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The influence of reduced gravity on human load-carrying capability and preferred load placement

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The Influence of Reduced Gravity on Human Load-Carrying Capability and Preferred Load Placement

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By
Leslie Ann Wickman
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SIGNATURE PAGE FOR DOCTORAL DISSERTATION

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Abstract

This study investigates issues associated with determining reasonable load sizes and locations for extravehicular personnel performing activities on extra-terrestrial planetary surfaces. The author performed original research on the effects of gravity level, speed of locomotion, load size, and load placement on human metabolic work in reduced gravity simulations for the purpose of providing spacesuit design and extraterrestrial mission operations planning guidelines.

Loads of various sizes were configured at neutral (i.e., evenly distributed about the torso, close to the normal body c.g.) and more extreme (high back, low front, and low back) body locations, and several measures of work performance (respiratory minute volume, oxygen uptake, heart rate, and subjective difficulty ratings) were taken as six physically fit test subjects (4 males, 2 females) walked or ran on an underwater treadmill while weighted for lunar (0.16-g) or martian gravity (0.38-g) at four different speeds: 1.2, 1.9, 2.4 and 3.0 meters per second.

The lowest average energy load placement position tested for all gravity levels was the torso position. The high back load position was a strong second across all gravity and speed combinations. The low front load 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.

Significantly less energy was required to carry a load of a given percentage of body mass in simulated lunar than martian gravity, and in martian than terrestrial gravity. These differences were accentuated as speed and load increased.

A much higher maximum percentage of body mass could be carried at the simulated reduced gravity levels than at earth gravity. The maximums reached in this test 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 short periods of time on the moon and Mars.

Load-carrying on the moon and Mars is more efficient (in kcalories/kg/meter) at 1.9 mps than at 1.2 mps, 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.

There was less difference between male and female energy expenditure at the reduced gravity levels than at earth-g.

Spacesuit designers should try not to restrict the user's normal range of motion for head, torso, arms (overhead reach, forward extension, side extension/abduction), or legs. Since relatively high running speeds can easily be sustained in reduced gravity, spacesuit arm and leg ranges of motion should not restrict extreme limb movements. Also, because stride length tends to be longer as gravity level decreases, hip flexion in the suit needs to accommodate a large range of motion.

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Finally, thanks be to God, hallelujah, it's DONE!

"*God shall wipe away all tears from their eyes; and there shall be no more death, nor sorrow, nor crying, nor pain, for the former things have passed away.*"
- The Book of Revelation, chapter 21, verse 4.

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List of Acronyms and Abbreviations

ARC: Ames Research Center
CO_2: Carbon dioxide
EV: Extravehicular
EVA: Extravehicular Activity
c.g.: center of gravity
cm: centimeter
g: gravity
kcal, kcalorie: kilocalorie
kg: kilograms
HBI: High Back Inner Load Position (on VLPB, 23 centimeters from body's centerline)
HBO: High Back Outer Load Position (on VLPB, 36 centimeters from body's centerline)
HR: Heart Rate
LBI: Low Back Inner Load Position (on VLPB, 23 centimeters from body's centerline)
LBO: Low Back Outer Load Position (on VLPB, 36 centimeters from body's centerline)
LFI: Low Front Inner Load Position (on VLPB, 23 centimeters from body's centerline)
LFO: Low Front Outer Load Position (on VLPB, 36 centimeters from body's centerline)
m: meter
min: minute
ml: milliliter
mps: meters per second
N: Newtons
NASA: National Aeronautics and Space Administration
NASA-ARC: National Aeronautics and Space Administration-Ames Research Center
NBTF: Neutral Buoyancy Test Facility
O_2: molecular oxygen
RMV: Respiratory Minute Volume
RQ: Respiratory Quotient
s: second
TM: treadmill
USARIEM: United States Army Research Institute of Environmental Medicine
V_E: pulmonary ventilation rate
VLPB: Variable Load Positioning Backpack
VCO_2: carbon dioxide production rate
VO_2: oxygen consumption rate
VO_2 max: maximum oxygen uptake capability

Chapter 1:
INTRODUCTION

This study was performed to investigate the energetics, biomechanics, and other human factors associated with walking, running, and load-carrying in reduced gravity environments, specifically on the surfaces of the Moon and our nearest planetary neighbor, Mars. The overriding purpose of the study was to provide design guidelines to extravehicular spacesuit designers and mission operations planners based on energy expenditure for spacesuit/life support system mass size and distribution, speed of locomotion, and gravity level.

