an external load of up to at least 140 (and for most individuals up to 270) percent of one's body mass. If an astronaut is in excellent condition, he or she should be able to carry a load of 250 percent of his or her body mass at 1.9 meters/second on the moon for an eight hour work day. Therefore a load factor of 3.2 to 3.5 could be considered optimum for lunar explorers, assuming the objective of transporting large amounts of mass far and fast. Otherwise, this "optimum" load could be considered absurdly high.

Figure 4: Energy expenditure per kilogram of total load per meter for simulated lunar load-carrying at 1.2 meters/second. Dashed vertical lines show individual and aggregate low points.

Figure 5: Energy expenditure per kilogram of total load per meter for simulated lunar load-carrying at 1.9 meters/second. Dashed vertical lines show individual and aggregate low points.

Figure 6: Energy expenditure per kilogram of total load per meter for simulated Martian load-carrying at 1.2 meters/second. Dashed vertical lines show individual and aggregate low points.

Figure 7: Energy expenditure per kilogram of total load per meter for simulated Martian load-carrying at 1.9 meters/second. Dashed vertical lines show individual and aggregate low points.

As seen in Figures 6 and 7, there are low points in the individual martian curves from 1.3 to 1.8 (aggregate low point of 1.8 for walking at 1.2 meters/second, 1.7 for running at 1.9 meters/second), with some indication that there may be a rapid increase in energy cost beyond 1.7 or so. On Mars it appears to be more efficient to travel at 1.9 meters/second than at 1.2 meters/second with or without an external load of any tested size (i.e., up to 80 percent of body mass). If an astronaut is in excellent condition, he or she should be able to carry a load of 50 percent of his or her body mass at 1.9 meters/second on Mars for an eight hour work day, so a load factor of 1.5 may be considered optimum for martian explorers.

As for earth load-carrying (plots not included), at the slower speed of 1.2 meters/second there may be a low point at about 1.15 to 1.18 load factor, but for the faster speed of 1.9 meters/second, most of the lines seem to simply increase from a load factor of 1 continuously. The slope of the earth energy cost curves is generally quite small up to a load factor of 1.2 to 1.3, but beyond that, and in some cases before that, there is generally a rapid rise in energy expenditure per kilogram per meter. If an individual is in excellent condition, he or she should be able to carry a load of up to 45 percent of his or her body mass at 1.2 meters/second, or 15 percent of his or her body mass (load factor of 1.15) at 1.9 meters/second on earth for an eight hour work day. Since the more efficient speed for earthbound load-carrying is 1.2 meters/second, the optimum load factor for earthbound walkers may be considered to be between 1.1 and 1.3.

Locomotion Range Implications for Spacesuit Design and Mission Planning

Figure 8 summarizes the average time and distance ranges in hours and kilometers for the average test subject using nominal (2000 kcalorie) and contingency (2600 kcalorie) eight hour EVA work day energy limits with the maximum and minimum loading conditions for all three gravity levels tested. As the table shows, in the unloaded condition on the earth one can travel farther for a given energy limit at the faster of the two tested speeds, but with the maximum load (in fact, with virtually any load) one can travel a greater distance at the slower speed with a given energy expenditure limit. Interestingly, for locomotion on the moon and Mars, whether an individual is carrying the maximum load or no load at all, he or she can always cover more ground on a given energy limit at the faster of the two tested speeds. The test subjects could for every gravity level and loading condition travel for longer times at the slower speed. It would be worthwhile to investigate the average ranges for energy limited reduced gravity load-carrying at additional speeds, since only two speeds were examined in this study.

These findings correspond to a previous study on lunar locomotion that was undertaken for NASA's Langley Research Center at Northrop Space Labs in Hawthorne, California, during the mid-1960's using a suspension rig and inclined plane technique to simulate the 1/6-g gravity vector normal to the walking surface of the treadmill (Hewes, 1967). This series of tests had two test subjects walking and running at different speeds with and without a pressure suit and 32.4 kilogram backpack (equivalent to a load factor of about 1.35, quite small for the moon). It was shown that the suited subjects were able to maintain a speed of about 1.6 meters per second for a continuous period of four hours over smooth, firm, level surfaces. Similarly, as Figure 10 shows, given an energy expenditure limit of 2000 kcalories, our test subjects could travel at 1.9 meters/second in simulated lunar gravity for an average of 3.4 hours with the maximum load factor of 3.7 (270 percent of body mass), or 5.9 hours with no load. The Northrop study also found that the maximum sustained speed (for up to 30 minutes) for the subjects was about 3 meters/second without exceeding the assumed maximum heat-dissipation rate of 2100 kiloJoules/hour (8.4 kcal/minute) of the spacesuit life support system. Two test subjects in our study performed simulated lunar-g locomotion tests at 3.0 meters/second. If their energy expenditure results are converted from kcal/kg/min to kcal/min, we find that one subject expended 8.6 kcal/min once he reached steady state during this test, and the other subject expended 8.4 kcal/min, almost identical to the findings of the Northrop study.

