NASA SP-84

Bioenergetics of Space Suits for Lunar Exploration

Roth

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BIOENERGETICS OF SPACE SUITS FOR LUNAR EXPLORATION

A literature review by

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Foreword

THIS REPORT was prepared for NASA under Contract NASr–115. It reviews environmental information currently available from astrophysical studies, and analyzes the metabolic load imposed on humans exercising under varied terrain and gravity conditions, the metabolic cost of mobility restriction in space suits, and the problem of thermal control in lunar space suits.

The manuscript was reviewed and evaluated by leaders in the scientific community as well as by the NASA staff. Although there was varied opinion about the author's interpretation of the data compiled, there was nonetheless complete satisfaction with the level and scope of the study. It is anticipated that this study will become a basic building block upon which research and development within the space community may proceed.

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Introduction

THE DESIGN OF SPACE SUITS has until recently required a bioenergetic analysis of a relatively static pilot in a rather well defined thermal environment. The potential for severe physical exertion outside the spacecraft, both in orbit and on the surface of the Moon and other celestial bodies, presents new problems in the design of optimal space-suit systems. Lack of concrete information regarding both the nature of the changing environment and the metabolic cost of exercise in subgravity states within this environment appears to compound the general design problem.

In this review, the lunar surface is taken as a model of a typical extraterrestrial environment. In Chapter 1 a review of the type of environmental information available from recent astrophysical studies is presented. Chapter 2 is devoted to an analysis of the metabolic load imposed on humans exercising under varied terrain and gravity conditions. An attempt is made to analyze in detail the mechanics of locomotion so that the effects of changing gravity conditions may be logically considered for different gaits and work loads. In Chapter 3 the metabolic cost of mobility restriction in space suits is considered. Chapter 4 is devoted to the problem of thermal control of lunar space suits. Both the exchange with the external environment and metabolically produced heat are covered. The problems of sensible versus latent heat loss in typical suit systems are reviewed. Several approaches to the internal cooling loops are discussed. Chapter 5 presents a brief review of the dangers of thermal overloads and water loss in man. These hazards are discussed in the light of data presented in the previous chapters and suggestions are made for preventive action.

CHAPTER 1

Lunar Terrain and Thermal Environment

THE CONTENTS of this chapter are not intended to be an exhaustive review of astrophysical data on the lunar environment. The data reviewed here are only those that set the envelope conditions to be expected on the lunar surface. Indirect experimental data are critically analyzed only where it is apparent that major suit design criteria are dependent on their interpretation.

Recent reviews of the lunar environment have been presented by Salisbury [284] and Speed et al.[305] These excellent reports are used as take-off points for the present discussion and will be augmented by Russian interpretations as presented in a recent Aerospace Information Division review.[211]

ATMOSPHERE

For several hundred years the lack of apparent cloud and sunset phenomena and the clear-cut delineation of shadows have suggested to astronomers the tenuous atmosphere of the Moon. The calculations of Dollfus [90] at Pic-du-Midi utilized the data obtained from photographs of the lunar twilight in orange light using a 20 cm coronagraph and polariscope. These studies led to the conclusion that the surface density of the lunar atmosphere is less than 10^{-9} terrestrial atmosphere.

From the far more sensitive analysis of the occultations of radio stars by the Moon, Ellsmore and Whitfield [105] and Costain et al.[74] have estimated the value to be less than 10^{-13} terrestrial atmosphere. Repulsion of ionized gas molecules by a positively charged lunar surface has been recently hypothesized as a mechanism for reducing the lunar gas density below even interplanetary space density.[250] The review of Brandt [48] suggests a lower limit of atmospheric density similar to that of the interplanetary medium of 10^3 to 10^6 particles/cm^3. The higher lunar atmospheric densities of the earlier Russian literature presented by Fesenkov [113] and Lipskiy [212] have received no corroboration from recent Russian astronomers.[211] It thus appears that the attenuation of cosmic and solar radiation, and the vaporization of meteors, would not be expected in this model lunar atmosphere, equivalent at the surface to a 1×10^6 ft altitude in a terrestrial atmosphere. [153]

The hypotheses regarding composition of the lunar atmosphere are many, but not pertinent to the present discussion. Some radiogenic krypton and xenon, as well as argon, radon, and helium, should be released from the interior.[98] If the composition of the rocks is silicic with an abundance of uranium and potassium, radon and argon should be most prevalent. Even if the surface is chondritic, xenon and krypton may be present in the uranium decay products. Basaltic thorium, potassium, and uranium should release all the above gases. Sytinskaya [324] has hypothesized that pulverization of 100 meters of surface rock by meteorites could well release about 10^{-13} atmosphere of xenon (95%) and krypton (5%), enough to account for the present atmosphere without invoking active volcanism. The release of trapped water and mercury vapor from the surface as well as from impacting meteorites is possible too.[143] Modifications of the atmosphere by the solar wind have also been hypothesized.[37]

The rapid escape of these gases into interplanetary space is most probable under the influence of reduced gravity and charge repulsion.[250] As has been pointed out by Green,[140] however, "local atmospheres" may result from volcanic activity in crater areas. The report of Kozyrev [196] is of interest in that it indicates the possibility of volcanic activity in the lunar craters Aristarchus and Alphonsus. The emission lines in the spectrum of reflected light from these craters (C_2 bands were detected in Alphonsus) suggest current volcanic activity. Green [140] lists multitudes of astronomic observations through the years suggesting volcano-like activity. Alternate hypotheses such as solar radiation or flares "illuminating" slowly diffusing gases have been presented to account for these spectral findings, as well as the transient obscuration of crater surface markings noted by other astronomers. The presence of a "local atmosphere," if such can exist, is of less significance to the thermal problems of explorers than is the possibility of a thermal "hot spot" on the surface. In any case, the possibility of both local corrosive or convective atmospheres and local sources of intense thermal radiation must at this point be considered as very marginal contingencies in the total space-suit problem.

In a recent study by the National Aeronautics and Space Administration and the U.S. Geological Survey, Gault et al.[120] calculated the probability of a dust cloud surrounding the Moon. A major fraction of this cloud resulting from debris of meteorites striking the surface was estimated to be a few kilometers deep with a spatial density of 10^5 to 10^7 times the spatial density of interplanetary debris. Differences in recorded mass-frequency data of meteoritic dust about the Earth present a potential extrapolated range of lunar dust density spanning about 6 orders of magnitude. That the highest impact rates chosen are probably not valid has been pointed out. These impact rates would imply a dust level which should give a readily detectable extension of the lunar cusps near the first quarter. No such extension has been observed, even though photometric techniques should be capable of detecting a cloud some 3 to 5 orders of magnitude less than that corresponding to the highest meteorite flux rate. From these considerations it would appear doubtful that there is any significant attenuation of solar radiation by this cloud layer. There may be a local problem of such dust clouds kicked up by the rocket exhaust, as described by Roberts [273] of the NASA Langley Research Center and by North American Aviation, Inc.[246]

THERMAL ENVIRONMENT

The Moon rotates about its axis with a period approximately equal to the period of revolution about the Earth, 27.32 Earth days (sidereal time). However, the duration of a day-night cycle on the Moon is slightly longer —29.53 Earth days (synodic time). The duration of lunar daylight and sunlight is, therefore, approximately 14.8 Earth days. In contrast to the constant rate of rotation, the rate of revolution about the Earth varies in accordance with Kepler's second law. This effect, added to the fact that the lunar equator is inclined to the ecliptic 1 1/2° in the direction opposite the inclination of its orbit, produces the libration effect. The Moon is, therefore, viewed from the Earth at a continuously varying angle and only 59% of its surface is visible from the Earth in a 1-year period.

Estimates of surface temperatures of the Moon made by Pettit and Nicholson [258, 259, 260] and by Geoffrion et al.[126] from radiometric data indicate the great differences between the illuminated and dark hemispheres suggested by the lack of an effective atmosphere. The maximum reported temperature is 130° C or 266° F and the very unreliable minimum, −153° C or −243° F. Figure 1 represents the larger gradient of temperature extending from the subsolar point to the limbs. The subsolar point is marked by a small cross. This figure represents the highest recorded temperature near the subsolar point at 98% illumination.

The lunar surface temperature appears to be dependent on the heat capacity, Sun ray angle, and emissivity with respect to short-wave radiation of the Moon. If the variation of the surface is ignored and the Moon is treated as a sphere, a heat-balance equation for the Sun–

Moon system may be written for any given time during the daylight period: [84]

$$S\alpha_{sm}F_{sm}\,dA_m - C\dot{T}_m - \sigma\dot{T}_m{}^4\epsilon_m\,dA_m = 0 \quad (1)$$

where

S solar constant at 1 astronomical unit, 0.0316 cal sec^{-1} cm^{-2}

α absorptivity

F geometrical shape factor $=\cos\phi=\sin\tau_{sm}\cos\beta_{sm}$

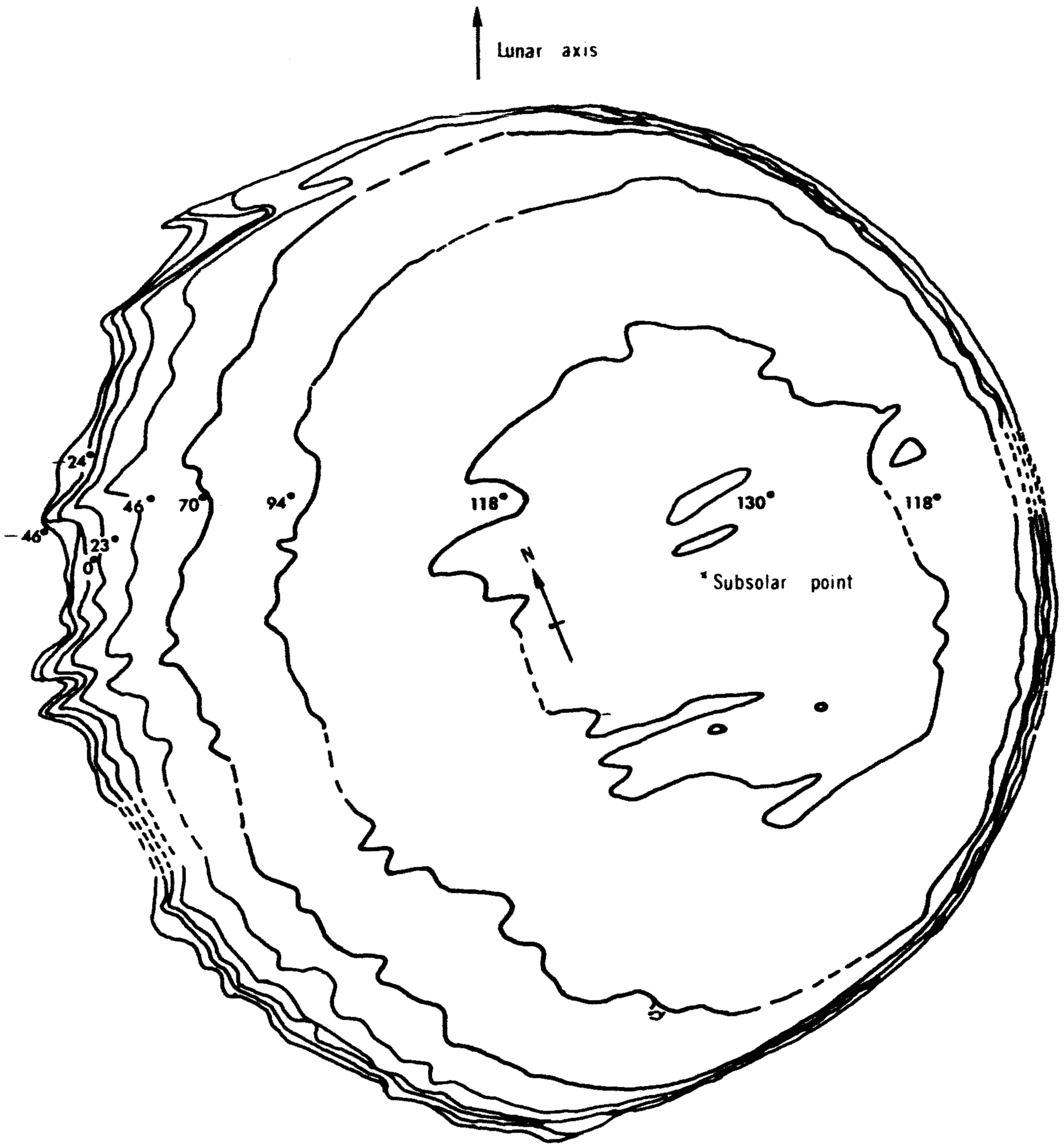


FIGURE 1.—Distribution of lunar temperatures in °C. Moon of September 26, 1958; begun 3:55, ended 7.01, u.t.; 63 scans; 0.98 illuminated. (AFTER SALISBURY.[284])

A area, meters^2
C heat capacity, cal gm^{-1} °K^{-1}
$\dot{T}$ rate of change of temperature with respect to time
T temperature, °K
σ Stefan-Boltzmann constant, 1.37×10^{-12} cal sec^{-1} cm^{-2} °K^{-4}
ϵ emissivity
s Sun
m Moon
τ time or time angle
ϕ Sun ray angle, deg
β latitude angle, deg

Figure 2 is a plot of the lunar surface temperature at various latitudes as a function of time angle, with noon being represented as 90°. During the lunar night the surface temperature appears to be independent of latitude. As will be discussed, the ratio α/ϵ of objects on the surface of the Moon will determine the temperature history of these surfaces with respect to the time angle and latitude, but the actual time profiles will follow those of the lunar surface described in figure 2. A consideration of experimental errors, theoretical assumptions, and variations caused by surface inhomogeneities suggests that reported temperatures have a probable associated error of ±20° C and that calculated temperature curves involving phase angle and latitude have a likely error of no less than 25° C over the most accurate portions of the curves.[118]

The rate of change of surface temperature during eclipses has been used to build a thermal inertia model of the lunar surface materials, to be discussed below. Radiomeasurements of lunar temperature have also been used to reveal equilibrium subsurface temperatures. The most recent value of −23° C or −7.4° F has been presented by Mezger and Strassl.[233] Calculations of the potential surface temperatures within lunar crevices at

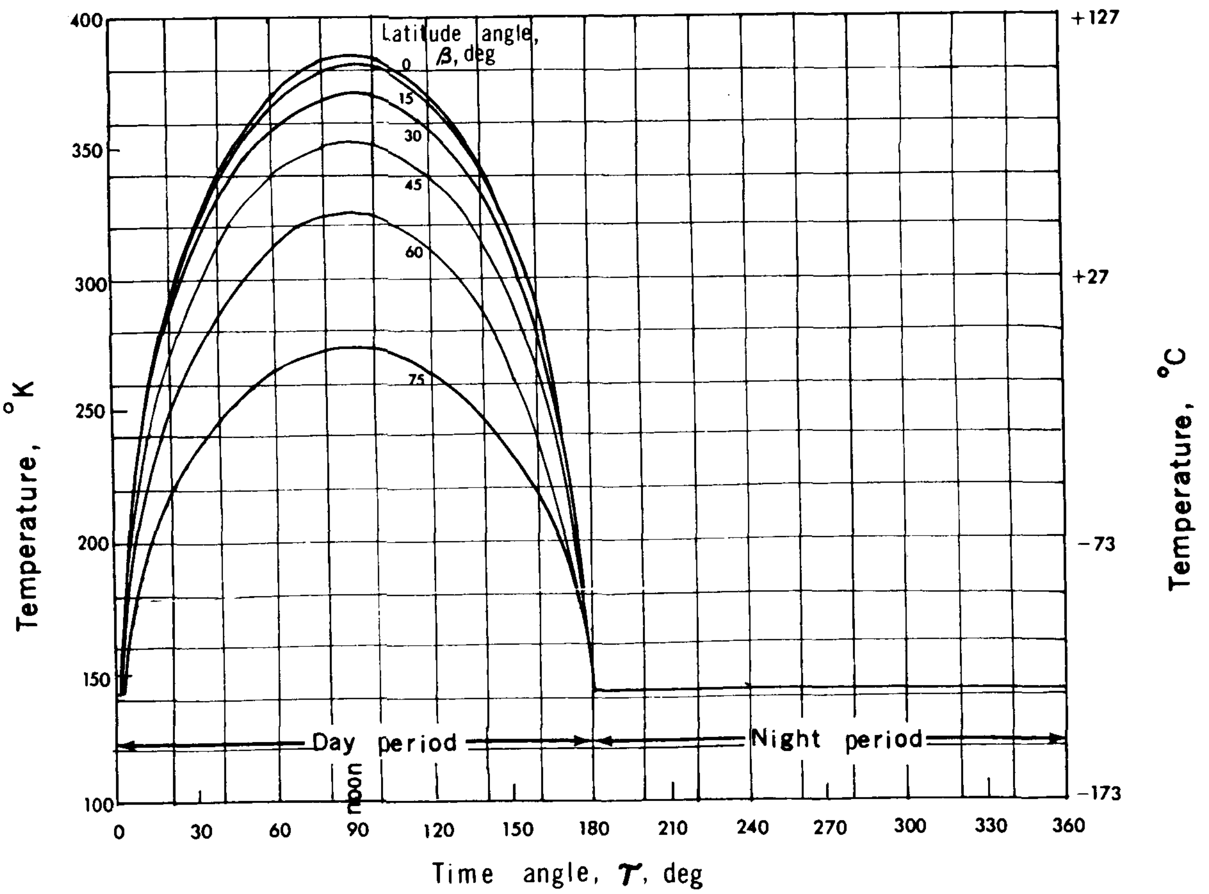


FIGURE 2.—Lunar surface temperature at various latitudes as a function of time angle. (AFTER DEMPSTER ET AL.[84])

different solar angles have been presented by Stevenson and Grafton[316] and point out the severe gradients to be expected.

Past Russian radiotelescope observations and theoretical calculations[211] appear to present temperatures somewhat lower than the American figures. The most recent figures reportedly presented by Troitskiy to the popular Russian press[264] give a maximum surface temperature of +115° C (240° F) during the daytime and a minimum of −150° C (−240° F) at night. A constant −50° C (−58° F) is calculated for a depth of 0.5 meter below the poorly conducting surface.

TABLE 1.—*Thermal Inertia Constants* [AFTER NIEDZ[245]]

Material	Thermal conductivity, K, cal/cm² sec	Density, ρ, gm/cm³	Specific heat, c, cal/gm	$(K\rho c)^{-1/2}$
Copper	0.9	9	0.09	1
Rock	5×10^{-3}	3	.2	20
Pumice	3×10^{-4}	.6	.2	170
Powder in vacuum	$3\text{–}10\times10^{-6}$	2	.2	500–900

The design of space suits, especially the footwear and gloves, requires some knowledge of the thermal characteristics of surface materials. Table 1 indicates the pertinent constants to be considered, where $(K\rho c)^{-1/2}$ is the thermal inertia of the potential surface material. As will be discussed in the section on lunar dust, the lunation temperature changes suggest porous powder or powder-aggregate in vacuum as the surface material. Recent studies by Bernett et al.[36] at the Jet Propulsion Laboratory have corroborated the effects of a vacuum of 10^{-6} mm Hg on thermal diffusivity and conductivity of fine powders of olivine basalt. It is of interest that increasing the pressure from 5×10^{-6} to 5×10^{-3} mm Hg had no marked effect on the thermal conductivity of the crushed basalt. Had the pressure been decreased to 10^{-10} mm Hg or lower, there might well have been a sintering phenomenon with subsequent increase in conductivity. For the −150 mesh material, the thermal conductivity in the air and in vacuum was increased approximately 60% at all test temperatures when the packing density was increased from 1.14 to 1.57 gm/cm³. Decreasing the average temperature of the crushed basalt specimen from 100° to −70° C caused a decrease in the thermal conductivity. For the particular distributions used, the particle size had a greater effect on the values of thermal conductivity measured in vacuum than on the values measured in air. The thermal conductivities of crushed olivine basalt and silica sand are not markedly different. The recent experiments of Wechsler and Glaser[337] support the conclusion that the composition of the crushed material has only a minor effect on its thermal conductivity.

The underlying lunar rock should have thermal characteristics similar to terrestrial igneous rock. The actual heat-transfer characteristics of the surface depend on the layering, aggregation, and depth of the surface materials. All that can be said at this time, with density and specific-heat factors still unknown, is that the average surface probably has a low thermal conductivity.

SURFACE COMPOSITION AND PHYSICAL PROPERTIES

The thermal balance of lunar explorers is critically determined by the composition, configuration, and gross morphology of surface structures. Soil mechanics and general lunar terrain (lurain) features derived from these parameters will be shown to determine the metabolic cost of exercise. The thermal insulative properties and local surface emissivities determine the radiative and conductive thermal loads to be experienced. The discussion of these features is divided into three parts: (1) composition, (2) subsurface structures, and (3) surface characteristics. The reviews of Salisbury[284, 285] and Head[165] are used as a point of departure.

Composition

The composition of the lunar surface is a matter of great conjecture. Kozyrev[196] interprets the luminescent spectra from the lunar crater Aristarchus as suggesting quartz or willemite. The interpretations appear somewhat speculative and at best may represent only a local surface sampling. The Russian astronomers have speculated widely on surface composition from photometric data and model experiments.[211] Terrestrial materials of red quartz, quartz sandstone, and "volcanic ash" have been suggested as giving color indices in reflected light similar to that found on telescopic observations of the lunar surface. These numerous interpretations do not contribute to the present study and will not be dealt with further.

The tektitic nature of the lunar surface has of late received much consideration.[14, 67] The arguments relating tektites to lunar crusts, blasted by meteorite impact to the surface of the Earth, have been countered by other investigators[72, 162] who present the case for terrestrial origin. The chondritic meteorites have also been used as a model of the lunar surface. Urey[327] has pointed out that the lower overall lunar density could be accounted for by the hypothesis of an iron deficiency relative to the silicate phase or addition of water (1%) to a chondrite-like material. O'Keefe and Cameron[249] have recently reviewed the evidence regarding the composition of the lunar surface and suggest that a granitic material, possibly similar to fine-grained volcanic rocks such as rhyolites or tuff, could be the origin of tektites and may well compose the lunar surface.

Surface Structures

More pertinent to the present discussion are the subsurface structures of the Moon. Prediction of these structures is entirely speculative and apparently depends on the choice of one of two schools of thought regarding the origin of the major lunar-surface features. Modern proponents of the volcanic-origin theory[141] contend that lunar craters are caldera produced when molten material is blown from beneath the surface, emptying lava reservoirs and fracturing the overlying rock. The depression results when overlying rock collapses, leaving a ring of volcanic debris. The maria would result from widespread internal melting. One would predict that the highlands should exhibit a complex of overlapping collapse structures of pyroclastic debris, extensive vesicular lavas, and intrusive dikes and sills. Lava flows and debris from secondary volcanic activity (from peaks in the centers of the craters) further complicate the picture. The possibility of large cavernous lava structures, such as those seen in terrestrial areas of previous lava flows, is increased by the reduced gravity (one-sixth that of Earth) which allows large unsupported roof spans. The danger of collapse would make highland operations quite hazardous. The maria, on the other hand, would exhibit much simpler structure than the highlands, with an extremely vesicular surface extending down to solid lava and surface features of scattered wrinkles, hills, domes, and occasional late craters. The vesicular tendency in the maria would also be exaggerated by reduced gravity to allow cavernous structures. The probable depth of vesicular material would be 20 feet.[284]

The meteoritic theory, on the other hand, holds that surface structures are related to high-speed impact of meteorites or other objects.[16] The flat floors of the craters may be composed of secondary lava flow. Under this theory the highlands would be of highly fractured basement rock overlain by rubble, rock flour, and meteoritic material. The subsurface configuration of the highlands would be safer for human operation under the meteoritic theory than under the volcanic theory.

The origin of maria under the meteoritic theory is similar to that under the volcanic theory, except for a greater tendency to cavern formation under the meteoritic theory, predicted from the reduced generalized degassing of the lunar surface. The lower transient atmospheric pressure has been hypothesized to allow the average vesicle size to reach a maximum of 6 feet in diameter (in contrast to a 3-foot maximum in the volcanic theory) and the depth of vesiculation to extend to 40 feet below the surface. The maria, under the meteoritic theory, would be more hazardous than the highlands. As will be discussed below, the telescopic observations of craters on the Moon surface do not distinguish clearly between the two theories, though the meteoritic theory has more supporting evidence. The theories, of course, are not mutually exclusive.

A recent model of the lunar subsurface has been presented by O'Keefe and Cameron [249] of the Goddard Space Flight Center. They feel that the surface of the Moon, especially in the maria, is analogous to the tuffaceous ash flows seen on Earth. These avalanches of volcanic ash are fluidized by contained gases [281] and spread for tens of thousands of miles. In these beds, the top surface is composed of loose porous ash; the middle is welded into a solid obsidian where heat has stayed the longest; the bottom, where heat escapes into the ground, has a nonwelded, collapsed porous structure. Hence, the surface of an ash flow tends to show the features of the underlying ground surface, though much collapsed in height and depth. This tendency of ash flows to reproduce the underlying topography may explain the "ghost craters" seen as subsurface structures in certain maria and previously used as evidence for loose dust. There is a question of the effect of absence of an atmosphere on the mobility of ash flows. McTaggart [220] implied that ash flows are supported by gas trapped in the advancing front. O'Keefe and Cameron [249] have calculated the flow factor for 1/6 g, zero-pressure conditions on the Moon and arrived at the fact that lunar flows should have about 32 times greater duration and extent than similar Earth flows.

Surface Features

Coarse

Photographic and visual observations of the Moon present differences in albedo and topography which have given us the most detailed knowledge of the surface. The grossest features, the highlands and the maria, are distinguished by the fact that the former have a 20% greater albedo. The bright highland areas are covered by nearly circular craters occurring at about 10 times the frequency found in the maria. The maria are always of lower elevation than the adjacent highlands [295] and because of their surface smoothness appear to be filled with lavas [199, 327] or dusts.[129, 137] Under proper illumination long, narrow cracks or rills up to 5 km in width and extending several hundred kilometers are found within the walls and regions adjacent to the maria.

For purposes of describing the possible slope obstacles to explorers, it will be of interest to define the crater parameters in greater detail. The craters vary in diameter from huge circular basins hundreds of miles across down to the limits of resolution for visual telescopic observations of about 1/8 mile.[198] The limit of photographic resolution is 1/2 mile. The majority of the craters are unlike terrestrial volcanic craters in form, having a greater depth-diameter ratio, but may be volcanic in origin because lunar gravity would permit boiling at 6 times greater depth than is possible in Earth volcanoes.[144] There are, however, rare small cone craters similar to terrestrial forms.[198]

Baldwin [16] has extrapolated explosive craters on Earth to the lunar craters and can account for the meteoritic origin of lunar craters on the basis of the diameter, depth, and rim height relations. Certain types of lunar craters are characterized by raised rims and a distinctly hummocky surface that grades outward into a system of subradial ridges. The floors of these craters are well below the general level of the surrounding lurain. Some hills or peaks are usually found near the center part of the floor. There is, however, only partial resemblance to the terrestrial meteorite craters.[294] The larger craters or circular basins are surrounded by mountains which are closer to being crater rims than typical terrestrial mountain structures. The gentler slopes (about 15°) of the rim areas of the larger basins are not typical of the smaller craters, a fact which is most important to keep in mind when outlining envelope conditions for lunar exploration.[195]

Baldwin [16] has plotted crater depth against crater diameter for lunar craters as well as terrestrial craters and explosion pits. He obtained a continuous curve with the equation

$$\log D = 0.1083\,(\log d)^2 + 0.6917 \log d + 0.75 \quad (2)$$

where D is the crater diameter in feet and d is the crater depth in feet. This is seen in figure 3 as a shape factor d/D plotted against D. At $D < 5{,}000$ feet (the limit of photographic telescopic observation is 2,600 feet) a dashed curve is shown. This extrapolation below $D = 5{,}000$ feet has been used by Kornhauser in plotting the average slopes (line from bottom to rim) and curves of the maximum slopes for reasonable crater profiles in figure 4.

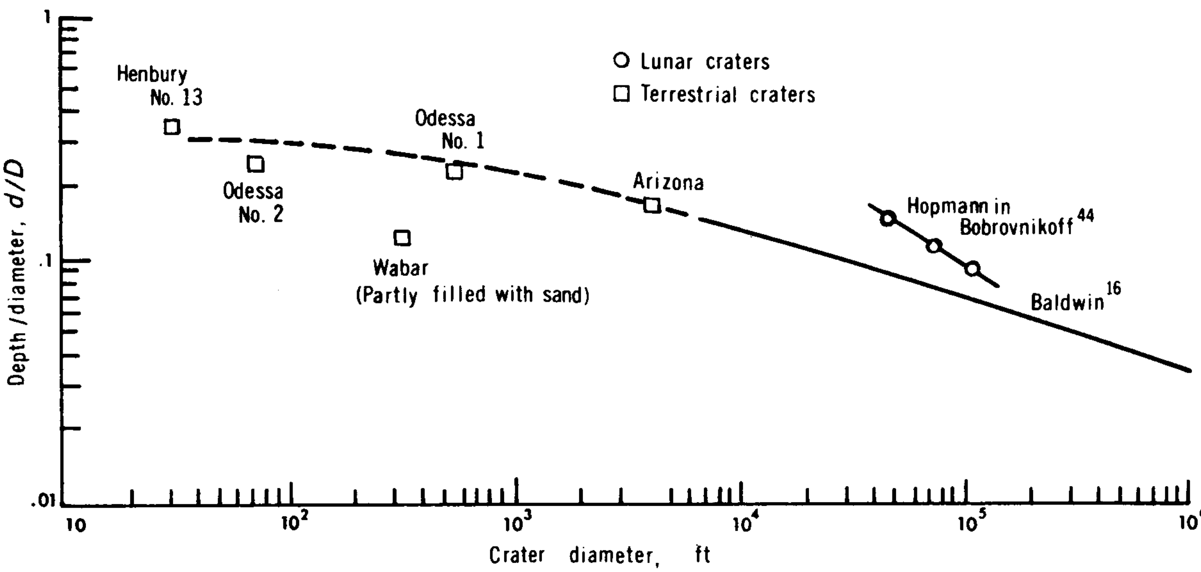


FIGURE 3.—Overall shapes of lunar craters. (AFTER KORNHAUSER.[195])

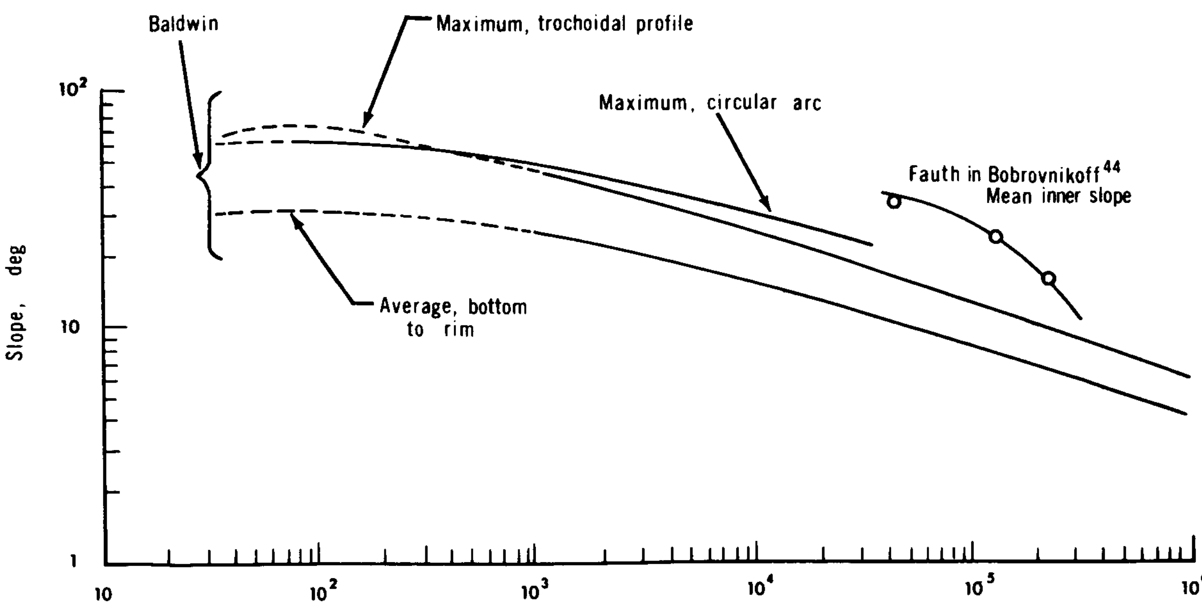


FIGURE 4.—Slopes in the lunar craters. (AFTER KORNHAUSER.[195])

In both figures 3 and 4, the *d/D* ratios and slopes which disagree with Baldwin's calculations do so in presenting greater values for these parameters for a given *D* value. The extrapolations of the lunar data alone, with no terrestrial points, would also have given greater *d/D* and slope values. Table 2 summarizes these curves for several crater sizes.

TABLE 2.—*Extrapolation of Lunar Data of Figure 4* [AFTER KORNHAUSER [195]]

Crater diam., ft	Av. slope, deg	Max. slope, deg
10^2	30	70
10^3	24	46
10^4	16	28

An important question for the lunar explorer is the frequency distribution of the craters with diameters less than 5,000 feet, at present not visible by telescopic observation. Bobrovnikoff [44] presents data on total numbers of craters of different sizes on the visible portion of the Moon, in the form of MacDonald's equation:

$$nD^2 \approx 7{,}150 \tag{3}$$

Since this is an approximate expression at both ends of the spectrum of sizes, it is shown plotted in figure 5 using actual counts of the larger craters, taken from table 4 of reference 16. Also plotted in figure 5 are counts of craters in localized regions of interest taken from plates D4–a and C6–a of reference 195. Current studies at Boston University are attempting to define these data on crater parameters.[117] When these number-size distributions are converted to percentage of lunar surface covered by craters, the results appear as in figure 6.

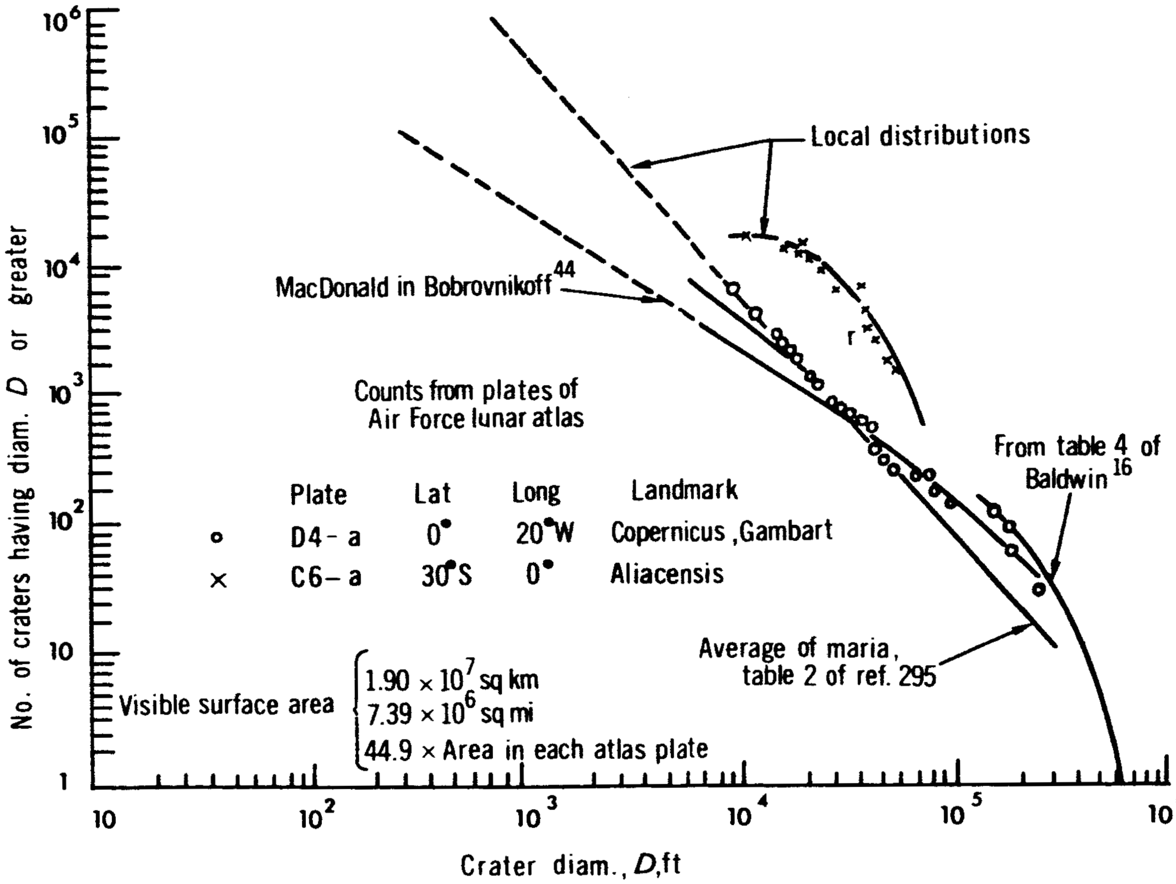


FIGURE 5.—Distribution of crater sizes on the Moon. (AFTER KORNHAUSER.[195])

Figure 6 shows that less than 10% of the Moon's surface is covered by craters. Note, however, that the area on the plates of reference 195 is about 165,000 square miles, and has about 30% of its area covered by craters. This is visibly not the roughest area of the Moon. The figures for frequency distribution of meteoroid events near the Earth is of such a tenuous nature that it is impossible to predict the expected crater frequency-size distribution to be expected on the surface of the Moon after several billion years of bombardment. The small-scale roughness is still beyond speculation. Attempts at defining lunar rubble block size and depth from terrestrial data have been made.[287] The nature of subsequent erosive processes, however, are unknown and becloud speculation of present rubble conditions.

It must be concluded that in some areas gross lurain features are easy to negotiate on foot, whereas other areas are literally peppered by very rough surface formations. When one adds to the pure crater problem the roughness contributed by exterior slopes of the crater rims, cracks, rills, escarpments, hills, boulders, and so on, it is clear that many lunar areas will be of borderline passability for man on foot or in a vehicle. In present

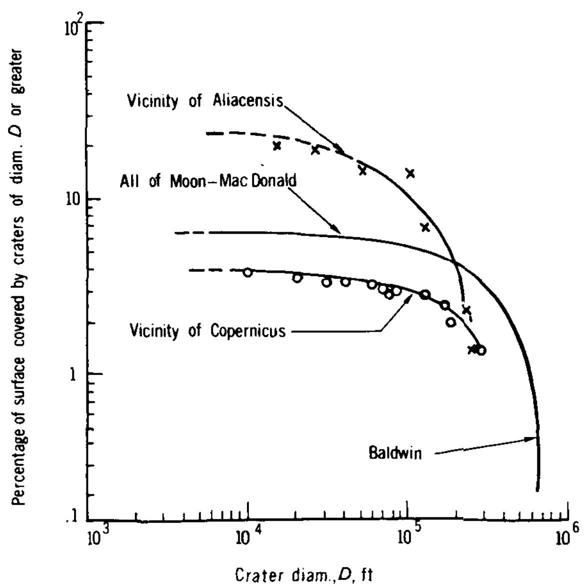


FIGURE 6.—Percentage of lunar surface covered by craters. (AFTER KORNHAUSER.[195])

planning for space-suit activity levels, prior to the data from surveyor vehicles, the possibility of rather severe slope conditions in routine as well as emergency situations must be included. Wide cracks and accidently perforated cavernous formations are contingencies which should be kept in mind.

Microtopography

Both meteoritic and volcanic theories of crater origin predict that large amounts of rubble are present on all the highland surfaces and surrounding maria craters. Lahee[204] reports that coarse angular fragmented rocks can have maximum angles of repose of about 35° to 42° at 1 g on Earth. Such debris would make foot travel most difficult were there no compaction or smoothing of the surface by the seismic activity suggested by Kopal[194] or infilling by finer material. Seismic waves of volcanic or meteoritic impact origin could reduce the surface roughness, and thereby the avalanche and suit-damage hazards. The severe scatter in depth-diameter or rim height-diameter plots of the lunar surface may reflect such activity. This surface roughness (measured in terms of feet range) may also be reduced by infiltration of lava flows and depositions produced by volcanic activity. The bursting of subsurface vesicles of the lava plains predicted by both volcanic and impact theories should produce pits with a maximum diameter of 6 feet and depth of 3 to 4 feet,[284] which could be subject to the filling processes outlined above.

Radar scatter studies have recently shed some light on the surface roughness problem. In contrast to visible light, radio waves of 10 cm wavelength or longer are reflected from the lunar surface as from a relatively smooth surface. Most of the power in radar signals reflected from the Moon is returned from a relatively small region in the central part of the lunar disk by specular reflection. Some of the signal, however, is also returned from the rest of the lunar surface out to the limb. From the fading of the reflected radar signals, the frequency distribution of slopes may be found for lunar surface features somewhat larger than the radar wavelength and smaller than the visible features of the topography. The studies of Evans [107] and Daniels [79] suggest that these small-scale structures have rim slopes of 6° to 12°. The average distribution of slopes for the small unresolvable features appears to be similar to that of the larger features of the topography, which may be estimated from studies of the variation of visible shadows. By combined analysis of the range and the spread in frequency of a reflected radar signal due to libration, Green and Pettengill [145] have been able to construct a map which shows that the radar reflectivity of the Moon varies considerably from place to place, suggesting an irregular distribution of microtopographv.

According to the review of Hayre,[163] recent studies present an overall surface roughness with a standard deviation of about 0.25 meter. This suggests that within the central (one-tenth radius) of the Moon, crevices deeper than twice the standard deviation (0.5 m) exist with a probability of only about 4.5%.

Evans [108] reviewed the experimental results of a number of authors in the field of radar studies. His conclusions concerning these efforts are as follows:

> The results of many experiments carried out in the wavelength range 3—0.1 meters indicate that the surface of the moon is smooth and undulating with average gradients of the order of 1 in 10, and on the average only about 10% of the surface is covered with small objects which are below the optical limit of resolution. The reflected signals are in many respects similar to those observed from aircraft over dry sandy terrestrial deserts at normal incidence. The measurement of the reflection coefficient (ρ) for the surface material is complicated by the fact that the observed signals suffer marked intensity variations due to interference from many scattering regions. If, however, it is assumed that the r.m.s. signal level provides a proper measure of the reflection coefficient, the average value obtained from many experiments is $\rho \approx 0.06$. This corresponds to a dielectric constant of $k_1 \approx 2.72$ which is similar to that observed for dry sandy soils on the surface of the earth.

It must be kept in mind, however, that the dielectric constant is a function of composition, surface roughness, and density and does not really specify the microstructure of the surface. It should also be kept in mind that radar echoes can sample only properties of reflecting surface averaged over territories of several thousand square kilometers. Salisbury [284] points out how extremely complicated the interpretation of radar reflection data has become. He warns against over-interpretation of the data, especially those studies tending toward low slope-angle interpretations which may be limited by radar resolving power.

Photometric studies provide a second line of evidence for surface roughness. Struve,[319] reporting on the work of VanDiggelen and others, has shown that the lunar surface is probably heavily pitted. This agrees with the findings of Barabashov [21] and Sytinskaya,[322] who maintain that the "microrelief" of the lunar surface is very great.

The study of Head [165] suggests a more severe roughness problem. He reviewed the literature of model impaction studies and added a few experiments of his own, using semi-solid fats as a model system. His model suggests a surface so peppered with craters that it would be fortunate indeed if a vehicle could land in an area not an integral part of a crater or on its rim. It would suggest that the climbing mode of locomotion would not be just an emergency exception, but the rule. The assumptions in such model building experiments are so gross as to relegate such a lurain concept to mere speculation, but such a speculation can, at this point, not be disregarded.

In conclusion, the small-scale roughness model for the maria is still vague. This model is of great importance to the design of both landing vehicles and suits. The volcanic theory suggests a relatively smooth structure if originally formed of pahoehoe-type lava [142, 147] or welded tuffs [249] or a rough structure if formed from aa-type lava flows.[142, 147] Meteoritic activity would tend to increase the small-scale roughness by cratering effects of large meteorites or decrease the roughness by filling of defects by the products of micrometeoroid erosion. Frequent block and flow structures of up to 3 feet in height should probably be included in present design models, as should small craters from a few inches to several hundred feet in diameter.

Lunar Dust

The Moon has some extraordinary photometric properties that must depend on the detailed structure of its surface. At full Moon, the distribution of brightness over the surface of the disk is nearly uniform, in contrast to ordinary diffusing spheres which appear brighter near the center when illuminated by a distant light source. The maria and highland regions have nearly the same photometric properties, both being characterized by a maximum apparent brightness at zero phase angle, with sharp changes in brightness before and after full Moon. Models of the lunar surface most satisfactorily explaining these results have the surface covered by deep holes with vertical walls and sharp edges or by a porous dendritic matrix. This microstructure on some scale greater than the wavelength of light is such as to give a very strong maximum of reflection in the backward direction. The lunar surface is characterized by innumerable areas of different brightness. This property (along with topography) has been of considerable value in mapping stratigraphic units on the Moon's surface.[194]

Polarization of moonlight as a function of phase angle gives information on the very fine structure of the surface.[91] As summarized by Speed et al.[305] and Hapke,[154] observed mean lunar polarization curves giving the proportion of polarized light as a function of phase angle show two distinctive features: (1) for small phase angles, a greater portion of light reflected from the surface vibrates in the plane of vision rather than in a plane perpendicular to the plane of vision (negative polarization), and (2) at phase angles of 28° the polarization becomes positive, and it reaches a maximum at a phase angle of about 100°. Maximum polarization is attained on the dark regions and minimum on the bright regions, and the polarization varies considerably more on the bright areas than in different places on the maria. The average polarization curve of the Moon is reasonably matched by mixtures of volcanic ashes (alkali-basalt composition); that is, by a powdered, opaque substance (fig. 7). Such powder may stick even to the steepest lunar slopes and, in view of the photometric data, to the walls of the cavities covering the surface as well. The polarization curve obtained from slopes and flat areas is the same, and is very different from that obtained with bare igneous rocks, whose zero of polarization is at a smaller phase angle (around 10°). Confirmation of this model will be presented below.

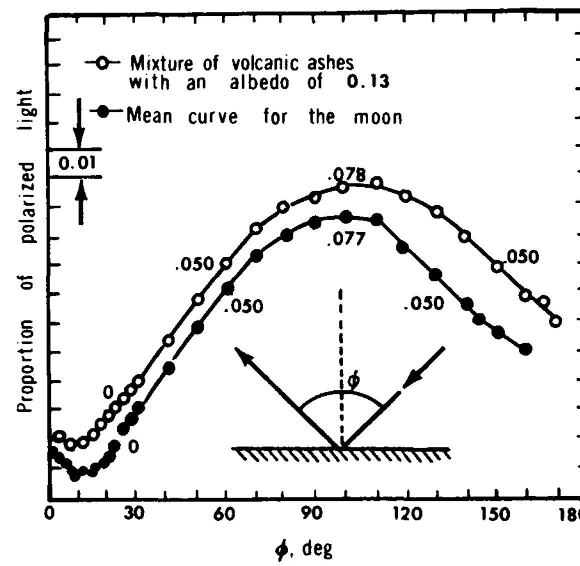


FIGURE 7.—Polarization of light reflected from the Moon. (AFTER SPEED ET AL.[305])

Temperature measurements of the Moon made during eclipses in both the infrared and microwave regions of the spectrum have yielded information about the thermal properties of the near-surface material. As summarized by Salisbury,[284] a line of evidence for the thickness of the dust layer is also provided by thermal radiation measurements. Pettit[259] concluded that the insulating surface layer, which he believed to be pumice, is 2.6 cm thick. Jaeger and Harper[181] found that their infrared curves fit best for a surface layer of dust 2 mm thick over pumice or gravel. Jaeger[180] developed a theory attempting to reconcile all the data into a consistent picture. Assuming thermal properties to be independent of temperature, the eclipse observations indicate a surface with so-called thermal inertia $(K\rho c)^{-1/2}$ of the order of 1,000. This may be interpreted as representative of finely divided granular material in vacuum, or at least a thin layer of this material a few millimeters thick overlying a better conductor (equivalent to pumice or loose volcanic gravel). The theory definitely rules out any larger part of the surface being covered by pumice or bare rock. This can be seen from figure 8, which shows measured temperatures during an eclipse (crosses), as obtained by Pettit,[259] together with the theoretical curves of Jaeger for homogeneous rock, pumice, and dust. Assuming a "midnight" surface temperature of approximately 120° K, Sinton[299] has calculated that a surface with $(K\rho c)^{-1/2}$ of the order of only 500 is required to explain the lunation temperature variation. This discrepancy could easily be removed, it seems, by lowering the "midnight" surface temperature. In fact, recent measurements by Murray and Wildey[240] show the nighttime surface temperature to be below 105° K.