1.1 Problem Statement

The basic difference between zero gravity and partial gravity locomotion radically alters the requirements of spacesuit design. In zero gravity, the astronaut uses his or her hands and arms to move from place to place, and to reposition his or her body, while the lower body, when attached to a foot restraint or other restraining device, is used primarily for stability and reacting loads. However, in partial gravity, the astronaut resumes a more earth-like posture, requiring use of the lower body for locomotion. Therefore, whereas spacesuits designed for use in zero-gravity do not require much lower body mobility, suits designed for use in partial gravity must accommodate large lower body joint ranges of motion. Also, the issues of balance and stability, which are virtually meaningless in zero gravity, take on great significance for partial gravity spacesuit sizing and mass distribution.

Much research has been conducted on the topic of terrestrial load-carrying by humans for the military and the outdoor sports industry which 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 apart 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.

1.2 Hypotheses

The first hypothesis is that for levels of gravity less than one, it will prove advantageous to distribute loads as close as possible to the normal anthropometric center of gravity, so as not to impose any unnatural static or dynamic moments on the body. Expected benefits include improved stability, energy conservation during walking, and decreased muscular and aerobic effort during tasks involving primarily the upper body. Early on in this project, KC-135 reduced gravity research aircraft flight experiments suggested this hypothesis, which led to further experimentation in the NASA Ames Research Center (NASA-ARC) Neutral Buoyancy Test Facility (NBTF).

Additionally, it is hypothesized 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 mps, and 15 percent load at 1.9 mps) will be greater than the one-g baseline, but significantly less than the product of the inverse g-level and the baseline load. This seems intuitive, because a load on the moon or Mars with the equivalent weight of a load on earth will have a much greater mass, and the mass and inertial properties of the extraterrestrial load will impose greater balance and control requirements than would the smaller earth-based package.

Finally, it is hypothesized 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. 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, and will certainly allow him/her to see farther down the forward path.

These hypotheses formed a basic framework for this research, but it was expected from the outset that many of the most interesting results of this investigation might be serendipitous. No serious research has previously been conducted in the area of load-carrying by humans in partial gravity, therefore meaningful predictions are hard to formulate, and have been pieced together from related areas such as terrestrial load-carrying and reduced-gravity simulations.

Chapter 2: BACKGROUND

This chapter gives an overview of several of the most pertinent topics related to this study, namely, the significant characteristics of the celestial bodies whose gravity levels are studied, the primary physiological effects of spaceflight, the basics of human energy expenditure, the most common methods of simulating reduced gravity, and a literature review of previous walking, load-carrying, and reduced gravity research.

2.1 Three Celestial Bodies of Interest

2.1.1 The Moon

Our nearest celestial neighbor and natural satellite at roughly 384,000 kilometers away, the moon has less than 1/80th the mass and just over one-quarter the size of the earth, producing one-sixth the gravity (1.6 m/s^2) of the earth by the law of gravitation ($F = GMm/r^2$, where "F" is the force between two bodies, "G" is the gravitational constant (6.67×10^{-11} $N{\cdot}m^2/kg$), "M" is the mass of larger body, "m" is the mass of smaller body, and "r" is the distance between the two bodies). The relatively large size of the moon as a satellite with respect to the earth is unusual in our solar system, and gives the earth/moon system the dynamic properties of a double-planet system. The earth and the moon make one revolution about their common center of mass every 27.3 days, but tidal friction is gradually slowing this revolution and causing the moon to slowly spiral outward.

The moon has virtually no atmosphere, with an average of 2×10^5 molecules per cubic centimeter measured at the surface at night, compared with about 2×10^{19} molecules per cubic centimeter on the earth's surface (Smith and West, 1983). The moon's surface is characterized by dark, relatively level lava flows and lighter, more rugged cratered regions. All areas are covered by a regolith layer of powdery soil and bits of rock produced by continuous meteoritic bombardment (Hartmann, 1983).