The table in Figure 8, in conjunction with the results presented in the previous section on efficiency and optimum load, can be useful tools for spacesuit designers and planetary surface EVA mission planners.

Figure 8: Summary chart of average time and distance ranges for nominal and contingency energy limits with maximum and minimum load in three gravity levels.

Conclusions

The lowest average energy load placement position tested for all gravity levels was the torso position, which confirms the first hypothesis that it will prove advantageous to distribute loads as close as possible to the normal anthropometric center of gravity. The high back position was a strong second across all gravity and speed combinations.

The second hypothesis was that a safe and reasonable load size for reduced gravity levels which produces a given workload measurement equivalent to a reasonable workload on earth (e.g., 30 percent load at 1.2 meters/second, and 15 percent load at 1.9 meters/second) will be greater than the one-g baseline, but significantly less than the product of the inverse g-level and the baseline load. As it turns out - based on evaluations of torso-configured loads, and weight only, not mass - the equivalent energy load for reduced gravities is significantly greater, by equal to or more than the inverse of the gravity level factor for load-carrying at 1.2 meters/second, and by considerably more than this factor at 1.9 meters/second. Specifically, for the same energy it takes to carry an external load of 30 percent of ones' body mass on the earth at 1.2 meters/second, one could carry 80 to 100 percent (high end for each case is from data adjusted 10 percent lower for roughly estimated water immersion effects) of his or her body mass (2.7 to 3.3 times the earth load) on Mars, and 250 to 270 percent of his or her body mass (8.3 to 9 times the earth load) on the moon at the same speed. At 1.9 meters/second, for the same energy that it takes to carry an additional 15 percent of one's body mass on earth, one could carry 65 to 85 percent of his or her mass (4.3 to 5.7 times the earth load) on Mars, and 270 to 450 percent of his or her mass (9 to 15 times the earth load) on the moon. The reason for this is probably that when the weight of the planetary explorer's external load is the same as his or her earth-carried load the explorer is carrying a smaller amount of body weight on the lower gravity planet, so the total load carried is lighter. It should be emphasized that these tests had no means of evaluating the greater mass of an equivalent-weight load on the moon or Mars, or the hypothesis that the mass and inertial properties of the extraterrestrial load may impose greater balance and control requirements than does the smaller earth-based package.

The third hypothesis was that a front load position may be advantageous, since higher speeds and thus longer stride lengths can be more easily attained in reduced gravity, thereby necessitating a forward shift of the body's center of gravity to keep the line of gravity moving ahead of the pushoff foot. The low front position made a good showing for lunar gravity, especially at the lower speed, but the weight mounting hardware appeared to interfere with the subjects' stride length especially at the higher speeds. The low front position was rated as least difficult for lunar gravity by a narrow margin. Because of these findings, further investigation of the low front position would be necessary to prove or disprove this hypothesis.

As stated above in slightly different terms, significantly less energy is required to carry a load of a given percentage of body mass on the moon than on Mars, and on Mars than on the earth. These differences are accentuated as speed and load increase, as seen from the slopes of the regression lines in Figures 1 and 2.

A much higher maximum safe load size as a percentage of body mass can be carried for eight hours per day at reduced gravity levels. The maximums reached in this test series were 45 percent for earth, 80 percent for Mars, and 270 percent for the moon, but it is recognized from the test results that considerably higher loads could be safely carried for shorter periods of time on the moon and Mars.

If carrying mass from one point to another on the lunar surface is a mission objective, a whopping load factor of 3.2 to 3.5 could be considered optimum for lunar explorers in excellent condition. On Mars, a load factor of 1.5 may be considered to be optimum for planetary explorers in excellent condition. The optimum load factor for earthbound walkers in excellent condition may be considered to be between 1.1 and 1.3,.

Load-carrying on the moon and Mars is more efficient (as evidenced by low kcalories/total kg/meter values) at 1.9 meters/second than at 1.2 meters/second, whereas on the earth this is only true for the unloaded condition. So, for a given total energy limit, more distance can be covered with a load on the moon and Mars at the higher of the two speeds.

Planetary spacesuit designers should accommodate the user’s normal range of motion for the entire body, especially for the head, torso, arms (overhead reach, forward extension, side extension/abduction), and legs. Since relatively high running speeds can easily be sustained in reduced gravity, spacesuit arm and leg section ranges of motion should not restrict extreme limb movements. Because stride length tends to be longer as gravity level decreases, hip flexion in the suit also must accommodate a large range of motion.

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