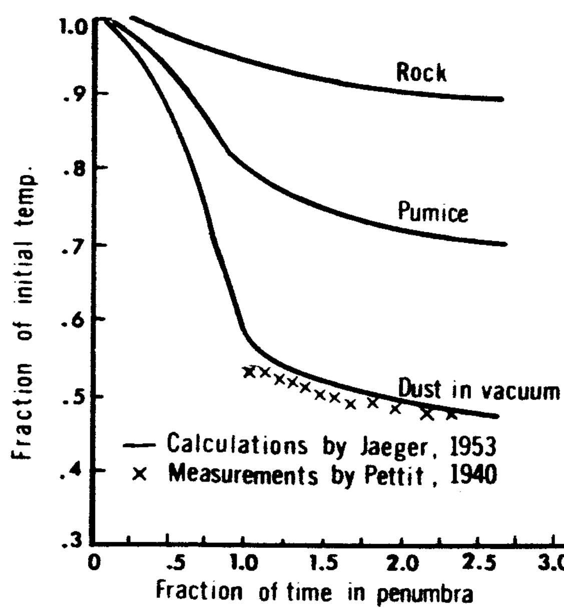


FIGURE 8.—Change of temperature during a lunar eclipse. (AFTER SPEED ET AL.[305])

Examination of Sinton's theoretical curves shows that a midnight temperature of about 98° K would be sufficient to raise the lunation thermal inertia the required amount to agree with eclipse calculations. More recently, Gibson,[128] following the work of Piddington and Minnett,[261] found that thermal radiation of 0.86 cm wavelength also indicated an average dust thickness of 2 or 3 cm.

Diurnal oscillations of microwave and millimeter-wave temperature observations as reported by Sinton[299] indicate, by their low amplitude and large phase angle factors, that the radiation giving rise to these temperatures originates beneath the surface of the Moon. Using either the variation in amplitude or phase lag of the thermal wave with depth, the mass absorption coefficient of the Moon's near-surface material can be calculated. Sinton has also measured the mass absorption coefficients for some terrestrial materials at a wavelength of 1.5 mm (no values given in the paper quoted) and finds that the observed coefficient, which falls between 0.1 and 0.083 gm^{-1} cm^{2} is closest to that basalt. Stone meteorites have coefficients near 9 gm^{-1} cm^{2}, while tektites have coefficients near 2 gm^{-1} cm^{2}. The fact that all the above measurements agree within an order of magnitude is very encouraging.

Thermal characteristics may also be an indicator of dust behavior. Klein[190] has made some preliminary experiments and calculations which suggest to him that, because thermal conductivity values on the lunar surface are so low, the dust cannot, as suggested by others,[343] be sintered by sputtering and vacuum welding. Dust, he feels, must exist as a loose powder with minimum point contact of individual particles. If the dust is loose, as Klein maintains, it appears that this can only be by virtue of the electrostatic charging mechanism advocated by Gold.[137] Other mechanisms have been called upon to put the dust in suspension, such as Gilvarry's suggestion[130] that seismic waves were responsible, but none appear effective on a continuous basis. According to Gold,[138] however, the local differentiation of albedo on the lunar surface suggests that dusts are probably generated from local stuff rather than from a general blanket.

As pointed out by Salisbury,[284] it is possible to make deductions concerning the looseness of the lunar dust from observations of the characteristics of lunar features themselves. The lunar rays, for example, have retained their distribution and shapes for at least 300 years. No matter what the rays are composed of, any appreciable rate of dust migration should have long since covered, or at least altered, them. Thus, we can say that the dust probably does not migrate at an appreciable rate, but may nevertheless be charged and loose. If, as is generally believed, the lunar rays are composed of finely divided material (rock flour), then the variation of ray brightness with phase angle is a second line of evidence that the dust is sintered. As reported by Bobrovnikoff,[44] the curves for the variation of brightness of rays have sharper peaks near the time of full Moon than the curves for neighboring regions. If solar radiation does produce an electrostatically charged dust, the number of dust particles "in suspension" above the lunar surface should reach a maximum at a phase angle of 90°. The self-shadowing effect of such particles would then act as a brightness inhibitor, tending to produce a smooth curve rather than a sharply peaked one. Finally, there are indications that the rayed craters have a much less porous surface than the older craters, indicating a possible evolutionary trend.[296]

Such deductions from the observed characteristics of lunar features are strongly suggestive of a sintered lunar dust layer; but, unfortunately, they are based upon assumptions of the nature of the lunar features observed—for example, assumptions that the rays are not self-replenishing in the first case, and that rays are composed of finely divided material in the second. It appears at this time, nevertheless, that the microrelief is great, that the dust layer is thin, and that the dust is not loose and does not migrate. The recent review of the extensive Russian literature[211] suggests that current Russian views also favor a porous sintered structure, though no direct evidence is presented. Studies of Sytinskaya[323] and Orlova[251] are pertinent to this point.

These studies, as well as the recent report of Gault et al.[120] on impaction of basaltic surface by hypervelocity projectiles, support the negative accretion hypothesis of Whipple.[343] Gault suggests that the flux ejected from the lunar surface will be at least 3 or 4 orders of magnitude greater than the flux of impacting meteoritic debris of the same mass. Only a small fraction of the debris has escaped velocity, and most returns to the surface as secondary missiles. The implication of an equilibrium dust cloud has already been covered in the section on the lunar atmosphere. There is an added inference that there must be a thin dust layer on the surface constantly agitated by impacts to form a heterogeneous mixture of material from all over the Moon. Analyses of the size distribution of ejecta fragments in these studies suggest that the surface material may be composed of a mixed rubble of unsorted rock fragments ranging from layer blocks to submicron particle sizes. This view, also expressed recently by Baldwin,[16] does not eliminate the possibility of a surface layer of fine dust covering several meters of unabraded debris. While the concept derived from these experiments appears valid, the quantitative aspects remain obscured by such unknown factors as the roles of high vacuum and complex surface targets and the absolute values for the primary flux of interplanetary solids on the Moon.

In recent months, studies in vacuum chambers on Earth have shed some light on the validity of photometric and thermal data. Salisbury et al.[286] and Stein and Johnson[312] have demonstrated that basaltic silicate powders sieved in chambers at 10^{-10} mm Hg show cohesion and adhesion with angles of repose of close to 90°. Gross adhesion in these experiments was estimated to be approximately 750 dynes/cm^2 (0.01 psi) although the stress at contact points between grains was estimated to be as great as 9×10^8 dynes/cm^2 (1.3×10^4 psi); this is the order of the bulk strength of the material. The effect of radiation on the cohesive properties remains to be investigated. Radiation "cleaning" may well allow for greater cohesion, though this is only speculative.

These quantitative findings, though possibly in error by an order of magnitude, lend credence to the hypothesis of Hapke [154] regarding the "fairy castle" structure of the lunar surface in interpretation of photometric data. They suggest that even in the highlands, powder must cover even the steepest slopes. They also suggest that coating of optical and reflective surfaces of space vehicles and suits may well be a serious problem on the lunar surface.

Assumptions regarding low thermal conductivity have also been corroborated. As discussed previously, in a study at the Jet Propulsion Laboratory [36] the thermal properties of sand and crushed olivine basalt were determined in vacuums up to 10^{-6} mm Hg. The thermal conductivity of the crushed olivine basalt was approximately one-hundreth as great when measured in vacuum as when measured in air at atmospheric pressure. The value measured in vacuum is in good agreement with the value for the lunar surface calculated from astronomical data.

To prove conclusively that the lunar dust is either sintered or loose, one must measure a characteristic of the dust itself that is directly related to the property of "looseness." Thermal conductivity appears to be such a characteristic because it will vary with the number of point contacts between dust particles; and the number of point contacts between particles defines the looseness of the dust. As pointed out by Salisbury,[284] should the dust be loose and bear an electrostatic charge, the strength of this charge will vary with the intensity of solar radiation. As the strength of charge varies, so should the thermal conductivity as the number of contact points increases or decreases. Correlation of conductivity parameters with solar flares may be the only way of settling the issue prior to the actual landing of surveyor instrumentation.

Soil Mechanics

As will be shown in Chapter 2, the mechanical characteristics of the lunar surface and subsurface structures are important considerations in determining the energy required for human locomotion. A lava surface on the Moon may well be similar to the terrestrial rock froths, which range in bearing strength from 200 psi to 12,000 psi. As already mentioned, the reduced lunar gravity and lack of atmosphere would tend to increase the size of voids in the mass. The nature and amount of volatiles producing the froth in lunar magmas is a major factor in bearing strength about which little is known. Fudali [118] believes it is unlikely that a lunar rock froth would have a bearing strength less than 100 psi.

The strengths of dust materials must also be considered. The question of particle size has significance in the bearing strength of dust layers. The information on this problem is meager. Past estimates have given a size range of 1μ to 300μ, with consensus at about 10μ.[297, 319, 340] The recent study of Hapke [154] suggests that the particle size of the surface layer is of the order of 10μ, and that the size increases with depth. In the absence of weathering, the grain should theoretically be angular. This angularity plus the high cohesive tendency should give surface layers of high porosity.

The bearing strength of a dust layer is a continuously varying parameter. Application of loads causes compacting and interlocking of particles, which increases bearing strength rapidly with depth of penetration. Under standard temperature and pressure conditions on Earth, the load necessary to penetrate 0.1 inch of finely ground pumice is 4 psi; to penetrate 5 inches, 25 psi. The bearing strength of lunar dust depends on the initial degree of compaction (void ratio) and the cohesion as determined by temperature,[331] seismic shaping, impacting, churning and scattering,[120] vacuum sintering, gas adsorption, and sputtering or cleaning by radiation.[292, 338] Many of these basic complexities in predicting lunar soil mechanics for locomotor devices have been reviewed by Bekker [30] and are discussed in Chapter 2.

Current studies of soil mechanics in simulated lunar environments have just begun to skim the problem. Unfortunately, most of the early studies were performed at pressures above 10^{-6} torr. Explanations of many of the contradictory results have come to light when experiments were repeated with graded pressures down to 10^{-10} torr, and with long "hold times" under vacuum. The pioneering studies of Geer,[125] Roddy et al.,[279] Halajian,[149] and Rowe and Selig[283] have been followed by those of Stein and Rostoker,[313] Salisbury et al.,[286] Sjaastad,[300] and Bernett et al.,[35] and recently reviewed by Vey and Nelson.[331] At lunar pressures of about 10^{-10} torr there is generally a definite increase in cohesive strength of dusty soils, with parallel increases in shear strength and both static and dynamic bearing capacity. However, as Vey and Nelson[331] so well point out, not all dusts behave alike. Silica in the 10μ size range shows increases in cohesive strength and internal friction. Olivine dust, another possible lunar material, shows an increased internal friction, but its cohesion appears to decrease in high vacuums. Apparently interparticle forces may be either attractive or repulsive, depending on the mineralogical composition of the soil and on vacuum levels. This point is crucial and places a limit on the value of vacuum-chamber data for predicting lunar soil mechanics for materials of unknown composition.

The effects of gravity on the lunar soil mechanics appear to depend on the degree of cohesiveness and porosity of the soil.[148] In tests of bearing strength a fully compacted, noncohesive soil fails in lateral shear. The bearing strength is gravity-dependent because the resisting forces in the soil are frictional and are a function of the weight of laterally displaced soil sliding along the failure plane. Everything else being equal, the sinkage of a given object in a fully compacted soil will be the same on Earth as on the Moon because the change in the applied load corresponding to the change in the gravity field will be offset by a similar change in the resisting force in the soil. On the other hand, a loosely deposited soil composed of fine, dry, nonspherical particles is highly compactable. It has inherently low shearing strength and fails in vertical shear or compaction. There appears to be no lateral displacement of this type of soil until it is fully compacted. It acts like a spring or shock absorber and, hence, its resistance to an applied load is independent of gravity. The sinkage of an object in this soil will be directly proportional to the gravity field. It is obvious, however, that the degree of interparticle cohesion plays a major role in determining the relative effect of gravity, and this is still a major unknown in lunar soil mechanics.

Predictions of compressive strength for the lunar dust by Fudali[118] suggest that 10 psi to give a penetration of 1 to 2 inches would be a conservative figure. The data of Vey and Nelson[331] support this contention. Bernett et al.[35] have shown that the minimum bearing capacity of loosely packed olivine dust (1.25 gm/cm^3) at 10^{-6} torr was greater than 0.1 kg/cm^2 (1.4 psi), while the maximum bearing capacity of densely packed samples (2.1 gm/cm^3) was about 7 kg/cm^2 (98 psi). Direct shear tests in the closely packed samples indicated cohesion up to 1 or 2×10^4 dyne/cm^2 (1.5 to 3×10^{-1} psi). These data for olivine dust, which was shown by Vey and Nelson[331] to be much less cohesive *in vacuo* than silica dust, were obtained in relatively poor vacuums.

The General Electric Company has assumed a 10 psi compressive strength at the surface[206] and Grumman Corporation[149] has assumed a frothy surface with only 2 psi compressive strength. These are temporary design figures for landing vehicles and locomotor structures. Recent NASA models have presented as guidelines compressive strengths of 12 psi.[242, 245] The effects of such predictions on human locomotor activity are presented subsequently.

This discussion of rocky froth and dust assumes a uniform distribution with depth. Vesicular subsurface structures modify the problem to a consideration of the load capacity of bridging structures. Previous artifical movement of soil also greatly modifies its load capacity, as does admixture with larger rubble. Kollbrunner et al.[193] and Winterkorn[349, 350] in studies for General Electric have considered the problem of chemical stabilization of lunar soils that are potentially unfavorable for building or locomotion. Head[165] has also reviewed the solidification problem for large structures.

METEOROID ENVIRONMENT

The meteoroid environment of the lunar surface has some bearing on the energetic design factors of space suits. Penetration of suits and environmental control units by meteoroids could acutely compromise a mission or require that the crew return with great haste to the lunar landing vehicle. The primary micrometeoroid particle or secondary ejecta from strikes on the lunar surface might erode the surface of suits or adhesively coat the surface and modify the thermal reflectivity of the garment.

Current mass-flux estimates for penetrating meteors in the near-Earth space follow the equation of Whipple:[342]

$$\log N = -14.50 - 1.35 \log m \qquad (4)$$

where

N flux rate, particles per m^2 per sec

m mass, gm

This equation is thought to be good only within a factor of 5. Smaller meteors with visual magnitudes between +21 and +30 (smaller than 10^{-8} gm) follow the equation:[47]

$$\log N = -17.3 - 1.70 \log m \qquad (5)$$

Sporadic meteoroid showers increase the flux rates by a factor of from several percent to as much as 20 times above the normal flux. The average flux rise is about 3 to 5 times, with no gross change in average velocity.[253]

Extrapolation of these equations to the lunar surface is most difficult. There are no direct data and concentration factors are very poorly understood.[47, 253] It is thought that in cislunar space, gravitational convergence[46] brings about a flux concentration of the puncture-sized meteoroids ($> 10^4$ gm) at about 7 Earth radii. The flux slowly decays to a space value of 78% of the near-Earth value. On the lunar surface a target would probably see three zones of oncoming meteoroids:[47]

I. That region of the celestial sphere at or near the Earth from which no flux would be received owing to capture and prefocusing by Earth

II. That region on the celestial sphere concentric to zone I through which increased flux would be received owing to gravitational focusing

III. That region concentric to zone II through which normal space flux would be received.

Superimposed on these factors is the flux change due to lunar phase shifts. At the first quarter this flux rate should be at a maximum 55% of near-Earth flux, decreasing to a minimum of 23% at the third quarter. These calculations are, of course, only a first approximation from rather meager data. The flux concentration for micrometeorites ($< 10^4$ gm) about the Earth-Moon system is also poorly understood. There are numerous data suggesting that the micrometeoroid flux in the zone of the zodiacal cloud (10^6 km) is 3 orders of magnitude less than in the near-Earth region.[47, 341] Calculations for the concentration of micrometeoroids about the Moon by gravitational factors have been presented by Dole[89] and Ginn.[131]

The secondary ejecta must be superimposed on this surface flux. Preliminary studies by Gault et al.[120] indicate that the flux rate for smaller fragments may be several orders of magnitude greater than near-Earth projections. This increased rate for low-velocity particles is possible for even the most porous models of the lunar surface.[121]

The erosive potential of the micrometeoroid environment on the lunar surface is still more difficult to predict. Using the NASA-Ames penetration criteria and acoustical micrometeoroid flux data, Orrok[253] has arrived at an erosion-rate estimate of 2,000 Å per year with a surface coverage time of 2 years in free space. Orrok feels that these acoustic flux rates overestimate the hazard, and predicts erosion rates of less than 100 Å per year. He feels that the experimental erosion data of McKeown and Fox[219] of 70 Å per year is more probably caused by radiation sputtering than by micrometeoroids. Secondary ejecta on the lunar surface will, therefore, probably be the major source of erosion of the space-suit surface. Inadequate data on this crucial point prevents any meaningful speculation on the problem.

RADIATION ENVIRONMENT

The effect of radiation on the surface layers of the Moon has already been covered. Effects of space radiation on the surface of the lunar suit should also involve vacuum-sputtering phenomena which may act synergistically with micrometeoroids to produce erosion and changes in emissivity. Reviews of the problem have been presented by Lad,[202] Jaffee and Rittenhouse,[182] Mayer et al.,[231] and Harrison and Yonts.[159] It is clear from these reviews that in the total analysis of the space-suit problem, vacuum sublimination and sputtering of the surface materials must be considered along with vacuum degeneration and radiation degradation of the subsurface structures. An exhaustive analysis of this problem is beyond the scope of this study.

Several bibliographies on the lunar surface have recently been compiled.[54,166,221,222] They may be consulted for data on many secondary problems probably overlooked in this brief review.

Data obtained from generalized surveys of the lunar surface, or even from focal surveyor samples, must be regarded with caution when reviewing energetic problems of the lunar explorer. There may well be focal areas of very deep dust or dust-covered unstable slopes that will increase the locomotion stress manyfold. Since their absence on the Moon has never been adequately demonstrated, there is the possibility of local talus slopes and sharp-edged boulder patterns requiring design of tear-resistant surface coatings on lunar clothing. The design of suits should, of course, take into account these many contingencies when engineering realities so allow. Details of these problems will be developed further in other chapters.

CHAPTER 2

Metabolic Cost of Locomotion and Work

THIS CHAPTER presents, first, a review of the metabolic cost and energetic efficiency of human locomotion and work in pertinent earthly environments. The effects of clothing, load carriage, and gaseous environments are covered. Finally, an attempt is made to extrapolate these costs to subgravity conditions and encumberances presented by typical space-suit designs. The data from this chapter will be used in subsequent chapters to evaluate the limitation of exercise by thermal and mechanical considerations of space-suit design.

METABOLIC COST OF WORK

General Considerations

Estimates of the expenditure of energy during various activities are useful for computing dietary requirements, for assessing the overall physiological severity of activities, and for determining optimum means and rates of work for any mission. In this chapter, an attempt will be made to restrict the discussion to the assessment of overall physiological severity of specific exercise patterns. Previous reviews [252, 255] have adequately covered the daily occupational energy requirements and this approach will not be attempted here.

In the past, most assessments of total energy need have been made from analysis of dietary intake and weight balance. This approach is, of course, inadequate for specific tasks. Indirect calorimetry using the oxygen consumption data obtained from Douglas bag analysis has been the source of most of the data generated by the Harvard Fatigue Laboratory [160] and Morehouse and Cherry [236] during World War II. More recent studies have utilized the light (<4 kg) portable respirator developed at the Max-Plank Institut für Arbeitsphysiologie.[239] This device measures the volume of expired gas directly, and simultaneously diverts a small fraction into a rubber bladder for future analysis. The Dortmund workers [208] used this device in their studies of German industry in World War II. Much of the material to be presented below stems from these and parallel studies in the military laboratories of the U.S. Armed Forces during and after World War II.

Some pertinent metabolic factors to be used are:

$$\begin{aligned} 1\ \text{kcal} &= 3.9685\ \text{Btu} \\ &= 426.9\ \text{kg m} \\ &= 3087.4\ \text{ft lb} \\ &= 0.00156\ \text{hp hr} \end{aligned}$$

$$Q = 5.0\dot{V}_{O_2}$$

where

Q energy expenditure, kcal/min

$\dot{V}_{O_2}$ oxygen consumption, liters/min

Standard external work efficiency ≈ 20%

Average body surface area = 1.85 m^2 (unless otherwise indicated)

These conversion factors have been made into a chart by Webb Associates [335b] as seen in figure 9.

In general, the values of energy expenditure for specific tasks in trained subjects are accurate from person to person within 15% as an outside figure. In the past, energy requirements for specific tasks have been presented as "net calories" after deducting the basal or resting metabolic rate determined from standard tables. Since exercise itself may change the energy requirement for body maintenance, it appears more significant to record the values as gross or total calories as determined for each task. Wherever possible, the values will be expressed as kilocalories (Calories) or Btu/m^2 of body surface per min, or the weight of exercising subjects will be recorded along with the rate of energy expenditure. No attempt is made to separate the specific dynamic action (SDA) of food from these figures. To what extent SDA is available for external work is still uncertain, and in most cases the times of studies relative to meals are not recorded.

The problem of the efficiency of energy conversion to external work is of interest. Factors which must be considered in appraisal of overall efficiency of performance include the rate of work, the load, the duration and quality of work, and the speed of recovery in intermittent tasks. It is, of course, quite difficult to assess all these variables independently for any given task. Efficiency is expressed by the formulas:

Gross efficiency (%) =

$$\frac{\text{External work performed}}{\text{Energy used}} \times 100 \qquad (6)$$

Net efficiency (%) =

$$\left(\frac{\text{External work performed} - \text{Basal energy}}{\text{Energy used}}\right) \times 100 \qquad (7)$$

The individual variation in mechanical efficiency for any given task is relatively small. Åstrand,[10] in his review of the literature on this point, suggests that during work on the bicycle ergometer the standard variation in mechanical efficiency was only ± 8% of the found values for athletes, normal healthy people, and people with heart and respiratory troubles, provided the work level was adapted to the capacity of the individual.

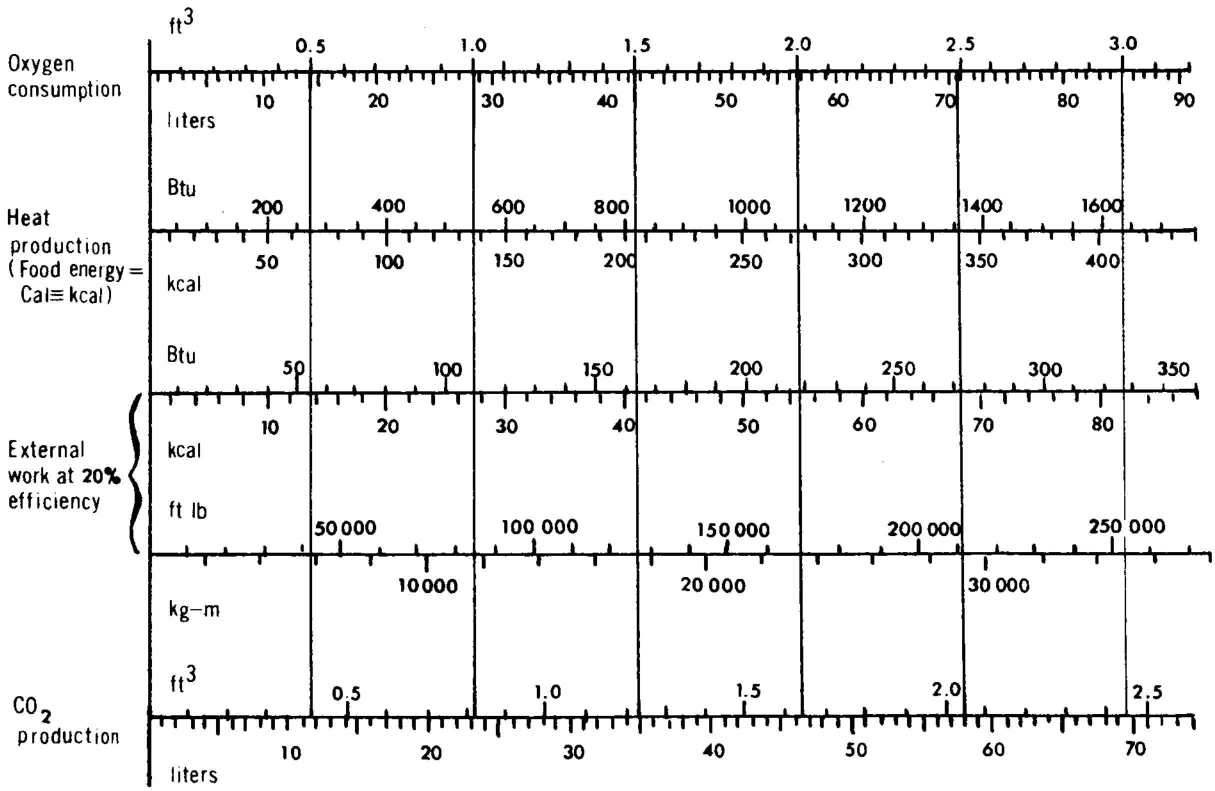


FIGURE 9.—Conversion chart for the interrelated metabolic data, assuming a standard respiratory quotient of 0.82. Given any one of the four quantities, the other three can be found by drawing a vertical line to the respective scales. Note that heat production and food energy are equivalent terms, and that the food Calorie is a kilogram calorie. (AFTER WEBB ASSOCIATES.[335b])

Since work and locomotion under lunar subgravity states will be shown to involve abnormal motor patterns and weight distributions, it appears worthwhile to review several concrete examples of factors that modify the efficiency of energy expenditure for a given task. The act of walking along a horizontal plane involves the arms and legs, which are raised or lowered as the trunk is propelled forward in the horizontal plane with a rise or fall of its center of mass. In this form of exercise, little external work is accomplished relative to the expenditure of energy for overcoming gravity, muscle "viscosity," inertia of limbs, and external wind resistance. It is, therefore, difficult to record the overall efficiency as ratio of work done to energy used. It is more useful to consider only the energy requirement for a particular distance and at a particular speed.

As Morehouse and Miller point out,[237] the comparative efficiencies of walking, running, climbing, and performing other progressions at various speeds are best evaluated by comparing energy expended in traveling a fixed distance. Slow rates of progression which are performed with low expenditures of energy are not efficient. Table 3 demonstrates the concept that the most efficient speed for a progression is not proportional to the rate of energy expenditure (kcal/hr), but rather to the quantity of energy used during each distance (kcal/mile). Table 3 also demonstrates that fewer calories are used in walking a mile at 3.5 mph than when the speed is slowed to 2.3 mph or increased to 4.6 mph. Speeds of grade climbing below 2.5 mph require expenditures of more calories each mile than do speeds of 2.5 to 3.5 mph. Less energy is expended when a 43-pound load is carried at 3 mph than at either slower or faster speeds. In carrying the load up a steep grade, the faster speed is more economical, but at the greater speed the rate of energy expenditure becomes so high that a steady state of physiological activity cannot be established and exhaustion occurs within a short distance. In the case of grade walking carrying a 43-pound load, it would appear that 1 mph is the optimal speed if the load is to be carried more than a mile, but 1.5 mph is optimal if the load is to be carried less than a mile. The same principles apply to skiing along the level. The faster speed is more economical but the high energy requirement at speeds above 5 mph prevent these rates from being continued for more than 1 hour. The optimum speed for walking and the many factors which determine it will be covered in greater detail at the end of this chapter.

TABLE 3.—*Energy Expenditures for Different Types of Progression at Various Speeds and Grades*[a] [AFTER MOREHOUSE AND MILLER[237]]

Type of progression	Speed, mph	Grade, %	Energy expenditure of 154-pound man	
			kcal/hr	kcal/mile
Horizontal walking	2.3	0	210	90
	3.5	0	290	85
	4.6	0	470	100
Grade walking	2.0	5.0	250	125
	2.5	5.0	290	115
	2.3	5.5	350	150
	3.5	5.5	450	130
	2.4	8.6	430	180
	3.5	8.6	560	160
Horizontal walking carrying 43-lb load	1.0	0	210	210
	2.0	0	270	135
	3.0	0	350	115
	4.0	0	540	135
(Running)	5.0	0	820	165
Grade walking carrying 43-lb load	0.5	35.8	370	740
	1.0	35.8	680	680
	1.5	35.8	890	595
Skiing along level	3.0	0	540	180
	5.0	0	720	145
	7.5	0	950	125
Swimming (breast stroke)	1.0		410	410
	1.6		490	305
	1.9		820	430

[a] The figures in this table were calculated from Harvard Fatigue Laboratory data for a 150-lb man.

A dominant factor in human energy efficiency is the time spent in performing the work. The longer the work period, the lower the energy efficiency. In order to achieve the highest energy efficiency, work should be performed at the most rapid rate within the limits of skill and endurance. The reason for the low economy of progression at a slow rate is that a large part of the energy used during the work is required for the maintenance of body functions (digestive, glandular, etc.) which do not contribute directly to the performance of the work. When the distance is traversed in a shorter time, the energy cost of these supportive functions is correspondingly reduced. Net efficiency, therefore, does not change significantly with exercise rate.

The increase in energy cost when work is performed at slow rates is shown in table 4. The 1 mile climb at 0.5 mph requires 2 hours. At 1.5 mph the climb can be completed in 40 minutes. At the slow rate of work the energy cost of maintaining the human machine must be met for 80 minutes longer than at the faster rate of work. This increased energy cost, amounting to 145 kcal, reduces the work efficiency from 24% to 6%.

TABLE 4.—*Relation of Efficiency to Rate and Load of Work*[a] [AFTER MOREHOUSE AND MILLER[237]]

[154-pound man carrying 43-pound load up 35.8% grade]

Speed, mph	Climbing 1 hour		Climbing 1 mile	
	kcal/hr	Efficiency	kcal/mile	Efficiency
0.5	370	13%	740	6%
1.0	680	14%	680	14%
1.5	890	16%	595	24%

[a] Data from table 3.

An additional factor in work efficiency as shown in table 4 is the work load. When the speed was increased from 0.5 to 1.0 mph, the work load was increased by 145, 548 foot-pounds per hour and the efficiency improved from 13% to 14%. At 1.5 mph the work load was 436, 444 foot-pounds per hour and the efficiency was 16%. However, work which requires an energy expenditure greater than 700 kcal per hour cannot be continued for much longer than 1 hour by an untrained man. Unless the man carrying the 43-pound load up the 35.8% grade (table 4) was well trained, he could not be expected to climb at 1.5 mph for more than an hour, as the energy expenditure at this rate is 890 kcal per hour. If the speed is reduced to 1.0 mph, the energy requirement is reduced to 680 kcal per hour and the work can be sustained for a longer period. If the distance is great, the speed should be reduced so that the climber is not exhausted by the work. Efficiency must be sacrificed for endurance in order to accomplish work of long duration. When the distance is short, greater speed or heavier loads are necessary if the work is to be performed with the greatest efficiency. The well-trained individual is able to carry on work at a higher level of energy expenditure; thus he is able to perform work at higher speeds for longer periods.

The steadiness of the rate of work is also a factor in efficiency. Work is done more efficiently if it is carried on at a steady rate. It costs energy to accelerate. In distance races, whether running, swimming, rowing or bicycling, energy must be conserved and a steady state established at a dangerously high level of energy expenditure. Under these conditions the race will be finished in the shortest time if the athlete has maintained a speed at which a maximum steady-state level has been established for the number of minutes required for the event.

There is also a factor of rhythmicity in the efficiency problem. Rönnholm et al.[280] have found that the energy expenditure of simple cyclic work, such as lifting weights by hand onto a table, is determined not only by the overall rate, but may also be markedly affected by breaking the work into short sequences between which rest pauses are interposed. Such an effect may, of course, be expected, if the work is carried out at a paced rate slower than that at which the maximum mechanical efficiency is attained. Speeding up the work would in such a case obviously improve the mechanical efficiency. However, the remarkable observation is that even at the optimum frequency of the work—20 or 30 lifts per minute—the introduction of an element of rhythm caused a marked increase in the mechanical efficiency.

At a muscular level, efficiency of positive work may be summarized by the following quotation from Hill: [170]

> When positive work is done, as in climbing a staircase or pedalling a bicycle uphill—in both of which the load is approximately constant—there is a particular speed at which the physiological cost, measured in terms of energy used and oxygen consumed, is a minimum. The existence of an optimum speed depends chiefly on the balance between two opposing factors. The first one is that the quicker a muscle shortens the less is the external force it can exert, for a given degree of stimulation; hence, if the external load is fixed, the muscle, in order to shorten quickly, has to make greater effort and be stimulated more strongly—which, of course, means more energy used. The second factor, working in the opposite direction, is that the slower a muscle shortens, the longer its contraction has to be kept up in order to carry out a given extent of movement; and a longer lasting contraction means more energy used. At a certain speed the best compromise is reached and the energy used is a minimum. This region of maximum economy is rather broad, and the speeds within this maximum are not always practical.

An excellent review of the power output of man has been presented by Krendel.[197] The material, however, is quite beyond the scope of this paper. The following sections will be devoted to the specific energy cost of exercise tasks which may be pertinent to analysis of lunar exploration.

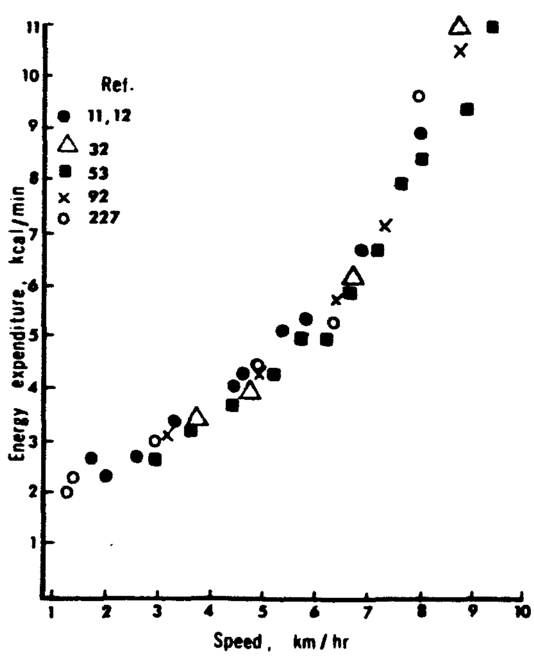


FIGURE 10.—Energy expenditure walking on the level at various speeds. (AFTER PASSMORE AND DURNIN.[255])

TABLE 5.—*Energy Cost of Walking and Running* [AFTER WEBB ASSOCIATES [335a]]

Speed of walking and running, mph	Energy cost kcal/m²min	Energy cost Btu/hr
1.2	1.7– 2.0	735– 870
2.0	1.5– 1.9	650– 820
2.4	1.6– 2.7	690–1,150
2.8	1.9– 2.4	820–1,040
3.0	2.2– 3.1	950–1,340
3.2	2.1– 3.3	910–1,430
3.6	2.4– 3.8	1,040–1,640
4.0	2.5– 4.0	1,080–1,730
4.3	3.6– 5.5	1,560–2,480
4.8	4.6– 7.6	1,990–3,290
5.0	5.6– 8.3	2,420–3,580
6.0	6.5–11.4	2,810–4,940
6.5	6.6–13.3	2,850–5,750

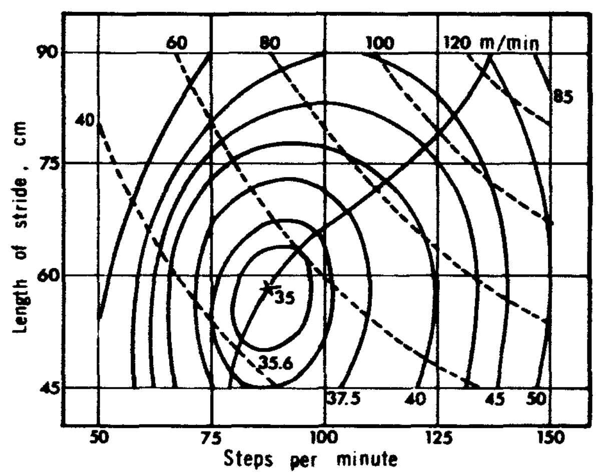


FIGURE 11.—Caloric consumption as a function of length of stride and cadence. Dashed lines represent speed in m/min; thin solid lines (contour lines), caloric consumption; heavy solid line, optimal combinations of cadence and length of stride for various speeds. (AFTER BRUNNSTROM,[55] REDRAWN FROM ATZLER AND HERBST.[11])

Walking and Running on Level

Several of the many studies that have been made of energy expenditure during walking on the level are presented in the composite graph of figure 10.[255] The subjects weighed between 60 and 75 kg. Webb Associates [335a] have compiled similar figures from other sources giving greater ranges. These are presented in table 5. Over the range of 3 to 6.5

km/hr (approximately 2 to 4 mph), energy expenditure appears to be linearly proportional to the speed, the relationship being expressed by the equation $C=0.8V+0.5$, where C is energy expenditure in kcal/min and V is speed in km/hr. At higher speeds, the energy expenditure increases at faster rates and appears to be proportional to the square of the speed.[270]

The effects of weight, sex, and race on walking at level speeds have been studied by Mahadeva et al.[223] The regression equation for weight effects was found to be

$$C=0.047W+1.02 \tag{8}$$

where W is gross weight in kilograms. Subjects walking under standard conditions at 4.8 km/hr (3 mph) showed no statistically significant effects of age, sex, and race. Length of stride and cadence, however, are also factors[55, 173] as demonstrated in figure 11.

TABLE 6.—*Relation of Speed and Body Weight to Energy Expenditure* [AFTER PASSMORE AND DURNIN[255]]

Speed of walking mph	Energy expenditure, kcal/min, for gross body weight of—						
	80 lb	100 lb	120 lb	140 lb	160 lb	180 lb	200 lb
2.0	1.9	2.2	2.6	2.9	3.2	3.5	3.8
2.5	2.3	2.7	3.1	3.5	3.8	4.2	4.5
3.0	2.7	3.1	3.6	4.0	4.4	4.8	5.3
3.5	3.1	3.6	4.2	4.6	5.0	5.4	6.1
4.0	3.5	4.1	4.7	5.2	5.8	6.4	7.0

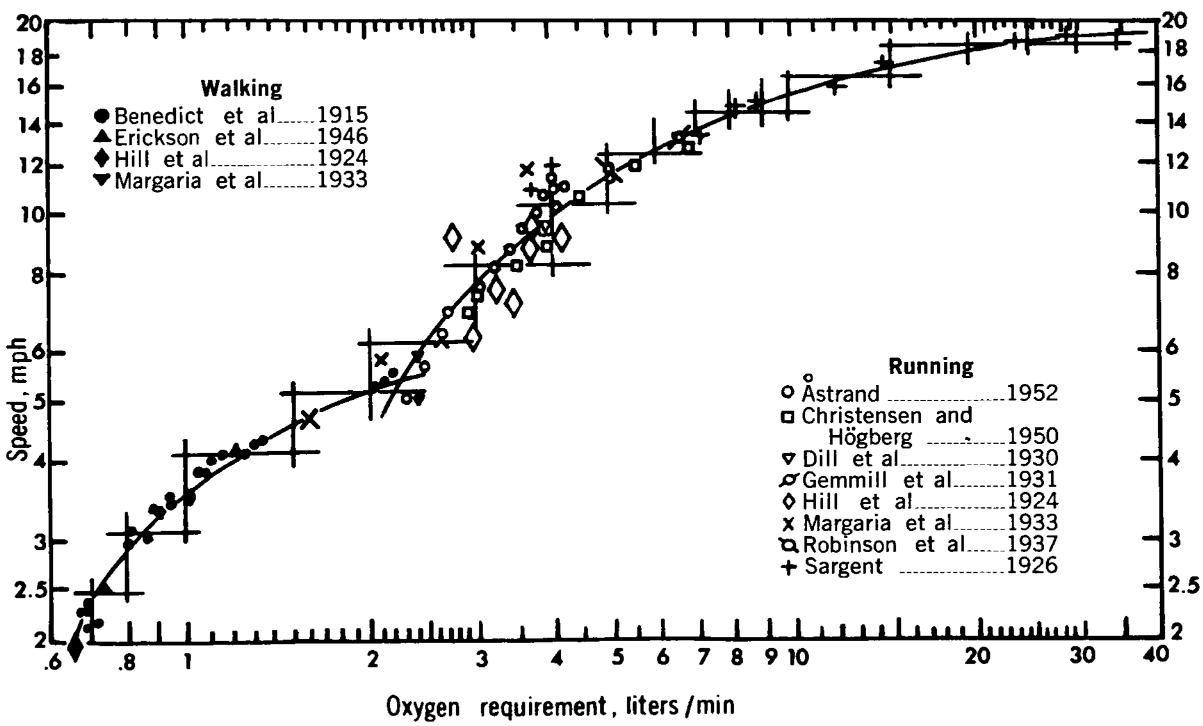


FIGURE 12.—Oxygen requirement at various speeds for men walking and running. To convert oxygen requirement to energy units: Multiply liters/min by 4.825 to get kcal/min, or by 19.3 to get Btu/min. (For other conversions, see fig. 9.) (AFTER DITTMER AND GREBE.[88])

An attempt to relate speed and weight to energy expenditure was made by Passmore and Durnin.[255] Table 6 presents such extrapolations, which are reportedly valid to an accuracy of ±15% for any individual walking at the steady pace for 1 hour or less. The results of these studies appear to be valid for walking on all hard, flat surfaces, indoors and outdoors, or on a treadmill. More recent studies of Malhotra et al.[224] and Buskirk and Taylor[62] define the energy penalty for excess body weight in other forms of exercise.

The energy expenditure of running is greatly dependent on the degree of training and efficiency of the subject. Figure 12 represents data points in the literature compiled in the WADC Handbook of Respiration.[88] As might be expected, the efficiency of energy utilization decreases markedly as the speed increases to very high levels.

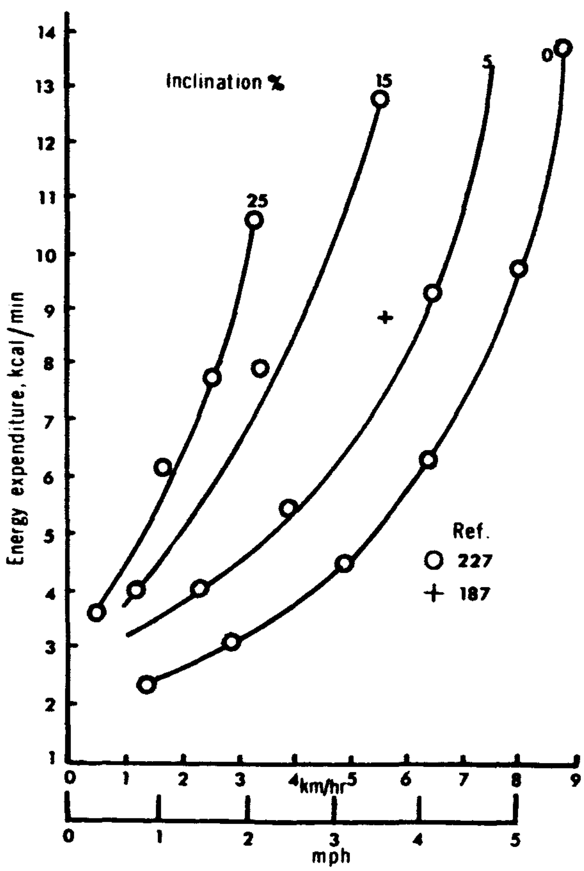


FIGURE 13.—Energy expenditure walking uphill at various speeds. Data from reference 227 are for a 70 kg subject; data point from reference 187 is an average figure for 16 subjects. (AFTER PASSMORE AND DURNIN.[255])

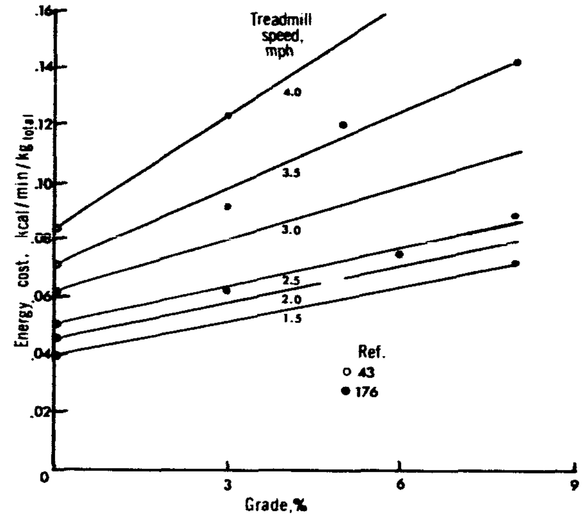


FIGURE 14.—Graph for estimating energy cost for rates of progression between 1.5 and 4.0 mph and grades up to 9% with loads up to 30 kg. (AFTER IAMPIETRO AND GOLDMAN.[176])

Walking on Inclines

Grade walking has also been the subject of many investigations.[43, 176, 187, 227] For the reasons outlined in Chapter 1, this form of exercise is quite pertinent to locomotion on the lunar landscape. Figure 13 reviews the effects of velocity and slope on energy requirements for a 70 kg subject. More recently, Iampietro and Goldman[176] have reviewed the grade and load factors in incline walking under different loads. Their own data (table 7) were combined with those of Bobbert[43] and plotted as a family of curves in figure 14. The energy cost in figure 14 is given as kcal/min/kg of total weight of subject plus load. The data plotted in figures 13 and 14 agree quite well. It is of interest to note that for grade walking over the ranges studied, the energy cost per unit weight is essentially the same whether the weight is of the body or the load. The pooled data from this study and the open literature were treated statistically and the following curve-fitting formula was evolved relating energy cost E for a 70 kg subject in kcal/min to progression rate V, load L, and grade G over the ranges $V = 1.5$ to 4.5 mph, $L = 0$ to 30 kg, and $G = 0$ to 9%.

$$E = 4.3 + (1.1V - 0.22^2) + (-6.3G + 8.2GV - 0.5GV^2 + 3.6G^2V^2) + (4.06LG - 1.77LGV - 0.003LV^2 + 0.24LGV^2 - 0.06LG^2V^2) \quad (9)$$

Variations in parameters such as stature, stride, physical condition, and skill at load adjustment all influence the energy cost for progression up smooth slopes. An example of the critical nature of the load carriage may be seen in the classical study of Bedale in 1924.[27] She herself, weight 56 kg, acted as subject and

TABLE 7.—*Energy Expenditure as a Function of Rate of Progression, Load Carried, and Grade.* [AFTER IAMPIETRO AND GOLDMAN.[176]]

Grade, %	Load, kg	kcal/min/kg subject wt. without load (a)	kcal/min/kg total wt. (b)	Mean kcal/min/kg total wt.	Standard error
Speed = 1.5 mph					
9	10	0.088	0.077	0.073	±0.007
	20	.091	.073		
	30	.096	.070		
Speed = 2.5 mph					
3	10	0.071	0.063	0.063	±0.007
	20	.078	.063		
	30	.088	.064		
6	10	0.084	0.074	0.076	±0.004
	20	.093	.075		
	30	.107	.077		
9	10	0.106	0.093	0.090	±0.004
	20	.114	.090		
	30	.121	.087		
Speed = 3.5 mph					
3	10	0.103	0.091	0.092	±0.006
	20	.116	.094		
	30	.128	.091		
6	10	0.136	0.120	0.121	±0.008
	20	.160	.125		
	30	.166	.119		
9	10	0.165	0.145	0.144	±0.014
	20	.182	.143		
Speed = 4.0 mph					
3	10	0.142	0.125	0.124	±0.017
	20	.148	.123		

[a] The 5-subject mean value of: $\dfrac{\text{Individual calculated energy cost (kcal/min)}}{\text{Individual subject dressed weight}}$

[b] The 5-subject mean value of: $\dfrac{\text{Individual calculated energy cost (kcal/min)}}{\text{Individual subject dressed weight + load}}$

measured energy expenditure while walking 100 meters carrying loads several different ways at 4.5 km/hr. Figure 15 illustrates three of the carrying parameters. Intermediary values were obtained when the load was carried on trays, on the head, and over the shoulders. The equivalence of Iampietro and Goldman's [176] load weight to body weight in grade walking would suggest that the packboard loading of subjects was probably close to optimum in load-carrying design.