2.1.2 Mars

Mars, the fourth planet out from the Sun and our third nearest neighbor (behind the moon and Venus) at 56 to 101 million kilometers, the Red Planet (named for the coloration due to its plentiful oxidized iron minerals) was once thought to be a likely place to support life. However its atmosphere turns out to be thin (5.9 to 15.0 millibars pressure at the surface, compared to 1013.5 millibars on the earth's surface) and oxygen deficient, and its surface is cold (130 to 300 degrees K), dry, and apparently lifeless, its soil containing no organic material. Mars has about one-ninth the mass of the earth, and just over half the size, yielding three-eighths of the earth's gravity ($3.7 m/s^2$).

Mars has many volcanic features as well as ample evidence of past tectonic activity. Its enormous annual dust storms, which mainly serve to redistribute fine debris, appear to be responsible for the seasonal color changes which were once thought to be evidence of plant growth. Mars' distinctive polar caps retreat as much as 40 degrees of latitude in the spring and summer, the southern cap all but disappearing. An interesting and perhaps useful feature for future exploration and colonization is that the permanent northern residual cap is H_2O ice, while both seasonal caps and the southern residual cap are all CO_2 ice. (Smith and West, 1983.)

One of the biggest challenges to be faced in exploring Mars is its rugged terrain: mountains three times as high as Mount Everest; canyons ten times as big as our Grand Canyon; dust bogs and huge boulders abound (Triplett, 1991).

2.1.3 Earth

Our home planet, earth, is the third planet out from the sun at a distance of 149,600,000 kilometers, and is quite unique. It is the only planet in our solar system equipped to sustain life as we know it, with just the right distance from the sun (for temperate climate and liquid water), the right size (for gravity and adequate atmosphere), the right atmospheric composition (21 percent oxygen, 79 percent nitrogen, water vapor, and other inert gases, and no poisonous gases), and a period of rotation which provides the perfect day/night work/sleep cycle.

Known as the Blue Planet due to the molecules scattering sunlight in its atmosphere, Earth is characterized by its swirling white clouds, the water which covers 71 percent of its surface, and its teeming plant and animal life forms. Earth's gravitational acceleration is 9.8 m/s^2, and its atmospheric pressure at the surface is 1013.5 millibars.

2.2 Physiological Effects of Reduced Gravity

Human exposure to microgravity has been studied extensively over the last three decades of manned spaceflight, but because humans have had little long duration exposure to partial-gravity, the findings from our studies of microgravity are currently our only clues to what may happen physiologically during an extended planetary mission.

Residence in the weightlessness of space appears to affect human physiology in much the same way as extended bed rest. Muscular atrophy, particularly of the large, lower body anti-gravity muscles, is common. Progressive bone loss is observed which is similar to that seen in disuse osteoporosis. Both of these symptoms can be largely attributed to the removal of the mechanical forces produced by gravity on the weight-bearing structures of the body. Another spaceflight phenomenon is the headward shift of blood and other bodily fluids, which creates increased pressure on the heart's aortic baroreceptors, which in turn suppress production of antidiuretic hormone, causing an overall reduction in blood volume.

Russian investigators have suggested a two-phase metabolic response to the stress of spaceflight (including such factors as weightlessness, hypokinesia, and radiation). The first phase is an increase in metabolism, and the second is a two-step decrease in metabolism to lower than the initial starting point (Prokhonchukov et al, 1984). Their study links the first phase increase in metabolic rate to a resultant increase in bone resorption, and the second phase decreases in metabolic rate to resultant abnormal tissue oxygenation and metabolic acidosis.

A major objective of both Russian and American space programs is to minimize the amount of time and energy devoted to physical conditioning and other countermeasures intended to ward off the cumulative adverse physiological effects of weightlessness, so that more spaceflight time can be freed up to perform useful space science or other productive work. Numerous countermeasures have been tried both in spaceflight and in ground-based bed rest studies with varying rates of success. These include various exercise programs utilizing treadmills, bicycle ergometers, and bungey cords; body-loading devices such as lower body negative pressure suits and elastic strap suits; a variety of pharmaceutical agents which have been effective in controlling bone loss for extended durations in bed rest studies; and finally, centrifugation of animals in space and humans on earth.

It appears that one of the most serious and potentially long-term effects of exposure to reduced gravity, bone mineral loss, may also be the most difficult to guard against. Whereas cycle ergometry is an effective way to maintain muscular and cardiovascular conditioning, when cycling at a vigorous rate (6000 N·m/min) for up to four hours per day, bed rest test subjects did nothing to reduce their rate of calcium loss; in fact, one study even showed that bone resorption into the blood actually increased with this type of activity in otherwise immobilized individuals (Vico et al, 1987). It is commonly accepted in the orthopedic biomechanics community that bone architecture is optimized with respect to local stresses, and cycling puts a force of only about one-third of the cyclist's body weight on the foot with each revolution.