Some German studies on the effect of extreme loads and slope on energy expenditure may be seen in table 8. The data compare favorably with those of Iampietro and Goldman.[176]

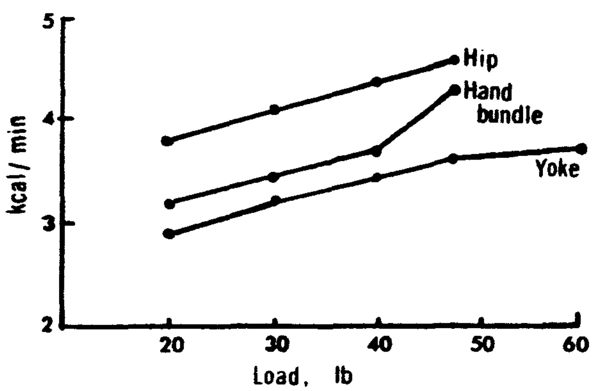


FIGURE 15.—Energy expenditure when carrying loads in various ways. (AFTER PASSMORE AND DURNIN,[255] DATA FROM BEDALE.[27])

TABLE 8.—*Energy Expenditure When Walking With Load at 1.5 mph on Firm Flat 10% Grade.* [AFTER ATZLER AND HERBST [12] AND GLASOW AND MÜLLER [134]]

Load		Energy expenditure			
lb	kg	kcal/hr	kcal/min	Btu/hr	Btu/min
0	0	500	8.3	2,000	33
22	10	550	9.2	2,200	37
44	20	630	10.5	2,500	42
66	30	730	12.2	2,900	48
88	40	830	13.9	3,300	55
110	50	950	15.8	3,800	63

Walking on Different Surfaces

From the discussion of the potential lunar surface in Chapter 1, it would appear that firm, even surfaces may be the exception rather than the rule in lunar exploration. It would, therefore, appear worthwhile to compare the metabolic costs of walking on rough, uneven terrain with those for the smooth, firm terrain recorded above. The difference between treadmill and road walking has been discussed by Daniels et al.,[80] who reported that the energy expenditures of young adult males walking at 3.5 mph (5.6 km/hr) were consistently about 18% lower on the treadmill than on asphalt roads or cinder paths. The recent work of Ralston suggests that there is little difference between treadmill and floor walking and that at speeds of 2.9 to 5.6 km/hr the motor contributed little to the energy of walking.[269]

The data of Glasow and Müller[134] for varied rough terrain are presented in the first part of table 9. A snowy terrain which simulates possible porous dust layers on the lunar surface presents an even more severe metabolic load. The differences between energy requirements for walking on a hard snow and a hard-surface road are also seen in table 9. The energies for soft snow cannot be so easily compared because of the 20 kg load being borne. The soft-snow figures may, however, be compared with the data of figure 14. If one assumes an 83 kg subject with a 20 kg load, the total load is 103 kg. When walking on a flat treadmill at 2.5 mi/hr, figure 14 predicts it should require $0.05 \times 103 = 5.15$ kcal/min. The value for soft snow in table 9 is 20.2 kcal/min, or almost 4 times as much. Of course, there is about a 9% increase in energy cost due to the encumbrance of arctic clothing,[329] but the general magnitude of energy difference is apparent. The studies by Milan [234] in the Antarctic of men walking in heavy winter gear are less quantitative in that no velocities are given. The values in table 10 are somewhat lower than the comparable figures of table 9 for snowy terrain. Depth and consistency of snow are, of course, critical factors in energy costs and may be different in the two studies.

The metabolic cost of sled pulling is another pertinent parameter that is worth evaluating. The U.S. Army Quartermaster Research and Development Center at Natick, Mass.,[329] has studied soldiers dressed in cotton fatigue uniforms and combat boots, walking on a treadmill while a rearward 17.5 lb pull was imposed on the subject to simulate sled pulling. The energy expenditures at a temperature of 70° F are recorded in table 11.

TABLE 9.—*Energy Cost of Progression for Adult Males* [ADAPTED FROM DITTMER AND GREBE [88]]

Activity		Subjects			Speed		Energy expenditure		O_2 requirement, liters/min (b)
		No.	Wt, kg (a)	Remarks	mi/hr	km/hr	kcal/min	Btu/min	
Walking, level, on:									
Hard-surface road		2	68–69	Carrying 9 kg clothing and apparatus	3.5	5.5	5.6	22.4	1.13
Grass-covered road					3.5	5.6	6.3	25.2	1.28
Furrow in field					3.4	5.4	7.0	28.0	1.43
Harvested field					3.3	5.2	6.9	27.6	1.41
Plowed field					3.3	5.3	7.7	30.8	1.57
Harrowed field					3.2	5.1	10.0	40.0	2.05
Hard snow		1	83		3.8	6.0	11.9	47.6	2.29
					5.7	9.1	15.8	63.2	3.22
Soft snow		1	83	Carrying 20-kg load	2.5	4.0	20.2	80.4	4.13
Walking, grade, uphill	2.7%	2	70	Soldiers	3.5	5.6	6.1	24.4	(1.23)
	5.0%	1	70	Trained individual	2.0	3.2	4.1	16.4	(0.83)
	5.0%	1	70	Trained individual	2.5	4.0	4.8	19.2	(0.97)
	5.5%	1	70	Soldier	3.5	5.6	7.5	30.0	(1.50)
	6.2%	2	70	Soldiers	3.5	5.6	7.8	31.2	(1.56)
	7.3%	2	70	Laboratory workers	3.5	5.6	8.6	34.4	(1.73)
	8.3%	1	70	Soldier	3.5	5.6	9.3	37.2	(1.87)
	8.6%	2	70	Laboratory workers	2.4	3.8	7.2	28.8	(1.43)
	8.6%	64	70	1 marathon runner, 23 sharecroppers, 40 trained individuals	3.5	5.6	9.3	37.2	(1.87)
	9.0%	2	70	Soldiers	3.5	5.6	9.3	37.2	(1.87)
	10.0%	7	70	Civilian public service workers	3.5	5.6	9.7	38.8	(1.93)
	11.8%	2	70	Soldiers	3.5	5.6	11.0	44.0	(2.20)
	14.4%	2	70	Soldiers	3.5	5.6	12.3	49.2	(2.47)
Walking, grade, treadmill, uphill	0%	2	70–79		2.6	4.2	3.9–4.4	15.6–17.6	0.80–0.90
	5.0%						5.4–5.9	21.6–23.6	1.10–1.20
	10.0%						7.4–7.8	29.6–31.2	1.51–1.60
	15.0%						9.7–10.3	38.8–41.2	1.98–2.10
	20.0%						12.2–13.0	48.8–52.0	2.48–2.65
	25.0%						14.7–15.8	58.8–63.2	3.00–3.23
Walking, grade, treadmill, downhill	0%	2	70–79		2.6	4.2	3.9–4.4	15.6–17.6	0.80–0.90
	5.0%						3.4–3.7	13.6–14.8	0.70–0.76
	10.0%						3.3–3.6	13.2–14.4	0.68–0.73
	15.0%						3.7–3.8	14.8–15.2	0.75–0.77
	20.0%						4.2–4.3	16.8–17.2	0.85–0.88
	25.0%						4.8–4.9	19.2–19.6	0.97–1.00

[a] Values for all subjects listed as weighing 70 kg are proportional calculations from values for subjects of other weights.

[b] Values in parentheses are calculations, assuming 1 liter of oxygen is equivalent to 5 kcal. The oxygen requirement per minute for a given rate of energy expenditure may exceed the oxygen uptake during any given minute if an oxygen debt is being accumulated, resulting in very high values for level running and swimming.

TABLE 10.—*Energy Expenditure in the Antarctic (Three Subjects)* [AFTER MILAN.[234]]

Age	Wt, kg	Surface area	Activity	kcal/hr/m²	kcal/min
33	70	1.78 m²	Walking, moderate pace, hard snow surface	147.5	4.4
			Walking, moderate pace, 6 in. new snow	192.7	5.7
			Walking up 10% grade, hard snow, moderate pace	165.0	4.9
			Walking down 10% grade, hard snow, moderate pace	163.8	4.8
33	75	1.94 m²	Standing in cold	87.4	2.8
				85.8	2.8
			Walking slowly, hard packed snow	150.9	4.9
			Walking, brisk pace, up 10% grade	213.2	6.3
				244.9	7.9
19	73.6	1.92 m²	Walking, level terrain, hard packed snow, stopping occasionally	129.7	4.1
				119.8	3.8
				93.8	3.0
				110.7	3.5
				153.7	4.9
			Walking, slow pace, subject warm	130.3	4.2
				130.2	4.2
			Walking up 10% grade, brisk pace	192.0	6.1
				218.2	7.0

TABLE 11.—*Metabolic Cost of Sled Pulling at Temperature of 70° F by Male Subjects Weighing 70 kg* [AFTER VANDERBIE [329]]

Activity	kcal/m²/hr		kcal/m²/200 yd		Pulse rate	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Walking 3½ mph	182	±11.5	5.89	±0.37	113	±5.1
Walking 3½ mph with 44 lb backload	214	±9.9	6.95	±0.32	124	±8.4
Simulated sled pull at 2½ mph	268	±16.0	12.16	±0.73	136	±14.8

These are for men not preacclimatized to arctic conditions. After a winter at Ft. Churchill, Manitoba, subjects repeated the studies and found an increase in efficiency of sled pulling at 2½ mph of only 6.8%, which is statistically significant at the 5% confidence level. No change in efficiency was noted at 3½ mph. An exercise of approximately 1,290 ft-lb/m²/min, causing a pulse of 125 beats a minute, can be continued for 5 hours, and that external work at the rate of 2,500 ft-lb/m²/min, causing a pulse rate of 150 beats per minute, can be continued for only 2 hours. Simulated sled pulling involves external work at the rate of about 2,100 ft-lb/m²/min, and it is estimated that this exercise could be maintained for 3 to 4 hours at the most, based on consideration of energy output and not on local muscle fatigue.

It can be seen that a relatively posterior pull can cause a very marked increase in energy cost. When the subjects pulled the weight of 17.5 lb, the metabolic cost of walking increased 80% compared with walking on the treadmill with no load. The high energy cost (268 kcal/m²/hr) and physiological strain of pulling against a rearward drag of 17.5 pounds is not surprising in view of the leverages involved. The body must be rocked forward against resistance from a fulcrum at the ankle.

The energy expenditure required for sled pulling under actual subarctic conditions at Ft. Churchill has been determined by Vaughan and Daniels.[330] They studied the relationship between drag and energy expenditure under a variety of sled-pulling conditions. Under the most difficult snow conditions, actual energy expenditure rates of over 500 kcal/m²/hr were recorded. The general relationship found was expressed by the formula

$$E = 12.93 + 0.02D + 0.0119D^2 \qquad (10)$$

where D is the average drag in pounds and E is in kcal/m²/200 yards. The predicted value for a mean drag of 17.5 pounds is 16.9 kcal/m²/200 yards. The mean value obtained for a drag of 17.5 pounds in the treadmill study, while wearing arctic ensembles, was found to be 12.16 kcal/m²/200 yards. Simulated sled pulling differs in at least one very important way from real sled pulling. On the treadmill the subjects walk over a smooth, nonskid rubber surface. In the field, such factors as snow depth, breakable crust, skids, and uneven walking surface are certainly responsible for part of the higher metabolic rates.

The metabolic cost of working in sand-dune terrain is also pertinent to the lunar problem. In 1953 Winsmann and Daniels [348] studied soldiers at Yuma, Ariz., walking at 2.5 mph for 30 minutes over courses of 1.25 miles. They wore jacket and trousers, lightweight ensemble with tropical boots. The mean maximum air temperatures were about 106° F. The ground surface temperatures ranged from a mean maximum of 134° F to a mean minimum of about 121° F. The energy expenditures for varying desert terrains under varying loads are seen in table 12. Increases in kcal/m²/hr according to the walking surfaces are tabulated below (from table 12):

	No. load	25 lb	30 lb	40 lb
From "level hard" to "down dunes"	41	49.3	54.6	65.3
From "down dunes" to "level sand"	26	37.6	32.5	38.1
From "level sand" to "up dunes"	70.7	90.6	71.7	76.5

The strain involved in walking on sand may be seen in table 13.

TABLE 12.—*Energy Cost of Walking and Carrying Pack Loads* [ADAPTED FROM WINSMANN AND DANIELS [348]]

[Speed = 2.5 mph; figures are averages of four trials on each of four subjects]

Activity	Mean kcal/m²/hr for —			
	No load	25 lb	30 lb	40 lb
Treadmill	131	144	–	150
Level sand surface	212.2	242.6	248.5	269.6
Level hard surface	145.2	155.7	161.4	166.2
Up sand-dune slopes (2.0–2.5 mph)	282.9	333.2	320.2	346.1
Down sand-dune slopes	186.2	205.0	216.0	231.5

Two-way variance analysis (no-load, 25 lb, 30 lb, and 40 lb)

Level sand surface
- At 5%, no-load energy cost differs from that of 25, 30, 40 lb
  - 25 lb energy cost differs from that of 40 lb
  - 30 lb energy cost differs from that of 40 lb
- Critical difference = 17.30

Level hard surface
- At 5%, no-load energy cost differs from that of 25, 30, 40 lb
  - 25 lb energy cost differs from that of 40 lb
- Critical difference = 8.7

Up sand-dune slopes
- At 5%, no-load energy cost differs from that of 25, 30, 40 lb
- Critical difference = 28.8

Down sand-dune slopes
- Not significantly different

Two-way variance analysis (4 surfaces)
- All surfaces differ from each other at 5%
- Critical difference = 25.2

TABLE 13.—*Strain of Walking on Sand with Various Packloads* [ADAPTED FROM WINSMANN AND DANIELS [348]]

Load	Mean final rectal temp., °F		Mean final pulse rate, beats/min	
	Level sand surface	Level hard surface	Level sand surface	Level hard surface
No load	100.8	100.0	126.9	101.4
25 lb	101.1	100.1	139.2	107.7
30 lb	101.3	100.2	146.3	113.3
40 lb	101.6	100.3	160.4	128.7

During the summer of 1954, additional measurements of energy expenditure were made on level sand and climbing up sand dunes at speeds of 2.1 to 2.7 mph. Because of the inherent difficulty in pacing subjects at an even speed up shifting sand, the metabolic rate information is expressed in terms of distance rather than time. The slope (base to top) was 11 to 12%. These results are shown in table 14.

The severity of physiological strain during load carrying in the dunes was indicated not only by the objective physiological data, but also by complaints by the subjects of moderate to severe chest pains localized over the heart area during various phases of this study. There was also noticeable hand swelling while climbing the sand dunes. This was evident in the men who walked without pack loads as well as those who carried them. In comparing the general condition and well-being of subjects engaged in heavy work in the Arctic (sled pulling at Ft. Churchill, Manitoba, Canada) with that of the subjects exposed to heavy work in the desert (load carrying at Yuma, Ariz.), it was observed that the men working in the Arctic had minimal respiratory distress after exercise, even with excessively high pulse rates. The men working in the desert, on the other hand, were often on the verge of exhaustion with relatively lower pulse rates. These results apparently reflect the different cardiovascular adjustments under conditions of different thermal acclimatization. This aspect of the problem will be covered in Chapter 5.

TABLE 14.—*Comparative Energy Expenditure While Walking on Level Sand and Climbing Sand Dunes, Carrying Various Packboard Loads* [ADAPTED FROM WINSMANN AND DANIELS [348]]

Activity	Mean kcal/m²/200 yd for—			
	No load	25 lb	30 lb	40 lb
Level sand	9.13	10.58	10.83	11.34
Up sand dunes (11–12% grade)	13.30	15.74	17.00	16.44

A striking similarity was noted between climbing over snow and climbing over sand. If men were climbing in tandem, the trail breaker had a difficult task. Climbing was easier for the first few men following directly behind. It again became difficult for the men at the rear, who had to climb over soft, loose sand or snow. The technique of placing the foot flat (toes and heel) while climbing, rather than going up on the toes, also appears to aid in reducing leg muscle fatigue on both sand and snow surfaces.

From these studies it would appear that the 40 lb pack represents the extreme upper load limit to carry in any sandy area on the desert. A rate of 2.5 mph and a continuous, nonstop, ½-hour walk also seem to be maximums for load carrying in this area. Anything beyond these limits results in excessive physical fatigue and stress, undoubtedly limits a soldier's fighting capacity, and perhaps could cause physical harm to the man. Carrying 40 pounds over sand dunes (slopes) for short distances was possible for men in good physical condition who were well acclimatized, but it was not recommended.

Climbing

Climbing mountains and negotiating very steep slopes are possibilities on the lunar surface. Table 9 indicates the rather severe progression in energy requirement as treadmill slopes up to 25% are negotiated. The 25% slope requirement of up to 15.8 kcal/min approaches the 20.2 kcal/min for walking on the level in soft snow with a 20 kg load. From table 9 it can also be seen that the negotiation of downhill slopes of 25% takes considerably more energy at 2.6 mph than does level treadmill walking at the same speed. The problem of negative work as muscles lengthen in exercise such as downhill cycling is adequately reviewed by Krendel [197] and will not be covered here.

More closely allied to the problem of mountain climbing are the studies of stair and ladder climbing. Table 15 reviews these studies. The stair values are combined motions of going up and down ordinary household stairs. Descending requires only one-third the energy of ascending.[255] Table 16 presents the data of Crowden [78] for London postmen on regular routes walking up and down stairs at the normal rate of 80 steps/min (40 up and 40 down) and walking between houses at a rate of 270 feet/min, or 3.1 mph.

TABLE 15.—*Energy Expenditure Going Up and Down Stairs and Climbing Ladders* [AFTER PASSMORE AND DURNIN [255]]

(a) Up and Down Stairs Without Load; Ht. of Each Stair, 15.2 cm

Ref.	Vertical speed, m/min	kcal/min for subject weighing—							
		59 kg	65 kg	69 kg	75 kg	79 kg	80 kg	83 kg	84 kg
256	14.8	6.0		8.4	9.8	9.7		9.3	
256	17.6	8.5		8.4	10.3	10.4		11.8	
94	Not stated		6.2				8.6		8.0

(b) Climbing Ladder;[207] Ht. of Each Step, 17 cm

Slope of ladder, deg	Vertical speed, m/min	Load, kg	kcal/min
50	9.1	0	7.7
		20	9.5
		50	14.3
70	11.1	0	9.0
		20	11.3
		50	17.1
90	11.9	0	11.5
		20	14.6
		50	25.4

Carrying heavy loads up stairs of greater than normal height simulates mountain climbing work. Table 17 represents typical data. Very severe loads of 60 lb at great vertical speeds can require more than 30 kcal/min. Climbing of ladders at severe slopes (table 16) also simulates quite closely the 600 kcal/hr reported for mountain climbing (p. 177 of ref. 335b). Addition of loads up to 50 kg in vertical ladder climbs gives extreme energy requirements of 25 kcal/min. Such severe conditions could possibly be met on the lunar surface in mountainous regions or during emergency egress from fissures or open-topped cavernous vesicles on lava plains.

TABLE 16.—*Energy Expenditure by Postmen Climbing Stairs at Usual Pace (four subjects)* [AFTER PASSMORE AND DURNIN [255]]

Age	Wt., kg	Postal load kg	Energy cost, kcal/min
56	82	11	9.8
46	85	16	11.5
27	68	16	9.8
25	77	16	13.8

TABLE 17.—*Energy Expenditure Carrying Loads Upstairs (three subjects)* [AFTER PASSMORE AND DURNIN [255]]

Ref.	Wt. kg	Height of step, cm	Vertical speed, m/min	Load carried, kg	Energy cost, kcal/min
254	63	15.2	8.2	8	8.0
				23	10.4
				38	14.2
254	77	15.2	8.2	8	9.0
				23	10.7
				38	13.2
183	65	17.2	17.2	10	16.2
				20	19.5
				40	25.2
				60	30.7

Construction Work

Since the possibility of construction work on the lunar surface will eventually be a problem, it appears pertinent to review briefly the typical energy requirements. Table 18 presents the values for males weighing 60 to 70 kg, as summarized by Passmore and Durnin,[255] for tasks simulating potential lunar work problems. Table 19 outlines energy requirements for typical arm work.

TABLE 18.—*Energy Expenditure in the Building Industry* [AFTER PASSMORE AND DURNIN[255]]

Subject	Wt., kg	Activity	Energy cost, kcal/min
		Making a wall with bricks and mortar at normal rates	4.0
		Mixing cement	4.7
		Miscellaneous work (carrying bricks, cement, or tools)	3.6
		Shaping stones with stonemason's hammer	3.8
		Preparing wooden straps for plastering	3.1
		Plastering walls	4.1
		Light work in laying stones or bricks	3.4
Av. of 2		Making road, preparing ground and laying blocks of flint	4.0
Av. of 2		Making road, beating blocks into ground with heavy wooden block weighing 20–28 kg:	
		One man beating alone	6.7
		Two men beating alternately	5.8
Age 35	62	Measuring wood	2.4
Age 35	62	Machine sawing	2.4
Age 35	62	Measuring and sawing	3.5
Age 35	62	Joining floorboards	4.4
Age 35	62	Miscellaneous work	4.5
Age 31	65	Chiseling	5.7
Age 31	65	Sawing softwood	6.3
Age 35	62	Drilling hardwood	7.0
Age 31	65	Sawing hardwood	7.5
Age 31	65	Planing softwood	8.1
Age 31	65	Planing hardwood	9.1
		Shoveling 8-kg load distance of 1 m:	
		Less than 1 m lift, 12 throws/min	7.5
		From 1–2 m lift, 12 throws/min	9.5
		Shoveling 8-kg load distance of 2 m:	
		Less than 1 m lift, 10 throws/min	8.5
		From 1–2 m lift, 10 throws/min	10.5
		Digging trenches, clay soil	8.5
		Shoveling 8-kg load distance of 1 m:	
		0.5 m lift, sand, 12 throws/min	5.4
		0.5 m lift, gravel, 12 throws/min	7.2
		1.0 m lift, sand, 12 throws/min	6.0
		1.0 m lift, gravel, 12 throws/min	8.4
		1.5 m lift, sand, 10 throws/min	6.0
		1.5 m lift, gravel, 10 throws/min	8.0
		Shoveling	6.0
		Shoveling	6.8
		Hewing with pick	7.0
		Pushing wheelbarrow with 100 kg load	5.0
		Pushing wheelbarrow at 4.5 km/hr on fairly smooth surface:	
		With 57 kg load	5.0
		With 150 kg load	7.0

Maximum Sustained Work Capacity

In emergency situations, the maximum sustained work capacity of men is of importance. Figure 16, compiled by Webb Associates (p. 182 of ref. 335b) from several sources,[1, 9, 20, 32, 275] illustrates that the maximum measurable work which men can sustain until exhausted is greatest for periods of less than 1 minute. When the oxygen demand can exceed the intake of oxygen, an oxygen debt is incurred. The problems of determining the efficiency of repayment of this debt have been reviewed by Lukin and Ralston.[216] Figure 16 has rather special data in that the

TABLE 19.—*Energy Expenditure Working With an Axe* [AFTER PASSMORE AND DURNIN [255]]
[*Subject: Age 23, wt. 82 kg*]

Wt. of axe, kg	Perpendicular blows		Horizontal blows	
	Speed, blows/min	Energy cost, kcal/min	Speed, blows/min	Energy cost, kcal/min
0.65	36	11.4	34	12.0
1.25	34	11.9	34	13.2
2.00	33	13.0	33	12.3
1.25	19	6.9		
1.25	35	11.0		
1.25	51	24.1		

kind of work is chosen to yield highest power for a given metabolic rate; hence the efficiency is 20%. Running, rowing, cycling, and cranking are the favored methods, with cycling and cranking combined showing the best efficiency. Physical conditioning is of the greatest importance, as is evident from the difference in the two curves, where, incidentally, even the "healthy men" are subjects who are young, physically active, and accustomed to the work used in the tests. Note the near plateau for the period from 5 minutes to 1 hour, showing that a superb athlete can sustain 0.5 horsepower for these times. Data beyond 1 hour are sparse, and the maximum level that can be sustained for 4 to 8 hours is not precisely known. It must be emphasized that these curves represent the very maximum levels for the most select individuals and are far above what even the average astronaut would probably be able to accomplish. The curves should, therefore, be used only as extreme upper limits of endurance.

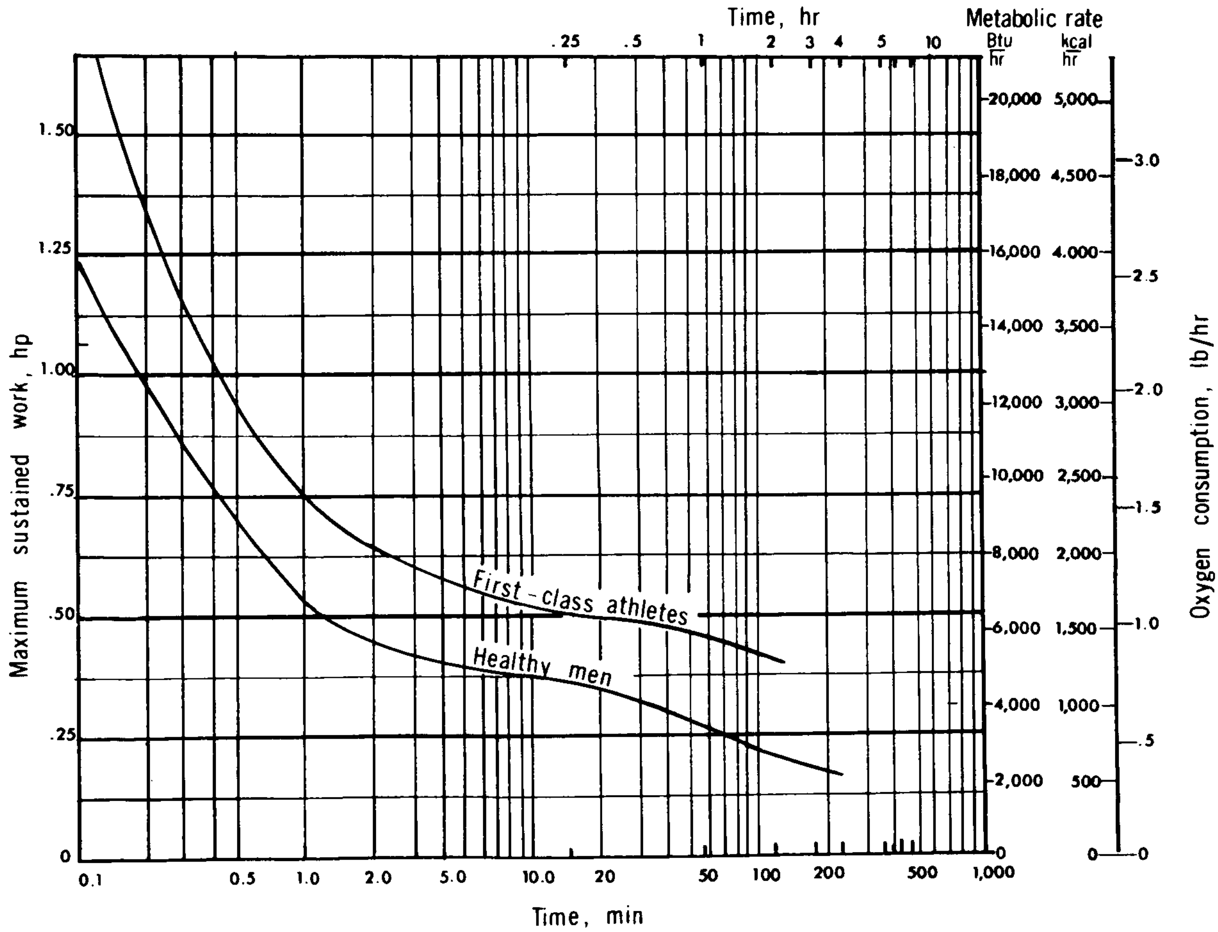


FIGURE 16.—Maximum sustained work capacity of men. (AFTER WEBB ASSOCIATES.[335b])

The problem of peak energy output or oxygen uptake has been a subject of interest to physiologists for many decades. It appears appropriate to discuss in brief the critical parameters that determine the energy maximum. The work of P. -O. Åstrand [9] and I. Åstrand [8] has done much to clarify the effects of sex and age on maximum work capacity. Between the ages of 20 and 35 the female population appears to have only 3/4 the maximum oxygen uptake of the males on a body-weight basis. The studies of I. Åstrand suggest that for male subjects, maximum aerobic work capacity decreases from an average of 3.0 to 2.2 liters/min from ages 35 to 63, or by a factor of 26% (21% when calculated per kg body weight). That of females decreases from 2.23 to 1.85, or by 17%. These decrements are of value in predicting the relative work loads that older scientists may be able to undertake in future lunar missions. Individual variations due to training and general health [10] are, of course, major factors determining these maxima. One cannot convert these oxygen consumptions directly to energy requirements since the anaerobic components of these work outputs are not clearly defined. Figure 17 presents a summary of the aging data for males, showing the variations expected in the athlete subjects of P. -O. Åstrand [9] and Robinson [275] and the more general population of Valentin et al.[328]

Some typical maximum oxygen uptakes of the pilot population are reported in the treadmill study of Naval Air Cadets by Slonim et al.[302] The mean peak was 4.05 liters/min with a standard deviation of 0.39 and a range of 3.22 to 5.17. These values agree well with Åstrand's values for gymnastic students.[9] The maximum oxygen uptake of the general Air Force population is recorded by Balke.[17, 19] Figure 18 presents these peak oxygen consumptions as found in a treadmill test at 3.4 mph with slopes increasing by 1% each minute. The performance rating is arbitrary. These values define upper limits of aerobic capacity to be expected from a select and average population of military personnel.

Additional Factors in Energy Utilization

The variations in work capacity brought on by multitudes of situational factors have been reviewed by Åstrand.[10] The more intimate day-to-day variations in the work capacity of lumbermen have been described by Lundgren.[217] The specific physiological effects of training have also been well covered by Åstrand.[10] Such factors as the decreased basal metabolic rate at rest, slower pulse at rest and during exercise, increased heart volume, increased muscular mass, increased vascularization and glycogen deposition in muscles, slight increase in blood volume, and decreased lactic acid level after severe work

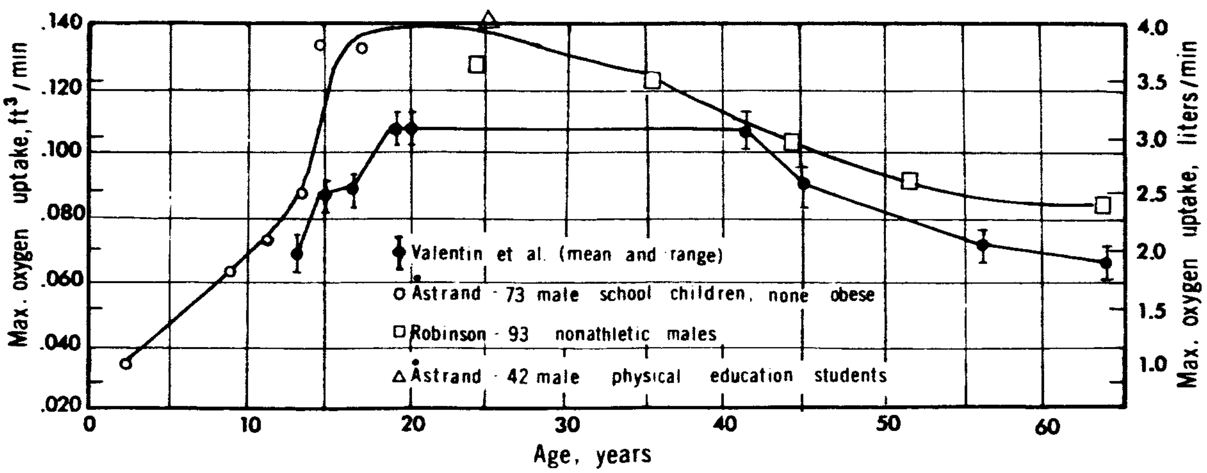


FIGURE 17.—Maximum oxygen uptake of males. (AFTER WEBB ASSOCIATES.[335b])

have been noted as resulting from training. No attempt will be made to review these factors in this section; however, the more pertinent effects of training on heat tolerance during exercise are discussed in greater detail in Chapter 5.

There are several factors modifying energy cost and maximum levels of exercise which may be somewhat afield from our immediate subject, but which are nevertheless pertinent to the lunar exploration problem. The first is the optimum dietary input for varied work loads. For short-term exercise such as ¼-mile runs or 100-yard swimming sprints, no consistent advantage in efficiency is apparent for diets high in carbohydrates or proteins and fats. For prolonged exercise, however, there is more evidence of the advantage of a high-carbohydrate diet. Christensen and Hansen [70] found that a subject could continue strenuous work three times as long on a high-carbohydrate as on a high-fat diet. Endurance was actually reduced when athletes were kept on high-fat diets for several days prior to endurance tests. From determination of respiratory quotients it was concluded that while trained athletes can utilize carbohydrate and fat indifferently during rest and light work, they increase the percentage of carbohydrate used when performing heavy work. Recent experiments in animals corroborate the increased utilization of C^{14} labeled fatty acids

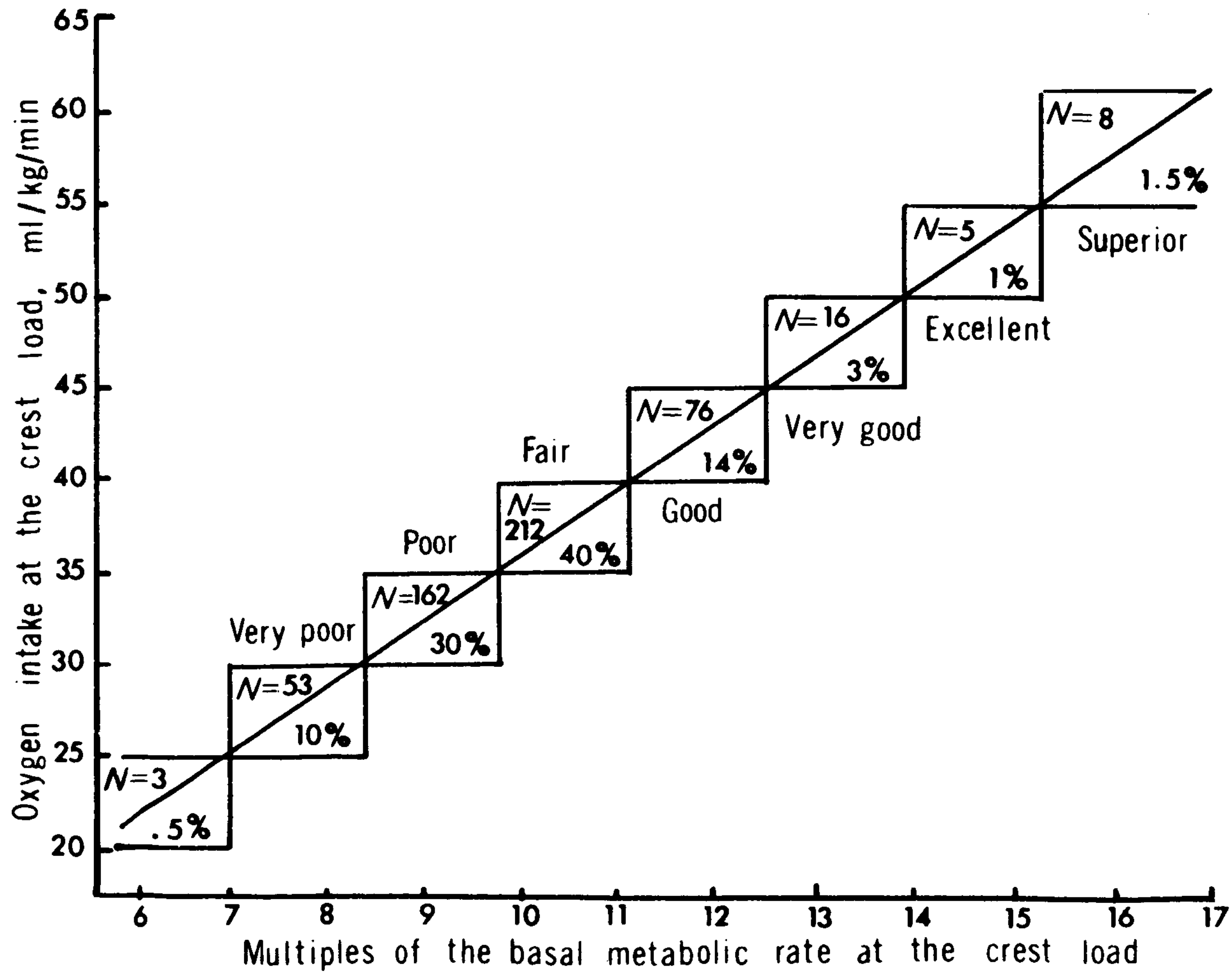


FIGURE 18.—The range of "physical fitness," determined by a standardized treadmill test of 535 male adults. (AFTER BALKE.[17])

during exercise,[81] but no comparison with carbohydrate utilization is recorded. That neither high- nor low-protein diets given over a period of 2 months affect the energy efficiency of exercise has been reported by Darling et al.[81] No other dietary factors, given in amounts that exceed the daily minimum requirements, appear to be unequivocally ergogenic in endurance exercise.[230]

The question of supplemental oxygen as an aid to exercise tolerance has been a matter of controversy for some time. Because pressures of oxygen both above and below sea-level equivalents are possible within the lunar space suit, a brief review of the oxygen question appears in order.

That a reduction in ambient oxygen pressure reduces work capacity is a well-studied phenomenon. The recent Himalayan Scientific and Mountaineering Expedition determined the graduated effects of oxygen depletion at different altitudes on men well acclimatized to these altitudes.[266] In reviewing the data, it must be kept in mind that these subjects were as well acclimatized to their environment as any group of subjects doing work at altitude would probably ever be.

Table 20 presents a summary of these studies. Control studies were carried out in London before the expedition. As on a previous Mt. Everest expedition,[265] higher levels of work intensity, oxygen intake, and ventilation were observed than in previous studies on nonmountaineers.[69, 175] The data for maximum 5-minute exercise are given in table 20, which shows that maximum work, maximum oxygen intake, maximum ventilation STPD, and maximum heart rate declined with increase in altitude. Maximum ventilation BTPS, on the other hand, was higher at altitude than at sea level, except at the highest camp. There was no significant difference in the values obtained at heights between 15,000 and 21,000 ft (4,600 and 6,400 m). One obvious factor affecting ventilation at altitude is the reduced work of breathing air of low density. In spite of this reduction, the ventilation BTPS fell at 24,400 ft. This result may be due to the hypoxia of respiratory muscles or a failure of subjects to exert maximum effort.

It appears that exercise at 20,000 ft (6,090 m) and above is halted by factors other than those operating at sea level. Subjectively, the overwhelming sensation which brings work to a close is breathlessness. Very high ventilation rates of about 200 liters/min BTPS—in fact, values approaching the resting 15-second maximum voluntary ventilation (MVV test) —were sometimes observed just before the breaking point at 21,000 ft (6,400 m) on Mt. Everest[265] and again on the 1960-61 expedition. Subjects performing the MVV test on Mt. Everest complained of respiratory fatigue and could not keep up maximum ventilation much longer than the 15 seconds

TABLE 20.—*Maximum Ventilation, Oxygen Intake, and Heart Rate During Ergometer Exercise at Various Altitudes* [AFTER PUGH[266]]

Altitude, ft	Barometric pressure, mm Hg	No. of subjects	Weight, kg	Ventilation, liters/min: STPD (a)	Ventilation, liters/min: BTPS (b)	Oxygen intake: STP, liters/min (c)	Oxygen intake: ml/kg/min	Heart rate, beats/min	Work rate, kg m/min
Sea level	750	6	72.7	97.9 ± 18.4	119.7 ± 22.6	3.40 ± 0.23	46.8 ± 3.2	192 ± 6	1,500–1,800
15,000	440	5	68	75.0 ± 7.3	164.8 ± 15.9	2.58 ± 0.12	37.9 ± 1.8	159 ± 17	1,500
19,000	380	4	65.5	61.4 ± 14.3	159.1 ± 37.2	2.14 ± 0.23	32.7 ± 3.5	144 ± 13	900–1,200
21,000	340	4	65.2	56.7 ± 8.6	168.8 ± 25.4	1.95 ± 0.11	29.6 ± 1.7	146 ± 11	900–1,050
24,400	300	2	67.5	35.2 ± 2.3	119.8 ± 7.7	1.40 ± 0.09	20.7 ± 1.3	135 ± 8	600

[a] STPD = Standard temperature and pressure, dry.
[b] BTPS = Body temperature and pressure, saturated with water.
[c] STP = Standard temperature and pressure.

required by the test. The conclusion was drawn that exercise at great altitude is limited primarily by fatigue of the respiratory muscles, and that extreme ventilation is the result of the low arterial oxygen tension—namely, 20 to 30 mm Hg at 1,200 kg m/min—secondary to the low alveolar oxygen. However, it is of interest to note that the ventilation equivalent (ratio of ventilation to oxygen used) was the same at 21,000 and 24,400 ft:

$$\frac{\text{Ventilation}}{\text{Oxygen intake}}=\underset{(21{,}000\text{ ft})}{\frac{169}{1.95}}=\underset{(24{,}400\text{ ft})}{\frac{120}{1.40}}=86 \qquad (11)$$

Generalized tissue hypoxia is, therefore, probably very much a limiting factor also at higher altitude.

As mentioned previously, these data are for athletes at the peak of altitude acclimatization. What about the work capacity of nonacclimatized athletes at high altitudes? Asmussen et al.[6] reported on the effect of reduced oxygen tensions on the maximum work capacity of such subjects. From these studies and others, Luft [215] concludes that at an altitude equivalent of 10,000 feet there is a 20% reduction in maximum work capacity, and at 13,000 feet, a 33% reduction. In Asmussen's study, maximum lactate concentrations were the same at the end of exercises at sea level and at an oxygen equivalent altitude. This suggests the same muscle lactate levels probably determine the maximum effort at sea level and at altitude. These data are probably more pertinent to the maximum work degradation of an unacclimatized astronaut suddenly faced with oxygen deprivation.

One other aspect of hypoxia is of interest in the operational sphere. It is common experience that acute exposure to moderate altitudes such as 15,000 to 16,000 feet for several hours is frequently followed by a feeling of drowsiness, headache, and a desire for rest. Balke [18] studied the effect of a previous 3½ hour exposure at 16,000 feet on several parameters of exercise tolerance on the progressive treadmill test described previously in the section "Maximum Sustained Work Capacity." Table 21 compares the performance of controls with that of previously hypoxic subjects in response to the progressive increase of treadmill slope of 1% per minute at 3.4 mph. There is a distinct, if not statistically significant, evidence of a measurable reduction in work capacity correlated with the subjective symptoms. These changes, however, are not significant enough to suggest routine abortion of high-work-load missions after accidental or emergency exposure to acute hypoxia of this degree.

TABLE 21.—*Effect of Previous Hypoxia on Maximum Work Capacity* [DATA FROM BALKE ET AL.[18]]

Parameter	Control	Previous hypoxia	Av. diff.	Standard deviation	P value
Av. maximal O_2 intake, ml/min	3,100	2,946	153.08	269	0.033
Optimal work capacity, m kg/min	1,091	1,054	36.92	75.18	0.06
Total test duration, min	32.8	31.0			
Time of maximal oxygen intake, min	32.0	30.5			

The augmentation of exercise tolerance at sea level by supplemental oxygen is still not a clear-cut picture. There have been several reports in the literature of the effects of oxygen on respiration and performance during heavy work. The most extensive of these was by Asmussen and Nielsen [7] who showed, among other things, that during moderately severe exercise on the bicycle ergometer the addition of oxygen to the inspired air resulted in a marked and sudden depression of respiration. To explain their findings they postulated that muscle working under partially anaerobic conditions liberated into the blood stream an unknown substance which stimulated the respiration and which was rapidly destroyed by high concentrations of oxygen. This was in addition to any effects which might be ascribed to the production of excess lactate.

More recently, Miller (cited by Bannister and Cunningham[20]) has reported, however, that he could detect no effect on any of the quantities which he measured when 100% oxygen was substituted for air for athletic and nonathletic subjects performing moderate and severe exercise on a treadmill.

In the most complete study of this point, Bannister and Cunningham[20] had two athletes and two nonathletic subjects run on a motor-driven treadmill up various gradients. The intensity of the work was adjusted so as to insure that each individual reached his breaking point between the seventh and tenth minute when he breathed atmospheric air. In other experiments he performed the same exercise while breathing 33, 66, or 100% oxygen. Pulmonary ventilation, alveolar P_{CO_2} and P_{O_2}, and blood lactate were measured frequently during each run. The time taken to reach a breaking point was also recorded. In all instances, addition of oxygen to the inspired air increased the time required to reach a breaking point. The performance was improved more by 66% and 100% than by 33% oxygen. With 66% oxygen three of the subjects did not reach a breaking point within 23 minutes, and the discomfort which they had experienced when breathing air was replaced by a feeling of positive well-being. In contrast, when breathing 100% oxygen they never felt elated, and all reached breaking points within 21 minutes. Oxygen reduced the pulmonary ventilation and the blood lactate response, and allowed the alveolar P_{CO_2} to rise to higher levels. While 33% oxygen had a smaller effect than 66% or 100% oxygen, no systematic difference could be detected between the effects of 66% and 100% oxygen on respiration. In another part of the experiment, two subjects exercised at a slightly lower intensity of work and sudden changes were made in the inspired gas mixtures, from air to 66% or 33% oxygen in the course of the runs. These changes were followed extremely rapidly by reductions in the pulmonary ventilation and increases in the alveolar P_{CO_2}. Subjective improvement occurred over the space of a few breaths. On switching back to air, the reverse changes in the pulmonary ventilation and the alveolar P_{CO_2} followed very rapidly. These effects were not observed during moderate exercise.

That oxygen at sea level was effective in increasing exercise tolerance in these experiments is quite evident, the studies of Miller notwithstanding. It was postulated by Bannister and Cunningham that the respiratory effects of inhaling high concentrations of oxygen were due to the abolition of an arterial anoxemia which was thought to be present when air was breathed during exercise of more than critical intensity. Relief of the anoxemia might exert its effects through the carotid and aortic chemoreceptors, or by improving cardiac function, or both. It was thought unnecessary to postulate the existence of an unknown respiratory stimulant liberated by muscles working under partially anaerobic conditions, though the possibility was not excluded. The actual cause of anoxemia in heavy exercise is still obscure. The rapid flow of blood through pulmonary capillaries may limit the time for diffusion across the pulmonary epithelium, or a pulmonary venous shunt may become effective under these severe exercise conditions.

Of interest is the fact that these experiments showed that the inhalation of 100% oxygen during severe exercise at sea level resulted in complete exhaustion within 12 to 21 minutes. In contrast, three of the subjects on 66% oxygen had not reached their breaking points when they stopped running after 23 minutes; the fourth reached his breaking point 2 minutes later than when he breathed 100% oxygen. There were no clear-cut differences between the pulmonary ventilations or the blood lactate and alveolar P_{CO_2} levels with 100% and 66% oxygen. A small difference in one direction with one subject was usually offset by a difference in the opposite direction with another.

The subjective effects were impressive. Three of the four subjects found the exercise much easier when breathing 66% oxygen. One subject noticed with surprise that he felt mentally elated when breathing 66% oxygen, but not when breathing 100% oxygen. The exercise was "incomparably easier" at this intensity than in any of the previous runs; breathing was effortless and he apparently stopped running more from boredom than from exhaustion. In the second series of experiments, when he ran for 24 minutes on 66% oxygen, he again noticed these effects, although he had completed a run to exhaustion on the previous day. Another subject felt breathless when on 100% oxygen, although the pulmonary ventilation was 19 liters/min less than when breathing air. With 66% oxygen his breathing was comfortable and he felt that he could continue to run indefinitely.