Biomechanics researchers at Stanford University developed a mathematical 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:

$$T = t * (w/W)^4 \qquad (1)$$

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 or applied static force on the subject's foot on the earth, and "W" is the weight or applied static force on the subject's foot in space. For example, the Skylab treadmill applied a static force of 1.1 times the subject's earth weight, while the Russian treadmill applied a static force of 0.7 times the subject's earth weight. According to Equation 1, in order to achieve the equivalent benefit of a moderately active earthling's 4 hours of daily walking, astronauts should spend 2.7 hours per day on the Skylab treadmill, or 16.7 hours per day on the Russian treadmill, provided that this is the only longitudinal bone loading they are undergoing. If the applied static force could be increased to 1.4 times the subject's earth weight, the treadmill walking time could be reduced to roughly one hour per day. The crux of Whalen's theory is that a small increase in the magnitude of the load pays off in greatly decreased exercise time.

As for artificial gravity, while it has shown promise for preventing microgravity induced osteoporosis in animals (Gazenko et al. 1981, and Stupakov et al, 1984), related experimentation with humans suggests that passive exposure to gravity (such as in passively standing or bed rest) or other forces (such as some of the static compression devices) may slow the rate of bone loss, but in order to prevent or even reverse the loss of bone, it appears that the large muscle masses must be actively involved (Thornton, 1981). Therefore, any spacecraft-based human centrifuge should be large enough to allow the crew to move around and exercise, and to prevent visual and vestibular confusion due to the Coriolis effect of a small radius centrifuge.

2.3 Energy Expenditure

Most of the energy required for physical activity lasting more than about three minutes is supplied by aerobic metabolism, which is dependent on the consumption and utilization of oxygen. Shorter duration exercise is powered by anaerobic metabolism, either using stored phosphagens in the muscles (for high intensity, short duration exercise) or anaerobic glycolysis (glucose breakdown for the beginning of sustained exercise before aerobic metabolism takes over). Oxygen consumption (VO_2) increases as an individual goes from a state of rest to increasingly strenuous levels of activity. An individual's maximum rate of oxygen consumption (VO_2 max) is a key determinant of peak power output and of maximum sustained power output, or the individual's physical work capacity.

The oxygen requirement for performing physical work is known to be 1.8 ml O_2 per 1 kg·m, and is quite consistent across individuals. Therefore, if the work output for a particular exercise is known, the rate of oxygen uptake can be estimated with a fair degree of accuracy.

The kilocalorie (kcal) expenditure equivalent to consumption of a given amount of oxygen varies from 4.4 to 5.0 kcal per liter of oxygen with the type of food fuels available and utilized, and the proportional utilization of the various fuel types varies with exercise intensity. The three types of food fuels available for muscular work are carbohydrates, fats, and proteins. For sustained low intensity exercise, a mixture of carbohydrate and fat is used. As exercise *duration* increases, the proportion of fat used increases gradually over time. As exercise *intensity* increases, carbohydrate usage increases until nearly pure carbohydrates are being burned near maximum exercise intensity. Use of protein during exercise is negligible under all but the most extreme circumstances (i.e. starvation), and is generally disregarded.

Each of the three fuels uses different amounts of oxygen to oxidize its molecules into the end products (CO_2 and water). Thus, the ratio of CO_2 produced to oxygen consumed (VCO_2/VO_2; called the Respiratory Quotient or RQ) varies between the three fuel types. RQ can be used to determine which fuels are being used for energy, and to convert measurements of VO_2 into kcals/minute.

This equation describes the oxidation of carbohydrate through the body's aerobic pathways:

$$C_6H_{12}O_6 \text{ (glucose)} + 6\ O_2 \ \text{-->}\ 6\ CO_2 + 6\ H_2O \qquad (2)$$

(Guidelines for exercise testing and prescription, 1991).

Since one mole of CO_2 is produced for every mole of oxygen consumed, the RQ of carbohydrate is 1.0. This process releases 5.0 kcal of energy for every liter of oxygen consumed.