These experiments differ from others reported in the literature in showing that there is an optimum level for the alveolar oxygen tension in heavy exercise and that if this level is exceeded, performance suffers. The limits between which this optimum value lies have not been determined. It may be that the inhalation of about 50% would be sufficient to produce the benefit which resulted from 66% oxygen, and that the disadvantages which result from an excess do not become apparent until considerably more oxygen is added to the inspired air.

The reasons for this optimum value are obscure. At rest, adverse effects do not occur until pure oxygen has been breathed for many hours, unless the pressure is greatly increased.[69] With 100% oxygen the symptoms experienced by these subjects were generalized rather than local. This, together with the fact that a small excess of lactate accumulated in the blood, suggests that the working muscles were not responsible. There is no reason to think that the heart was adversely affected when pure oxygen was substituted for 66% oxygen. The load on the heart was reduced, since there was probably no increase in the oxygen consumption and the arterial blood was carrying nearly one extra volume percent of dissolved oxygen.

Irritation of the respiratory tract by the oxygen or from the dryness of the gas, inhaled as it was straight from storage cylinders, cannot be excluded. However, when 66% oxygen in nitrogen was supplied direct from cylinders it did not have this effect, and in any case not all the subjects complained of respiratory distress. The comments of three of the subjects suggested that the effect was nervous. When breathing 66% oxygen they felt an elation which was strikingly absent when breathing pure oxygen. The feeling of elation may have been due partly to the absence of the expected unpleasant sensations which normally accompany exercise of this severity and partly to the unexpected feeling of enhanced physical capability. However, the known factors which produce distress were not increased when pure oxygen was inspired, and yet the subjects felt depressed rather than elated. It was tentatively suggested that the depressant action of 100% oxygen as compared with 66% oxygen might be due to increased cerebral circulation resulting from the excess of circulating CO_2 and lactate.[191] Such an increase would nullify the protection from the deleterious effects of high-pressure oxygen afforded to the brain by the cerebral vasoconstriction which occurs at rest when pure oxygen is breathed.[186]

It would thus appear worthwhile to study the effects of elevating the PO_2 within space suits during emergency periods of high work load. The optimum level would be determined by the trade-off between the relief of fatigue and the deleterious effects of both cerebral oxygen toxicity and the increased resistance of joint movement within space suits due to elevated internal pressure. This latter point will be discussed in greater detail in Chapter 3.

EFFECT OF LUNAR SUBGRAVITY

Data have been presented on the energy requirements in varied earthly environments. It now appears appropriate to review the effects of subgravity conditions on locomotor and work activity.

The role of gravity in work loads has fascinated physiologists for many years. The effects of gravity are, of course, intimately related to the general laws of motion defining body dynamics. The first part of this review will, therefore, be devoted to the theoretical considerations of body dynamics with reference to gravity effects. Experimental data on the dynamics of human gait will then be presented. This will be followed by some theoretical calculations on the energy partition of gait phases. Data of the several energy studies in simulated subgravity environments will then be reviewed. Finally, some fruitful avenues for future work will be suggested.

The classical studies of Braune and Fischer,[50] Marey,[225] Amar,[4] and the Webers[336] and the review by Steindler[315] form the background for most of the analytic work in human mechanics and are the basis for the present discussion. No direct quotations from specific studies will be indicated except where controversial material is discussed. The subject matter will be developed from simple considerations to the more pertinent complexities. The importance of these considerations to later analyses of energy partition in subgravity will soon be evident.

Transformation of Rotary into Translational Movement

The motions of an inert body described by Newton's three laws of motion form the basis for all static and kinetic studies. According to the first Newtonian law, such a body remains at rest if resting, or persists in linear uniform motion if moving, as long as no external force is applied to it. Rest or uniform motion are thereby defined as passive states, any change of which requires an action of a definite force upon the body. Neither the velocity nor the direction of a moving body can be changed without the influence of such a force, and the tendency of the body not subject to a force to retain its passive state is known as inertia.

The second Newtonian law informs us about the quantitative value of this force. It states that when a force is applied to a resting body or a body in uniform linear motion, it will cause the body to move with a change in velocity, or impart to the body an acceleration which in direction and in degree is proportional to the amount of force and is inversely proportional to the mass of the body ($F=ma$). This mass of the body represents merely the sum total of all its material points. Therefore, it is a quantum and not a weight, and the unit of measurement used is the amount of mass points of distilled water contained in the space of 1 cubic centimeter at 4° C. This is a 1 gram mass.

The weight of a body is the expression of the gravitational force which applies to the mass of this body. Since g, the acceleration due to gravitation, is known to be approximately 980 cm/sec^2, or 32 ft/sec^2, for all terrestrial objects, and since the weight of the human body can be determined, the mass of the body can easily be calculated from the equation $W=mg$.

All kinetic calculations are ultimately directed toward ascertaining the muscular forces which move the body or parts of it. If we determine the gravitational force of a terrestrial body by weighing it, we simply put into practice the third law of Newton. This law stipulates that if a force meets with a resistance, a counterforce or reaction is created opposite in direction to the primary force, and furthermore that if both forces are not only opposite but also equal in size, they will neutralize each other so that the resultant force will be zero and the body will be in equilibrium as though no force at all were operating upon it. As a body is weighed on a scale the weight on the other half of the scale represents the resisting counterforce which, if adequate to balance the body, indicates its weight.

A law of statics states that any force applied to a body can be resolved into a translatory force and so-called couple of rotating forces, the latter being so arranged that the line connecting their points of application goes through the so-called center of gravity. This center of gravity represents the one mass point of the body which is so situated that the gravitational force for all other mass points of the body can be imagined to go through it. If the applying force goes through the center of gravity, then its rotatory moment must be zero and no rotation of the body about the center of gravity occurs. In this case the body is subject to a straight line movement in the direction of the force, all mass points describing parallel lines. This type of movement is translatory movement.

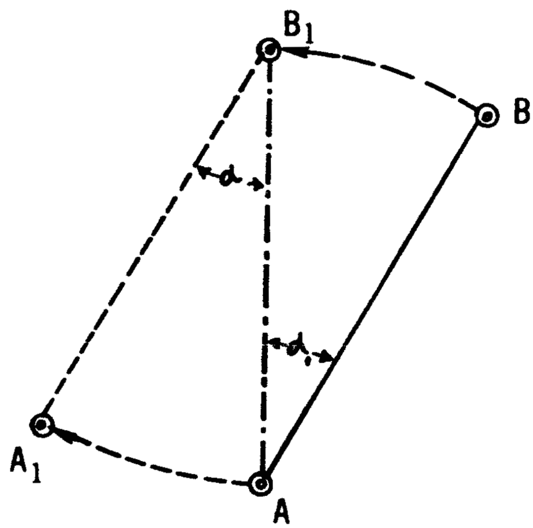
In the case of the human body, there is little passive equilibrium. Few, if any, of the articulations coincide with the line of gravity. Most of the joints have their centers at some appreciable distance away from the weight line, and rotatory forces are therefore active about practically all of the superimposed articulations. This means that equilibrium is only possible if muscle forces oppose and hold in check the rotational moments derived from rotatory components of the gravitational force. In other words, equilibrium maintained by the body in an upright standing position is an active and not a passive one, and rotatory muscle forces must be constantly engaged in opposing and neutralizing the gravitational rotatory forces. Thus energy is required to maintain an upright posture.

Both forward progression of the center of gravity and the movement of extremities involve the translation of rotatory body movements into linear translatory forms of motion. Figure 19 demonstrates how combinations of two or more rotatory motions can be arranged to result either in a translatory progression, if the angles are equal and opposite, or in the summation of the rotatory effect, flexory or extensory, if the angles are not opposite in direction. In the human gait the mechanism consists not only in periodic lengthening and shortening of the extremities but also in a periodic forward and backward swing. The axes for the lower extremity would be the hip joint, the knee joint, the ankle joint, and the contact point of the ball of the foot which rotates against the floor. The latter, in this scheme, is a fixed center of rotation of the system and it is so made by the weight of the body and the friction force produced by the weight. Only the existence of such a stable point of application makes possible the elongation of the standing extremity.

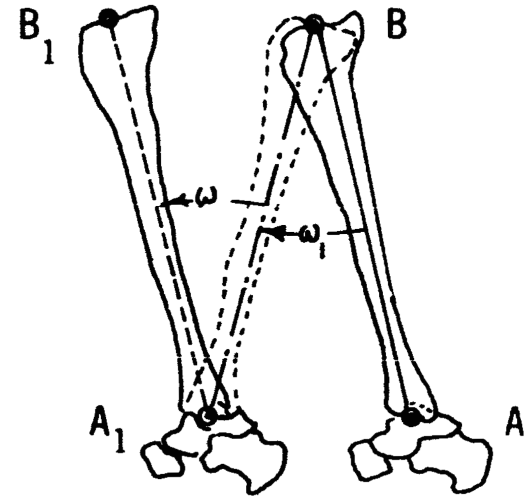
As this elongation is accomplished, a counter pressure is produced which will give the body an acceleration in its direction. If the leg is set perpendicularly to the ground, the counter pressure is created in a perpendicular direction and the acceleration imparted to the body is straight upward. But in locomotion the extremity is not planted perpendicularly but obliquely to the ground. The result is that upon elongation of the limb the acceleration imparted to the body is in the forward and upward directions. The friction force created by the downward pressure of the elongated extremity is essential for forward progression. With friction at a minimum, as for instance when walking on a highly polished surface or on ice, elongation of the limb (and progression) becomes extremely difficult.

In the next phase of the gait, elongation changes to shortening; in other words, all parts of the lower extremities are simultaneously brought into flexion. The point of the foot is brought toward the hip joint in a straight translatory direction by the summation of the rotatory movements in the different joints. The algebraic sum of all rotatory angles must be zero because the resultant effect is a translatory motion. However, the point of application of all the rotating forces is no longer the ground but the body, and the limb is drawn against the body as a fixed point. This shortened condition of the limb corresponds precisely to the position which preceded that of elongation, and all parts of the limb are now parallel to their positions at the former period of shortening. The difference from the first to the second analogous period of shortening is the step. Because the total result was a translatory movement, we can say that the sum total of all angles of rotation which have occurred, in both the elongating and shortening phases, is zero. Compared with the simpler problem of the rod which consists of one rotating link, as in figure 19, we are dealing here with the algebraic sum not of two single angles of rotation but of two sets of angles.

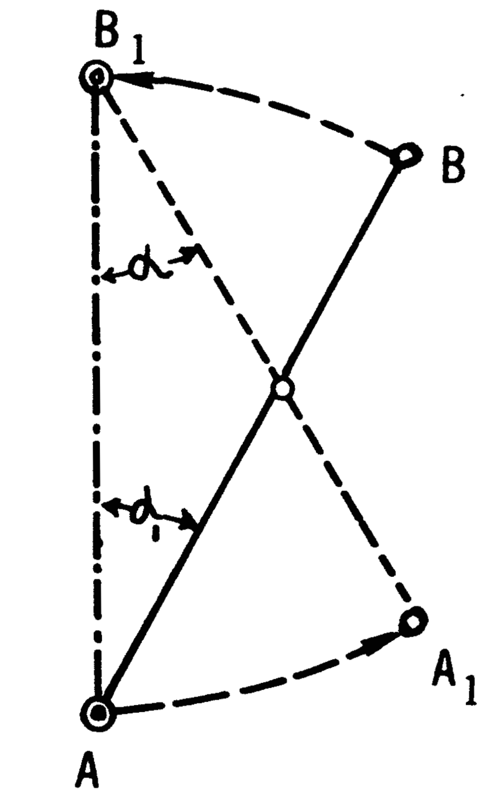
Between the two phases of elongation or the two phases of shortening, a forward or backward swing of the extremity has taken place. What happens in regard to the angles of rotation and their direction in the swinging movement of the leg? As the leg swings backward the hip is extended, the knee flexed, the foot plantar-flexed, and all rotations occur in the same direction (fig. 20). As the leg is swinging forward the hip is flexed, the knee is extended, and the foot is dorsiflexed; again all rotation occurs in the same direction. The effect of this summation is that the point of the foot describes not a translatory motion to or from the hip joint, but an angular motion about the hip joint (fig. 21). These are the basic rotations involved in the human gait. Details are discussed in the following paragraphs.



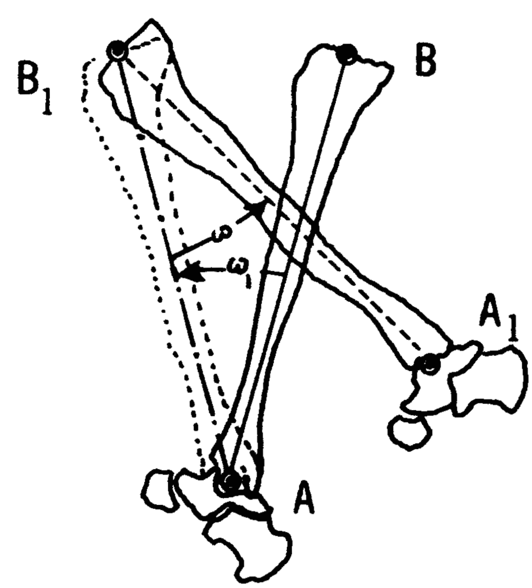
(a) Transformation of two rotatory motions (around A and B) into a translatory motion. $\alpha = -\alpha_1$; $\alpha + (-\alpha_1) = 0$.



(c) Application of theorem of part (a). Transformation of two rotatory motions (about ankle and knee) into a translatory forward motion of the leg. $\omega = -\omega_1$; $\omega + (-\omega_1) = 0$.



(b) Transformation of two rotatory motions (around A and B) into a summated rotatory motion. $\alpha \lesseqgtr \alpha_1$; $\alpha + \alpha_1 = S$ (summated angle).



(d) Application of theorem of part (b). Transformation of two rotatory motions (about ankle and knee) into a summated rotation. $\omega \lesseqgtr \omega_1$; $\omega + \omega_1 = \delta$ (summated angle).

FIGURE 19.—Conversion of rotatory to translational movement. (AFTER STEINDLER.[315])

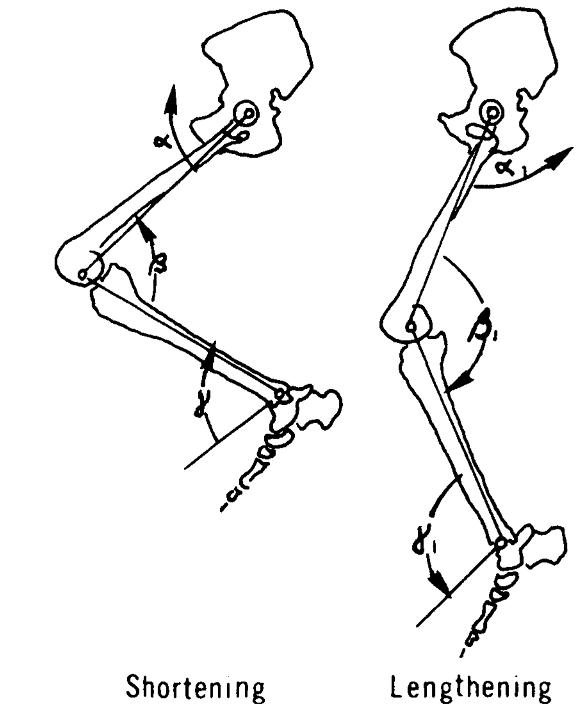


FIGURE 20.—Transformation of a number of rotatory motions into a translatory motion of the lower extremity. $\alpha+\beta+\gamma=0$. (AFTER STEINDLER.[315])

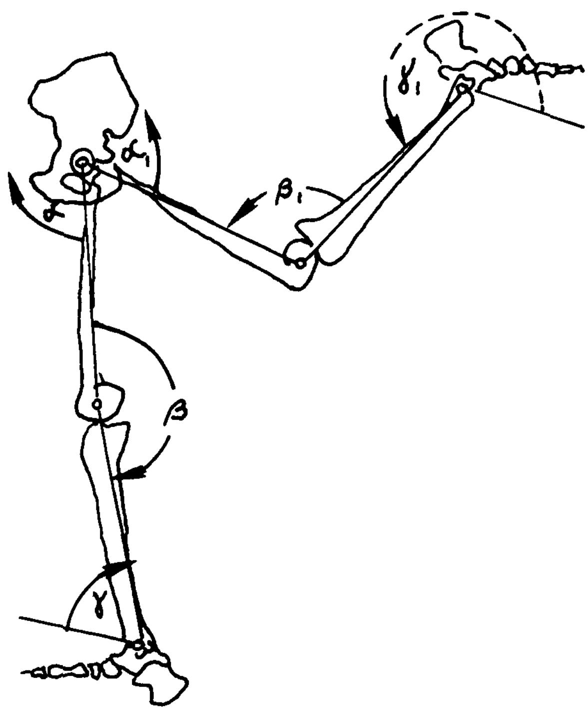


FIGURE 21.—Transformation of a number of rotatory motions into a summated rotation of the lower extremity (backward swing). $\alpha+\beta+\gamma=\delta$ (angle of summation). (AFTER STEINDLER.[315])

Energetics of Human Motion

This brief description of the basic mechanical principles of gait suggests immediately that the energetics can indeed be difficult to assess from first principles. It will, however, be worthwhile to consider both linear and rotatory energetics, since it is the rotatory motion which expends much of the energy of locomotion. These basic concepts can theoretically be used to calculate the energy required for any external work. While the general expression for velocity is the ratio of distance covered to time elapsed, or $v=d/t$, the special expressions for rotatory motion are $v=\omega r\pi/180t$ and $a=\omega r\pi/180t^2$, where r is radius, ω is angular velocity, t is time, and a is acceleration. Furthermore, according to the second Newtonian law, the force generally expressed by the product of mass and acceleration ($F=ma$) is, in rotatory terms, $F=m\omega r\pi/180t^2$. The moment of force about a point or about an axis perpendicular to it is the product of the magnitude of force and the perpendicular distance from the point or axis.

In human locomotion, gravitational forces play an almost universal role either in supporting or in counteracting the forces created by muscle contraction. Among other things, the latent energy which is stored in the supported body by the action of the gravitational force, and which can be appreciated by the fall of a weight when such support is released, plays a great part in the mechanism and plan of human locomotion. The work performed by the falling body constitutes an essential part of the locomotor scheme, a point which is illustrated particularly well in the human gait. This work performed by the falling body represents its "living force" or kinetic energy.

The work performed in falling is $W=wh$, where w is weight (or gravitational force) and h is height of fall. Since $w=mg$ (where g is acceleration), and the height of the fall has a definite relation to the time consumed in falling, namely, $h=gt^2/2$, the work performed in falling and the actual energy displayed and released by the fall is

$$W=wh=\frac{mg^2t^2}{2} \tag{12}$$

Since $gt = v$ (velocity), the general formula for the kinetic energy—that is, the energy displayed by the fall—is $mv^2/2$. This energy has ample application in all computations of human motion carried out under the effect of any accelerating force, as, for instance, under the force of gravity. If this were the only energy factor, all would be simple. In the human gait, however, this kinetic energy produced by the gravitational force calls for constant checks or, in other words, for the creation of counter forces by which kinetic energy is destroyed before it has spent itself in visible motion. Regulation or checking of kinetic energy plays almost a universal role in all forms of human motion and, as we shall see, complicates many of the analytic approaches to the energy of locomotion.

In dealing with physical bodies subject to the force of gravity the value of their masses must be ascertained, because upon this value the force is directly dependent ($F = ma$; $a = F/m$). The mass resists movement, and this body resistance is called inertia. The amount of mass is the measure of the body's resistance to linear, translatory motion. In human locomotion we are interested principally in the inertia which the body offers to rotatory motion. This resistance is also greater, the greater the mass. But it is likewise dependent upon the distance of the mass point from the center of motion. It can be shown that this resistance of a body to motion around a center is proportional to the mass and also proportional to the square of the distance r of all its mass points from the center of motion. Thus, for the inertia of a mass point:

$$I = mr^2 \tag{13}$$

For all mass points the integration would be $I = \Sigma mr^2$, which is a mathematical expression of the moment of inertia of a body relative to a point or an axis of rotation.

This inertia ($I = \Sigma mr^2$) represents the amount of resistance of a body to rotatory motion produced by a certain force. Because of the irregularity of the human form it is not easy to calculate the appropriate values for inertia, either for the body as a whole or for its parts. The problem has to be simplified. In order to determine the inertia for any body of geometrical form, a simplification of this formula is obtained by first choosing the center of gravity as the mass point representative of the sum of all mass points of the body subject to gravitational force. Then, since the different mass points of a rotating body must have different distances from their rotatory center, a theoretical average distance of all mass points from the center of rotation is introduced just as though in a solid body all mass points were equally spread over the surface of the cylinder, having thereby the same average distance from the axis. This average distance of all mass points is called the radius of gyration ρ. Its value can be determined by calculation for any body of regular formation.

The formula for inertia is thus expressed by the equation $I = m\rho^2$. It represents the amount of resistance of the body to rotation about an axis going through the center of gravity. As will be seen later, ρ varies with the angle the rotation axis forms with the length axis of the body. The moment of rotation or the rotatory effect M of any force is the product of the force and the distance of its point of application from the center (Fd). The angular acceleration of the body moving about a fixed point or axis is directly proportional to this rotatory moment. It is also inversely proportional to the moments of inertia ($I = m\rho^2$). Therefore, the acceleration equals the rotatory moment divided by the inertia, $a = M/I$. It is clear that the rotatory moment and the moment of inertia in rotatory motion bear the same relation to each other that force and mass bear in purely translatory movement ($a = F/m$).

Amar [4] has calculated the moments of inertia for the different portions of the body presented in table 22. More recent material on centers of gravity and moments can be found in references 23, 321, and 345. The inertia values apply to rotation about an axis going through the center of gravity and perpendicular to the longitudinal axis of the limb. The moments of rotation have been calculated by Fischer [115] and others for different muscles and muscle groups in the various joints of the body. These rotation moments (force times perpendicular distance from center of rotation) must be calculated both for the movement of the proximal limb against the distal (for instance, trunk against thigh) and, vice versa, for movement of the distal limb against the proximal (thigh against trunk). In addition to this, the rotational moment changes constantly with the position of the joint. For example, table 23 gives Fischer's computation of the rotation moments of the iliacus muscle with respect to trunk (M_1) and thigh (M_2) at different positions of the joint.

One more qualification is necessary. The human limb does not move about axes going through the center of gravity; the axes of rotation go through joint points at the end of the limb. The axes of the movements are, therefore, parallel to and some distance removed from an axis which goes through the center of gravity. The inertia of a body rotating about such a parallel axis is the inertia I_0 for the center-of-gravity axis, $I = m\rho^2$, plus the inertia of a body of the same mass m which has for its radius of gyration the distance e between the center of gravity and the center of the joint, or $I_0 = I + me^2$ for rotation about a joint axis perpendicular to the longitudinal axis of the limb.

It can furthermore be shown that the radii of gyration in a cylindrical body are smallest for rotation about a length axis and greatest for rotation about an axis vertical to it (dis-

TABLE 22.—*Moments of Inertia of the Different Parts of an Adult Human Body Weighing 65 kg* [AFTER AMAR [4]]

Part of the body	Mass, kg	Shape assumed for the calculation, and manner in which calculation is done	Moment of inertia, I, cm^2 kg
Bust (trunk and head), 50% of total wt.	$\frac{32.5\ kg}{g}$	[a] Cylinder of {height $h=0.88$ m; radius $r=0.13$ m} (Axis of reference: axis through base of cylinder and perpendicular to axis of cylinder)	8,600
Upper arm	$\frac{2.20\ kg}{g}$	Treated as truncated cone. Center of gravity, 0.145 m from shoulder; $h=0.35$ m; $r=0.047$ m; $r_1=0.040$ m	33
Forearm	$\frac{2.04\ kg}{g}$	Treated as truncated cone. Center of gravity 0.54 m from shoulder; $h=0.35$ m; $r=0.045$ m; $r_1=0.027$ m	37
Fingers		Approximation	V 0.04 IV 0.12 III 0.14 II 0.12 I 0.06
Whole upper limb	$\frac{4.20\ kg}{g}$	Treated as truncated cone. Center of gravity 0.32 m from shoulder; $h=0.70$ m; $r=0.047$ m; $r_1=0.027$ m	300
Lower leg	$\frac{4.4\ kg}{g}$	[b] Treated as truncated cone. $h=0.44$; $r=0.062$; $r_1=0.038$	130
Whole limb	$\frac{12\ kg}{g}$	$h=0.88$; $r=0.086$; $r_1=0.038$	1,460

[a] Formula for moment of inertia of cylinder referred to axis perpendicular to axis of cylinder and through base of cylinder: $I = m(3r^2 + 4h^2)/12$.

[b] The center of gravity in the whole lower limb is 0.38 m from hip joint. The radius of gyration can be found from $I = m\rho^2$, which gives $\rho = 0.34$ m.

tribution of mass points). Taking the whole extremity as a more or less cylindrical body, it can be shown that the moments of inertia relative to all axes which go through the center of gravity and which are vertical to the longitudinal axis of the member are the largest ones and are equal in size; that the moment of inertia relative to the longitudinal axis is the smallest (table 24); and that the moments of inertia for all axes vertical to the length axis but not going through the center of gravity, i.e., for the transverse axes going through the ends of the limb, are also equal among each other and are greater than the greatest moment for any center of gravity axes ($I_o = I + me^2$).

TABLE 23.—*Rotation Moments M_1 and M_2 Which the Iliacus Muscle Exerts on Trunk and Thigh for a Specific Stress of 1 kg and Different Positions of the Leg* [AFTER FISCHER [115]]

Hip joint angle, deg	Moment in respect to trunk, M_1, cm kg	Moment in respect to thigh, M_2, cm kg
−10	−24	+24
0	−24	+24
+10	−24	+24
+20	−24	+24
+30	−24	+24
+40	−24	+24
+50	−24	+24
+60	−24	+24
+70	−24	+24
+80	−29	+29
+90	−35	+35
+100	−39	+39

These concepts cover all situations in the movements of the body. For instance, in forward movement of the humerus from the shoulder joint the swing is about a frontal axis perpendicular to the length axis of the limb. This axis does not go through the center of gravity, but parallels the transverse axis going through this center at a certain distance from it. In the more complicated case, under the same principle, the combined moment of inertia of two portions of the body—for instance, forearm and upper arm—can be calculated. In this case the total moment of inertia I_t of a system of two bodies relative to any axis going through the common center of gravity and vertical to the longitudinal axis is

$$I_t = I_1 + I_2 + \frac{m_1 m_2}{m_1 + m_2} d^2$$

where

I_1, I_2 individual moments of inertia
m_1, m_2 individual masses
d distance between individual centers of gravity

Comparing the inertia moments for the different axes going through the center of gravity as the axes change from the transverse to the longitudinal direction, it can be seen in table 24 that the inertia moment becomes smaller as the axis is inclined less to the longitudinal axis; consequently, it is smallest for the longitudinal axis of the limb itself and greatest for the axis perpendicular to the longitudinal axis.

TABLE 24.—*Radii of Gyration for Axes Through the Center of Gravity.* [AFTER STEINDLER [315]]

Angle between axis of rotation and axis of extremity, deg	Radius of gyration, cm, for—			
	Thigh	Calf	Upper arm	Lower arm
0	4.56	3.09	2.77	2.73
5	4.65	3.19	2.84	2.88
10	4.89	3.45	3.05	3.28
15	5.28	3.85	3.36	3.85
20	5.75	4.34	3.74	4.51
25	6.29	4.86	4.17	5.21
30	6.86	5.41	4.61	5.91
35	7.44	5.96	5.05	6.61
40	8.01	6.50	5.49	7.28
45	8.56	7.00	5.90	7.90
50	9.08	7.48	6.29	8.49
55	9.56	7.91	6.64	9.02
60	9.98	8.29	6.95	9.49
65	10.35	8.62	7.23	9.89
70	10.66	8.91	7.46	10.23
75	10.90	9.12	7.64	10.49
80	11.08	9.28	7.77	10.69
85	11.18	9.38	7.84	10.80
90	11.22	9.41	7.87	10.84

Computation of the different radii of gyration is greatly simplified by the fact that a constant relation exists between the length of the limb and the radius of gyration for perpendicular axes on one hand, and between the diameter of the limb and the radius of gyration for movement about the longitudinal axis. This relation is established as follows:

(a) For all transverse axes through the center of gravity: For head and trunk $\rho = 0.23l$ (length); for the upper arm $\rho = 0.27l$; for the thigh $\rho = 0.26l$; and for the foot $\rho = 0.31l$. On an average $\rho = 0.30l$. This applies to all motion about transverse axes through the center of gravity.

(b) For rotation about the longitudinal axis through the center of gravity the relation between the radius of gyration and the diameter of the limb is $\rho = 0.35D$.

These simple relations make it possible to determine the value of the radius of gyration for the limb as 0.3 times the length for the transverse axis and 0.35 times the diameter for the longitudinal axis through the center of gravity.

It was apparent long ago that the resistance of the human limb to rotatory motion in the respective joints could be expressed. The radii of gyration, the distances of the centers of gravity from the axes of the joints, have been carefully calculated for the extremities by Braune and Fischer.[50] All necessary values are given and it is necessary only to substitute these into the general formula to calculate the resistance to rotatory motion or the inertia of the limb for rotation about any particular axis.

Seemingly, these are purely theoretical considerations, but they have an enormous application in the problems of locomotion of the human body. Thousands of details characterizing the various phases and types of locomotion thereby find their explanation. These considerations explain the fact that one can rotate a limb much more easily and with much less expenditure of muscle power about the longitudinal axis than about a transverse axis of the same terminal articulation. They also explain why the so-called rotatory movements of body and limbs, which can be carried out with comparative ease, play such an important part in the accumulation of momentum; for instance, in the twisting movements of the body in forward progression. These considerations explain numerous phenomena of swing and rotatory twists used in the human gait and in many other locomotor activities, such as jumping and running. In fact, without the appreciation of the comparative ease with which twisting and rotatory movements of the body and limbs are performed about longitudinal axes, it would hardly be possible to understand even the elements of the dynamics of locomotion. But appreciating in a general way and being able to make quantitative use of the data in predicting energetics of complex tasks are two different matters. The subtle twisting and rotatory movements in human locomotion, as will be pointed out below, modify to a great extent the energy requirement, and their interactions are the most poorly understood.

The basic data presented above are quite inadequate for total analysis of the locomotion problem. The human body is a complex system of elastic masses whose relative positions change as the masses move. To represent this system in exact analytic terms requires a dynamic analysis of an infinite number of infinitesimal rigid masses and an infinite number of degrees of freedom. The problem of developing a mathematical model reduces to one of simplifying the number, shape, and biomechanical properties of idealized body masses in such a way as to generate a closely approximate solution to the problem.

Such an approach has been recently applied to the problem of analyzing the stabilization of man in space by Whitsett[345] in a thesis presented to the United States Air Force Institute of Technology. Whitsett utilized the inertial principles outlined above to predict with reasonable accuracy such forces as the torques which man in zero gravity could exert under specific orbital conditions. He developed a 14-segment model of the body, with each segment rigid and homogeneous. The degrees of freedom were limited to 24 as follows: 6 rigid-body degrees of freedom as to position and orientation, and 18 local degrees of freedom as hinge points (9 hinges, each with 2 degrees of freedom). The masses of all segments were estimated by the equations of Barter[23] and the centers of mass were obtained from the data of Dempster.[85] In preliminary tests, this model approach appeared to offer much in terms of semiquantitative prediction of body response to work tasks under subgravity conditions as well as under the zero-gravity condition.

Similar preliminary studies have been performed by the Behavioral Sciences Laboratory of the U. S. Air Force Aerospace Medical Division in an analysis of the self-rotation maneuvers and translation potentials of men in zero gravity.[200, 289] Computer models of the system appear to offer a more quantitative solution to these dynamic problems.

A preliminary attempt at analysis of locomotor problems on the lunar surface by a similar approach has been presented by Gaume and Kuehnegger of the Martin Company.[123] In this study, only a general approach is presented for computer analysis of the problem. The force required can theoretically be determined both for movement of the body links in relation to the center of gravity of the whole body and movement of the whole body as represented by translation of its center of gravity. These data could possibly be coupled to the force equation of Hill[170] and Krendel[197] for each muscle about each joint to give a reasonable approximation to the energy requirement for any given locomotor task. No actual calculations have yet been made by the Martin group (now at Northrop Space Laboratories) using this projected approach.[200]

In a recent study, however, performed for NASA by Operations Research, Inc., a theoretical biomechanical analysis is presented of body movements under 1 g and 0 g conditions.[189] It appears appropriate to review in detail the calculations of this group, for they appear to offer one of the most pertinent analyses of the problem yet presented in the open literature. It must be recognized that the validity of this approach has yet to be demonstrated by concrete experimentation.[189] It is also obvious, as will be demonstrated below, that the simplifications prevent a total analysis of complex locomotor functions in a quantitative sense. Nevertheless, as the sophistication of the method is improved, it appears that this approach will be of great value in the analysis of future locomotor missions in unusual environments, especially in the case of the present problem, the design of lunar space suits. The material to be presented is taken with little editing from the Operations Research report, based on calculations made by the Research Division, College of Engineering, New York University.

In this investigation the following simple motions were studied:

1. Forearm flexion: With the arm in a horizontal position, the forearm is flexed at maximum effort until the limits of the elbow joint are reached.

2. Forearm extension: With the forearm in the fully flexed position and the upper arm in a horizontal position, the forearm is extended at maximum effort until the elbow joint limit is reached.

3. Knee flexion-extension: This is a continuous motion as occurs during the swing phase of walking.

4. Hip extension: Extension of the thigh as it occurs during the swing phase of walking, the instant before the heel of the foot contacts the ground.

5. Shoulder flexion: With the arm in a horizontal position, the whole arm is flexed, maintaining the elbow locked, until an approximate 90° position is reached on the shoulder.

6. Shoulder extension: The procedure of item 5 is reversed.

The following definitions of work apply:

1. Engineering work: The algebraic sum of the work done in accelerating and decelerating the body parts.

Illustrative example: Assume that a human being weighing 180 lb is raised by an elevator 1 foot and then lowered 1 foot. The engineering work is the sum of 180 ft-lb for raising and -180 ft-lb for lowering; the total engineering work is then zero.

2. Muscle work: The numeric sum of the work done in accelerating or decelerating body parts (angular or linear) is always positive.

Illustrative example: Assume that a human being weighing 180 lb raises himself 1 foot and then lowers himself. The work for raising himself is 180 ft-lb, and for lowering himself, $0.52 \times 180 = 94$ ft-lb. The total muscle work is then 274 ft-lb. (This negative work factor of 0.52 is discussed below). This example covers antigravity work. The same principle is applicable to work in rotatory acceleration against internal resistance.

3. Gravitational work: That portion of the muscle work used solely for the purpose of overcoming the weight effects (g × Mass) of the limbs.

4. Muscle work at zero g: The algebraic sum of muscle and gravitational work. The gravitational work is considered positive if the gravitational moment is in the same direction as the joint moment (see below) and negative if the sense is opposite the imposed joint moment.

The analysis is as follows. The work done at a joint is defined as

$$W_j = \int_{\theta_1}^{\theta_2} M_j \, d\theta_j \qquad (14)$$

where

W_j work, ft-lb
M_j moment about joint, lb ft
θ angle at the joint, radians
j any specific joint

The work done by several joints in question is thus represented by the area under the M_j vs θ_j curves of figures 22 to 25.

The moment about a joint can be represented by the following equation:

$$M_j = m_t a_{t,y} \bar{r}_t \cos \theta_j + m_t a_{t,z} \bar{r}_t \sin \theta_j + I_t \alpha_t + W_t \bar{r}_t \sin \theta_j \qquad (15)$$

where

m_t mass of all segments below the joint considered, W_t/g
$\bar{r}_t$ distance from combined CM (center of mass) of segments to joint axis
α_t angular acceleration of combined CM
$a_{t,y}$ linear acceleration of combined CM in the y-direction
$a_{t,z}$ linear acceleration of combined CM in the z-direction
θ_j angle of joint under consideration
I_t mass moment of inertia of all segments below the joint being considered
W_t weight of all segments below the joint considered

To illustrate the meaning of these terms, consider an analysis of the moments above the shoulder joints. The mass m_t would then be the combined mass of the upper arm, the

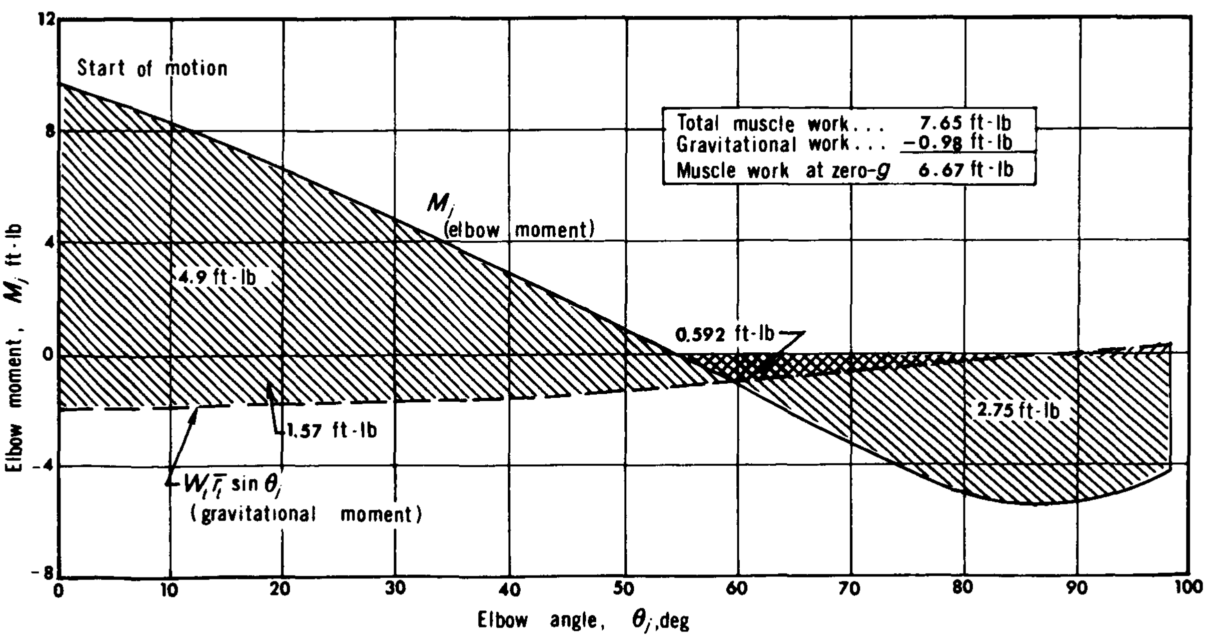


FIGURE 22.—Work done at elbow joint in forearm flexion. (AFTER KING AND MANS.[189])

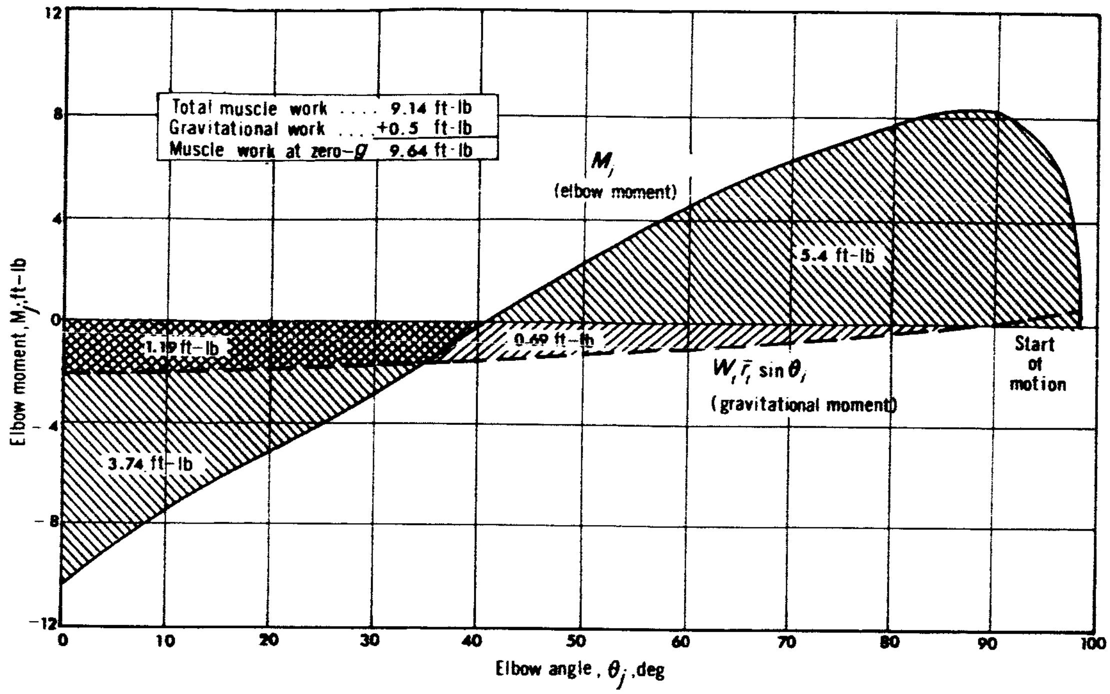


FIGURE 23.—Work done at elbow joint in forearm extension. (AFTER KING AND MANS.[189])

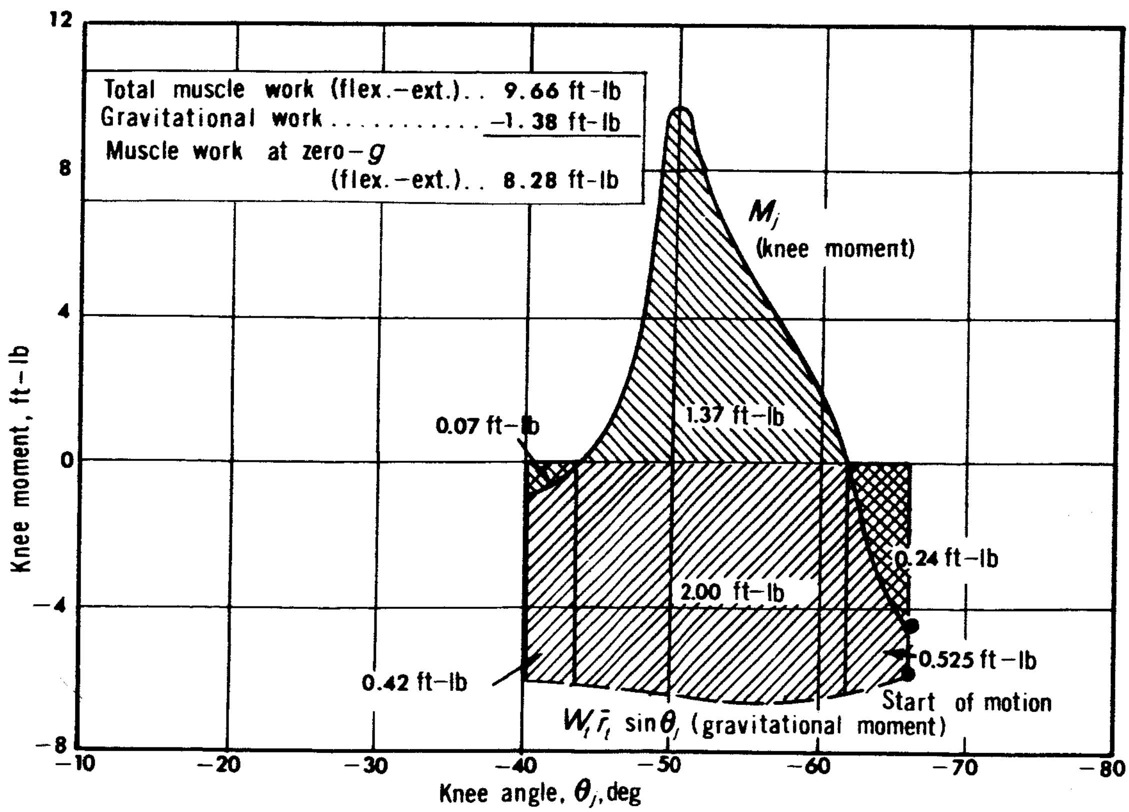


FIGURE 24a.—Work done at knee joint in swing phase of walking. (a) Knee flexion. (AFTER KING AND MANS.[189])

forearm, and the hand. The factor $\bar{r}_t$ would be the distance between the center of mass of the upper arm, forearm, and hand and the center of the shoulder joint. The remaining terms can be explained in a like manner. Examination of equation (15) reveals that the moment about the joint is made up of four terms. The first three terms represent the dynamic effects which influence the joint motion and the last term ($W_t\bar{r}_t \sin \theta_j$) represents the effect of the weight of the body components. The gravitational or weight effects have a definite influence on the moments about the joint.