Fat, which is the primary form of stored energy in the body, has a much higher caloric concentration than carbohydrate (9.3 kcal/gm vs. 4.1 kcal/gm). This equation describes the oxidation of fat through aerobic metabolism:

$$2\ C_{51}H_{98}O_6 \text{ (tripalmatin)} + 145\ O_2 \ \text{-->}\ 102\ CO_2 + 98\ H_2O \qquad (3)$$

(Guidelines for exercise testing and prescription, 1991).

Here, when the body burns fat for fuel, 145 moles of oxygen are required for 102 moles of carbon dioxide produced, so the RQ is 102/145 or 0.70. This process releases only 4.7 kcal of energy for every liter of oxygen consumed.

As mentioned previously, protein use during exercise is generally disregarded as negligible under normal circumstances. For informational purposes, however, the caloric density of protein is 4.3 kcal/gm, the RQ for protein utilization is 0.80, and aerobic protein use releases just 4.4 kcal of energy for every liter of oxygen consumed. As can be seen from this discussion, carbohydrate is the most efficient of the three fuel types.

Assuming normal use of carbohydrate and fat as the fuels used, the following equation can be used to convert liters of oxygen consumed per minute to kcalories expended per minute:

$$VO_2*(4 + RQ) = \text{kcal/minute}. \quad (4)$$

In this study, energy expenditure results are expressed in terms of kcal/kg/minute, since it takes approximately the same number of kcalories per kilogram of body mass to perform a given amount of physiological work, independent of body size. For example, a 50 kilogram person cycling at the same rate as a 100 kilogram person for one hour will burn roughly half the kcalories of the larger person. There are some individual variations based on sex, age, body composition, and metabolic rate, but this is commonly accepted as the best way to normalize energy expenditure across varying subject body sizes.

To give the reader an idea of typical energy expenditure rates, Figure 2-1 shows a variety of common activities with their corresponding rates of energy expenditure, as well as the time necessary for a 78 kilogram subject (the mean subject body mass in this study) to burn 2000 kcalories at each particular activity. The 2000 kcalorie figure is a number that one of NASA's working groups decided on as a reasonable limit for an extravehicular astronaut's normal eight hour work day on a planetary surface (First Lunar Outpost Study, 1992).

TYPE OF ACTIVITY	ENERGY EXPENDITURE *(kcal/kg/minute)*	TIME REQUIRED *for average 78 kg subject to expend 2000 kcalories*
SLEEPING	0.015	28.5 hours
SITTING QUIETLY	0.022	19.4 hours
STANDING	0.03	14.2 hours
WALKING @ 1.2 mps	0.07	6.1 hours
BICYCLING @ 2.5 mps	0.07	6.1 hours
JOGGING @ 2.4 mps	0.16	2.7 hours
ROWING @ 20 strokes/minute	0.2	2.1 hours

Figure 2-1: *Energy expenditure rates for various activities with corresponding durations for utilization of 2000 kcalories (proposed limit for nominal planetary EVA work day).*

Just as physical work capacity is dependent on VO_2 max, VO_2 in turn is dependent on the cardiovascular system capacity to distribute oxygenated blood throughout the body to working muscles. Maximum heart rate can be roughly predicted (to within 15 beats per minute) by subtracting the subject's age from 220, or it can be accurately obtained along with corresponding VO_2 by graded exercise testing to exhaustion. Heart rate in normal, healthy individuals increases linearly and reliably with oxygen uptake during graduated exercise (Donald, 1955; Kroemer et al, 1990). There is some variation between individuals in this relationship, and therefore heart rate should be translated into a more universal standard before comparisons between individuals are made. There is substantial precedent which has been established for using heart rate as a measurement of work rate within individuals in the animal kingdom at large (Lund, 1989).

In the same way as VO_2 and heart rate increase linearly, respiratory minute volume (RMV), also referred to as ventilation (V_E), and VCO_2 increase linearly. (Respiratory Minute Volume and VO_2 are often considered to have a quite linear relationship as well, especially for light to moderate levels of exercise. Guyton, 1991.) This is because ventilation is actually regulated by the body's need to remove CO_2 from the bloodstream. Since more CO_2 is produced and less oxygen is consumed when the body uses carbohydrate (with its higher RQ) rather than fat, VCO_2 and RMV are higher while VO_2 and heart rate are lower for a given work rate when carbohydrate is the primary fuel substrate. For this reason, when very accurate caloric rate measurements are essential, RQ values are necessary. For this study, when RQ values were unavailable, VO_2 and VCO_2 values were derived from the VO_2 versus heart rate and VCO_2 versus RMV plots for each subject (Figures 4-1 to 4-6), and RQ values were calculated.