If we now consider the moment about a body joint under a weightless condition, where $g=0$, then $W_t=0$ and the last term in equation (15) is reduced to zero. The moment about the joint under a condition of weightlessness would therefore be

$$(M_j)_{g=0}=m_t a_{t,y}\,\bar{r}_t \cos \theta_j + m_t a_{t,z}\,\bar{r}_t \sin \theta_j + I_t \alpha_t \quad (16)$$

In the same manner the work which is done by gravity can be expressed as follows:

$$W_g=\int_{\theta_1}^{\theta_2} W_t\bar{r}_t \sin \theta_j \, d\,\theta_j \quad (17)$$

In the analysis of body work done at a joint under conditions of zero-g, the work done under conditions of the earth's gravitational field ($g=32.2$ ft/sec^2) was calculated by graphical integration of curves of M_j plotted against

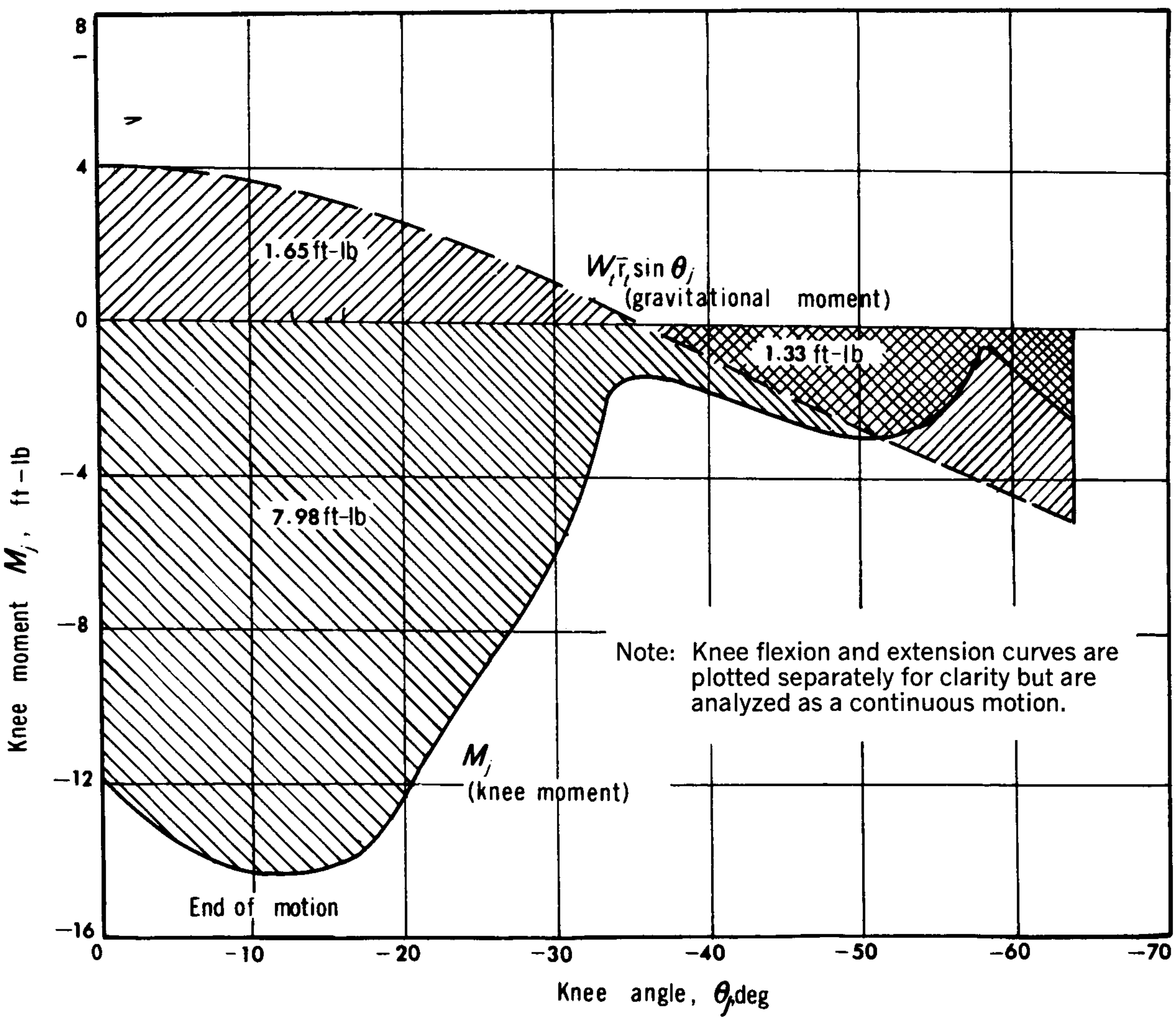


FIGURE 24b.—Work done at knee joint in swing phase of walking. (b) Knee extension. (AFTER KING AND MANS.[189])

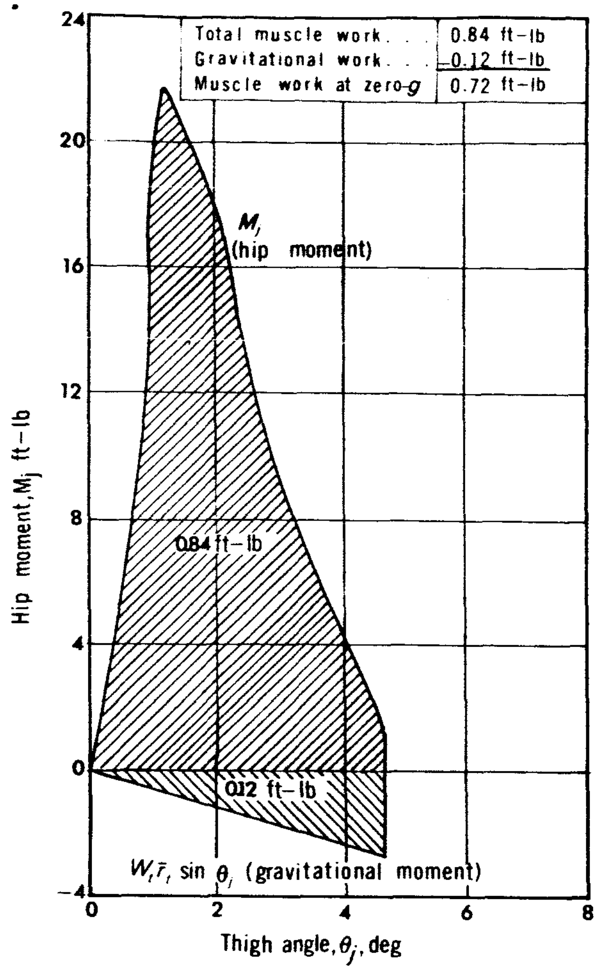


FIGURE 25.—Work done at hip joint in hip extension. (AFTER KING AND MANS.[189])

θ_j (figs. 22 to 25) obtained from data presented in the following references: knee joint;[267] hip joint;[52] upper extremity.[73] The moment contribution of gravity was obtained from the term $W_t\bar{r}_t \sin \theta_j$ plotted against θ_j with the work W_g of equation (17) again being obtained by graphical integration. Thus the work under zero-g was obtained from the following expression:

$$(W_j)_{g=0} = \int_{\theta_1}^{\theta_2} M_j \, d\,\theta_j - \int_{\theta_1}^{\theta_2} W_t\bar{r}_t \sin \theta_j \, d\,\theta_j \quad (18)$$

Calculations based on the above equations may be seen in table 25. A negative sign is attached to the gravitational work if it acts in opposition to the muscle work and thus necessitates more effort in the gravitational situation. Conversely, if the gravitational forces aid the motion, then more work output would be required under conditions of zero-g.

Several difficulties arose in this study. The analysis of the shoulder motions is based on an extension of the elbow data with compensations for increased weight and change in location of center of mass. It is, therefore, an approximate analysis and should not be relied upon too heavily.

An attempt was made to analyze separately the knee flexion and knee extension information as obtained from swing-phase walking data. The results obtained were not logical. It was, therefore, assumed that since this is a continuous motion, it must be analyzed as such. This procedure yielded usable information as presented in line 3 of table 25.

TABLE 25.—*Partition of Energy in Joint Movement.* [AFTER KING AND MANS [189]]

Motion	Muscle work at g=32.2 ft/sec^2, ft-lb	Gravitational work, ft-lb	Gravitational work at g=32.2 ft/sec^2, % of muscle work	Muscle work at zero-g ft-lb
Forearm flexion (fig. 22)	7.65	−0.98	−12.8	6.67
Forearm extension (fig. 23)	9.14	.5	5.5	9.64
Knee flexion and extension (fig. 24)	9.66	−1.38	−14.3	8.28
Hip extension (fig. 25)	.84	−.12	−14.3	.72
Shoulder flexion	23.0	−2.94	−12.8	21.06
Shoulder extension	27.4	1.5	5.5	28.9

A thorough analysis of available hip motion data was not made. Erroneous results were obtained from an analysis of hip flexion records. The analysis of hip extension data led to the results shown in table 25. In deference to the reasoning presented on knee data in the preceding paragraph, the hip moments in the swing phase show a period of constant moment which could be analyzed as equivalent to the discontinuity and thus led to reasonable results.

Apparently the brevity of the investigation and lack of data on specific joint motions prevented a more complete analysis of the problem at hand. Yet, on the basis of the above figures, it was concluded that (1) in general, where gravity is acting in opposition to the motion imposed by muscular effort, approximately 10 to 15% less muscular work would be necessary to perform the same motion under conditions of weightlessness, and (2) conversely, in circumstances where the gravitational environment aids in performing the motion (extension of the shoulder, elbow, etc.) approximately 5 to 10% more muscular work would be required to perform the same motion at 0 g. No further work along this line has been performed by these investigators.[189] These figures are illuminating in that they present a much lower gravitational factor for these specific joint movements than has been speculated in the past. These studies suggest that the quite naive concept of sixfold reduction in metabolic requirements for work in the lunar environment, seen sprinkled throughout the lunar design literature, requires much modification.

The material covered above is, of course, an idealized approach to the zero-gravity problem for future work. What, however, can be done about estimating the subgravity factor for present engineering decisions? How can an incomplete joint-by-joint analysis be extrapolated to a complex locomotor function such as walking? A brief review of what is known about gait may help to determine the necessary factors for this extrapolation.

Description of Gaits

Steindler[315] in 1935 attempted a review of the pertinent literature on gait analysis. Much of the material presented in this section will be based on his review of the older German literature of the 19th century. As mentioned above, the human body consists of an upper piece, the trunk and arms, which is balanced on a lower piece on which the propelling force applies. The condition of passive balance obtains as long as the balanced body maintains the same velocity and there is no change in the acceleration of the propelling lower piece to overcome the inertia of the balanced body. Otherwise the upper part tends to rotate about its center of articulation with the lower part until the former's line of gravity falls outside the articulation. If the contact between the two parts is by a hinged joint (point of contact), the slightest shift of the line of gravity will destroy balance. The rotatory force, or moment of rotation, involved is

$$M = I_0 + mg\cos\alpha \tag{19}$$

where

$I_0 = m\rho^2 + me^2$

α angle of inclination

m mass of the body

As a matter of fact, external forces (air resistance) oppose the progression of the upper piece. The upper piece, to avoid loss of equilibrium, opposes these forces with an added acceleration, namely that of gravity, by assuming a forward inclination. Therefore, in human locomotion a certain inclination of the body against the limbs forms part of the dynamic scheme, and the degree of inclination varies with the external forces that resist progression.

The acceleration of the propelling force constantly rises to a maximum and decreases to zero. With every forward impulse of the lower body, there is a danger of inertial forces causing the upper body to fall backward. When such interrupted forces apply upon the lower structure (the legs), which carries the trunk, the latter must repeatedly counteract backward fall by forward inclination, the degree of inclination depending on the resisting force (air resistance and inertia) that applies to the trunk. In this case the angle of inclination must vary according to the function of acceleration which is imparted to the body by the interrupted force. The equation of equilibrium will be

$$ma + ksv^2 = I_0 + mg\cos\alpha_1 \tag{20}$$

where

a acceleration of propelling force

k air resistance constant

s surface factor

v velocity

I_0 moment of inertia

α_1 new angle of inclination from vertical

Now, if $R=ksv^2=$ Resistance of the air, and α is the previous angle of inclination from the vertical, $R=I_o+mg\cos\alpha$ (from eq. (19)). Then

$$ma+I_o+mg\cos\alpha=I_o+mg\cos\alpha_1$$

or

$$ma+mg\cos\alpha=mg\cos\alpha_1$$

and therefore

$$a=g(\cos\alpha_1-\cos\alpha)$$

Thus, the amount of force developed by inclination is always proportional to the cosine of the inclination angle. Fluctuating inclination forces under certain surface conditions could therefore be a factor in determining energy requirements of locomotion. These forces must be added to the basic rotatory motions already described in the analysis of the energy of gait.

Another series of motions also complicates the picture. These motions result from the bipedal mode of human locomotion. In order that the propelling leg may develop a forward propelling acceleration, it must be opposed to the ground in a diagonally backward position so that the downward pressure may be resolved into a horizontal as well as a vertical component. When an individual is standing still there is equilibrium between superincumbent weight and the counter pressure from the floor. As the extremities are lengthened or shortened in alternation by the muscles, the effect of this action reaches the supporting base as active downward pressure, provided pressure effects act exactly in the vertical direction.

If there is a lengthening of the extremity by the action of the extensors, the result is an upward movement of the center of gravity or of the body as a whole; on the other hand, when the extremity is shortened by the flexor action, the effect is a decrease in the ground pressure followed by a downward movement of the center of gravity of the body as a whole. However, the pressure which results from the extension of the limb by muscle action does not reach the ground in a vertical direction but in an oblique direction. Therefore, the pressing force must be resolved into horizontal and vertical components. The vertical component is directed upward and, therefore, is counteracted by the force of gravity. The center of gravity of the body under the action of this vertical component will move upward as soon as this component exceeds in amount the downward effect of the gravitational force.

The horizontal component, on the other hand, imparts to the center of gravity or to the body as a whole a movement or an acceleration in the forward direction. These components are seen in figure 26. Accordingly, in human locomotion the forward progression is a combination of rhythmic forward propulsion and vertical elevation of the center of gravity in the sagittal plane. Because of the opposing force of gravity, the propelling force also imparts accelerations in the horizontal and the frontal plane, as will be seen later in the graphic description of gaits. Under 1g, these may be rather insignificant. As will be seen shortly, they may be relatively more significant in subgravity environments.

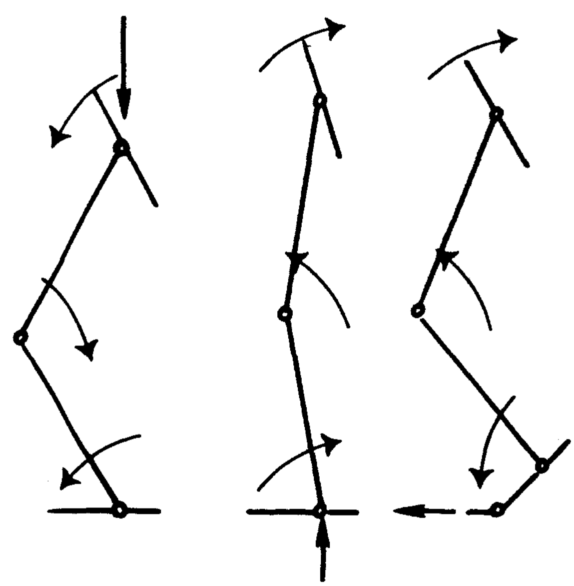
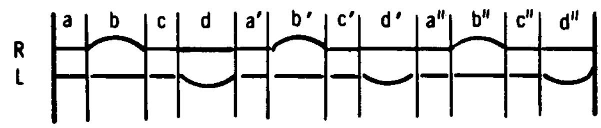


FIGURE 26.—Vertical elevation component and horizontal component in the human gait. (AFTER STEINDLER.[315])

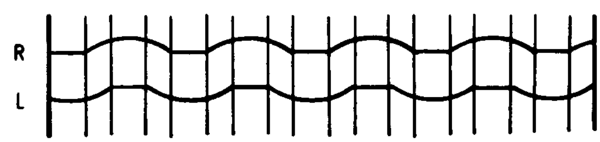
In the case of the frog or kangaroo, with their saltatory gait, the sudden upward and forward propulsion of the body results in severe loss of balance. This is restrained by bringing the legs forward in an extended position before the ground is met. In the alternating bipedalism of the human, only one extremity at a time is used as a propelling force; the other one is allowed to swing forward. At the end of the swinging period the limb set forward to the ground in flexed position receives the impetus imparted to the center of gravity by the other limb, and by muscle contraction restrains it from its forward and downward path until a position is reached where the center of gravity is balanced over the supporting foot. This position is reached when the center lies directly over the supporting base—the standing leg. Then, by a sudden extension action of the articulations of the lower extremity, another impulse is given to the body in a forward and slightly upward direction. So we see that the human gait may be described as a constant and alternating play between the two extremities, one of which is in touch with the ground and imparts to the body its acceleration while the other, swinging free, carries the momentum forward with the body. At the completion of the swing the leg again touches the ground, first restraining the downward and forward tendency of the center of gravity and then again assuming the role of a propeller of the body.

At the moment when the center of gravity has passed forward beyond the supporting base of the standing leg the balance of the body is lost. This loss of balance occurs long before the supporting leg has left the ground in order to swing forward in the next phase. It is quite proper, then, to describe the human gait as a constant play between loss and recovery of balance. The essential features of this play are as follows: The propelling force is furnished by the extensor action of one leg while the other one swings forward. When the swinging leg touches the ground it displays a restraining action, followed quickly by a propelling phase. Accordingly, while from a descriptive point of view the human gait consists of alternating phases of swinging and support, from the mechanical and dynamic point of view it can be described as an alternation of propulsion and restraint. Naturally, the restraint which is called for to recover the lost equilibrium can operate only within certain limits. The restraining effect of the leg, which begins the moment it touches the ground, depends upon the point to which the lost equilibrium is recoverable. The possibility of recovering the lost equilibrium by the restraining leg varies with the type of locomotion.

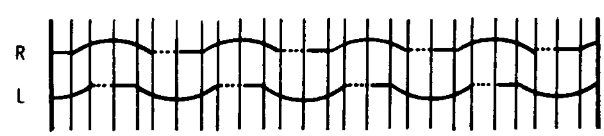
In order to quantitate the gravity factor under different gait conditions, it becomes necessary to break up the progression into its component parts and portray them graphically. The Webers [336] have diagramed the differences in swing and support phases of several different gaits. These are seen in figure 27.



(a) The walk. Note periods of double support between single-support-and-swing periods.



(b) The run. Note absence of period of double support and appearance of phase of double float instead.



(c) The sprint. Note the prolonged swinging time and the periods of double float before and after periods of single support.

FIGURE 27.—Diagrams of phases in human locomotion. Horizontal lines denote support; curved lines denote swing; dots denote the period in which the body moves over the forward extended leg, before the real support is assumed by the leg. (AFTER THE WEBERS.[336])

What are the basic differences in leg motions between walking and running? In walking with increasing velocity, the time in which both legs are on the ground gradually disappears. In running with decreasing velocity, the time in which both legs are floating is gradually decreased to zero. Thus, the walking and running types of locomotion gradually melt into each other. The Webers[336] examined the point of transition and found the borderline between the two types of locomotion at a step length of 0.82 m and a duration of the step of 0.32 sec. This amounts to one-half the natural swinging time of the leg hanging free from the trunk. The upper limit of velocity in walking is given by the lower limit of time in which both legs are supported.

In running, however, the upper limit of velocity is not reached as it is in walking by gradually shortening the time of double support, as there is no double support to begin with. How, then, is the upper limit of velocity reached in running? One difference between walking and running is that in running, different cadences may result in different step lengths, according to the longer or shorter period in which both legs are floating in the air. This is possible because there are different heights of the center of gravity, or of the hip joint, which can be chosen in execution of the step. In one instance the femoral heads may be carried lower, with the result that the extension force of the propelling leg is greater and, therefore, the velocity of the body as a whole is increased. At the same time, the body flies farther at each step than the mere span of the posterior leg would provide for. In this case, before the forward leg is set to the ground, the posterior leg is yanked forward by the flying trunk during the period of the double float. On the other hand, as the femoral heads are gradually carried higher, the trunk is thrown up higher and the propelling leg is thrown up along with the trunk. Therefore, as the femoral head is lifted higher the propelling leg is lifted from the ground a progressively longer time before the other leg touches the ground. Thus in running the position and movement of the center of gravity determine the different ways in which the length of the step can be regulated. As will be shown subsequently, the length of step influences the partition of energy between gravitational and nongravitational factors.

There is another difference between walking and running. Muscular forces may change the normal movements of the body in walking, but such a change cannot occur in running in the time during which the entire body floats free in the air, and occurs only in small measure during the short period when one leg is touching the ground. The time to change the dynamics of progression by active muscle contraction is when both legs are touching the ground and, therefore, the longer this period lasts the more liberty one has in progression. This is evident in walking, and especially in the slow walk. In a fast walk this period is very short and there is less latitude in changing motion. There is still less in running.

The difference between ordinary running and sprinting is that in running the moment of contact of the leg with the ground is almost the moment of propulsion; whereas in sprinting, the moment of contact does not coincide with the moment of propulsion because contact is made when the leg is still in a forward position and before it has attained verticality. The object of the sprint is to make the leg swing longer; therefore, it is necessary that the projectile impetus imparted to the body be greater than the one in running. As seen in figure 27(c), the double float periods of the sprint are as follows: First, with the beginning of the propelling action of the leg a strong forward and upward impulse; second period, a full swing from backward to forward; third period, forward swinging leg touches the ground until the femur is again vertically above the foot. Then the first period begins again. To the length of the step must be added the forward movement when both legs are hanging free.

The leg mechanics in various gaits have been presented in qualitative detail to pave the way for the discussion of the energetics of gait, especially for the changes brought about by subgravity conditions. Intimately connected with these leg movements are trunk and upper limb movements which increase the total energy efficiency of various gaits.

It is obvious that both the propelling and the restraining effects of the limb must be imparted to the trunk. The point of application of these forces to the trunk is the hip joint, and since this point is at some distance from the center of gravity, a rotatory effect in all planes must be the result. Indeed, such a rotatory effect can also be noted in the transverse and the frontal planes of the body. Hips and shoulders rotate in both these planes in addition to their movement forward with the whole body; also they rise and fall with the body in the vertical direction. It is obvious that a rigid analysis of the gait will be rather complicated, for consideration must be given to the movement in forward progression, the up-and-down movement, the oscillations from right to left, and the oscillations forward and back; in short, movements in the three cardinal planes of the body and about the three rotational axes, as well as the general forward progression of the body as a whole. From these data, deductions can be drawn as to the velocity at which different portions of the body move in each of these planes during the different phases of the gait. From the velocity, conclusions can be drawn as to the acceleration of these movements. Finally, the determination of these accelerations opens the way for computing or estimating the locomotive power behind these motions and the gravitational factors involved.

The actual displacements of the center of gravity and the secondary determinants of gait, first described in detail by Braune and Fischer,[51] have been summarized by Saunders et al.[288] A review of the quantitative aspects of the problem is found in the compilations of Steindler,[315] Klopsteg, Wilson, et al.[192] and Fenn.[111, 112] Only a semi-quantitative review will be presented at this point. The material is taken with little editing from the review of Saunders et al.[288]

The displacement pattern of the center of gravity may be regarded as constituting the summation or end result of all forces and motion acting upon and concerned with the translation of the body from one point to another during locomotion. In adult males and females, it is estimated that the center of gravity of the body lies in the midline at a distance from the ground corresponding to about 55% of the total stature (individual variations being ±1.25%). With reference to the vertebral column, the center of gravity occupies a position anterior to the second sacral vertebra. In walking, the pathway described by the center of gravity in the plane of progression is a smooth undulating or sinusoidal curve. From this curve it is determined that the center of gravity is displaced twice in a vertical direction during the cycle of motion from its position at the heel-strike of one foot to the subsequent heel-strike of the same foot; that is, as the body passes successively in a double pace over first the right limb and then the left. The total amount of this vertical displacement in normal adult males is about 1.6 inches, or 4 cm. Individual variations are so small that they may be neglected. The summits of these oscillations occur at 25 and 75% of the cycle, each corresponding to the middle of the stance phase of the supporting limb while the opposite limb is in the middle of the swing phase. At 50%, or the middle of the cycle, the center of gravity falls to its lowest level; this position corresponds to the interval of double weight bearing when both feet are in contact with the ground. As the curve is followed in ascent and descent, it is found to fluctuate evenly between the maxima and minima of displacement with few if any irregularities. At its maximum height during walking, the center of gravity of the body is always slightly lower than it is when the subject is standing.

The center of gravity of the body is also displaced laterally in the horizontal plane. Relative to the plane of progression, the center of gravity describes a sinusoidal curve, the summits of which alternately pass to the right and to the left in association with the support of the weight-bearing extremity. The curve is smoothly undulating without irregularities and it is similar in form to that of the vertical displacement. The total lateral displacement in normal walking is approximately 1¾ inches (4.5 cm) measured from the extremes of the deviation from right to left (fig. 28). When the vertical and horizontal displacements of the center of gravity of the body are projected on the frontal plane, they describe a rough figure eight, occupying approximately a 2-inch square, since the vertical and horizontal deviations are almost equal. A three-dimensional picture of the pathway of the center of gravity in the line of progression is that of a spiral along which the center moves with almost even velocity.

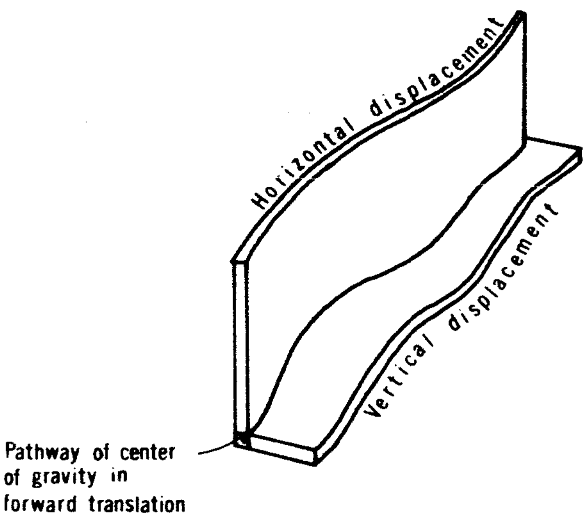


FIGURE 28.—Pathway of the center of gravity in locomotion, produced by the intersection of the horizontal and vertical displacements. (AFTER SAUNDERS ET AL.[288])

In translating the center of gravity along a smooth undulating pathway of low amplitude, the human body conserves energy. If there were no compensatory rotation of pelvic, hip, knee, and ankle joints, the undulations would be much more severe. In such a system, locomotion would produce something analogous to the process of stepping-off distances with a pair of compasses or dividers. The pathway of the center of gravity of the system in forward translation would be a series of intersecting arcs. The radius of these arcs would be equal to the length of the levers representing the extremities and, with each step, the angular rotation at the hip in flexion would equal that in extension. The energy cost to a person using the compass gait would be exceedingly high. In a human being with average stature and length of stride, the center of gravity of the body would have to be elevated approximately 3¾ inches, which is double the normal vertical displacement. At the point of intersection of the arcs, the abrupt change in direction of the forward acceleration would require the application of force of considerable magnitude. (As discussed in Chapter 3, the gait of a person in a pressurized space suit probably approaches the compass gait.)

The modifications of this basic gait can be broken down into several components or determinants. These are:

(1) Pelvic rotation
(2) Pelvic tilt
(3) Knee flexion

These three determinants of gait act to flatten the arc through which the center of gravity of the body is translated. The first—pelvic rotation—elevates the extremities of the arc, and the second and third—pelvic tilt and knee flexion—depress its summit.

(4) Foot rotation mechanisms
(5) Knee rotation mechanisms

These two mechanisms are coordinated to obliterate the abrupt inflexions at the point of intersection of the arcs of translation of the center of gravity. This smooths the gait by establishing a sinusoidal pathway for its progression with a great reduction of energy cost.

(6) Lateral displacement of pelvis

Excessive lateral displacement is corrected by the existence of the tibiofemoral angle. This, together with relative adduction at the hip, reduces the displacement to about 1¾ inches so that it approximates the vertical displacement. Thus the deviation of the center of gravity is almost symmetrical in the horizontal and vertical planes.

The movements of points other than the center of gravity are, of course, quite complex. Figure 29 presents a qualitative analysis of such movements during walking. Klopsteg, Wilson, et al.[192] review more quantitatively these movements which, as will be seen below, can contribute much to the total kinetic energy of locomotion. Fenn [111] has calculated that the shoulder movements, for example, add to the kinetic energy of arm movements in running by about 30 to 50%. It must be remembered, however, that these movements are effective in reducing the total energy of walking. Subgravity states or restriction by inflated space suits may alter this ideal pattern established through long evolution of the neuro-skeleto-muscular system.

The actual electromyographic correlates of these complex movements have been studied in great detail [192] and have contributed much to the design of artificial limbs. Unfortunately, there is no definitive quantitative relationship apparent between action potentials and force developed which would greatly aid the evaluation of energy of progression. Another mode of study has been the force plate. The plate on which a subject walks is rigidly attached to four columns, the deformations of which are recorded by strain-gage techniques. By synchronizing readings with photographic techniques and foot patterns (carbon paper), all ground reactions including torques may be determined. The inertia of

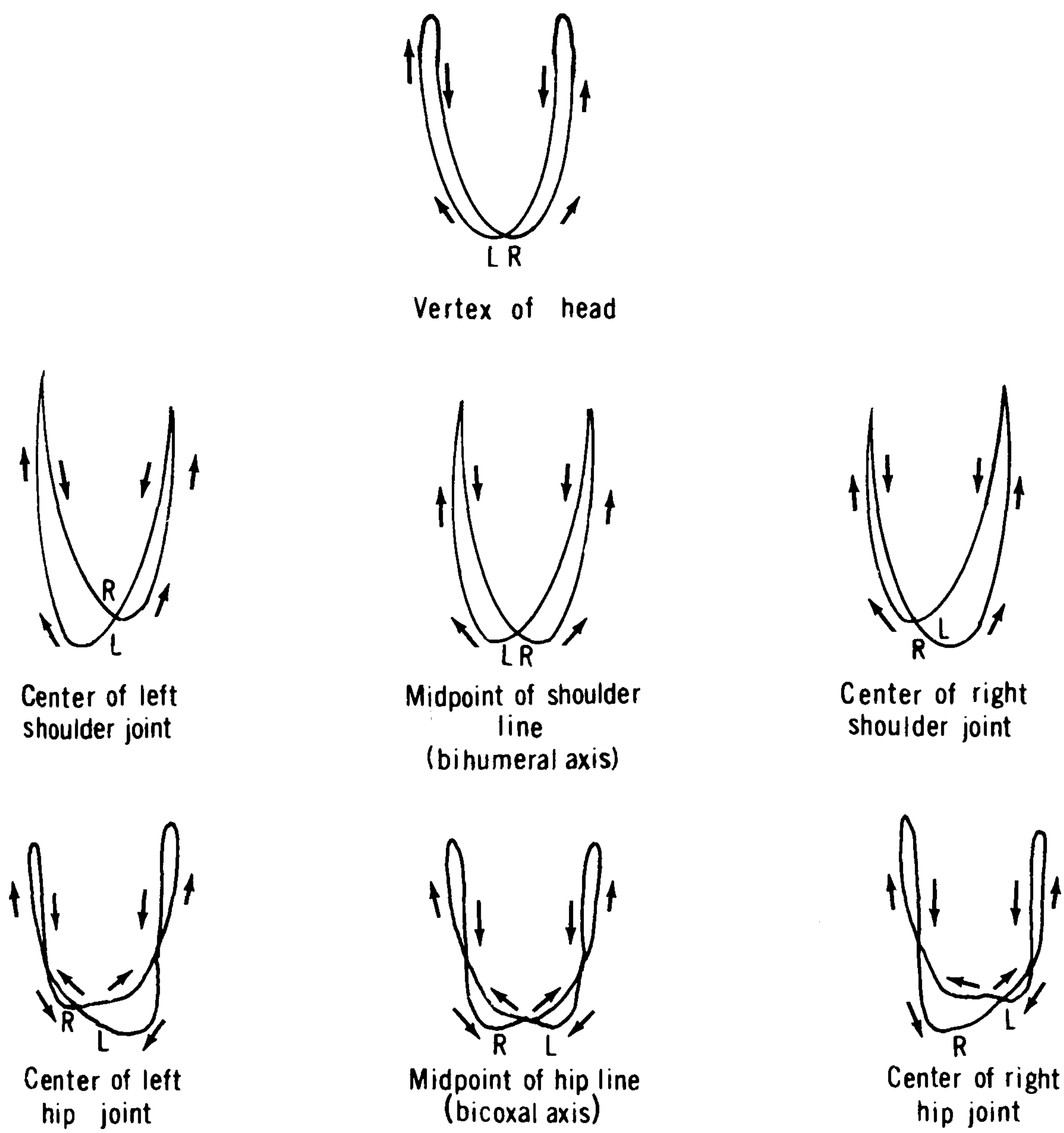


FIGURE 29.—Frontal projection of path curves. On each side complete sinus curve with single step (up and down); and one sinus curve with double step (right and left). (AFTER BRAUNE AND FISCHER.[49])

the plate systems may cause up to 50% inaccuracy in impact load measurements, but slowly applied loads can be measured within 2 to 3% accuracy.

Figure 30 represents typical force-plate results for normal subjects walking on the level. The vertical force component has a double-peaked shape because of the vertical upward and downward accelerations of the body. The difference between the magnitude of the vertical force and the body weight is proportional to the vertical acceleration.

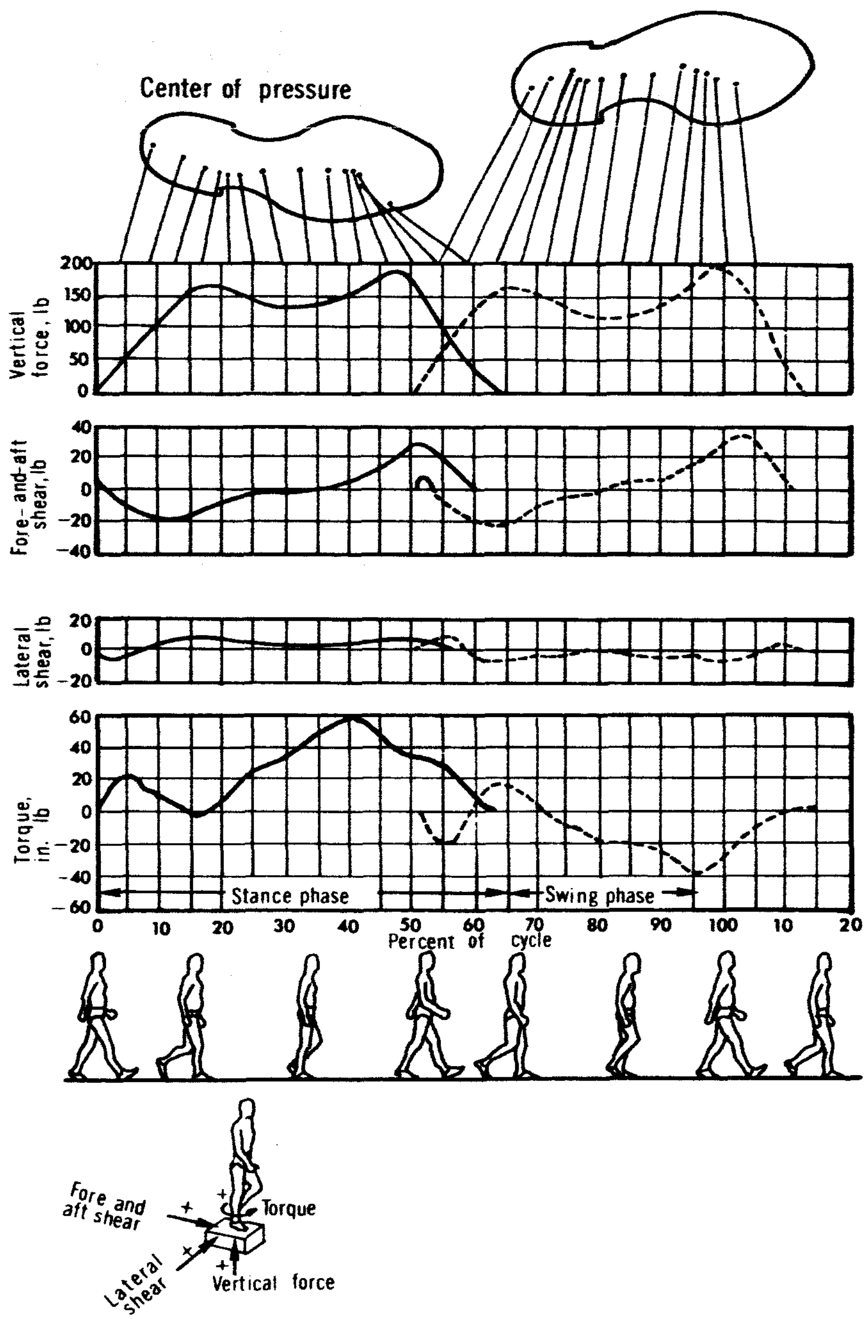


FIGURE 30.—Typical force-plate results for a normal subject during level walking. (AFTER KLOPSTEG AND WILSON.[192])

As the heel strikes the ground the force rises quickly to a magnitude equal to or slightly greater than the body weight. The unlocking of the stance knee results in the dip in the curve. As the leg prepares for a push-off phase, the knee again locks. Extension of the knee and ankle at this point imparts the forward and upward acceleration to the body. This causes the curve to again exceed the body weight.

The fore-and-aft shear curve has a sinusoidal shape. The variation in the force is due to the fact that upon heel strike the leg must first retard the forward motion of the body, and then a fraction of a second later, must provide the "push off" or forward acceleration necessary to continue the motion. The small positive component at the start of the curve implies that near the end of the swing the leg has decelerated to zero and the foot is actually moving aft at the instant of heel strike. The lateral shear force is of relatively small magnitude but is important to provide lateral stability in walking. As the body weight is shifted from one leg to the other, the lateral force must be directed inward with respect to the body to prevent the subject from falling sideways.

The force torques and shears are of interest because they define the stresses to which the surface is exposed under these conditions. It would be of value to predict from these graphs the effects of lunar soil on the locomotor patterns of individuals walking on the model lunar surface with varied suit designs and load parameters. The problem is outlined at the end of this chapter.

Energy Analysis of Gaits

By means of elaborate experiments combining the measurement of changing moments of inertia, photography of movement, force-plate analysis, and other techniques, attempts have been made to quantitate in detail the energy partition of walking and running gaits. The 19th century work in this field by Marey,[225] Braune and Fischer,[50] Amar,[4] the Webers,[336] and Chauveau[68] was followed by the studies of Cathcart and Stevenson[65] and Fenn[111, 112] and by the detailed studies of Elftman.[103, 104] Because a quantitative analysis of the metabolic loads in lunar environments (in restrictive pressure suits under subgravity conditions) requires a thorough understanding of these principles, a more complete review will be presented here. A fitting prolog to this discussion is several paragraphs from the review of Saunders et al.[288]

> The energy level of a body is the sum of its potential and kinetic energies. If no work is done, the energy level is constant, as in the classical example of a simple pendulum where the loss of potential energy is exactly compensated for by the gain in kinetic energy. When the energy level is not constant, then work must be done in order to produce the change in energy level. In the computing of the energy levels for the different segments of the lower extremity, it is found that the levels are not constant. The difference is a measure of the work done by the muscles at the joints. The net result is the forward displacement of the body, but a large portion of the energy is dissipated in the rotations of the segments. These effects are referred to as the output and input of energy respectively.
>
> From studies of the energy levels, it has been established that the output of the ankle and hip is considerably greater than the input; therefore, most of the energy required for level walking is provided by the muscles acting on these joints. In the case of the knee joint, the output is so much less than the input that this joint predominately absorbs energy. However, the knee decreases the vertical motion of the body by flexion; and, although energy is dissipated in the process, the overall energy requirement is less than would be necessary in walking over a rigid knee. Additional energy is absorbed by the knee to decelerate the leg and foot during the swing phase. Nonetheless, not all of the energy absorbed by the knee is lost. A considerable portion is stored and is returned to the system in the later part of the swing phase by imparting continued forward acceleration to the body at the time when most of the potential energy is lost. Thus locomotion is not only due to the "push" of the member in support but also to the "pull" of the deceleration at the swinging knee.
>
> The energy expended during straight and level walking at a constant cadence is divided approximately equally between the production of rhythmic oscillations of the legs and the elevation and depression of the center of gravity of the body. If the human mechanism were a truly efficient machine, the kinetic energy in the system would be converted into potential energy and would be stored until it is required to initiate movement of one or more of the segments of the body. However, since the muscles, when stimulated, expend energy both during contraction and elongation, energy storage is never complete or recoverable.

The factors which permit this energy storage and recovery are discussed below. They involve the precise timing of the muscle contraction to the displacements of the moving segments, the limiting of the muscle contraction to very brief periods of activity, the action of two joint muscles, and the basic molecular considerations in the development and maintenance of tension in the muscles.

The most essential factor in energy analysis is to determine the path of the total center of gravity of the human body during locomotion, because from it the velocity and acceleration of the body as a whole can be determined. The path has been briefly described above, and will be analyzed in greater detail. It must be remembered that the paths of the partial centers of gravity of trunk and head, as well as of the system of trunk, head, and arm, and, finally, the center of gravity of the whole body, are similar to the paths of the center of the hip joint or the center of the shoulder joint (fig. 29). In the sagittal or frontal (coronal) plane the centers of gravity carry out oscillating and symmetrical movements in regular periods. Those periods equal the duration of either a double step or a single step, and at the same time the center of gravity proceeds in the direction of locomotion.

In order to calculate energies, the accelerations of centers of gravity must be obtained. By analyzing the velocities of the center of gravity of the whole body, the accelerations in three planes of space may be determined. Details of the analysis may be found in Steindler[315] and will not be reviewed here. The total compound acceleration of the center of gravity of the body has been calculated from the values of the three components in the three planes. Figure 31 presents a summary of these calculations by Braune and Fischer[50] from analysis of 31 phases of the walking gait. From the vertical acceleration component alone, the downward force during each step was calculated from the simple relationship $F = wa/g$ (where w is weight and g is acceleration due to gravity). In the graph the heavy horizontal zero line gives the weight of the resting body, while the curve indicates the fluctuations in force, either reduced by the restraining force or accentuated by downward move of the center of gravity. As the curve shows, these restraining forces give the center an upward acceleration which diminishes the downward pressure, though never, in walking, abolishes it. In running, it is abolished during the double float (figs. 27(b) and 27 (c)). It is interesting to compare these values with the force-plate data of figure 30. From these accelerations, a first approximation of the energy requirements can be obtained.

Normal Walk

These theoretical considerations can now be put to practical use in computing the work performed in locomotion. In order to simplify the calculation, one may without too great error exclude for the moment the lateral motions in the frontal and the rotatory motion in the horizontal plane. Then there is left merely the motion involved in straight progression and the up-and-down movement. It must be remembered also that in all movements there is a periodic play between the propelling force and the restraining force. For this reason velocity curves show periodic fluctuations to maxima and minima, and acceleration alternates from maximum to zero, and vice versa. By integration the sum total of the work performed can be computed from the acceleration curve, since the total work W would be equal to the force F $(=ma)$ times the distance: $W = mad$.

In order to simplify the matter still more, we accept what has been established by previous investigations of Marey[225] and Braune and Fischer;[50] namely, that for each element of movement, the ratio between the propelling force and restraining force can be estimated. This restraining component of force for the vertical movement would be the one which restrains the fall of the elevated body; for the pendulum swing of the leg, the one which restrains the swing at approximately one-half of the total swinging phase; for the forward propulsion, the one which receives and retards the acceleration in the plane of progression. The energy expended in restraining the body in these diverse movements is estimated at about 52% of the energy expended in propelling it. In other words, if a certain amount of force of the propelling

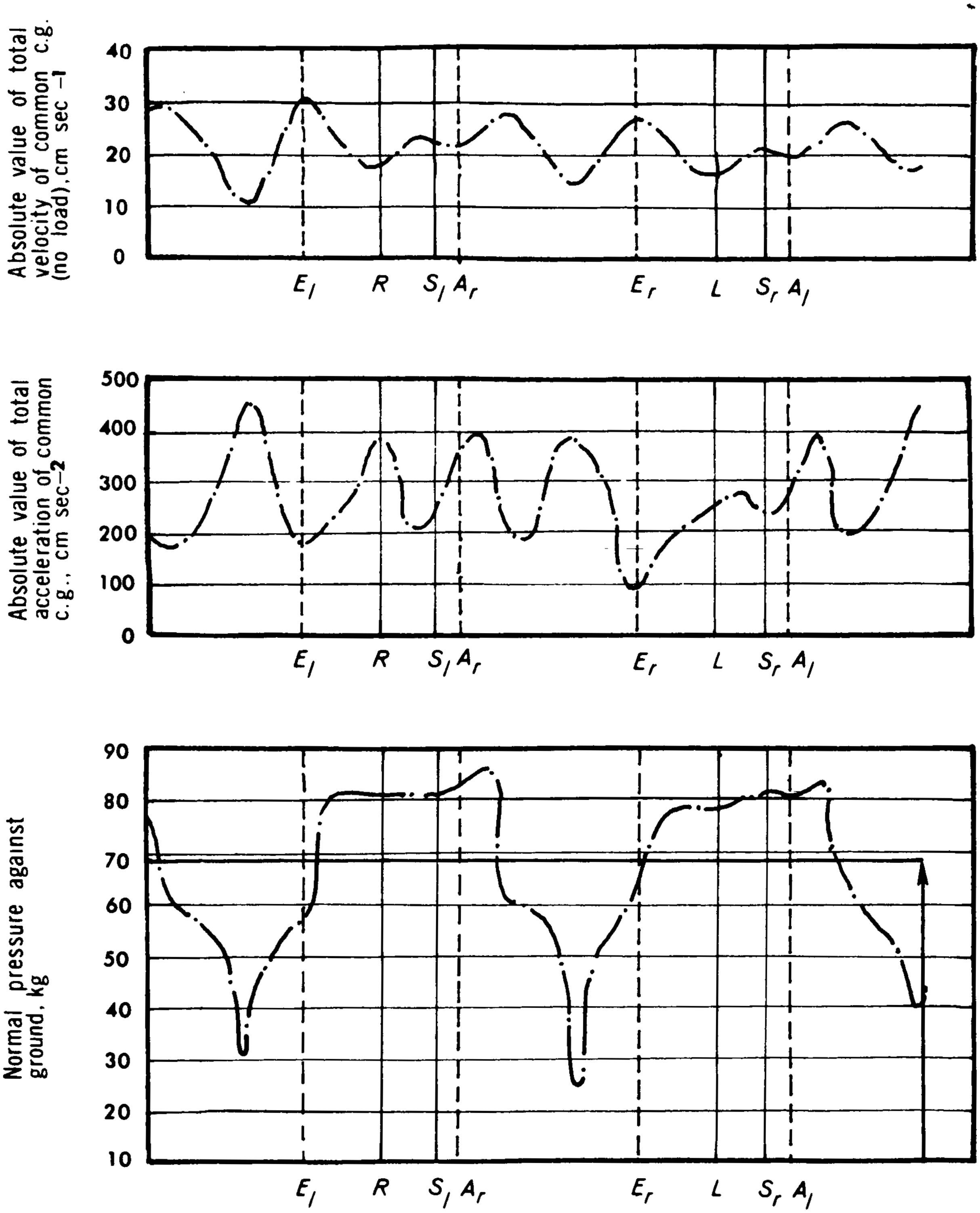


FIGURE 31.—Compound velocity and acceleration curves of the center of gravity of the body in walking. The symbols at the bottom of the figure denote: R and L, the setting down of right and left heels; S_r and S_l, beginning of right and left swing; A_r and A_l, beginning of right and left support (sole); E_r and E_l, end of right and left support (sole). (AFTER STEINDLER,[315] FROM DATA OF BRAUNE AND FISCHER.[50])

leg gives the center of gravity a certain acceleration forward, the receiving leg at the next moment expends in its action of restraint about 52% of this amount, and a similar relation applies to the restraint and propulsion in the vertical direction. Here the extension of the extremity gives the center of gravity an upward acceleration which raises the body to a certain height. From this height it falls approximately the same amount and is then restrained from continuing its fall by the musculature of the lower extremities. Here, also, the restraining factor is about 52% of the propelling. If this coefficient of restraint is accepted, it will enormously simplify the task of calculating the work. It will only be necessary to compute the visible or effective work and add to it the coefficient of restraint, which asserts itself in isometric contractions of the muscles without visible motion.

This important "negative work" factor (0.52) must probably be reserved for slow walking gaits. Zuntz, as reported by Cathcart and Stevenson,[65] gives a figure of 0.40. Cathcart and Stevenson report a much higher figure, 0.70, as the fraction of equivalent positive work that results from tension exerted while a muscle is being stretched in a decelerative process. Positive work is done against viscous factors, while viscous factors aid negative work. As Fenn [111] points out, these estimates are of somewhat doubtful value since we never know exactly what positive work antagonistic muscles are performing during complex decelerative movements in man. The actual *in vitro* muscle data on which negative work factors are based also do not account fully for steady-state and recovery factors. In addition, since a muscle loses tension at less than the isometric rate when shortening, the necessary rate of tension redevelopment or heat production is less during stretching than during shortening. Since work against viscosity varies much with speed of movement, Fenn chose the low estimate of 0.40 as the factor for the negative work of sprinting.

More recent studies along this line have been presented by Abbott and his coworkers.[1,2] These investigators in some ingenious experiments compared the positive work of cycling with the negative work of resisting the cycling, the legs exerting the same forces in similar movements at the same speed. It was found that the ratio of the oxygen cost (above resting values) of negative work to that of positive work decreased from 0.42 at 25 rpm to 0.19 at 52 rpm. Only at the lower rates of work does the factor 0.52 of Chauveau seem appropriate. In other experiments, working against motors at controlled forces and speeds, it was found that when the rate of negative work was increased at constant speed the rate of oxygen consumption increased rapidly, but when the rate of work was increased at constant force, the oxygen consumption remained relatively constant. Thus the factor for the relative costs of positive and negative work varies with both force and speed of contraction. The theoretical bases behind these facts are discussed by these authors and in the review of A.V. Hill.[172]

Can one make a first approximation of the work partition in walking? Assuming a factor of 0.52 for slow walking, Amar [4] calculated the total work for this activity as follows:

$$W = W_r + 0.52W_r = 1.52W_r = 1.52wd \quad (21)$$

where

W total work
W_r visible (positive) work
w weight of body
d distance of travel of center of gravity.

Analyzing the total work further, the muscle force exerting pressure downward is resolved into two components, one vertical and one hotizontal. The vertical component opposes the force of gravity and causes upward acceleration; the horizontal is the forward propelling force. In addition there is a pendulum movement of the limb in the interval between the pressure-producing periods of support. Therefore, the analysis of W, the work for forward progression, covers three constituents:

(1) W_1, the work of the upward moving forces
(2) W_2, the work of the forward forces
(3) W_3, the work of the pendulum movement of the swinging leg

Each of these components in the walking gait can now be analyzed. If a man's weight w is

65 kg and if he rises a distance d of 4 cm with each step, then

$$W_1 = 1.52wd = (1.52)(65)(0.04) = 3.952 \text{ kg-m/step} \quad (22)$$

if a restraint coefficient of 0.52 is assumed. (To avoid misunderstanding, it should be stated that kg–m refers to kilogram-meters of work and is equivalent to mkg or kgmm used elsewhere in the literature.)

For W_2, the horizontal component of the muscle friction force, a restraining factor of 0.52 is again assumed. The evaluation of W_2, of course, depends also upon the acceleration. The general equation for the kinetic energy in this motion is $W_2 = mv^2/2$. To be sure, forward acceleration increases and decreases constantly according to the particular phase of the step, but an average velocity of about 0.6 m/sec may be assumed for slow walking. The work of forward movement, therefore, is

$$W_2 = 1.52\left(\frac{1}{2}mv^2\right) = 1.52\left(\frac{1}{2}\right)\left(\frac{65}{9.81}\right)(0.6)^2 = 1.812 \text{ kg–m/step}$$

The symbol W_3 is the work of the pendulum movement of the swinging leg and has the following value: $W_3 = \omega^2 I/2$, where ω is the angular velocity and I is the moment of inertia. The latter, as has been discussed, equals mass times the square of the radius of gyration. Now, the moment of inertia for the whole leg has been found as 0.146 (table 22). Taking an average value of 129° per step for ω, the swing ing arc, as expressed in radians, equals $(129/180)\pi$ or $(43/60)\pi$. Then,

$$W_3 = \frac{1.52}{2}\left(\frac{1}{2}\right)\left(\frac{43}{60}\pi\right)^2(0.146) = 0.281 \text{ kg–m/step.}$$

The sum $W_1 + W_2 + W_3 = 3.952 + 1.812 + 0.281 = 6.045$ kg–m work per step in horizontal walking. If we calculate the step length as 0.778 m, the entire muscle work performed in horizontal walk per meter distance covered would be $6/0.778 = 7.7$ kg–m.

From this first approximation showing that a man weighing 65 kg displays 7.7 kg–m work/m, or 7,700 kg–m/km distance, walking at a moderate speed of 5 km/hr, it can further be calculated that for each kg of his weight carried the distance of 1 m the computed work is 7.7/65 or 0.119 kg–m. That is to say, the so-called horizontal meter-kilogram would require 0.119 kg–m of work. It must be remembered that these calculations have eliminated the energy cost of many auxiliary movements and are only first approximations. This serious omission will become evident in the discussion to follow.

More rigid partitions of antigravity work and inertial work for walking have been presented by Braune and Fischer[50] and Pottevin and Faillie.[263] These journals were not available for review. The study of Benedict and Murschhauser[32] suggests that only about 13% of the total energy (oxygen consumption) of walking is antigravity work. The data of these investigators can be recalculated to give the values presented in table 26.

A single subject was exercised on a treadmill many times over a period of several months. The average raising of the body per minute (a) was recorded kymographically through a string fastened to the subject's belt. The speed-of-walking categories were arbitrarily chosen by the authors in the range of average velocities of column (b). Columns (c), (d), and (e) are self-explanatory. Each value in column (f) was calculated from an average of 10 values of total energy utilization (oxygen consumption) exhibited by the subject when most closely approximating the average velocities of column (b). Column (g) is a direct conversion of column (f) to horsepower by the formula

$$\text{hp} = \frac{\text{kcal}}{\text{min}} \times 60 \times 0.00156$$

(since 1 kcal = 0.00156 hp hr as listed at the beginning of this chapter). Column (h) is calculated as follows: hp for raising body = Weight × Average raising of body × $g/(4.47 \times 10^6)$, where weight is 71 kg, average raising of body is in m/min, and (g) is 980 cm/sec^2. The percentage of total energy expenditure going into raising the body against gravity is recorded in the last column (i) as (h)/(g) × 100.

It can be seen from these data that for the several speeds of walking, the raising of the body with each step increases in proportion

TABLE 26.—*The Energy Partition of Walking* [CALCULATED FROM THE DATA OF BENEDICT AND MURSCHHAUSER [32]]

Speed	(a) Av. rate of raising of body, m/min	(b) Av. forward speed, m/min	(c) Av. no. of steps per min	(d) Length of step, (b)/(c), cm	(e) Raising of body per step, (a)/(c), cm	(f) Total energy, kcal/min	(g) Total power, hp	(h) Power for raising body, hp	(i) (h)/(g) × 100, %
Walking:									
Low	2.88	69.3	108.2	64.0	2.66	3.65	0.34	0.045	13
Medium	6.69	109.0	130.9	83.3	5.11	6.21	.58	.104	18
High	7.90	144.5	152.4	94.8	5.18	10.92	1.02	.123	12
Running	13.76	147.6	181.9	81.1	7.56	9.72	.91	.214	24

to the total energy expenditure. Thus the relative cost of antigravity work for lifting the center of mass in walking remains the same at the low level of about 13%. The slow run, at about the same speed as the fast walk, entails a much greater elevation of the body relative to energy expenditure, with 24% of the total energy going into antigravity work. The overall energy efficiency of locomotion at a slow run, however, is greater than that at a fast walk where it is probable that relatively more vigorous movement of the arms is required. It should be pointed out that these investigators neglected the displacements of the center of gravity within the body brought about by limb movements.

It is of interest to note that Benedict and Murschhauser report a step lift rate of 3.78 m/min for another subject while he was walking at a speed of 75.9 m/min. Since his body weight was 73.1 kg, this corresponded to 276.2 kg-m or an energy requirement of 0.65 kcal/min for raising the body. The work against gravity was calculated to be 23% of the total energy increment above energy requirements for standing due to walking.

This value is similar to that presented by Smith [303] who pointed out rather gross differences between individuals in this respect. This author reports that the step lift work accounts for from 5% to 18% of the external work expended in walking. It should be pointed out that this energy for walking is given as the increment above that required for standing. For a single subject the percentage increased from 8% to 18% as the rates of forward progression increased from 43 to 78 m/min. In general, the work for standing alone was almost 1/3 of the total (oxygen consumption) required for walking. If we assume the 10% figure to be typical, then antigravity work would represent less than 7% of the total energy requirement for walking (oxygen consumption).

Data from the more recent studies by Elftman [101, 104] were not available in time for this report. The very recent accelerometer data of Cavagna et al.[66] on walking will be presented after the discussion of the study of Fenn [111, 112] on running. The data of Cavagna et al. become more meaningful in the light of the more rigid energy partition studies of the running subject.

Walking with a Load

The general nature of the walking step is the same when a load is carried, but the length of the step is decreased and the periods of support, especially the double support, are prolonged. The foot is placed flat on the ground and the contraction of the muscles of the calf of the leg is increased. The vertical oscillations are decreased both by the reduction of the length of the steps and by giving the knee slight flexion. When the load is carried on the head the center of gravity is raised and the stability of the body is lessened. It is better, therefore, to carry the load on the shoulders or the nape of the neck. When it is carried from the nape of the neck the body oscillates more in the antero-posterior plane. If a load is carried on the shoulder, the body adjusts itself to balance and the center of gravity remains approximately the same as before. But it is not possible by such adjustment to balance a load exceeding one-half or at the most two-thirds of the weight of the trunk. The recent studies of Iampietro and Goldman [176] suggest that with a well-placed load, the load weight may be simply added to the body weight with no efficiency penalty in calculating the total energy required in walking. This is of importance in the design of life-support pack systems.

Ascending Walk

The elevation of the body in ascending a stairway is produced by the contraction of the quadriceps and by the forward flexion of the trunk. The leg in gradual straightening sustains the whole weight of the body, while the rear leg by a movement which combines oscillation and flexion is brought up to the upper stairstep. In this case the horizontal distance between steps is reduced, as is also the period of oscillation, while the period of double support is correspondingly lengthened. In order to compute the work, one must add to the work of horizontal progression that which is accomplished by ascent, the latter being equal to the weight of the body multiplied by the height ascended. So the additional computation of the work would be $W=wh$ (where h is height), or if a man carries a load w_1, $W=(w+w_1)h$.

Walking on an inclined plane offers a situation which is a combination of that of ascending a stairway and that of walking on the level. It is therefore equal to walking on the level plus climbing up the stair. The period of double support is prolonged, the quadriceps and the anterior muscles of the thigh are contracted in the carrying leg, and the muscles of the calf cause the displacement of the rear leg. It must also be considered that in ascending an inclined plane the inclination of the body calls for a greater static effort than would be necessary in the ascent of a stairway of equal height. Therefore, one would expect that the expenditure of mounting to a given height on an inclined plane would be greater than that required to traverse the corresponding horizontal distance and then to reach the given height by means of a stair. As will be discussed below, the marked change in auxiliary motions of locomotion makes difficult the direct extrapolation from level walking.

Descending Walk

In descending a stairway the body is held upright, the carrying leg is bent, and the other leg is moved fully extended to the lower stairstep, where it becomes the carrying leg. The force of gravity is counteracted and a uniform rate of descent is maintained by the action of the gastrocnemius and the soleus muscles. In rapid descent of a stair the body bends so as to bring the center of gravity forward at the same time the flexion of the carrying leg is reduced. It bends somewhat, however, when the lower step is reached by the other leg. Also, the toe of the foot alone touches the ground at first contact. This is in contrast to the case of the slow descent, where the foot is placed flat on the ground.

In the descent of an inclined plane the body is inclined in order to maintain the same length of the pace. The muscle work is practically the same as that involved in descent of a stair of the same height as the plane, followed by progress on the level for the corresponding distance. Owing to the bending of the knees, however, the oscillations of the center of gravity appear to be considerably less than when walking on the level. Most of the work in this type of walking is done by the quadriceps.

Running

The partition of energy expended during sprinting has been studied thoroughly by Fenn.[111, 112] These studies will be reviewed in detail since they present the upper limits of energy expenditure in locomotion and allow a relatively quantitative estimation of antigravity work. Fenn summarized the energy partition of average men running at the maximum speed of about 8.2 yd/sec (25 to 30 km/hr) as shown in figure 32. The actual rate of useful work, 2.95 hp, was measured from a photographic analysis of the sprinters. The useful work against gravity in running is estimated by

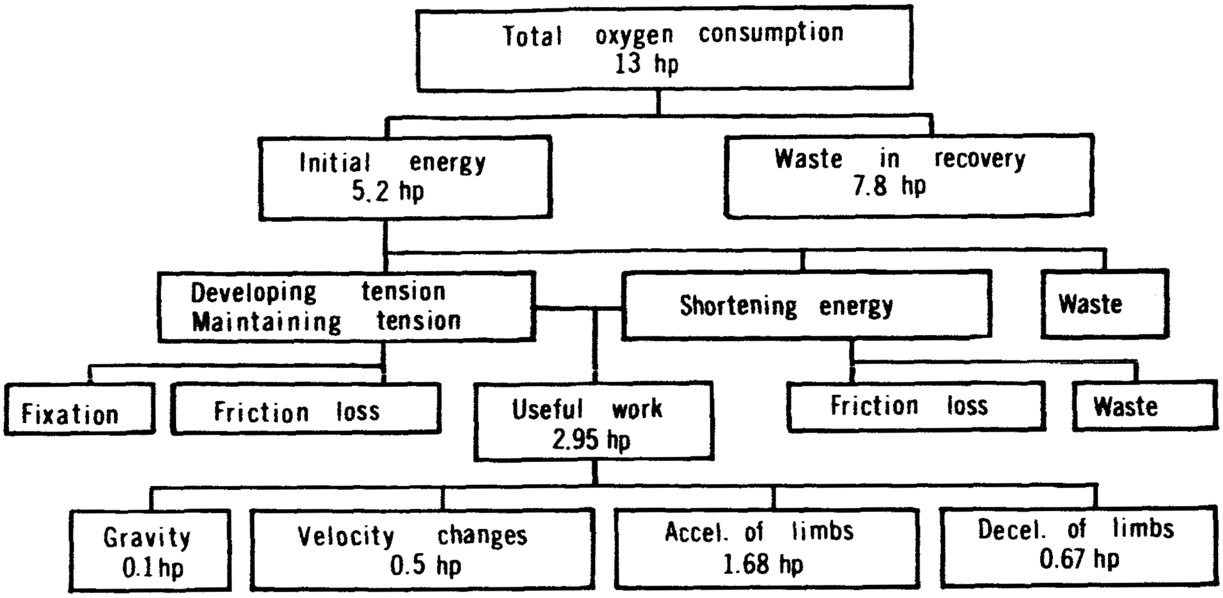


FIGURE 32.—Partition of energy in sprinting at 8 yards/second. (AFTER FENN.[111])

this study to be only about 3% of the total useful external work and 0.77% of the total energy expenditure (oxygen-consumption equivalent of 13 hp).

The category of "shortening energy" includes an unknown amount lost in overcoming friction and in development of energy for contraction. Energy for isometric contraction in fixation of joints is difficult to evaluate, as is the energy wasted in the metabolic processes. Thus, of the 5.2 hp initial energy, 2.95 hp can be accounted for with some degree of accuracy and 2.25 hp is left unaccounted for in three categories—fixation energy, waste heat, and frictional losses. The interesting relationship between speed of contraction and viscosity or internal "friction" factors has been recently reviewed by Podolsky.[262] The general diminution in work output of muscles with increasing speed of contraction appears to be due to both the diminished rate of energy expenditure and the viscous frictional loss, with no clear-cut partition of the two factors.

In his first paper, Fenn[111] studied the kinetic energy changes in the limbs during running. By photographic analysis of runners, he was able to calculate the changing angles of the limbs relative to the body. These data were applied to the center of gravity-mass data of Braune and Fischer[49] to give changing radii of gyration as described earlier in this report. Since the kinetic energy of any part of the body with relation to the body depends on its translational velocity with respect to the center of gravity of the body, plus its energy of rotation, the kinetic energy of the body as a whole may be calculated for any given movement from the formula

$$\frac{w_0 v_0^2}{2}+\frac{w_1 v_1^2}{2}+\frac{w_1 \omega_1^2 \rho_1}{2}+\frac{w_2 v_2^2}{2}+\frac{w_2 \omega_2^2 \rho_2}{2}+\ldots \quad (23)$$

where

w_0 total body weight
v_0 velocity of center of gravity of body with respect to ground
v_1, v_2 velocities of body parts in relation to center of gravity of whole body
w_1, w_2 weight of body parts
ρ_1, ρ_2 radii of gyration of body parts
ω_1, ω_2 angular velocity of body parts

In this study, the movements of the centers of rotation relative to one another were not accounted for. In the case of the shoulders it was calculated that these movements could account for 30 to 50% of the kinetic energy of the arms. Since the kinetic energy of the arms is small compared with that of the legs, and since the hips move very little relative to one another, omission of these joint movements causes an underestimation of only about 10% in the total kinetic energy of the limbs. Another factor is the constantly changing common center of gravity. The backward and forward rocking of the body and the changes in position of the center of gravity due to limb movements does add some error to the calculations. However, the shifts of the center of gravity of the body occur at velocities about 1/10 those of the limbs, and the total effect is not large. It will be discussed below.

The sum of all the increases in kinetic energy divided by cycle length gives horsepower. Table 27 gives the result of summed energy increases for one cycle. It can be seen that the energy contribution of the arms is only 1/4 that of the legs. The average rate of energy expenditure in the arms and legs is 1.68 hp. This represents 1.68/13 or 12.9% of the total rate of energy expenditure of 13 hp as

TABLE 27.—*Increases of Kinetic Energy of Arm and Leg During One Running Cycle* [AFTER FENN [111]]

	kg m	
Arm		
Upper		
Forward	0.43	
Back	.31	
Lower		
Forward	2.17	
Back	2.51	
Sum		5.42
Leg		
Upper		
Forward	3.38	
Back	3.35	
Lower		
Back	9.91	
Flex. of knee	4.33	
Forward	2.93	
Sum (as a whole)		22.82
Sum (by parts)		25.09
Arm and leg		30.51
Horsepower		1.68

measured by oxygen uptake. This considerable portion of total energy consumption was neglected in the discussion of the energy partition in walking.

The gravitational and energy transfer factors involved in this kinetic energy tabulation are of prime interest to the present discussion. In calculating the horsepower, it was assumed that each time the kinetic energy of a limb increases there is a corresponding expenditure of energy by muscles, and each time it decreases a corresponding amount is dissipated as heat. If it were stored temporarily as potential energy, it could reappear as kinetic energy either in some other part of the body or at some other phase of the cycle in the same member.

The question, therefore, arises as to whether the entire energy of downward movements is determined by gravitational factors alone. As was discussed previously, analysis of walking by Braune and Fischer [49] suggested that gravity played little role in aiding pendular movements. The studies of limb movements by King and Mans [189] also suggested that, in general, gravitational factors aid the work of downward movements of limbs only by a factor of 5%. Fenn calculated from velocities of the upper and lower limbs in downward movements that gravitational factors alone acting on the leg as a pendulum could account for only 1/2 the velocity of movement. In the case of the upper leg alone, only 13 joules of the 43 joules kinetic energy of the downward movement could be contributed by gravity. These 13 joules has to be subtracted from the kinetic energy of the upper leg during its backstroke. Fenn also pointed out that the weight of the lower leg does not serve to pull the upper leg down. Actually, the upper leg would fall more rapidly if the lower leg were absent. Likewise, the arm will fall to the side from the horizontal position less rapidly if a heavy weight is carried in the hand than if the hand is empty (provided friction, etc., is negligible). Its natural period as a pendulum is increased by the weight. The leg is pushed downward to some extent to make contact with the ground. On the forward stroke of the upper leg the maximum kinetic energy is reached at an angle of 75° with the horizontal. At this point a negligible fraction (4%) of the 13 joules has been restored to the leg in potential form and the remainder may be assumed to come from the kinetic energy it now possesses. Hence the kinetic energy as listed in table 27 requires no correction for gravity at this point.

From table 27 it appears that the upper leg develops a kinetic energy of 3.35 kg m on its backward stroke and a similar amount on its forward stroke. About 1.3 kg m of the forward stroke comes from gravity, and none of the backward stroke. Similar analysis for the more complex movements of the lower leg suggests that in one of the three phases of its travel, from the time the toe leaves the ground to the time the lower leg reaches maximum backward elevation during knee flexion, work is done against gravity. In the other two phases no effective antigravity work is done during kinetic energy peaks. The antigravity work in the knee flexion phase amounts to 1.58 kg m. Therefore, the 4.33 kg m of table 27 should read 4.33 + 1.58, or 5.91 kg m total work. On the whole, corrections of the leg energies for gravity involve a deduction of 1.3 kg m for the upper and an addition of 1.58 kg m for the lower leg, resulting in a negligible effective correction. Similar analysis of the arm reveals an insignificant gravity correction in the overall energy balance sheet of the body.

Even though the storage of energy as potential energy of position and its reappearance as kinetic energy is not an important factor in evaluating the mechanical horsepower of sprinting, it is possible that there could be such storage of energy in stretched tendons and muscles. Fenn concludes in his discussion of the controversial aspects of this point that:

> The tendons can be dismissed because the actual positions reached by the limbs in swinging are not sufficiently extreme to stretch the tendons without the participation of actively contracted muscles. Likewise the resting muscles could not exert appreciable tensions in the positions occupied by the limbs at the end of their strokes. If the limb were stopped entirely by frictional forces all its energy would be degraded to heat and there would be none to store. Suppose, therefore, that muscles must contract and exert a tension F against a moving limb for a time t such that Ft equals the decrease in momentum of the limb. In doing so the muscle is stretched and might be supposed to have stored up a certain amount of potential energy. It cannot retain this store of energy, however, without continuous contraction. If it has any potential energy it is continuously losing it at a certain rate and continuously redeveloping it. The balance between those two determines the amount of tension maintained and the energy of maintenance. A muscle may therefore be said to "charge storage" at a rate which would expend the energy value of the stored energy many times over a few seconds. In the movements of running, a study of the movies shows that the tension is maintained during the reversal of direction of motion of the limbs for the acceleration is practically constant during this period. Presumably in this case then the maintenance expenditure is less than the cost of redeveloping the tension and the backstroke must necessarily be somewhat quicker if the tension is already developed.
>
> But however that may be, the energy which the muscles save by thus avoiding the necessity of redeveloping a certain tension for the back stroke is no measure of the amount of potential energy corresponding to that tension; which is the question at issue for the present discussion. Nor can potential energy be measured by the work which the muscle will do when it is allowed to shorten.
>
> In conclusion it appears that during the reversal of a limb, the muscles are continuously innervated so that tension is maintained, redevelopment of tension for the back stroke is avoided and the energy equivalent of a certain amount of oxygen is saved. Such a saving of oxygen does not mean, however, a saving of mechanical energy. The kinetic energy observed in the return stroke may nevertheless have to be redeveloped *de novo* in spite of the fact that the necessary tension is still there. As a guess it might be said that the storage of energy would not be over 25% of the kinetic energy of the limb before reversal.

As discussed above in the calculations for the work of walking, Fenn chose the factor of 0.4 as the fraction of positive work required for deceleration of a moving limb by stretching muscles. In figure 32, this negative work factor is added to the total kinetic energy of limb movement (1.68 hp) to give a total of $1.68 + (1.68)(0.4) = 1.68 + 0.67 = 2.35$ hp.

Another factor in energy balance is the transfer of energy across the body by inelastic impacts. Fenn points out that when the foot is in contact with the ground in running it is occupied in exerting a force F backward on the ground for time t, so that Ft represents the momentum mv imparted thereby to the body. Much of this goes, for example, not directly into the body but into the other leg, which is being carried forward at a greater velocity than the body. When this leg reaches the end of its forward stroke, its momentum must be shared with the body as a whole according to the law of the conservation of momentum. In this way momentum can be transmitted about the body from one part to another, by a series of inelastic impacts. It is therefore pertinent to inquire to what extent kinetic energy can disappear from one limb only to reappear in another and so be counted twice in estimating the horsepower of sprinting.

Fenn has calculated that for the forward swing of the leg, the fraction of energy transferred to the body in general through the restraining hamstring muscles would be about 0.23 for the extended leg and 0.18 for the leg with knee bent. Moreover, Fenn points out that

> when one leg is going forward the other leg is going back so that the body is being twisted simultaneously in opposite directions. Thus neither leg will be able to twist the body and hence no energy can be transferred. The body is thus steadied by the opposite limbs in such a way that it behaves as if its moment of inertia or mass were much larger than it is. Hence the energy transfer is far less.

The transfer of energy through the body from one leg to another was calculated to be less than 1/10 of the energy of movement.

The question of transfer of energy from the upper to the lower leg and vice versa can be answered from the data at hand. As Fenn pointed out,

> when the kinetic energy disappears from the upper leg a corresponding amount should appear in the lower leg. A study of one of the photographs shows that in this runner, at least, the successive increases of kinetic energy in the lower leg cannot be derived in appreciable degree from the upper leg. Instead the kinetic energy contents of both upper and lower legs tend to increase and decrease more or less together. To test this point for all runners, the kinetic energy of the whole leg was determined for each point in the running cycle by adding together the figures obtained for upper and lower legs separately. The successive increases in kinetic energy of this combined curve were then determined and added together. The resulting sum [22.82] is shown in table 27. These figures are all slightly less than the corresponding figures [25.09] which were obtained by adding together the separate increases of the upper and lower legs. On the average, however, the difference is small, 22.82 kgm. m as compared to 25.09 kgm. m or a 9 per cent difference. Hence at most 9 percent of the kinetic energy could have been counted twice. This does not necessarily mean that 9 per cent was in fact transferred from upper to lower leg or vice versa. Possibly therefore the figure 1.68 horsepower for the arms and legs is 9 per cent too high and the true figure is 1.53 hp. This small reduction, however, is completely offset by the previous estimate that the movements of the shoulders if allowed for would increase the observed kinetic energy of the limbs as a whole about 10 percent.

Another major factor in the analysis of total energy is the movement of the center of gravity of the body with respect to the ground. By analyzing the shift in center of gravity of the total body mass brought about by movement of the limbs, Fenn [112] was able to show that the whole body rises synchronously with the rise of the center of gravity within the body. The total effective body rise, which reaches a maximum just at the end of foot contact, is equal to the sum of the rise of the center of gravity with respect to the ground and the rise of the center of gravity of the total body mass, which are of about equal magnitude. Since the rise occurs during actual foot contact, the runner does not leap into the air more than 0.76 cm. He raises both himself and the center of gravity while his foot is on the ground and then lets his body drop a distance of 3.06 cm while he is in the air. Since the average rise of the body as a whole was about 3.12 cm and the average rise of the center of gravity within the body is 2.92 cm, the total effective rise is 6.04 cm. Assuming an average weight of 68 kg and a cycle length of 0.5 second, the body is lifted 6.04×4 or 24.16 cm per second. The horsepower can be calculated as

$$\frac{68 \times 24.16 \times 980}{746 \times 10^4} = 0.215 \text{ hp}$$

Since the rising center of gravity within the body stems from limb movements, this energy should not really be counted as an extra energy expenditure. Therefore, only (2.92/6.04) (0.215) or about 0.1 extra horsepower is needed for elevation of the whole body. (See fig. 32.) Thus, a grand total of 0.215/2.95 or 7.3% of the external work used in running goes to work against gravity, and 1/2 of this, or 3.7%, is unaided by the kinetic energy of the limbs. Antigravity work may also be expressed as 0.1/13 = 0.77% of the total energy (as oxygen uptake) used in sprinting. It is of interest to compare these sprinters traveling at 8.2 yd/sec with those of Benedict and Murschhauser[32] running slowly on a treadmill at 147 m/min, or about 2.5 yd/sec. Fenn's subjects rose 3.12 cm/step while Benedict and Murschhauser's rose 7.56 cm/step. Marey and Demeny[226] report a rise of 3.3 cm/step for free runners at 7 yd/sec velocity. Thus it appears that slow treadmill running involves a greater percentage of work against gravity than does sprinting on level ground. This is seen in the comparative figures for antigravity work as percentage of total energy used (oxygen consumption), 0.77% for Fenn's sprinters as opposed to 24% for Benedict and Murschhauser's runners. That walking on a treadmill involves more antigravity work than walking on level ground at the same speed is a possibility for which no good data appear available.

There arises a question of the reutilization of this potential energy by the elevated body. The restoration of this energy in the "bounce" of the runner falls into the same category as the storage and reutilization of energy in the pendulum swing of the limbs. By extension, the knees are put into a position where they can develop tension. As Fenn points out, this "passive" tension over and above the "active" tension of the muscle must be maintained by active energy. All that the body can gain is the energy required to develop this tension. Thus the bounce factor does not appear to be very important in vertical energy conservation. As seen below, Cavagna et al.[66] interpret this point quite differently.

The backward and forward movements of the center of gravity within the body appear to be minimized by the fact that the backward and forward movements of limbs are compensatory on both sides of the body. Changes in velocity of the pelvis are also counteracted by movements of the center of gravity which oppose them. The lateral movements were not analyzed.

From studies of ground pressure with a force plate, Fenn determined that the forward pressure on the ground as the extended leg hits accounts for 0.34 horsepower, and the backward pressure, an expenditure of 0.5 horsepower. The difference between these is 0.16 horsepower, an appropriate factor for wind resistance.

Thus, the partition of external energy of sprinting at about 8.2 yd/sec (25 to 30 km/hr) is seen in figure 32. Of the 2.95 horsepower of useful external work, only about 3% is used against gravity, 15% in horizontal velocity changes, 60% for acceleration of the limbs, and 22% for decelerating limbs.

It would thus appear that the speed and mode of locomotion are both significant in the determination of energy partition and gravitational factors. A recent Italian study sheds more light on this question. Cavagna et al.,[66] stimulated by the finding of Margaria[227] that there is a forward velocity at which the oxygen consumption per kilometer traveled is a minimum, proceeded to study by means of a triaxial accelerometer the energy partition of walking at several speeds. They integrated the accelerations of the instrument (fixed to the waist) with photographic analysis of limb and trunk displacements. Figure 33 demonstrates graphically how the accelerations applied to the trunk increase with speed. The vertical accelerations increase the most; the forward accelerations, the least. The extents of vertical swinging were similar to those found by Benedict and Murschhauser[32] in recording the vertical swing from the waist of a subject walking on a treadmill. These authors found values of from 25 mm in walking at 3 km/hr to 50 mm in walking at 9 km/hr.

Cotes and Meade[75] found vertical displacements of 5 to 50 mm for steps up to a length of 0.9 m and concluded that the displacement increases with the square of the step length. This, however, is not in agreement with results of Cavagna et al.,[66] particularly at high speed, when the length of the step is 1 m or more. Apparently the vertical displacement increases with the length of the step, but it tends to approach a constant value when the step is over 0.9 or 1.0 m.

The lateral displacements of the trunk are at a minimum at about 3 or 4 km/hr and increase at higher or lower speeds. Actually 3 or 4 km/hr is the speed at which oxygen consumption per kilometer is at a minimum. The work in the forward, vertical, and lateral directions

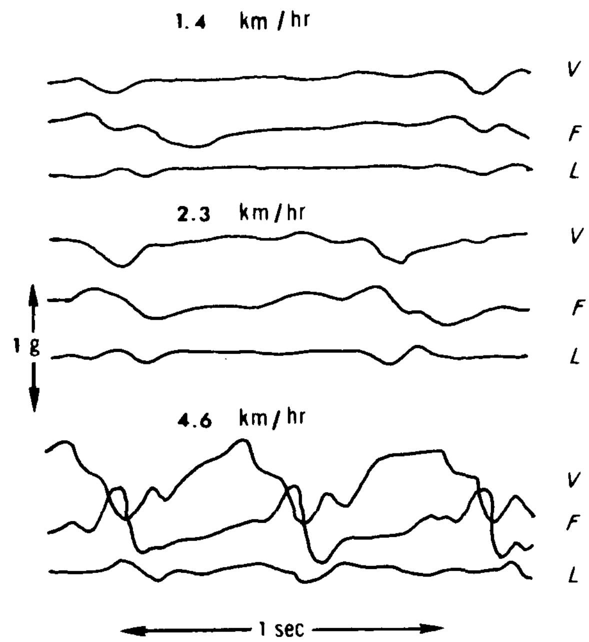


FIGURE 33.—Accelerametric diagrams of subject walking at various speeds. Heavier lines indicate right heel is on the ground. *V*, vertical; *F*, forward; *L*, lateral. (AFTER CAVAGNA ET AL.[66])

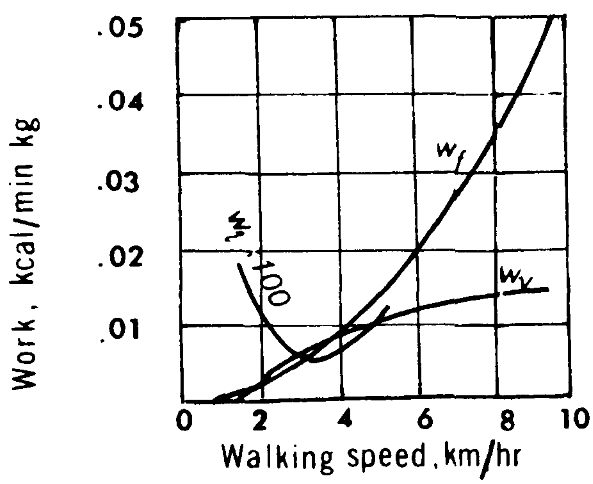


FIGURE 34.—Work due to speed changes of the trunk in forward direction (W_f), work done against gravity, calculated from vertical displacements of the trunk (W_v), and work calculated from speed changes of the trunk in lateral direction (W_l)$\times$100, as functions of walking speed. (AFTER CAVAGNA ET AL.[66])

was calculated and recorded in figure 34. The lateral work is about 1% of the vertical work at 4 km/hr. The work in the forward direction is roughly defined by

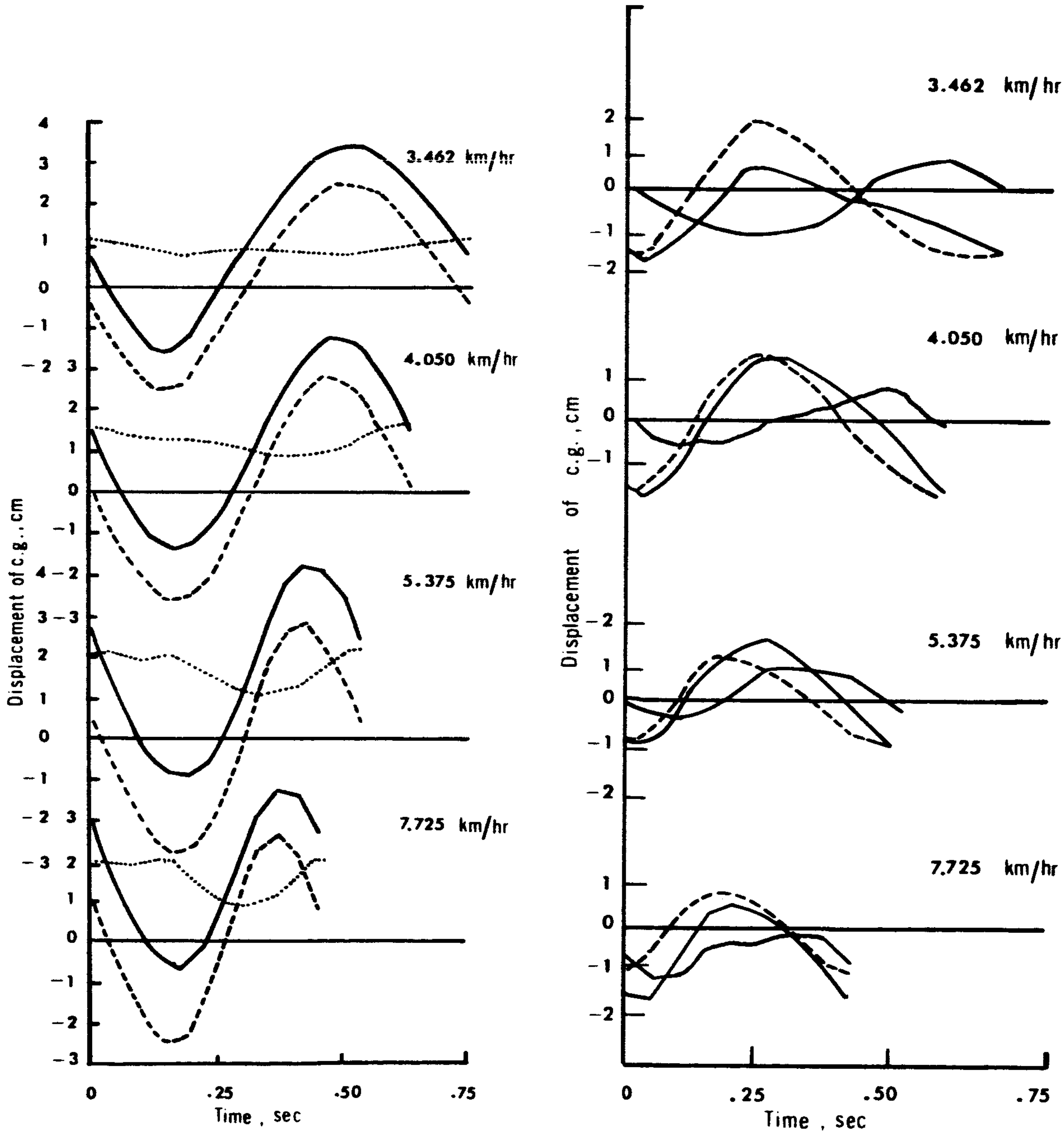
$$W_f = 5.2 \times 10^{-4}\,\bar{v}^2 \qquad (24)$$

where $\bar{v}$ is mean forward velocity. It is of interest that the work required for Fenn's sprinter to maintain speed in the forward direction at about 27 km/hr amounted to 2.6 hp. This figure for a 70 kg male amounts to 0.39 kcal/min kg. Extrapolation of the velocities in figure 34 to 27 km/hr gives approximately this energy for W_f.

It must be remembered that some of the work W_f may be transferred to W_v during the lift of the body; and, vice versa, some of the potential energy of the body may be transferred to an increase in forward speed during the body fall at each step. This aspect, however, will be more extensively treated later.

As determined by Fischer[115] and Fenn,[111] the displacements of the center of gravity by limb movements were calculated for only the forward and vertical directions. In figure 35 (a), the vertical displacements of the trunk, as calculated by double integration of the accelerometric tracing, are given (dashed line) together with the displacements of the center of gravity within the trunk, as calculated through motion picture analyses (dotted line). The instant at which the right heel touched the ground was indicated both on the motion picture frames and on the accelerometric diagram, and it was considered the zero time for the cycle. The continuous line is the sum of the two, the final displacement of the center of gravity. Data for different speeds of walking from 3.4 to 7.7 km/hr are given. In figure 35(b) forward movements, relative to the position of the body moving at the average constant speed, are given. The zero line is the position of the center of gravity within the body when standing in the erect posture.

The center of gravity within the trunk is consistently higher when walking than when standing because of the more or less permanent flexion of the arms and legs. The vertical displacement of the center of gravity within the trunk is approximately constant when walking at low speed and the displacements of the center of gravity parallel the displacements of the trunk. Therefore, the data obtained from the accelerometer fixed to the trunk appear to be representative of the displacement of the center of gravity. Motion picture analysis, however, is necessary to obtain an accurate description of the movements of walking at speeds higher than 5 km/hr.



(a) Vertical displacements.

(b) Displacements in forward direction.

FIGURE 35.—Displacements of center of gravity within the body (dotted line) and of the trunk (dashed line). Continuous line is the sum of the two, the final displacement of center of gravity. Zero line is position of center of gravity of body when standing in erect position. (AFTER CAVAGNA ET AL.[66])

From these displacement curves for the center of gravity, the curves of acceleration and also of work can be graphically determined. Figure 36 is a graphic description of this work with the same time coordinates as figure 35. Neglecting the work due to lateral displacements, which is insignificant, the sum of W_f and W_v gives the total external work W_t. The vertical displacements d_v of the center of gravity have been replotted from figure 35(a). When the center of gravity of the subject moves in a direction opposite to the gravitational and/or inertial forces, "positive" work must be accomplished by the subject's muscles (work curve rises).

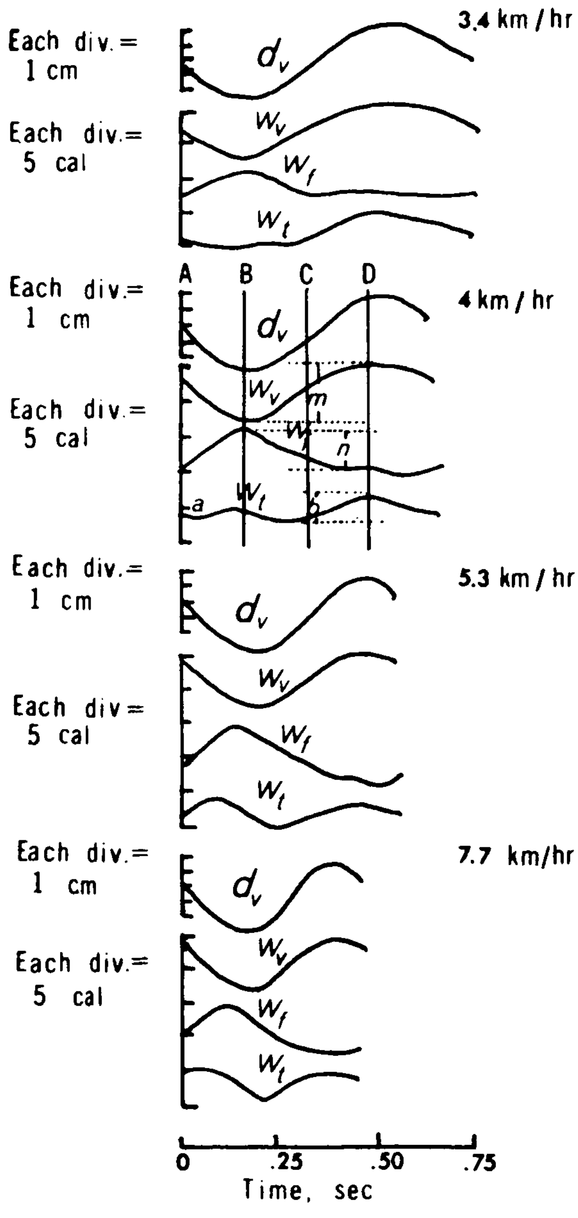


FIGURE 36.—Work due to speed changes of center of gravity of body in forward direction (W_f), work due to vertical movements of center of gravity of body (W_v), and sum of the two (W_t). Displacements of center of gravity of body in vertical direction are labeled (d_v). (AFTER CAVAGNA ET AL.[66])

It immediately becomes apparent that the problems raised by Fenn[111, 112] and others regarding the interplay between work done against gravity, work due to forward speed changes, and work to accelerate and decelerate the limbs are with us again. Cavagna et al. approach the negative work problem in the following way. They agree with the concepts of Hill regarding negative work factors and point to the experiments of Margaria as a quantification factor. Margaria[227] had shown that in uphill walking (positive work), the efficiency as expressed by the ratio of body lift to energy expenditure approaches a maximum value of 0.25, while in downhill (negative work) walking or running, it approaches 1.20. Using the energy requirements found in this study as a test of their partition hypothesis, Cavagna et al. analyze figure 36 as follows:

> The total negative or positive work per step is given by the difference between the highest and lowest values of W. As for W_t, the curve has two maximums and two minimums; the work is given by the sum of the two differences, a and b of figure 36. This sum is smaller than the work performed in the vertical direction only, m, evidently because the work done in lifting is sustained in part by the inertial force of the forward-moving body. For this reason the work against gravity alone is not representative of the whole work performed in walking, leading paradoxically to a higher value than when the work calculated in the forward movements is also considered. Also, the total work done against gravity, m, cannot be added to the total work due to acceleration in forward direction, n, to obtain the total work per step without incurring a very appreciable error; this is because the changes of W_f and W_v at each instant are mostly of opposite sign, one taking place at the expense of the other.

The failure on the part of Fenn[111, 112] to consider seriously the transfer of part of the vertical work to the horizontal is criticized by Cavagna et al. with the analysis of their own data. The curves for 4 mph in figure 36 are dissected in the analysis as follows:

From A, when the heel touches the ground, to B, the main episode is the change of energy of the falling body from potential to kinetic; at B, in fact, speed is at its maximum. The energetic level of the body, however, has increased a little, of the amount *a*, representative of the positive work performed, which is due to muscular activity represented by the forward push by the leg which is behind. From B to C, the kinetic energy of the body is transferred to potential again, as the lifting of the body takes place.

The highest positive work takes place in C to D, this being the expression of the active intervention of the muscles in the second part of the body lift. Evidently the kinetic energy of the body, when its center of gravity is at its lowest, is not sufficient to provide for raising the body the required height, and an additional activity of the muscles must take place. The greatest amount of work done by the muscles in level walking at low and moderate speed, is spent in raising the body, the forward push being sustained mainly by the energy of the falling body.

The questions raised by Fenn regarding the efficiency of transferring "falling energy" of the center of gravity of the whole body as well as of the pendular limb movements to forward progression arise once again. Fenn, as discussed above, minimizes this transfer. Cavagna et al. have added W_f and W_v only from phase to phase to give W_t in figure 36. Also, in figure 37, total external work W_t and work done against gravity W_v were plotted (in kcal/km kg) against walking speed. The difference between the two curves is interpreted as the utilization of the kinetic energy of the forward moving body in the lift of the body itself. The external work seems to reach a maximum value at about 4 km/hr, the speed at which walking has been found to be most economical.

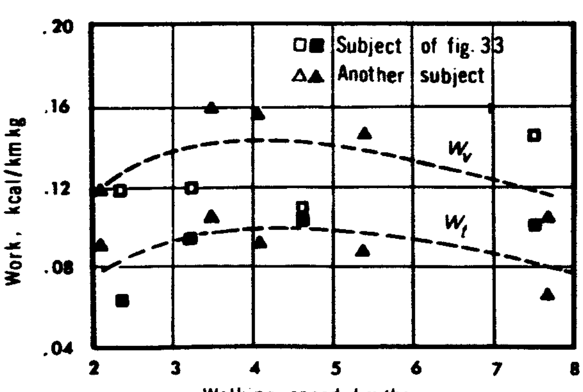


FIGURE 37.—Work done against gravity (W_v) and total external work (W_t) plotted against walking speed. (AFTER CAVAGNA ET AL.[66])

How does this approach to partition of energy agree with oxygen consumption figures? Assuming that the efficiency for "positive work" is 0.25 and for "negative work" is 1.20, as the data of Margaria[227] for uphill and downhill walking seem to suggest, the total energy consumption will be the sum of the negative and positive work, each divided by the respective efficiency:

$$\frac{W_{t,pos}}{0.25}+\frac{W_{t,neg}}{1.20}=\frac{W_t}{0.21}$$

The work being about 0.1 kcal/km kg at 4 km/hr, the energy consumption in level walking at this speed can be calculated as 0.1/0.21=0.48 kcal/km kg, which is the same as the value found by Margaria in direct determination. All the mechanical work done in level walking at 4 km/hr is, therefore, considered as external work available for locomotion. The internal work—work required to overcome muscle viscosity and to sustain (a) muscle isometric contractions involved in making the body rigid and in fixating the joints and (b) equal and opposite movements, which do not contribute to the displacements of the center of gravity of the body in the surrounding space—appears negligible from the above analysis. Cavagna et al. feel that "only at low speeds, because of the static contractions of the muscles, and at high speeds because of considerable stiffening of the limbs and movements not involving a displacement of the center of gravity" is the internal work of significance. This is presented graphically in figure 38. Presence of a dip in such an oxygen consumption curve at 4 km/hr has been reported in the past by Atzler and Herbst,[11] Ralston,[270] and others.

As indicated above, one can question the degree of transfer of "falling energy" to forward progression, and also the determination of W_t by the method of figure 36. Too, the utilization of the efficiencies of negative work and positive work from the uphill and downhill walking studies of Margaria to arrive at an overall efficiency of 21% in level walking may be questioned. In the discussion of the studies of Abbott and his coworkers[1,2] regarding negative work, it was suggested that only when muscles are performing the same movement patterns can positive and negative work be compared. This is obviously not the case in uphill and downhill walking. It is possible that the failure to account completely for the energy of acceleration and deceleration of the limbs is compensated for by errors arising from transfer-of-energy considerations in the calculation of W_t. Partition and quantification of these potential errors are not possible at this time. The negative work factors and the efficiency of use of elastic energy will be further complicated by changes in gait determined by subgravity conditions. They should nevertheless be kept in mind in the evaluation of these data, which otherwise appear to account adequately for the energies of walking.

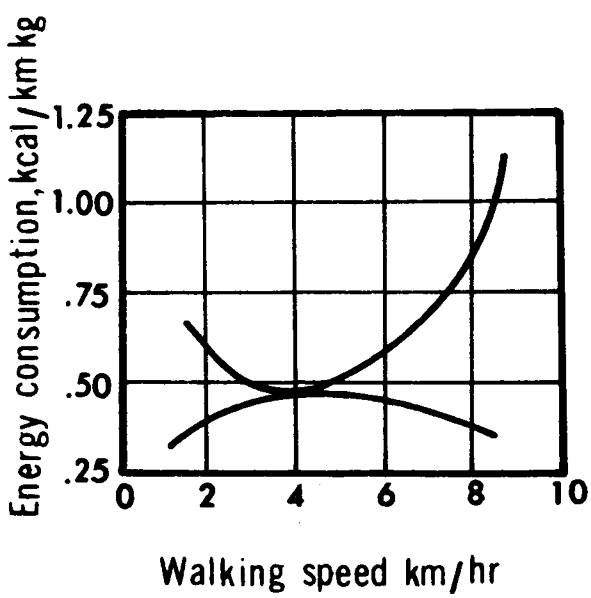


FIGURE 38.—Energy consumption due to external mechanical work, assuming efficiency of 0.21 (lower line) and effective energy consumption found in direct determinations (upper line), plotted against walking speed. (AFTER CAVAGNA ET AL.[66])

Studies in energy partition are currently being pursued under NASA contract by Dr. H. J. Ralston and his coworkers at the Biomechanics Laboratory, School of Medicine, University of California. No recent material has been published as yet. The general conclusions reached above regarding effects of velocity and mode of locomotion on energy partition appear to be corroborated by these investigations. The added work factors involved in the loading of lower extremities or immobilization of hip, knee, or ankle are also being pursued.[268, 269, 270] It is of interest to relate a mountaineering maxim[244] that "one pound increase in shoe weight is equivalent to three pounds increase in back weight." No formal studies could be uncovered to substantiate this, though Ralston[268] is currently studying the general problem. Effects of weight distribution and sandy terrain on energy partition are quite pertinent to the lunar problem.