2.4 Reduced-Gravity Simulation Techniques

A true reduced-gravity environment exists when the gravitational forces exerted on an object are partially or completely negated by a centripetal acceleration of the object through certain trajectories within a gravitational field. This is exemplified in parabolic aircraft flight or orbital spacecraft flight. For obvious reasons, this environment is difficult and expensive to provide, and for experimental purposes, must often be simulated.

There are various techniques for simulating microgravity and partial gravity here on earth. These include water immersion, suspension rigs, gimbal systems, and air bearing tables. Each simulation technique offers particular advantages, however, water immersion has been chosen as the primary medium for the described experiments, since it allows extended duration three-dimensional total body reduced gravity simulations.

Significant contributions have been made through water immersion studies and simulation techniques to a wide variety of national and international space projects in the areas of pre-flight training, operational and hardware verification, and task timelining. The experience gained by the EVA astronaut crews in their underwater training has consistently been a significant factor in the successful accomplishment of EVA mission objectives.

Archimedes' principle states that an object submerged in or floating on a fluid is buoyed up by a force equal to the weight of the displaced fluid. During water immersion tests, because the human body on average is slightly denser than water, generally ninety percent of the human body's weight is supported by the water's buoyancy. The submerged subject breathes using a spacesuit life support system, scuba, or hookah gear. The subject is ballasted or bouyed to attain either neutral buoyancy or varying degrees of negative buoyancy. A major disadvantage is the viscosity of the water which, being twelve times denser than air, produces drag and damping on the movement of humans and equipment. It has been estimated that this effect is responsible for an increase of 5 to 10 percent in energy expenditure for treadmill walking (Newman, 1992).

Water immersion is the most commonly used simulation medium for EVA research, and has been used quite successfully to simulate zero-gravity and partial-gravity. John Duddy (1969) of Lockheed Missiles & Space Company has compiled an extensive bibliography of water immersion studies for spaceflight simulation which is listed in the bibliography to this document.

2.5 Literature Review

2.5.1 Locomotion Research

During locomotion, different energy exchanges are employed in walking than in running. For walking, when at least one foot is in contact with the ground at all times, an out of phase transition between gravitational potential energy and forward kinetic energy takes place within each stride. For walking at intermediate speeds (about 1 meter per second, or mps), this energy exchange accounts for up to 70 percent of the total energy required, thus relying on muscles to provide the remaining 30 percent (Cavagna et al, 1977). For running, where there is a period within each stride that the body is airborne, potential and kinetic energy cycles are substantially in phase, and humans (and other animals) store energy during the deceleration phase in forcibly stretched muscles, tendons, and ligaments, and also possibly in bent bones. This energy storage/exchange concept for running works much the same way as a bouncing ball or a pogo stick spring stores mechanical energy in an elastic form, later to be recovered as gravitational and kinetic energy (McMahon, 1984).

Since gravitational potential energy is reduced in lower gravity conditions, some researchers (Margaria and Cavagna, 1974) have predicted that the lower available potential energy for given displacement and velocity changes in the body's center of mass during walking will not be adequate to sustain a constant average speed, and therefore the muscles may have to do more mechanical work to compensate for the more unbalanced energy exchange. Other researchers (Gazenko et al, 1981) have suggested that an increased forward lean of the body and an increased forward component of the pushoff force may help to compensate for this 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.

Variations from optimum stride length in running has been shown to produce increasingly greater energy demands (Daniels, 1985). Other researchers have found that the total mechanical power for walking can be minimized by using a step frequency which is 20 to 30 percent lower than the freely chosen step frequency for a given speed (Cavagna and Franzetti, 1986).

Experiments done at Harvard University have indicated that the energy cost of running is determined simply by the energy expenditure of muscle in supporting the weight of the body, whereas this is not so in walking (Farley and McMahon, 1992).

2.5.2 Load-Carrying Research

Previous research has investigated the relationship between metabolic energy expenditure and load-carrying while standing, walking, or running, with varying subject body weights, load sizes, walking/running speeds, surface inclinations, load-carrying techniques, and terrains.

A study by Martin and Nelson (1986) indicated that increasing load size resulted in decreased stride length and swing rate, along with increased stride rate and forward