Experiments in Energy Requirements

In the past few years there have been several lines of experimentation which give some vague insight into the problem of energy requirements for work in subgravity states. The difficulty of maintaining steady subgravity conditions in aircraft has prevented adequate empirical studies of the work of walking in constant subgravity. There are, however, several parallel studies in which some of the projected difficulties have been tested.

Hess and Konecci[167] have attempted to study the ability of subjects to perform torque and linear force work while suspended from three helium-filled balloons enshrouded by a parachute canopy. Subjects were sedentary workers who wore a Navy MA–1 step-in harness assembly with risers attached to the fabric cuffs. The effects of reduced traction on pushing and pulling were studied by the use of a Chantillion push-pull meter. The tests in figure 39 are as follows: "Pulling I" is the pulling of a handle with both hands while facing the load; "Pushing" means pushing with both hands the handle directed against the load; "Pulling II" is pulling by means of a web belt around the waist while facing away from the load; "Applying torque" involves pulling the handle of a metered torque wrench against a fixed nut from a fixed position with feet 17 inches apart while facing the nut. Unfortunately no figures are given for the effective weights of the subjects during these tests. Only "reduced g" is stated. It can be seen, as expected, that the reduced-g traction in all conditions decreased the effective loads pulled or pushed and the torque applied. The torques were least degraded. Each test varied in difficulty from subject to subject. There was a high within-subject correlation between performance in high- and low-traction environments.

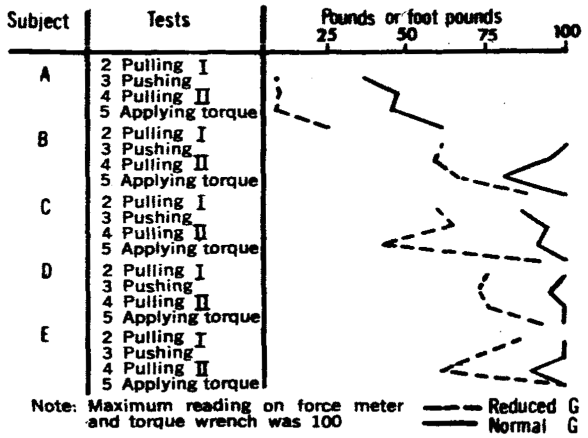


FIGURE 39.—Mean performance profiles on force and torque application tests. (AFTER HESS AND KONECCI.[167])

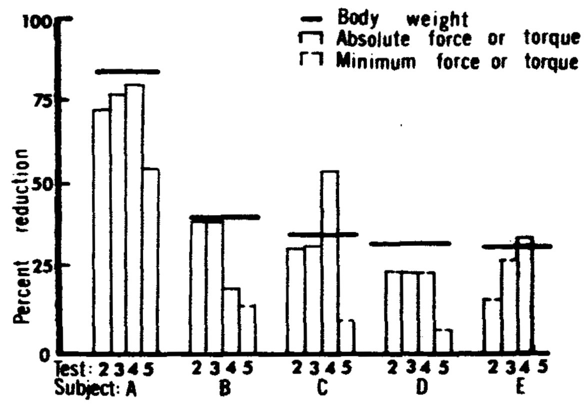


FIGURE 40.—Percentage reductions in force and torque applications, and body weight, under simulated reduced gravity. (AFTER HESS AND KONECCI.[167])

Figure 40 shows the correlation between percentage reduction in body weight and the force or torque. It should be mentioned that failure to suspend the subject through the center of gravity (second sacral vertebra) probably had some effect on results by changing the normal patterns of force moments about the body. No mention is made of the energy expended in performing these tasks. At the American Rocket Society Meeting in December 1962, the Douglas Aircraft Company demonstrated the effects of the balloons on walking. No formal reports of these studies were available to the author. In these demonstrations suspensions were again from the shoulder and would be expected to further complicate interpretation of results.

The studies of Dzendolet[96] and Dzendolet and Rievley[97] on the application of torques in zero-gravity maneuvers indicated that bracing was a critical requirement in such work. That subgravity work also requires bracing procedures is made evident in the studies of reduced-traction environments by the Boeing Company. Springer et al.[311] attempted to study the effect of a one-degree-of-freedom tractionless environment on the metabolic cost of work, hypothesizing that the development of unusual force patterns should require the use of muscle groups other than those normally employed, with consequent reduction in energy efficiency. The self-paced task consisted of a horizontal reciprocating movement of the handle of a modified wall exerciser. A 7 or a 15½ lb weight was elevated and dropped 22½ inches as a result of the maneuver. The subject used his right hand and braced with the left hand on a vertical bar, while standing on a one-degree-of-freedom platform. Lock pins held the platform for control studies. Reciprocation, always parallel to the long axis of the push bar, was attained by ball-bearing sheaves. Tables 28 and 29 indicate that for the 7 lb load there was a 12% increase and for the 15 lb load, a 29% increase in oxygen consumption for the task when performed in the tractionless rather than the fixed-base environment.

More recent studies of Streimer et al.[317] with the same test apparatus have included the addition of several more degrees of freedom to the suspensory apparatus holding the subject. In the 0 and 1-df (degree of freedom) tests, subjects were seated, in restraint, in a chair bolted to the 1-df reciprocating platform described above. In the 2-, 3-, and 4-df tests the subjects were seated in a special chair which is part of a suspensory system previously described.[317] Briefly, the system suspends the subject in a bent-L frame with the short axis of the L parallel to the ground and the long axis at an oblique angle to the vertical plane. The end of the short arm is affixed to a bearing plate at the subject's center of gravity.

TABLE 28.—*Metabolic Cost for 7 Pound Load* [AFTER SPRINGER ET AL.[311]]
[10-minute work period, 14 subjects]

	Oxygen consumption, liters/min/hp		
	Range	Mean (a)	Standard deviation
Tractive	28–49	36.7	6.5
Nontractive	33–50	41.2	5.1

[a] 12% mean increase, significant at 0.01 level. Standard error of the mean of the differences = 0.98. Produce-moment r between tractive and nontractive states = 0.59.

TABLE 29.—*Metabolic Cost for 15½ Pound Load* [AFTER SPRINGER ET AL.[311]]
[10-minute work period, 10 subjects]

	Oxygen consumption, liters/min/hp		
	Range	Mean (a)	Standard deviation
Tractive	25–37	29.8	3.9
Nontractive	32–50	38.6	5.9

[a] 29% mean increase significant at 0.001 level. Standard error of the mean of the differences = 1.35. Produce-moment r between tractive and nontractive states = 0.69.

Shoulder harness and lap belt retain the subject in a relatively immobile position in a seat affixed to the bearing plate. This arrangement permits freedom of reaction in a vertical plane only. The other end of the frame is attached to a universal gimbal which permits rotation in a horizontal plane and translation in an arc of 8-foot radius. This circular motion against gravitational forces required an energy input, but this input (except for the small amount lost in system friction) was reintroduced as the system returned to the null point. The maximum vertical displacement observed was ½ inch. The system is constructed in such fashion that, by its adjustment capabilities, lines drawn through the overhead and horizontal pivot points intersect at the resting subject's center of gravity. This system is nearly tractionless and closely simulates those characteristics of 0 g most pertinent to force and power production by the man. It was possible to provide, via mechanical locking methods, a limited combination of degrees of freedom for purposes of experimental investigation. These may be described as follows:

(a) 2 df—Subject free to translate horizontally in all directions

(b) 3 dfA—Subject free to translate horizontally in all directions and rotate in a vertical plane

(c) 3 dfB—Subject free to translate horizontally in all directions and rotate in a horizontal plane

(d) 4 df—Subject free to translate horizontally in all directions and to rotate about his own center of gravity in planes parallel and perpendicular to the floor

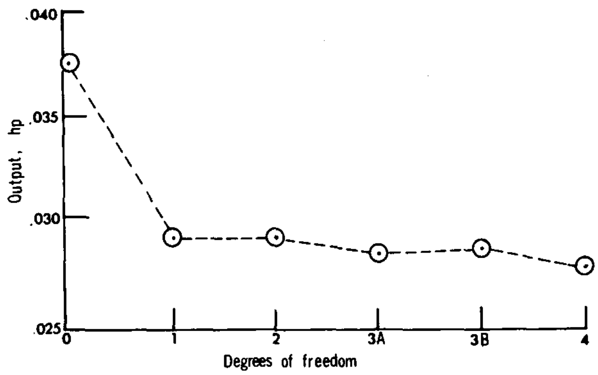


FIGURE 41.—Horsepower output with various degrees of freedom on reciprocating task; 15-pound load and 22-inch stroke. (AFTER STREIMER ET AL.[317])

The reduction in horsepower output observed with increasing degrees of freedom is seen in figure 41. The differences between 2, 3A, 3B, and 4-df are not significant statistically. Figure 42 shows how the energy efficiency of work decreases as the degrees of freedom are increased. At 4-df, there is a 70% increase in the oxygen/horsepower ratio over that of 0-df. The difference between efficiencies for 1–df and those for 2–df were not statistically significant at the $P=0.05$ level; nor were any other comparisons of efficiencies except those between 0 or 1–df and 3A, 3B, and 4–df. Even though the actual resistance to motions created by friction in the system was not defined, it is apparent that a severe metabolic penalty can be expected for work in a tractionless environment, of which subgravity states are special cases.

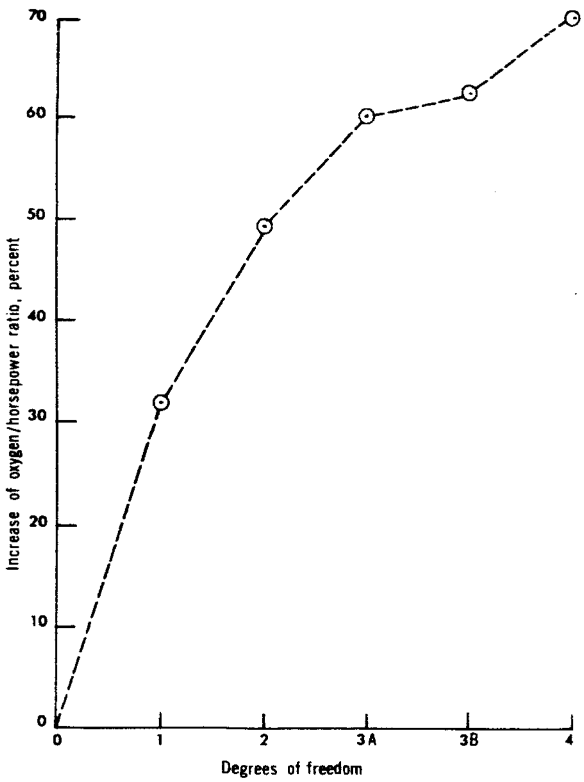


FIGURE 42.—Percentage increase of oxygen/horsepower ratio for a reciprocating task; 15-pound load and 22-inch stroke. (AFTER STREIMER ET AL.[317])

The conditions of this study are far more severe, in a traction sense, than would be expected in a lunar environment. They actually approach the zero-gravity envelope. Nevertheless, the results show that the use of alternate muscular patterns for accomplishing a task can impose a considerable metabolic load.

How various subjects responded psychologically to similar changes in traction has recently been studied by Jacobs.[179] The air-bearing platform he used as a severe test of learning, though again quite different from a lunar gravity problem, gave some insight into the value of previous educational experience in the learning process. Details of the paper are beyond the scope of this report.

There are several other approaches to reduced-traction environments. The Swedish have recently initiated studies on the effect of slippery surfaces on the mechanics of walking.[64] As discussed above, body equilibrium is lost with the take-off of the propelling foot when the center of gravity momentarily lies beyond the anterior border of the base support. It is regained as soon as the swinging leg is extended forward and the heel touches the ground. The horizontal component of the force applied by the foot when it touches the floor acts forward and is counteracted in normal walking by a frictional force of the ground acting in the opposite direction. Both static and dynamic friction are proportional to the normal force which exists between two surfaces and are independent of the area of the surfaces. Thus, in subgravity states the reduced normal force adds to the problem of slippage on encounter with surfaces of low coefficient of friction. Walking on ice under 1 g, with its attendant changes in gait, is a good model for such activity. The Royal School of Gymnastics of Sweden in cooperation with the Swedish Royal Institute of Technology has embarked on a study of these gait changes brought about by low-friction surfaces. While only preliminary data have been published, force plate and electromyographic studies have demonstrated different foot pressure and muscle patterns which are encountered under these conditions. Data from these studies should be of value in analysis of potential compensatory patterns in subgravity gaits.

Animal studies in zero gravity shed little light on the walking problem. Gazenko et al.[124] report that in the studies of Kasyan and Yuganov it was sufficient to rotate mice at only 0.2g while in zero–g trajectories and "the animals stop rotating and acquire the ability to fix the position of the body and perform rotations without noticeable disturbance of coordination." These oft-quoted studies probably have little meaning in terms of setting 0.2g as the lower limit for adequate coordination in walking. The coincidence of the 0.2g value with the values of Loret [214] may be entirely fortuitous. The instability in vehicular flight path reported in previous American studies on humans may well have been a contributing factor to the difficulties of the mice in the Russian studies.

Studies in zero-gravity parabolas within C-131 airplanes have indirectly provided some interesting data regarding tractionless environments.[298] Under these conditions, in walking while suspended upside down by magnetic shoes, slipping or "skating phenomena" resulted from inadequate magnetic traction. A review of the "skating phenomena" suggested that to walk in normal gravity, man must exert a force parallel to the surface on which he is standing in order to accelerate the center of gravity of his body about 330 cm/sec^2. For forward progression, the coefficient of friction must be such as to allow the appropriate frictional force between the foot and the surface. Now, $f=\mu n$ where f is frictional force, μ is the appropriate coefficient of friction, and n is force normal to the contact plane of the two objects. If a shear force greater than the frictional force is applied, sliding occurs. The data presented by Simons [298] can be handled better by using the values of Klopsteg, Wilson, et al.[192] As seen in figure 30, a 150-lb subject produces a surface shear, primarily in the fore-and-aft direction, of about 35 lb. The necessary coefficient of friction to avoid slippage is

$$\mu=\frac{f}{n}=\frac{35}{150}=0.23 \qquad (25)$$

Simons suggests that since the main quantities necessary to evaluate the "efficiency" of such a system (whether or not sliding will occur) are the applied shear force and the static frictional force, it may be convenient to treat these as a ratio rather than to consider whether they are equal or not. This ratio between the frictional force and the applied, or shear, force might be called the "skating index." If the index were a fraction less than 1, sliding or "skating" would occur. If it were 1 or greater, normal walking would be possible. The index is a balancing point between the unit mass, unit center of mass, horizontal shear forces, and vertical shear forces on the one hand, and the area of contact, magnetic force, and coefficient of friction on the other. It could be of value as a constant for the attraction qualities of dynamic systems.

Other studies in zero-gravity parabolas present more empirical data on subgravity locomotion. The preliminary studies of Loret [214] were performed for the purpose of optimizing manned orbital satellite vehicle design with respect to artificial gravity. The experiment involved an evaluation of the ability of man to walk unaided under various levels of fractional gravity (less than 1 g and more than 0 g). The fractional gravity levels were obtained by flying a C-131 aircraft through Keplerian trajectories. Personal communication with Sharp,[293] who conducted these experiments, leads to the conclusion that sudden roll, pitch, and yaw movements in the parabolas made it difficult for the subject to maintain balance. Only 1 subject was studied, in 5 to 7 parabolas. No pressure suit was worn. That the plane was unsteady was obvious from the fact that prior to losing his balance, the subject was seen to separate from the floor of the aircraft. This factor alone would negate any conclusions from this study regarding walking in a steady 0.2g environment. Sharp is currently studying the unusual locomotor patterns in zero gravity using Velcro sneakers and walkway systems.

Roberts [272] has recently followed up the preliminary studies of Loret with comparative analysis of gait at 0.1 to 1.0 g in the C-131. Photographic analysis of the "shirt-sleeved" subject permitted calculation of stride parameters in subgravity. In figure 43 the velocity, step length, and step frequency are plotted for two subjects at different gravity levels. It can be seen that to maintain a constant velocity, subject B increased step length while subject A increased frequency. In the region of 0.2g there was indeed decompensation of gait. In figure 44 the times required for respective phases of walk may be seen. The swing time appeared to be altered most significantly. A rough approximation suggests that in the range of $0.25 \leqq g \leqq 1$, swing time varied inversely as the 6th root of the gravity level; in the $0.1 \leqq g < 0.25$ range, inversely as the 5th root of the gravity level. In comparison with the normal-gravity swing-time/support-time ratios of 0.5 to 0.8, the ratios in these experiments increased from 0.65 at normal gravity to 0.9 at less than 0.2g. As a result of this changing ratio there was a noted loss of body control during walking; the low-gravity gait was described as a "fast walk in slow motion." Force-plate studies in subgravity are currently planned by this group.

Roberts [271] has reported a study being initiated at the U.S.A.F. Air Institute of Technology to devise a semiautomatic system for maintaining steadier subgravity environments in the research aircraft. In this system, which the Lear Corporation has already installed in the C-131 aircraft, the pilot nulls a cockpit instrument programed to produce various preselected trajectories. This approach seems to be a most significant advance in the very urgent quest for data on subgravity locomotions.

Many of the principles outlined above become evident in the studies of Lomonaco et al.[213] performed in Italy. These will be reviewed in detail, for they shed much light on the energetics problem. Two suspension devices were used to reduce traction and simulate subgravity conditions. Figure 45 illustrates these two approaches. The overhead runway was 23 m long and the pavement beneath was horizontal and flat. On the left the subject is suspended from a steel cable by a moving lever system with adjustable counterbalancing devices. The weight of the moving assembly was about 40 kg. The weight factor made this counterbalance device unsuitable for metabolic studies. This approach does, however, avoid the elastic recoil problems of the cord suspension illustrated on the right of the diagram. The elastic bundle of this suspension was 80 cm long without load and stretched to 240 cm with a 70 kg load. The elastic cable and trolley weighed only 7.7 kg; the frictional drag force was probably less than 5% of the weight of the average subject. As will be seen, however, this 5% takes on increased significance as floor frictional factors are reduced.

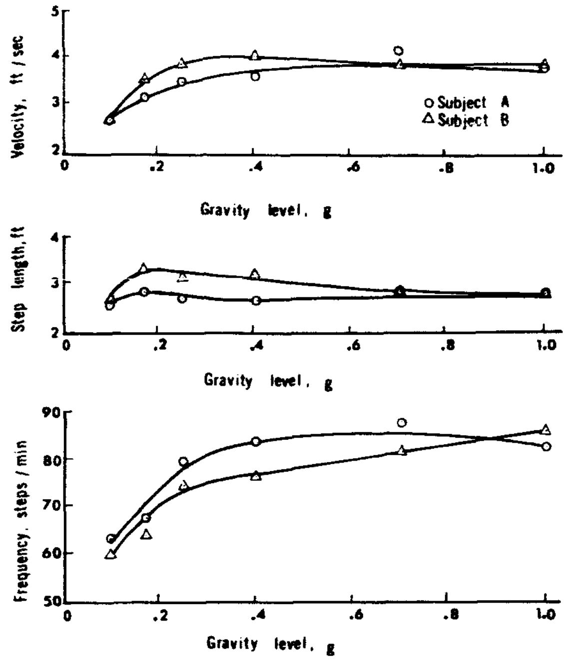


FIGURE 43.—Step relationships of low-gravity walking. (AFTER ROBERTS.[272])

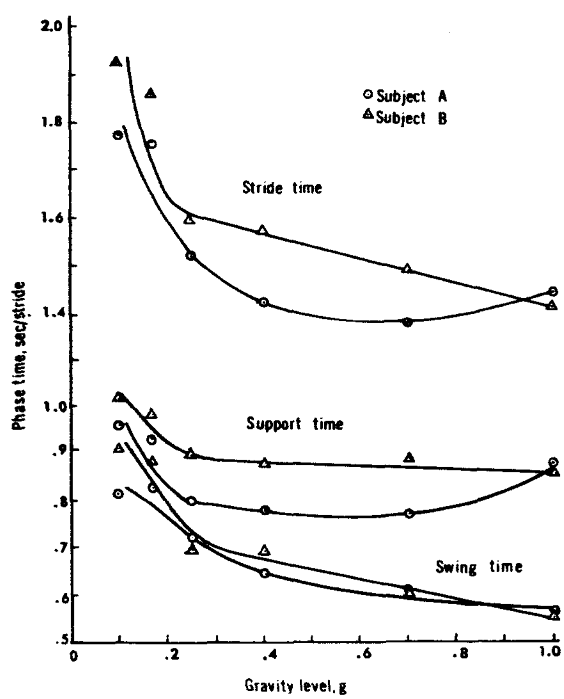


FIGURE 44.—Phase times of low-gravity walking. (AFTER ROBERTS.[272])

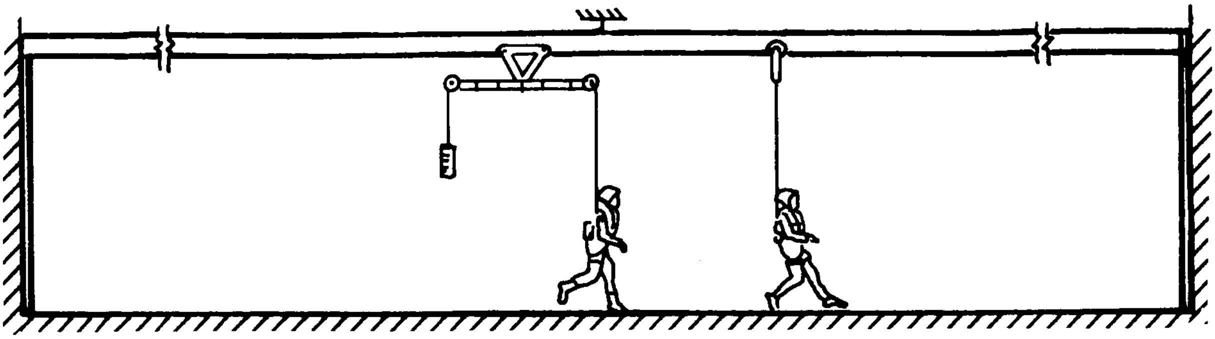


FIGURE 45.—Disposition of counterbalancing (left) and elastic-bundle suspension about a human subject. (AFTER LOMONACO ET AL.[213])

All eight subjects studied were attached to the elastic bundle by means of a padded girdle with the suspension point at the center of gravity (second sacral vertebra) of the subjects. Reduction of weight was accomplished by increasing the number of elastic cords until the subject's weight, as recorded on a scale, reached the appropriate level. Reductions of weight to 1/2 and 1/20 of the original level were used. Oxygen consumption and ventilation rates were recorded from a meter attached to the subject's back. Vertical accelerations were measured at waist level by an accelerometer, and a flashing light on the deltoids gave a timing signal.

After the first trials, it was found that attachment of the elastic cord through rings at the center of gravity caused the subjects to roll into a prone position. The suspension was modified (details not specified) to avoid this rotation. Little was said about this crucial point. It was also discovered that at less than 1/20 weight (2 to 4 kg weight) walking was impossible because of "friction factors." This was, therefore, the lowest level that could be studied adequately.

A description of the gait at about 1/20 weight sheds some light on the problem of experimental technique. It is noted that the addition of only 1 kg to the feet made walking much easier. Without the added foot weight the subjects made "frog-like" movements and propelled themselves by what appeared to be inertial impulses similar to those used in zero-gravity studies. A film was made of these movements but was not available for review. It appears from the general description that rotatory movements around the suspension cable as an axis were prominent. The role of this cable system in upsetting normal locomotor patterns cannot be over-

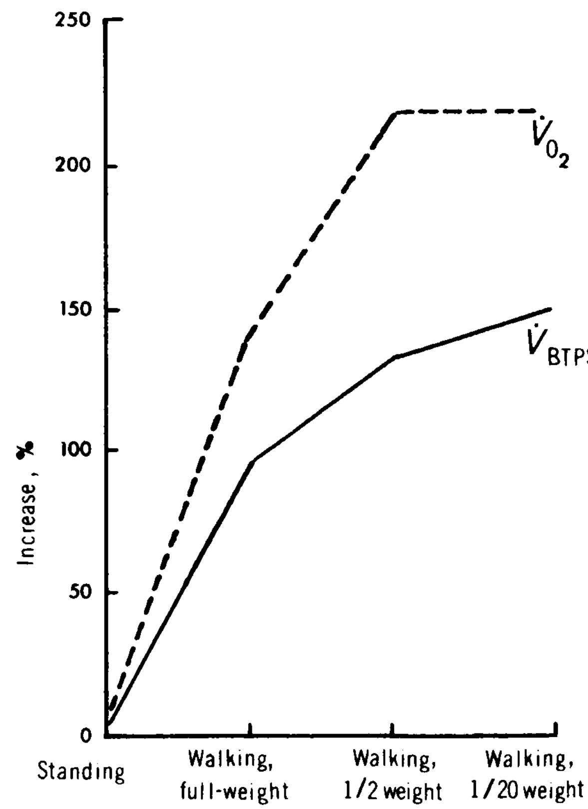


FIGURE 46.—Percentage increase in consumption of oxygen and in ventilation under varied weight conditions. (AFTER LOMONACO ET AL.[213])

TABLE 30.—*Pulmonary Ventilation, Oxygen Consumption, Respiratory Quotient, and Kilocalories/liter Under Different Weight Conditions* [AFTER LOMONACO ET AL.[213]]

Activity	$\dot{V}_{BTPS}$, l/min	Diff., %	$\dot{V}O_2$, ml/min	Diff., %	Respiratory quotient	Diff., %	kcal/l	Diff., %
Standing	9.498±0.980	—	354±57	—	0.76±0.06	—	0.182±0.028	—
Normal walking	18.616±1.889	+95	845±99	+139	0.74±0.05	−3	0.221±0.021	+21
Walking, 1/2 weight	22.012±4.503	+132	1,131±155	+219	0.72±0.05	−5	0.247±0.044	+36
Walking, 1/20 weight	23.557±4.124	+148	1,136±216	+221	0.73±0.08	−4	0.229±0.028	+26

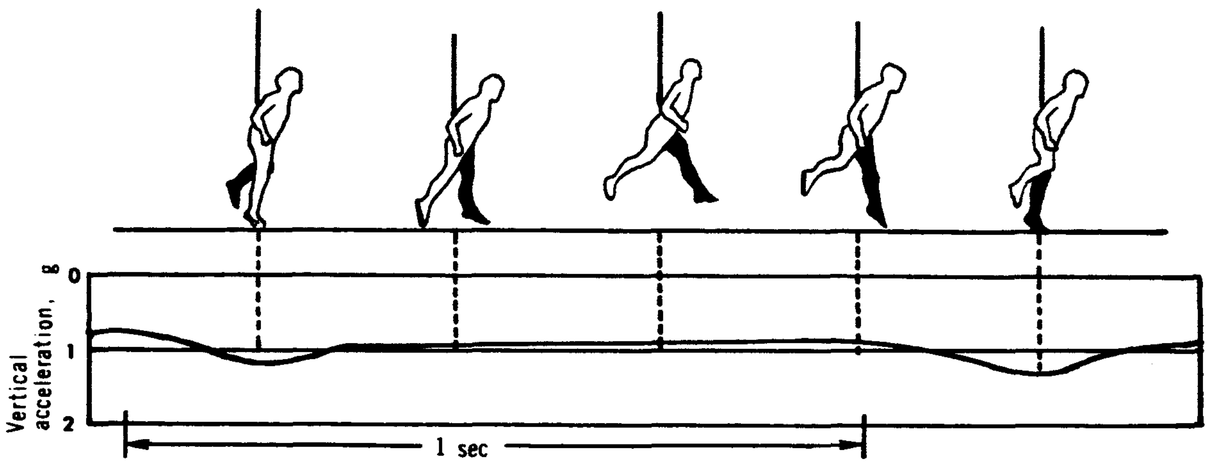


FIGURE 47.—Schematic diagram of movements in walking with 1/20 body weight, and corresponding accelerogram. (AFTER LOMONACO ET AL.[213])

emphasized. The relative rotatory movements at 0.5 and 0.05 weight were not indicated.

Figure 46 and table 30 demonstrate the changes in oxygen consumption and pulmonary ventilation in standing and walking at 3.6 km/hr at full weight and 1/20 weight. The increase in oxygen consumption of 34% above that experienced at normal weight may at first appear paradoxical. Description of the gait patterns, however, make this increased oxygen consumption quite reasonable.

Figure 47 shows sketches from the photographic analysis of gait together with a record of the accelerations along the vertical axis. It can be seen that the subject is leaping through the air. It is reported that as the weight is reduced, the stride is elongated and the number of steps decreased for any distance covered. Figure 48 demonstrates the "vertical accelerograms" at several different weights.

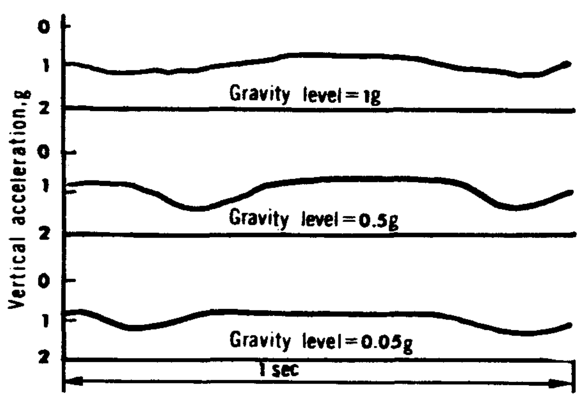


FIGURE 48.—Comparative accelerograms at normal, 1/2, and 1/20 weight. (AFTER LOMONACO ET AL.[213])

Because of rotations of the body in suspension about varying axes, this uniplanar recording appears inadequate for defining vertical accelerations. There is no definite statement regarding the effects of training on oxygen consumption or mode of locomotion. It was speculated that training would probably reduce these metabolic overloads. It was also hypothesized that the excessive limb movements were needed to help the body overcome inertia, to maintain equilibrium, to prevent excessive rotations from starting, and to damp those that had started. It was also noted that during a session on the device at reduced weight, subjects felt light and elated. The normal weight environment felt quite burdensome for some time after their removal from the suspension.

From the previous analysis of normal gaits, it appears that the extra arm motions and the leaping gait would impose a severe metabolic burden. The studies of Fenn [111, 112] suggested that the rapid limb movements of sprinting added a considerable energy factor. The pseudo-reduced gravity in the present studies would decrease the relative amount of energy required for the large leaps. The extra limb movements would, therefore, become the major factor in the excessive oxygen consumption. It must also be remembered that the use of new muscle patterns in a task, as demonstrated above in the traction-free studies, would also decrease the energy efficiency of locomotion. The role of the elastic cord in modifying the transfer of energy during the high leaping bounds is still not clear. Dr. A. H. Schwichtenberg of the Lovelace Foundation, after a brief visit to the laboratory where these experiments took place, felt that the harness suspension itself may upset the balance of the individual and increase the metabolic burden. It must also be mentioned that the 3.5 kg frictional drag of the pulley system poses a significant load when the normal force at the floor is only 2 to 4 kg.

Another significant parameter is the actual coefficient of friction between foot and surface and the "skating or sliding index" discussed above. The report did not mention these details. The subjects apparently wore sneakers, the soles of which were covered with carbon black so as to mark on the paper-covered floor the stepping points during each walk. Since the coefficient of friction determines the minimum angle of push-off, it also will determine the character of the gait and the overall energy efficiency. Some of the extra energy requirement noted in these studies may well arise from the steeper angle of push-off indicated in the description of the gait and predicted by the lower force normal to the ground plane. The steeper angle may well dictate a less efficient conversion of the energy expended in the production of forward motion and contribute to the high energy expenditure. These studies suggest that the total energy expenditure for walking a given distance on the lunar surface may be greater than that predicted from a simple elimination of the energy requirement for the vertical component of the gait. The total energy requirement will certainly be greater than 1/6th that required for locomotion on the earth. How much greater cannot be determined from these experiments. That the energy requirements for covering a given distance will be greater than on the surface of the earth also cannot be predicted at this time.

These studies are apparently being continued with attention to the several details mentioned here. Knowledge of the effect of space suits, both inflated and uninflated, on such an apparatus would also contribute much to the present study. Finally, a thorough analysis of the force and energy factors by the methods of Fischer, Fenn, Elftman, Cavagna, and others might help determine the role of the apparatus in these gait and energy anomalies and would possibly aid in training lunar explorers or even suit designers.

Ralston [268] has recently reported that similar suspension studies are being initiated at the University of California. He expressed the belief that the increase in oxygen consumption in reduced-weight conditions would be predicted by those working with artificial limb systems. Slight changes in muscle patterns present high inefficiency factors which very often are not improved by training.[109, 232] Ralston argues that the evolution of the complete locomotor system has been along an inflexible optimum corridor as far as energy conservation is concerned. Any deviation in one of its parts from optimum function results in compensatory mechanisms which are remarkable, yet wasteful of energy.

Another approach to subgravity locomotion has been initiated by Hewes and Spady of the NASA Langley Research Center.[169] Subjects walk along an inclined plane at the appropriate angle with respect to the vertical while suspended by slings from a man-operated overhead trolley. The slings around the head, chest, hips, and calf maintain a tilt of 80.5° with respect to the vertical to give a simulated lunar gravity normal to the inclined plane. The trolley is propelled to keep up with the subject. Out-of-travel-plane motion is severely restricted by the slings and maximum travel distance was limited to 20 ft, but in spite of the handicaps, some basic subgravity locomotor principles have been obtained. No oxygen consumption data were obtained during these studies.

In spite of the unusual vestibular condition, no vertigo was experienced. While walking rapidly, all subjects (in street clothes and tennis shoes) experienced difficulty which was absent at a slow walk. With less traction, it took about 3 times as long to negotiate the track under lunar as under Earth gravity. There was slippage, loss of balance, and a forward lean of about 60°.

Addition of sling-supported loads up to 40 Earth-pounds in the form of backpacks actually improved the gait and speed of travel. Sixty pounds of load appeared equivalent to 40 pounds in its effect on travel speed. Hewes [168] reported that on one occasion a 250-pound supported backpack was used with no gross retardation of travel speed. Rapid movements, however, caused the inertial effects of the heavy pack to interfere with normal locomotor patterns.

Jumping tests were of interest in that under lunar gravity, maximum heights of 8 to 9 feet could be reached (equivalent to 12 to 14 feet on the lunar surface where no sling factors are at play). Under Earth gravity only 20 to 22 inches could be reached. The initial crouch, coordination on take-off, and control in the air were difficult and required much practice for optimization. Apparently the 4 seconds required to reach maximum height under lunar gravity allowed enough time for angular momentum to be a detrimental factor. No injuries were sustained in uncoordinated falls from 12 to 14 feet. Forward and backward flips were easily accomplished even with backpacks. It was easier to jump to the top of 4-ft stairs or ladders than to climb. Hand-over-hand upward pulling with feet dangling was even easier than stepping up the rungs.

Several studies with the inflated International Latex Co. space suits suggested that they reduced locomotor function.[168] Table 31 gives the relative performance at 1 g and 1/6 g of subjects in pressurized and unpressurized suits. The course of 20 feet was too short for a significant study of maximum forward velocity, but the jumping data adequately point out the gravitational factors in suit limitation of performance.

TABLE 31.—*Performance Under Simulated Subgravity in Space Suits* [AFTER HEWES [168]]

Gravity	Suit pressure, psi	Max. forward vel., fps	Vert. jump max. ht., ft	Broadjump horiz. dist., ft
1 g	0	11.3	1.7	5.4
	3.5	9.2	1.0	3.3
1/6 g	0	5.4	7.7	12.0
	3.5	4.0	4.6	7.0

An inclined plane and counterweight suspension system to simulate lunar gravity has recently been initiated by Hazard [164] at the Space-General Corporation. After inclining a treadmill at 80.8° to simulate lunar gravity and suspending the subject by appropriate harness and counterweight along the plane of travel, studies of oxygen consumption were made. Preliminary results indicate that during a 20 minute walk at 1.7 mph on a 3° slope, subjects consumed 52% less oxygen under "lunar gravity" than under Earth gravity. Unfortunately, sling suspension of subjects in the plane of locomotion appears to be dynamically unsuitable for simulating subgravity energetics. Further studies by this group should be interesting.

In view of these experiments it would appear that the 1/6 g environment on the Moon may actually increase by some factor less than 34% the basic metabolic burden of locomotion rather than decrease it. This burden might be relieved significantly by training. One can certainly not rely on a 5/6 reduction in the metabolic cost of locomotion, or even hope to burden the subject with 6 times the normal weight of space suit and gear and retain the normal energy consumption. However, addition of optimized weight to a backpack system may well decrease the total metabolic cost of locomotion by improving the surface friction relationships.

This review of factors in locomotion suggests several ways in which the basic patterns of subgravity energy partition may be studied. The techniques should place in the hands of suit designers the capability of rationally modifying weight distributions and joint placements and of optimizing the expected new locomotor patterns from several points of view.

EFFECT OF LUNAR SOIL MECHANICS

In Chapter 1, the unusual problem of soil mechanics on the lunar surface was outlined. The many unknown factors make direct analysis of human locomotor potentials most difficult. In recent years, however, theoretical studies of vehicle dynamics in unusual terrains have progressed to the point where general performance criteria and design optimization may be predicted with some degree of certainty from soil mechanical constants. Unfortunately, a similar analysis for human locomotion has not been performed. Data from lunar surface survey vehicles may be more profitably utilized if the relations between soil mechanics and human locomotion are more fully known. The following material is presented as a first approximation to the problem.

Bekker, in his classical book on land locomotion,[31] has outlined the basic principles of soil mechanics and vehicle performance. He has recently extended these principles to the surface of the Moon and planets.[28] The following analysis is adapted from these studies.

Since the foot exerts both horizontal and vertical force against the soil (fig. 30) both the horizontal stress-strain relationship (soil thrust) and vertical stress-strain relationship (flotation) must be defined. For the horizontal soil thrust:

$$\tau=\frac{c+\sigma\tan\phi}{y_n}\{\exp\,[-K_2+(K_2{}^2-1)^{1/2}]\,K_1 j-\exp\,[-K_2-(K_2{}^2-1)^{1/2}]\,K_1 j\} \tag{26}$$

where

- τ stress
- j strain
- c Coulombian soil cohesion
- σ normal load
- ϕ angle of soil friction
- y_n maximum of the function enclosed between braces
- K_1, K_2 slip coefficients that determine the shape of the curve for a given soil [31]

In the case of loose granular masses that do not exhibit peak values of τ before these values become constant with reference to deformation j, equation (26) may be simplified:

$$\tau=(c+\sigma\tan\phi)\left[1-\exp\frac{-j}{K}\right] \tag{27}$$

and, instead of two soil values K_1 and K_2, several examples of only one value of K is needed to define the $\tau\,(j)$ function. Figure 49 represents these relationships diagramatically.

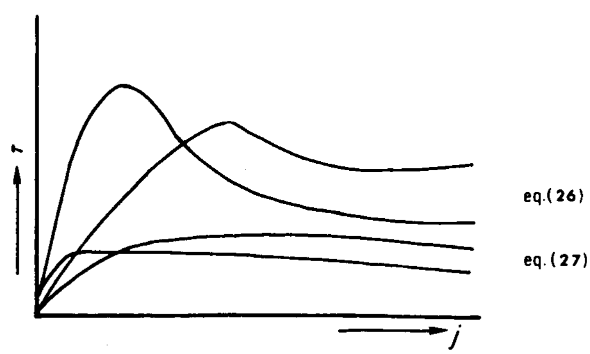


FIGURE 49.—Horizontal stress-strain relationship in soils. (AFTER BEKKER.[28])

For the vertical stress-strain relationship that affects sinkage and motion resistance due to compaction, the following equation has been established:

$$\sigma=\left(\frac{k_c}{b}+k_\phi\right)z^n \qquad (28)$$

where

σ normal load (ground pressure)

k_c, k_ϕ cohesive and frictional moduli of deformation, respectively

b small dimension (width) of the loading area, or radius of that area if it is circular

z vertical deformation (sinkage)

n empirical soil value that defines the shape of the σ (z) curve in a given soil (exponent of sinkage)

Figure 50 represents these relationships diagrammatically for different values of n.

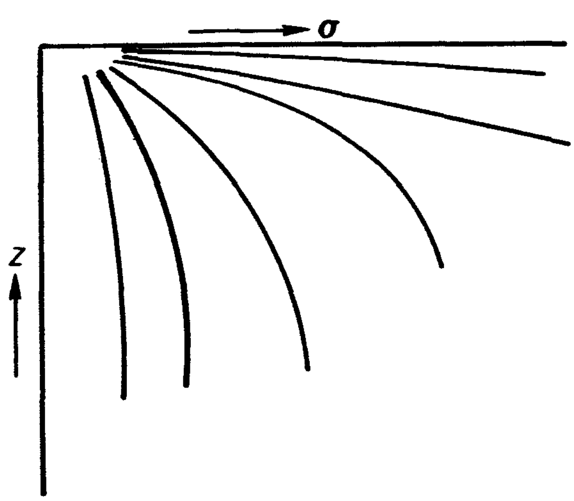


FIGURE 50.—Vertical stress-strain relationship in soils. (eq. (28)). (AFTER BEKKER.[28])

Methods and instrumentation for measuring the soil values $c, \phi, K_1, K_2, k_c, k_\phi$, and n are available.[31] These values can be calculated from data obtained by a Bevameter device, a series of towed wheels that sink and slip under variable loads. Unfortunately, as discussed in Chapter 1, not all of these values can be predicted from indirect lunar data or even laboratory simulation. For a dry, strong, granular powder, the values of c and k_c are 0. However, vacuum sintering of granules will result in positive cohesion of as yet unknown value, possibly higher than that produced by moisture films on earth. The value of k_ϕ is also unknown, though the terrestrial range of 0.1 to 5 is most probable. The lower value is for the consistency of wheat flour, and the upper value for dry packed beach sand. The value for n probably lies in the range of 0.05 to 1, but this is still uncertain for lunar soils. The values of K are also uncertain. The angle of repose ϕ is probably around 32° *in vacuo*[331] but may be as low as 15° or as high as 40°.

If the above constants are available, the energetics of locomotion can be predicted from the following relationships. The horizontal thrust that can be produced is

$$F_x=b\int_0^1 \tau\, dl_x \qquad (29)$$

where

F_x thrust

l_x length of contact area

b width of contact area

Substituting the horizontal stress-strain relationship for loose granular soils with no peak τ (eq. (27)) gives

$$F_x=b\int_0^1 (c+\sigma\tan\phi)\left[1-\exp\left(\frac{-j}{K}\right)\right]dl_x \qquad (30)$$

Opposing the producible thrust is motion resistance R_c produced by wasteful compaction of the soil. This may be deduced from the flotation equation and from the ratio of foot length l_x to stride length l_s. In human locomotion, compaction resistance occurs only at foot contact, so only l_x/l_s of the compaction resistance is effective.

$$R_c=\frac{l_x}{l_s}b\int_0^{z_0}\sigma\, dz=\frac{l_x}{l_s}b\int_0^{z_0}\left(\frac{k_c}{b}+k_\phi\right)z^n dz \qquad (31)$$

where z_0 is vertical deformation (sinkage) at onset of step.

There is also the problem of "bulldozing" resistance R_b. Should lunar soils be fluffy beyond terrestrial standards, the ensuing sinkage should not cause excessive bulldozing resistance because of the loose nature of the soil. Yet, the power requirement against "bulldozing" resistance can be considerable in a light snow terrain where the swing phase of stepping is inhibited by the snow. "Bulldozing" resistance in walking is most difficult to assess, but the general principles have been covered by Bekker.[31]

The maximum drawbar pull (DP) that can be obtained on any surface is the difference between the producible thrust and the total resistance R.

$$(\mathrm{DP}) = F_x - R = F_x - (R_c + R_b) \qquad (32)$$

From the drawbar pull one can calculate the percent slope ζ that can be negotiated by any locomotive vehicle of weight w:

$$\zeta = 100 \frac{(\mathrm{DP})}{w} \qquad (33)$$

The horsepower for any horizontal locomotive task may be determined from

$$\mathrm{hp} = \frac{Rv}{\eta \left(1 - \frac{v}{v_s}\right)} \qquad (34)$$

where

R total resistance of soil
v velocity forward
v_s velocity of slippage
η mechanical efficiency of entire system relative to forward motion

This approximation to the relationship between soil mechanics and locomotion omits many complicating situations in the human locomotor system. It is hoped, however, that it will provide a theoretical framework for interpretation of lunar geophysical data in terms of human locomotor energetics. Because of present uncertainties in lunar soil constants, it would appear wise to design shoes with potential for variable weight-bearing area.

CHAPTER 3

Metabolic Cost of Mobility Restriction

FOR MANY YEARS it has been evident that the protection derived from pressure suits has not been without cost to the effectiveness of the flier. The decrement in performance produced by physical, physiological, and psychological factors has led to searching analysis of space suit weight, resistance to movement, limitation of range of movement, restriction of field of vision, ventilation, cooling, and a host of other factors. Fortunately for the pilot, his task has been sedentary. With the advent of orbital space stations and lunar exploration, the above problems have become magnified as the stresses of locomotion and extravehicular environments expand.

In this chapter, the basic factors in mobility analysis of space suits are considered first. Next the mobility restrictions of some operational pressure suits are reviewed. A brief study is then made of the physics of the balloon effect and bellows compensation. Finally, the test results of the metabolic cost of locomotion in pre-prototype lunar suits are discussed.

CONSIDERATIONS IN ANALYSIS OF SPACE-SUIT MOBILITY

The assurance of maximum function for the user of a space suit requires a thorough investigation of the biomechanics of the man-suit system under all work conditions. A recent review of the basic concepts behind such analysis has been made by Contini et al.[73] at New York University for the Wright Air Development Division. These investigators have reviewed many of the biodynamic concepts outlined in Chapter 2 of this report in an attempt to define a series of studies which may optimize the man-suit system. Ideally, the biomechanical analyses should start with a time analysis of all significant motions within a suit and extend through a kinematic analysis of the geometry of motions to the kinetic analysis of the forces involved. The time components consist of analyses of cadence, temporal patterns of movement, and variability of cycle times with progressive encumbrances.

The kinematic analyses treat the body as a rigid physical system and plot the movement of key body points through the three space coordinates and time. The approaches can be trajectory, coordinate, or vector; the methods can employ such techniques as stick diagrams and gliding cyclograms; and the recording can be by means of the triaxial system or kinetospheric and strophospheric diagrams of Dempster. The kinetic analysis can be made through the study of dynamic equilibrium in force systems, work-energy systems, or impulse-momentum systems. Many of these approaches have actually been used in the discussion of the energetics of gait in Chapter 2.

Examples are given by Contini et al. of several tests of these approaches. In the study of the flexion-extension cycle of the lower arm and wrist, plots were recorded of such variables as decrease of rate of movement with increased restrictive loads on the naked arm. These were compared with similar curves made with the wrist system pressurized in a vacuum box. The kinematic and kinetic sequences are then followed through as described above to give appropriate equations of motion, and finally plots of kinetic energy against time similar to those of figures 22 to 25 of this report. Similarly, kinetic energy-displacement curves can be generated for gloved and naked wrist systems to quantitate restrictive effects of the suit component. Finally, with the addition of oxygen consumption figures, the actual metabolic or power load imposed by the suit component may be determined. All of these factors may then be fed back into the establishment of optimum design parameters.

This is, of course, the optimal approach to the design of the motion-dependent components of a space suit. Ideally, most of the tasks required for the performance of a mission can be thus analyzed. A compromise must then be made between this ideal and other physiological requirements such as kinesthetic, thermal, and gaseous. After trade-off studies, a final design is achieved. All too often, of course, time-emergency considerations impose the factors of expediency. The sequence then faces modification by an "off-the-shelf" restriction, and system designer must then introduce components which are far from optimum in one or another functional regime. Since the danger of this occurrence constantly lurks in the background, it appears pertinent to review briefly the restrictions in the bioenergetics and mobility which present "off-the-shelf" pressure-suit designs impose.

MOBILITY RESTRICTION IN PRESENT SUITS

The mobility of men in several full-pressure-suit configurations has been studied by the Boeing Company.[310] While the mobility patterns studied were primarily for intravehicle work environments, some of the data are applicable to the extravehicular problem. The data may be of use to those making rough estimates of work capacity of subjects in similar suit configurations prior to initiation of actual development programs.

An empirical method was developed for the comparison of the restriction of body movements imposed by pressure suits. Measurements of gross body movements have been adopted from Dusek and Teichner.[95] A separate technique for arm and hand movements was required because pressurized suits do not permit the arm motion of the Dusek-Teichner method. Several models of currently available full-pressure suits have been used in these tests to establish the method. The suits investigated were the B. F. Goodrich Mk II and Mk IV and the Arrowhead Rubber AX 6-10 and AX 9. Control values were established with subjects clad in lightweight loose-fitting coveralls. Measurements were then made with the suits both unpressurized and pressurized to 3.0 psig. The weight distribution of these suits is recorded in table 32. Gross body motions and attenuation caused by full-pressure suits were investigated; the motions included standard movements whose reliability and intercorrelations had been established.[95]

Body flexions were determined for three subjects in four full-pressure suits, B. F. Goodrich Mk II and Mk IV, and Arrowhead Rubber AX 6-10. In addition to the determination of the attenuation of body movement, the torques required to deflect the upper and

TABLE 32.—*Weight Distribution of Space Suits* [AFTER SPRINGER AND BOMMARITO [310]]

Component	Mark II,		Arrowhead AX 6–10,		Mark IV,		Arrowhead AX 9,	
	lb	oz	lb	oz	lb	oz	lb	oz
Suit	19	6	9	6	11	0	12	0
Helmet	6	4	6	4	5	0	5	0
Gloves	0	12	1	0	0	8	1	0
Boots	5	10	3	6	3	6	3	6
Underwear	1	0	1	0	1	0	1	0
Total	33	0	21	0	20	14	22	6

lower arm of two suits were recorded. Upper arm movement was determined in a vertical plane rotated 50° anterior of a lateral direction. Lower arm movement was investigated with the upper arm strapped vertically to the body and also while the upper arm was fastened 45° laterally. The hand movements were studied too, but results will not be covered in detail. The following tests were performed:

1. *Standing flexion:* The subject stands with his toes on the edge of a box and reaches downward as far as possible without bending his knees. The position is held for 5 seconds while the experimenter records the distance from fingertips to box.

2. *Head movement - Ventral:* The goniometer for measuring angular motion is attached to a lateral surface of the subject's head and is set at zero with the subject seated and his head in a normal upright position, upper jaw parallel to the floor. The angular extent of tilt of the head is then recorded when the subject moves his neck in ventral flexion as far as possible without moving the chest or shoulders.

3. *Head movement - Ventral to dorsal:* The goniometer is attached to the lateral surface of the subject's head and is set at zero when the subject is seated with his neck in ventral flexion. The subject then extends his head as far back as possible without moving his shoulders. The angular extent of movement of the head is recorded.

4. *Head movement - Lateral:* The goniometer is attached to the dorsal surface of the subject's head and is set at zero when the subject is seated and has moved his head as far to his right as possible without moving his shoulders. The subject then moves his head to the left as far as possible. The extent of the angular movement from right to left is then recorded.

5. *Head rotation:* The subject is standing, bent forward at the waist while holding the seat of a chair so that his back and neck are parallel to the floor. The goniometer is attached to the cranial surface of the subject's head and is set at zero when the subject has rotated his head to the right as far as possible. He then turns his head to the opposite side as far as possible and the extent of rotation is measured.

6. *Upper leg - Extension backwards:* The goniometer is attached to the lateral surface of the upper left leg proximal to the knee. The subject faces and touches a wall with his left hip and leg extending slightly beyond into an open doorway. The goniometer is set at zero with the subject pressing his left hip against the edge of the wall. He moves his left leg backward and upward while keeping the knee straight and the left hip in contact with the edge of the wall. The position is held while a reading is made.

The results were:

1. *Standing flexion:* Figure 51 and table 33 show the suit comparison on the basis of standing flexion measurement. The greater restriction of body bending shown by the Mk II suit correlates with its greater bulk and weight. The Mk II at 33 lb weighs nearly half again as much as the next lighter suit, as tested

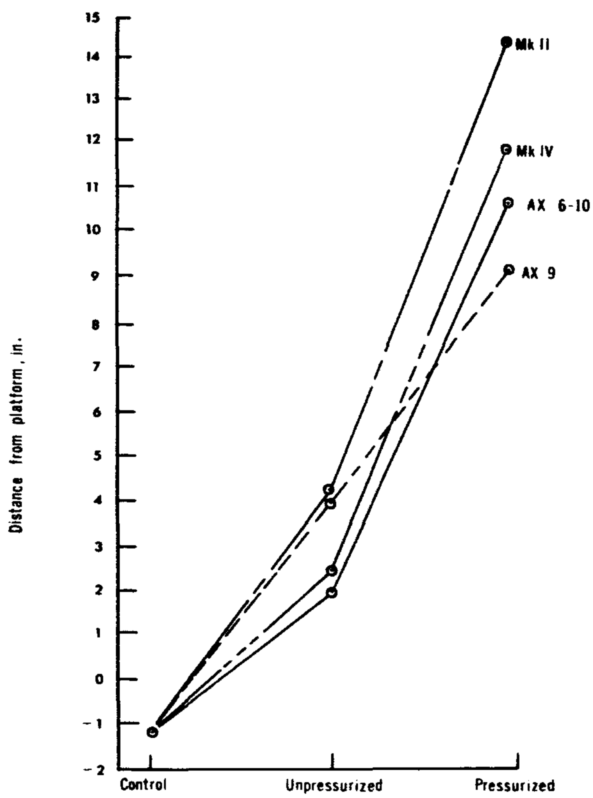


FIGURE 51.—Suit comparison, standing flexion, average of three subjects. (AFTER SPRINGER AND BOMMARITO.[310])

TABLE 33.—*Summary Data on Body Flexion in Space Suits (Average of Three Subjects)* [AFTER SPRINGER AND BOMMARITO [310]]

Suit	Suit press, psig	Test 1 Standing flexion, in.	Test 2 Head flexion-Ventral, deg	Test 3 Head flexion-Ventral to dorsal, deg	Test 4 Head flexion-Lateral, deg	Test 5 Head rotation, deg	Test 6 Upper leg, Extension backwards deg
Arrowhead AX 6-10	0	+2.1	52	92	19	115	30
	3.0	+10.8	27	68	5	56	5
Arrowhead AX 9	0	+4.1	61	105	48	144	35
	3.0	+9.3	37	77	17	81	24
B. F. Goodrich Mk II	0	+4.4	52	91	22	104	28
	3.0	+14.4	21	42	4	75	2
B. F. Goodrich Mk IV	0	+2.6	61	102	43	111	28
	3.0	+12.0	31	63	10	87	18
Control	0	−1.0	61	119	90	151	29

without the backpack. The other suits were similar to each other in weight. Changes in body position momentarily caused suit pressure fluctuations of up to ±0.2 psi. It was found that by instructing the subject to change positions slowly, the pressure fluctuation could be minimized.

The overall fit of the suits varied also. The AX 9, for instance, was quite snug in the chest and abdominal areas when compared with the other suits. This was true for all subjects. Considerable ballooning occurs with the Arrowhead AX 6–10 around the buttocks. The excess material acted as a reservoir for entrapped air. When the subject bent over, the excess material in the area of the buttocks literally "popped-out". It was then difficult for the subject to stand as straight as he had originally. The excess material had to be forced back into folds before the subject could stand straight again.

This phenomenon was particularly noticeable in the AX 6–10, although all suits displayed similar characteristics. The situation was not entirely due to the excess fabric, however. The type of "tie-down" or "hold-down" strapping for the helmet contributed to the attenuation of motion. The tie-down strap, or straps, which ran under the crotch effectively restrained the suit fabric until movement was attempted. The subsequent extension and compression of the suit tended to unfold the excess material and refold it in a different fashion.

On the Arrowhead suits, both AX 6–10 and AX 9, the single strap running under the crotch could be slipped during the bending operation, while the tie-down straps of the Mk II and Mk IV suits were attached to frontal areas of the suit. This restricted movements more in the Mk II and Mk IV than in the AX 6–10 and AX 9 suits when the suits were pressurized. The AX 9, because of its tighter fit, allowed greater deflection than the AX 6–10 with suits in the pressurized state, as shown in figure 51.

Body motions are considerably restricted in the Mk II because of the bulk and weight. Arm movements are easier than with other suits, however, as the Mk II incorporates three ring-seal joints in each arm—around the shoulder, the upper arm, and the lower arm. The pressure-sealed ball bearing rings allow 360° rotation of adjoining parts. The Mk II suit is unique in this respect.

2. *Head motions:* The results of tests of motions of the head (tests 2 to 5) are presented in table 33. For head flexion, the degree of freedom corresponds with the size of neck ring provided in the suit. The Mk II and AX 6–10 suits require a helmet with a larger ring than the Mk IV or AX 9 suits. The larger neck ring impairs ventral, dorsal, and lateral motions of the head.

In the unpressurized condition the small neck ring of the Mk IV helmet (Mk IV helmet is also used on AX 9) provided no detectable attenuation of ventral motion. On the suits utilizing the Mk II helmet (both AX 6–10 and Mk II) an attenuation of 9° is noted, the deflection being cut from 61° to 52°.

Pressurization of the suit further restricts the head movement. Again the bulk and stiffness of the Mk II suit provides more hindrance than the other suits. The larger neck ring of the Mk II helmet also plays a part, as the AX 6–10 attenuates movement more than the Mk IV. Although the Mk IV and AX 9 utilize the same helmet, the AX 9 provides less restriction. This is apparently due to the construction of the suit immediately below the neck ring. The Mk IV has an excess of material in the frontal neck portion of the suit to facilitate entry into and exit from the suit. These provisions are made in the rear section of the neck on the AX 9. The ballooning of this neck area in the Mk IV hinders ventral motion.

The helmet "tie-down" cables also are not conducive to any extreme ventral motion. The cables on the AX 9 suit allow the helmet to slide along them more readily than the cables of the Mk IV suit, resulting in less attenuation with the AX 9.

For head flexion, ventral to dorsal, the total angle through which the head and neck may be flexed and extended in the "fore-and-aft" or sagittal plane is covered by this measurement. Here the size of the neck ring is the dominant factor in determining the restriction provided by the unpressurized suits. With the suits pressurized, however, the dominant factor is the tie-down cable attachment. The connections of the two Arrowhead suits are similar, and those of the two Goodrich suits are similar. The tie-down accommodations and the previously mentioned entry and exit provisions combine to provide, while pressurized, more attenuation in the Mk IV suit than in the AX 6–10. Due to a better "fit", the AX 9 is the least restrictive. The bulk of the Mk II again makes it the most restrictive. As shown in table 33, the pressurized suits restrict ventral to dorsal movement to approximately one-third to two-thirds of that possible with loose-fitting coveralls.

Lateral head movement (bending the head from side to side in the plane of the shoulders) is practically eliminated in a pressurized suit. The neck ring, of basically the same design in all four suits tested, extended outside the ventral neck lines of all four subjects and nearly touched the shoulders. With the head held erect the ring was immediately above the trapezius muscle.

When the suit is unpressurized, the fabric provides enough flexibility to allow the neck ring to move slightly. The outside diameter of the neck ring on the AX 6–10 and Mk II suits is approximately 11 inches, while the ring on the Mk IV and AX 9 suits has an outside diameter of 9¾ inches. The smaller ring on the Mk IV and AX 9 suits allows more lateral head movement than the larger ring, as shown in table 33. Nevertheless, considerable restriction results in the unpressurized suits, while in the pressurized state lateral movement is practically eliminated.

Rotation of the head on the vertebral axis in a horizontal plane is the movement which permits maximum use of the window area designed into pilot compartments. Each of the four suits permits 360° rotation of the helmet on the suit within the ball-bearing neck ring. The limitation of motion results from interaction of several factors, among which are: (a) the sizing and fitting of the suit to the individual subject, (b) the location of the ring as determined by the distance from the subject's shoulder to the top of the head, (c) flexibility of the suit fabric, (d) the condition of the ball-bearing race in the neck seal, and (e) the helmet face-seal adjustment itself.

3. *Upper leg - Extension backwards:* Very little restriction, as shown in figure 52, was imposed on the subjects by the unpressurized suit during the backward extension of the leg. A more favorable weight distribution actually resulted, since the helmet forced the head away from the wall. In fact, the movement was made easier by donning the unpressurized AX 9 suit.

During the pressurized operation, the Mk II and AX 6–10 suits tended to arch back of the subject forward, placing him in an unnatural position for backward leg movement. This defect certainly is partially responsible for difficulties in walking. The Mk IV and AX 9 allowed the subject to stand nearly erect and more favorably balanced.

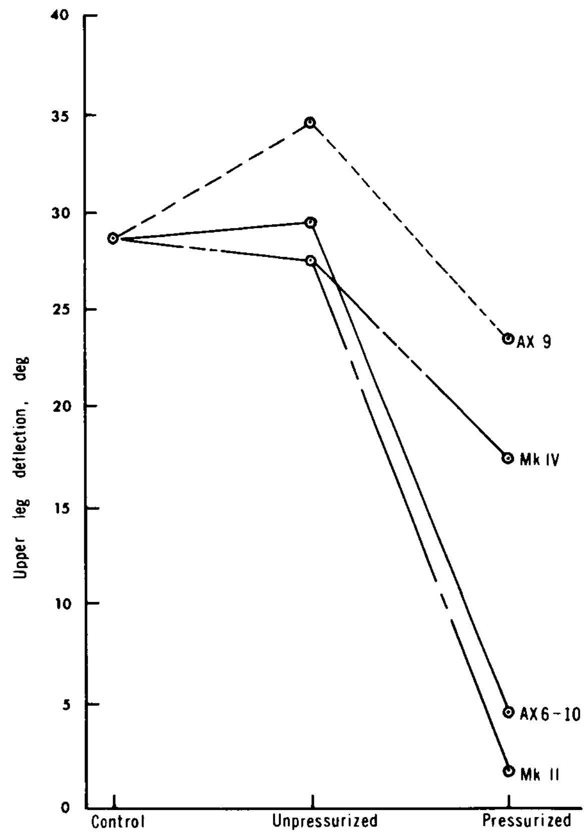


FIGURE 52.—Suit comparison, backward extension of upper leg, average of three subjects. (AFTER SPRINGER AND BOMMARITO.[310])

4. *Arm motions:* Arm motion is hampered to a considerable degree in all respects. The data indicate that the force required to bend the arm at the elbow or shoulder increases with increased pressure differential. For example, to move the arm from the shoulder 60° from neutral requires, in the B. F. Goodrich Mk IV suit, 198 lb-in. at 3.0 psig, 235 lb-in. at 3.5 psig, and 288 lb-in. at 3.8 psig. (The "neutral" position of the suit is that position which the suit construction forces the relaxed arm to assume.) The same movement in the Arrowhead AX 9 requires 172 lb-in. at 3.0 psig and 208 lb-in. at 3.5 psig. It was not possible to maintain the Arrowhead AX 9 suit at a pressure higher than 3.5 psig, as the relief valve released any pressure above this value.

With the upper arm confined tightly to the body in a vertical position, lower arm movement of 105° from the neutral position required 87 lb-in. for the Mk IV and 67 lb-in for the Arrowhead AX 9 when each suit was pressurized to 3.5 psig.

5. *Wrist motions:* It was determined that a pressurized full-pressure suit (B. F. Goodrich Mk IV) imposed an average restriction to hand movement of 10° over the control value in the downward direction with the wrist pronated. For the same position, the restriction to upward movement of the hand is 16°. In this position, the torque required to move the hand to various angles was:

		Torque, lb-in.
Downward	20°	23.7
	40°	37.9
	60°	60.6
Upward	10°	24.8
	20°	38.3
	30°	45.3

With the arm in the same position and the hand turned 90° so the palm faces the body, the pressurized suit imposes a small (1° average) restriction to downward hand movement, but actually assists the hand to move upward 11° more than the control value. This effect arises from the fact that pressurization of the suit frees the lower arm more than the unpressurized condition.

6. *Walking:* Although no numerical interpretations were made, it was observed that walking in pressurized suits was very difficult. The subject's balance was quite unstable as the feet were shifted. Walking was accomplished by shuffling the feet to and fro with the legs stiff, while weaving the body from side to side to remove the weight from the foot to be moved. The actual metabolic penalty for walking will be covered below. This is quite reminiscent of the potential energy consumed in compass gait, discussed in Chapter 2.

Several studies are available on the decrements imposed by Navy full-pressure suits in pilot tasks[57, 58, 110, 146] and orbital repair tasks.[146] Since these involve mostly the problem of reaction times, kinesthetic sensation, and low-grade exercise, they will not be discussed in this report.

Thus, it can be seen that the restriction of most movements is rather severe in typical inflated pressure suits. No comparative data were readily available for the Mercury, Gemini, or Apollo suits, though the Mercury suit is a slight modification of the Mk IV. However, the energy requirements for walking in these suits will be discussed below.

BALLOON EFFECT AND BELLOWS COMPENSATION

Prior to analysis of the metabolic loads imposed by inflated suits it will be well to consider the basic causes of mobility restriction and the possible cures. An inflated rubber balloon will assume a shape such that the pneumatic forces are exactly balancing the forces in the rubber membrane. Should the rubber balloon originally have been molded in a cylindrical shape, long and thin, then when it is pressurized it will tend to assume the familiar hotdog shape. If an effort is made to bend such a balloon a resistance will be encountered, and when the applied bending moment is released the balloon will again straighten out. The resistance encountered as the balloon is bent is the result of two factors: First, the rubber material of the balloon itself resists the deflection, and second, there is a resistance that results from a change in volume as the balloon is deflected. In this example the greater portion of the applied work in bending the balloon goes into the compression of the contained gas. A similar situation exists with the torso, arms, and legs of a conventional pressure suit. When one of these suits is pressurized the limbs will assume a shape dependent upon the manner in which the fabric has been cut and sewn. In this natural shape the fabric forces are exactly balancing out the pneumatic forces, and it is only through an effort on the part of the suit occupant that these "flexible" members can be deflected from their natural positions.

In the past, various rotary joint and bellows systems have been employed to reduce the work required in flexing ballooning components of the suit. Results have generally been unsatisfactory. A recent study by the Space-General Corporation has shed some light on this problem.[304] Most of the material to be presented will be taken directly from this report.

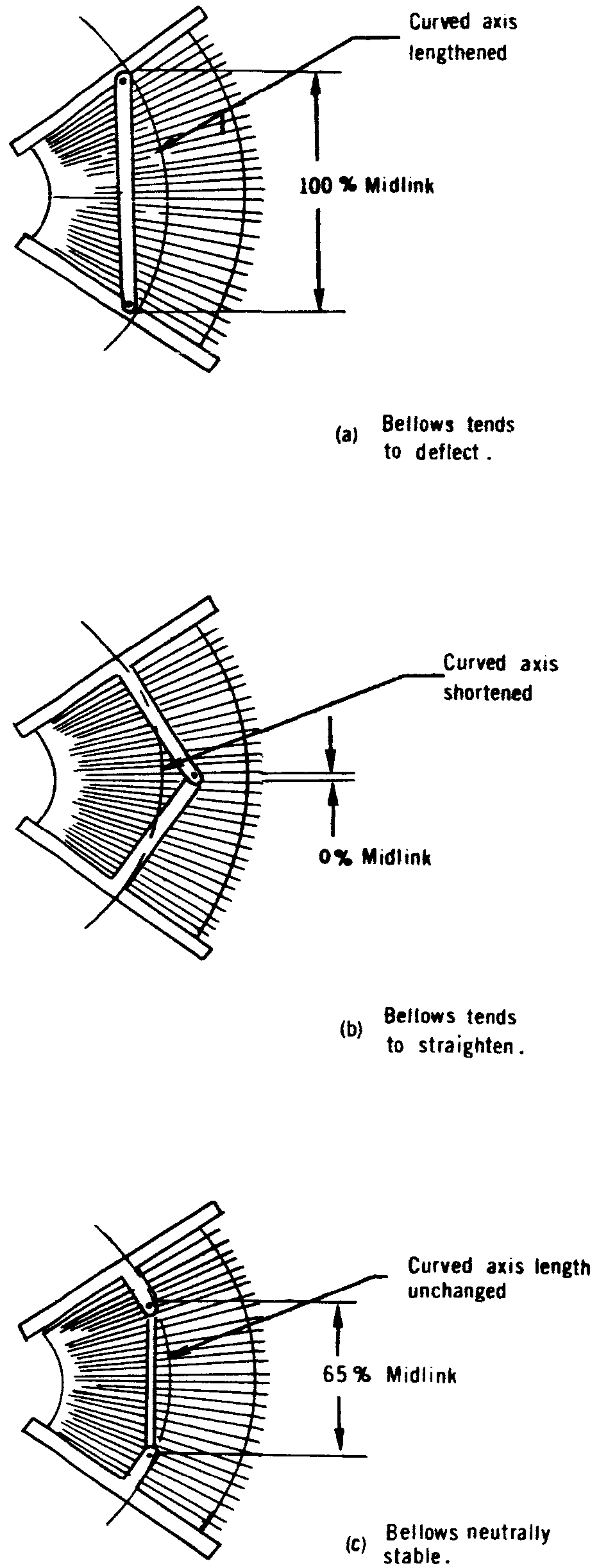


FIGURE 53.—Effects of midlink length of bellows. (AFTER SPACE-GENERAL CORPORATION.[304])

Ideally, any link system designed to restrain a bellows and attain maximum flexibility must have the geometric factors precisely proportioned so that pneumatic forces will exactly balance the bellows spring forces. In figure 53(a) a restraint linkage is shown in which the pivot pins have been placed directly in alinement with the ends of the bellows. In this instance, the length of the link between the two pivot pins could be said to be 100% of the total bellows length. Hereafter a bellows such as this will be referred to as a 100% midlink bellows. In figure 53(a) the curved axis of the bellows is shown for the bellows in the deflected position. The volume contained within this bellows is equal to the cross-sectional area of the bellows times the axial length of the bellows. In this instance, since a straight line is the shortest distance between two points, the length of the curved axis must be longer than the straight-line length of the axis when the bellows is not deflected. Accordingly, when the bellows is deflected the volume must be greater than when the bellows is straight. Since the volume is increased when the bellows is deflected, expansion work will have been done, and if the metallic bellows itself is not too stiff, sufficient work will have been done by the pneumatic forces to completely overcome the spring forces of the bellows. The bellows will end up cocked over until the convolutions at the inside of the arc are stacked solidly together or until the pneumatic forces have been just balanced out by the increasing stiffness of the bellows as they are deflected. Thus it has been determined that a bellows restraint system with a 100% midlink is unstable and that the bellows configuration will seek some deflected position of equilibrium. However, to have produced a reaction such as this is encouraging in that a system has been demonstrated which does not tend to stiffen when pressurized but tends to deflect instead.

In the next example, the restraint linkage has been changed from the 100% midlink to the other extreme. In figure 53(b) the restraint links are shown rigidly affixed to the ends of the bellows, with a single pivot point in the middle. This can be called a 0% midlink situation. Compare the lengths of the bellows axes when deflected and when straight. It is quite obvious that in the 0% midlink case the ends of the bellows are closer to each other in the deflected position, and the curved axis of the bellows is now shorter (for reasonable angles of deflection, as illustrated) than when straightened. In this case the volume has decreased because the axial length has decreased and, therefore, compression work was done on the gas contained within the bellows. This situation results in a bellows configuration which tends to remain straightened.

It would seem logical then that there must be some intermediate midlink length in which the length of the bellows axis, in effect, does not change as the bellows is deflected. In such a case, there would be no net change in volume, and therefore no net work required to deflect such a restrained member. By laying out several different midlink lengths, it was determined through a process of trial and error that with a 65% midlink there was no net volume change at all. The 65% midlink bellows is illustrated in figure 53(c). To be practical however, it must be recognized that this ideal situation with no net volume change at all is not exactly what is wanted, because the metal bellows material does have some spring resistance to being deflected. Therefore, it is necessary to move toward the 100% midlink configuration in order to have some net pneumatic work of expansion as the bellows deflects. This overcomes the resistance to deflection of the bellows spring forces.

In figure 54 the bellows volume change is shown as a function of midlink length for various deflection angles through 70°. For the 65% midlink there is no apparent volume change for any angle of deflection. Thus the 65% midlink would be ideal if the bellows were, in effect, made of tissue paper; that is, if it had no spring resistance at all to deflection. But there is, of course, a spring resistance, and indicated on the graph are design points for the body, wrist, and arm bellows. The body design point is the result of calculations, but the wrist and arm bellows points are the result of actual test. The theory outlined above is, of course, applicable to the design of flexible pressurized members of any size, or materials of any inherent stiffness. The restraint theory can be applied even to the design of all-fabric joints.

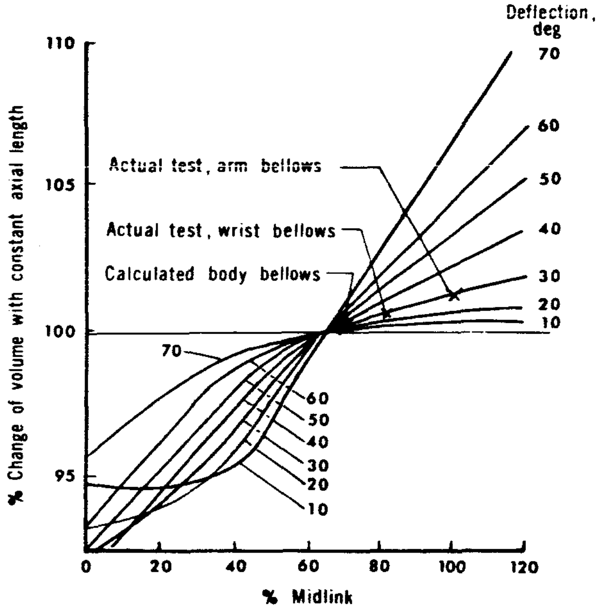


FIGURE 54.—Theoretical volume change of bellows as function of midlink length at selected deflections. (AFTER SPACE-GENERAL CORPORATION.[304])

In order to verify the correctness of the restraint linkage theory, several bellows assemblies were procured by Space-General from the Metal Bellows Corporation. Means were provided to adjust the bellows deflection and to regulate the internal pressure; also a scale was provided, and means to measure the angular deflection. Thus it was possible to measure the deflection forces so that the deflection moments could be calculated at the same time that corresponding angles of deflection were measured for any desired level of internal pressurization.

Figure 55 demonstrates how seven of the individual bellows elements may be attached to give an arm assembly. The results of the test of a single one of these elements is seen in figure 56. The graph shows that the bellows could be deflected 16° in either direction with no net bending moment being required and that only 10 lb-in. were required to deflect it further to its limit of ±28°. With seven of these bellows stacked in series to form the upper portion of the arm, the total moment required to deflect the assembly will still be only 10 lb-in. since the bending moment of one bellows is transmitted in turn directly to the base of the adjacent bellows element.

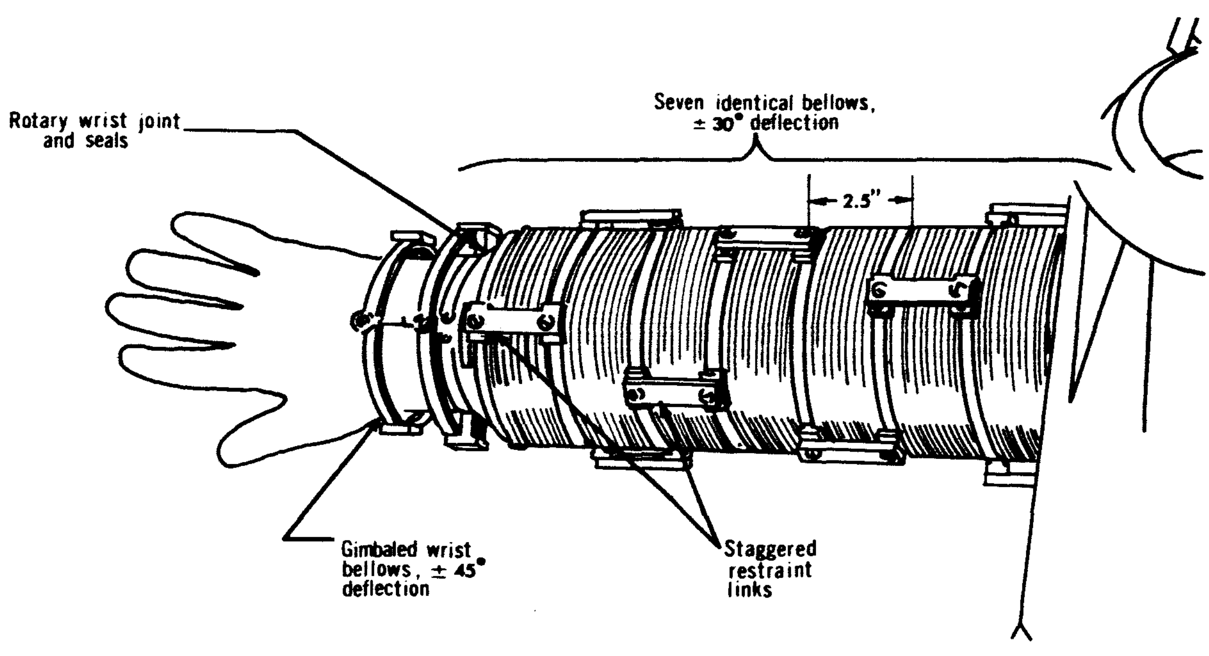


FIGURE 55.—Proposed arm configuration. (AFTER SPACE-GENERAL CORPORATION.[304])

Extrapolation of the curves of figure 56 also shows that the bending moment required when nonpressurized is only 3 times the 10 lb-in. required at 5 psi at maximum deflection. The bending moment when nonpressurized is, of course, entirely the result of the spring forces produced by the metal bellows elements themselves. From these tests it is to be expected that this arm design will require a bending moment of only 10 lb-in. to deflect the arm to the extreme limits of its flexion. This limit is reached when the bellows convolutions are stacked solidly on the inside of the curve. Furthermore, the proposed arm design will require no bending moment at all to deflect it up to 55% of its maximum deflection.

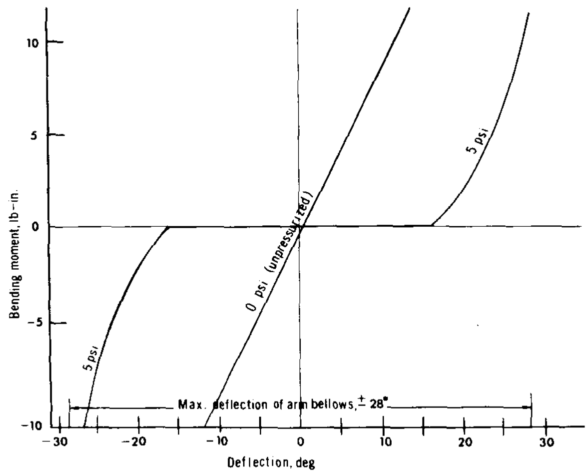


FIGURE 56.—Test results for arm bellows; 0.004 in. material, 6.73 in. outside diameter, 5.98 in. inside diameter. (AFTER SPACE-GENERAL CORPORATION.[304])

Early in 1962 an actual test was made of this concept under pressurization. An arm assembly was sealed inside a tank and the pressure reduced to 5 psi below atmospheric. As the pressure in the tank was reduced, thus in effect pressurizing the arm, the only observable difference in the ease of movement of the arm was attributed mainly to the bearing friction in the restraint linkage ball bearings. When pressurized to the 5 psi design pressure differential, this friction was sufficient to cause the arm to "remain" in substantially whatever position it was placed. In other words, the pneumatic forces were so precisely balanced out by the bellows spring forces that no net force remained to cause the bellows to straighten against the small forces of bearing friction. It therefore appears that a minor degree of friction will be experienced in the restraint linkage bearings as the arms are moved. Once a given position is reached, however, it will not be necessary to continuously fight the tendency of the members to straighten out, as would be true in a conventional full-pressure suit.

These preliminary tests suggest that the link principle outlined above may reduce considerably the immobility of present suits. To be sure, application to the all-important hip joints will be difficult, but probably not insurmountable. Difficult metal-to-fabric junction design and weight factors will always be problems which must be considered when metallic bellows are employed. The basic design philosophy, however, appears worth pursuing.

The Aerospace Medical Research Laboratories at Wright-Patterson AFB are currently working on fabric designs which compensate for pressure-volume work in joints.[290] Preliminary results of this study group have recently been published.[188]

METABOLIC COST OF WALKING IN SPACE SUITS

Let us now return to the actual metabolic cost of locomotion in current space-suit assemblies. In the spring of 1963 the AiResearch Manufacturing Division of the Garrett Corporation compared the effects of unpressurized and pressurized suits on metabolic requirements of walking. The pre-prototype suit being developed by the International Latex Corporation for the Apollo mission was used. The data to be presented were communicated by Wortz of the AiResearch Manufacturing Division.[352]

The suits were in the condition in which they were delivered by the International Latex Corporation except for the taping of one shoulder joint in an emergency repair. This probably had little effect on the energy requirements. The environmental conditions of the experiments were as follows:

Chamber wall air temperature	96° F
Suit inlet temperature	70° F
Suit inlet-air dewpoint	40° F
Chamber pressure	3.5 psi (34,000 ft)
Suit pressure	Unpressurized and 7 psi (3.5 psi above ambient)
Suit weight	20–30 lb
Subject weight	Not given

The subjects walked on a treadmill set horizontally. The technique of measuring oxygen consumption was thought to give values 8% lower than those obtained by standard spirometer techniques. The motion pattern of walking was similar to that reported in the Boeing study[310] described earlier in this chapter. Results are seen in table 34.

TABLE 34.—*Metabolic Cost of Walking in an International Latex Full-Pressure Suit* [FROM DATA OF WORTZ[352]]

Condition	Speed, mph	Energy Requirement (Btu/hr)		Comments
		Average	Range	
Resting unpressurized	0	250	200–300	May go up to 1,000 when excited
Walking unpressurized	2.0	1,200	870–1,500	
	.4	1,300	1,100–1,500	Can tolerate for >½ hour
Walking pressurized	1.2	1,800	1,720–2,000	Few subjects tested; fatiguing
	2.0	2,020	....	Only 1 subject, tolerated for only 7 min

It appears that pressurizing the suit to 3.5 psi above ambient almost doubles the metabolic cost of walking at 2 mph. The metabolic cost of walking in street or gym clothes is seen from figure 10 and table 5 to be about 500 Btu/hr at 0.4 mph, 800 Btu/hr at 1.2 mph, and 720 Btu/hr at 2 mph. Table 34 shows that the pressurized space suit increases the cost by a factor of about 2.6 at 0.4 mph, 2.3 at 1.2 mph, and 2.6 at 2 mph. These figures, it must be remembered, are not corrected for the 8% which should be added to the energy values in table 34.

At this time no data are available for other locomotor tasks in pressurized suits. Climbing and sand-dune walking will, if possible at all, probably exact a relatively greater toll than horizontal walking. Considering the difficulties of subgravity locomotion previously discussed, a still greater metabolic penalty is possible. The compensatory movements which Lomonaco et al.[213] report for their suspended subjects may be quite difficult in present suits. It is doubtful, however, that such extensive movements will be required with an optimum weight-compensated suit system.

One may, therefore, speculate that walking at 1/6 g at the relatively slow pace of 2 mph (3.2 km/hr) on a hard, flat surface in the current pre-prototype suits pressurized at 3 psi, as a very upper limit, may require $1{,}800+0.08(1{,}800)+0.30\,[1{,}800+0.08\,(1{,}800)]$ or about 2,500 Btu/hr. The factor 0.3 is for the very upper limit of compensatory movements. It is possible that the subgravity condition may decrease the energy of locomotion below that on earth. The unusual gaits partially dictated by current earth simulators and no doubt responsible for the added oxygen consumption in recent tests may confuse this issue at present. The addition of a factor of 0.3 suggested by the Italian studies is certainly an upper limit. The factor may actually turn out to be negative.

From figure 16 it can be seen that very healthy, trained men can sustain this work load for a maximum of 2 hours. Figure 57 summarize these predictions of the metabolic cost of walking at different speeds in pressurized space suits. The addition of a sand-dune environment (table 12) will probably more than double this figure to about 5,000 Btu/hr. Figure 16 suggests that work at this rate can be kept up by very healthy men for

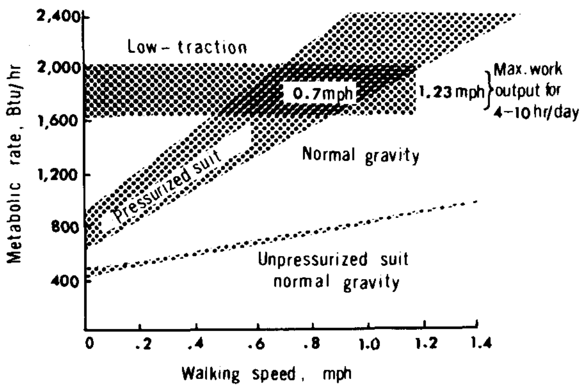


FIGURE 57.—Metabolic cost of walking in pressurized space suits. (AFTER GARRETT CORPORATION.[3])

periods of only about 5 minutes. Since the basic antigravity work and the downhill slippage factors would be reduced, gravity reduction would no doubt aid dune climbing considerably. On level sand, subgravity may aggravate the metabolic load by decreasing the force normal to the ground and thereby decreasing frictional factors and increasing the sliding index. The energy for lifting of limbs required in walking on soft sand would, of course, be reduced. One could, therefore, not expect too much aid from the subgravity factors involved in loose sand environments.

Finally, by what factor can a compensated bellows system, such as has been described, reduce this metabolic load? It will depend, of course, on whether weight considerations will even permit such an approach. It will also depend on how effectively the hip and knee joints, and possibly the ankle joints, can be mobilized through this approach. The arm joints do appear to be well mobilized. Rotating seals for shoulders should also increase arm mobility but decrease reliability. A new design concept for these rotary seals has also been presented by the Space-General Corporation.[304]

It would thus appear that the 1,600 Btu/hr cooling capacity of current space-suit specifications underestimates the actual emergency requirements. Even if the subgravity compensation penalty (which is the least reliable of the above factors) were eliminated, the 1,600 Btu/hr figure is still too low. A 2,000 to 2,500 Btu/hr level would appear more appropriate to cover emergency situations lasting several hours under the least favorable surface conditions.

CHAPTER 4

Thermal Control in Lunar Suits

A PRIMARY REQUIREMENT for design of thermal controls for extravehicular space suits is to protect man from the extremes of the projected external thermal environment. The additional metabolic loads reviewed in Chapters 2 and 3 superimpose on these basic external heat inputs a variable obligatory internal heat source which, in some situations, may be the overwhelming input. Let us now briefly consider the external inputs to the internal temperature control system and compare them with internal loads.

EXTERNAL THERMAL LOADS

The thermal environment of the Moon is covered in Chapter 1. The radiant input, surface reflectivity, lunation effects, surface temperatures, and other factors were discussed. There are several mission-oriented considerations which should also be mentioned as modifying these inputs. The sudden changes in thermal loads are most striking. In some instances the worker may be on the sunlit side of a vehicle where he receives radiant heat from the vehicle as well as from the Sun, Earth, and Moon. The total radiant input in a deep crater may be very severe. At other times, he may be required to work on the shaded side of the vehicle or even on the shaded side of the Moon. In many instances, such as in crevice operations, one side of the worker may be subjected to heating while the other side is radiating out to the heat sinks of outer space and the nonilluminated portions of the crevice. In addition, maintenance work may require close contact with cryogenic tankage or high-temperature auxiliary power units. These sudden changes in external environment suggest that insulation will have to play a major role in thermal control. Design requirements should account for all of the unusual conditions mentioned above, for the entire period of the extravehicular mission.

It would appear that suit components in contact with the body should be kept below about 75±5° F at any point except for short-duration emergencies. The temperature within the suit and in contact with the body should be in the 70° to 80° F range, with air outlets reaching a maximum 80° to 90° F.

A rigid analysis of the external factors of thermal problems is beyond the scope of this report. A theoretical analysis of the general thermal design problem for suits in space operations has been presented by Auxier.[13] This report emphasizes the importance of local reflective environment in thermal control and the wavelength dependence of absorptance parameters. It goes far in relating the analysis to the design of adequate ground-based simulators. The problem of nonuniform radiant inputs and unusual suit-surface temperatures has been well covered in the studies of Cramer and Irvine.[76, 177, 178] The proposed solution of a water jacket appears somewhat drastic when mobility of the man in the environment is desirable.

A completely passive thermal coating plus a porous outer layer of insulation would appear to be the best solution for the external heat problem, with a liquid or gaseous dynamic system for internal loads. The theory of external thermal coatings for lunar problems has recently been reviewed by Dempster et al. of the NASA Marshall Space Flight Center[84] and Buna[56] of the Martin Company. Mathematical models of the basic problems are outlined for the storage of cryogenic materials on the lunar surface. The approach is quite applicable, as is the study of the measurement of solar absorptance and thermal emittance of spacecraft coatings by Fussell et al. of the NASA Goddard Space Flight Center.[119]

Several suit-specific insulation studies have been published. A feasibility study by Whisenhunt and Knezek[344] of the Ling-Temco-Vought Corporation presenting a first approximation of passive insulation in extravehicular suits appears worth reviewing in detail since many of the factors are clearly outlined. A more rigid analysis is beyond the scope of this report. Their basic approach is the use of an insulated coverall garment, with supplementary control of critical sites such as flexible joints, helmet, feet, and hands by other aids. Many of the basic thermal transport parameters may be of value to those analyzing the thermal problems of outer suit layers and will be presented below.

These investigators approach the problem by assuming that the desired goal is the lowest thermal load on the internal cooling system compatible with the general mechanical design limits of the suit. Porous materials evacuated to the space vacuum present the most efficient insulation. Figure 58 shows the effect of low air density on the thermal conductivity of a typical glass fiber insulation. This is used as a model insulation system with a conductivity as low as 0.01 Btu–in./hr–ft²–°F.

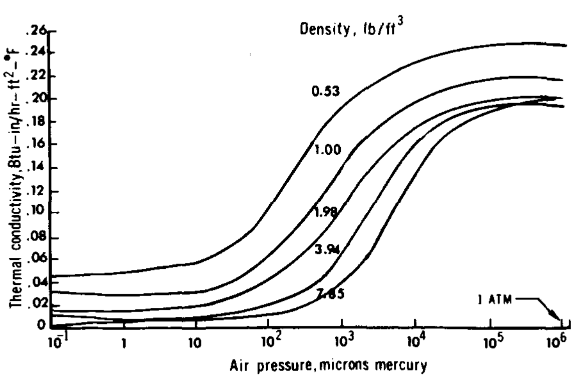


FIGURE 58.—Thermal conductivity of a typical unbonded glass fiber insulation; 75° F mean temperature. (AFTER WHISENHUNT AND KNEZEK.[344])

How effective is this insulation in the lunar night as well as the lunar day?

The simplest condition for the analysis is the lunar night, which can last as long as 14 days. In the case of protecting the crew member from heat loss in the lunar night cycle or within the shade of a vehicle or geologic formation, the limiting condition described by the environment is absolute zero. If one assumes a 400 Btu/hr output for the resting man, of which 40% is lost through the critical insulation areas such as hands, feet, and helmet, there remains a 250 Btu/hr heat loss through the normal insulation areas. For a suit with an area of about 25 ft², the maximum permissible heat loss is 10 Btu/ft²–hr. Heat loss is a function of surface emissivity as well as thermal conductivity and thickness of insulation. Figure 59 shows the effect of surface emissivity on the thickness of typical glass fiber insulation required to attain the permissible 10 Btu/ft²–hr with internal temperature of 90° F. This figure shows that a coating with an emissivity of 0.93 (white nylon parachute cloth) can be used with a 0.25-inch-thick glass fiber vacuum-pore insulation to accomplish this. Any other heat rates may be obtained by using the data on insulation thicknesses presented in figure 60.

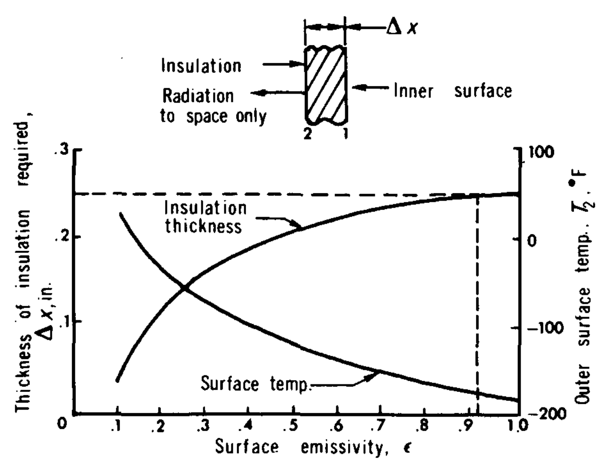


FIGURE 59.—Effect of surface emissivity on glass fiber insulation thickness required. Insulation conductivity, 0.01 Btu-in./hr-ft²-° F; heat loss to space, 10 Btu/hr-ft²; inner surface temperature $T_1 = 90°$ F. (AFTER WHISENHUNT AND KNEZEK.[344])

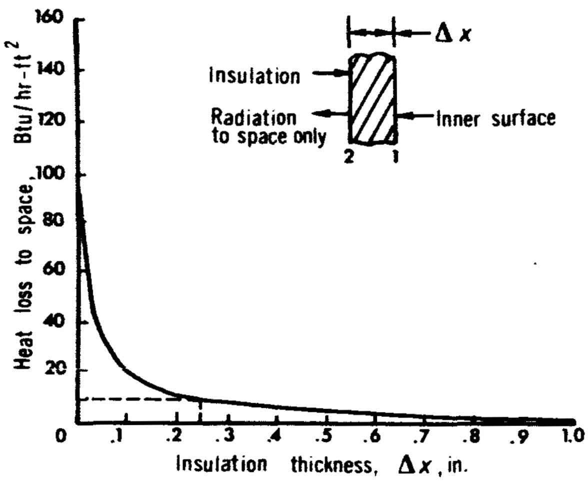


FIGURE 60.—Effect of glass fiber insulation thickness on heat loss to space with no external heating. Insulation conductivity, 0.01 Btu-in./hr-ft²-° F; surface emissivity $\epsilon = 0.93$; inner surface temperature $T_1 = 90°$ F. (AFTER WHISENHUNT AND KNEZEK.[344])

It thus appears that the heat loss problem in the shaded environments can be well controlled by a passive system. It must be kept in mind, however, that the 40% loss through critical insulation areas at the periphery may be critical in the final design. The ability to transfer heat from warmer parts of the body during the lunar night must not be neglected in more detailed analyses of the problem.

On the daylight or heat-input side, the surface temperature and resulting heat input per unit area is a function of the solar absorptivity-to-emissivity ratio (α/ϵ) of the surface. Most of the radiation will be absorbed and reemitted to space, the surface temperature approaching the adiabatic equilibrium temperatures for specific (α/ϵ) ratios shown in figure 61. For example, a white parachute fabric with an emissivity of 0.93 and an α/ϵ ratio of 0.6, covering 0.25 inch of glass fiber insulation, gives a thermal absorption rate for the noncritical suit areas of 4 Btu/hr–ft².

From figures 1 and 2 in Chapter 1, it can be seen that when the crew member is on or near the lunar surface, the maximum temperature likely to be encountered is 250° F. For an α/ϵ ratio of 1, figure 61 indicates a suit absorption rate of 7 Btu/ft²–hr. This would be the very maximum external load for the cooling system under the worst exposure conditions. The above figures are for a combination of vacuum-pore glass fiber and parachute cloth. Figures 61 and 62 show how materials with lower values of (α/ϵ) and other porous insulations would affect thermal transfer rates.

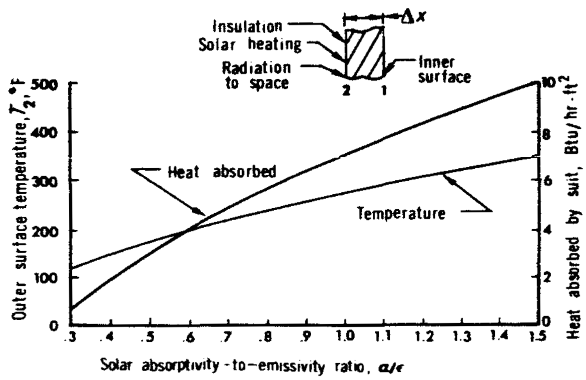


FIGURE 61.—Effect of radiation properties on heat load of suit exposed to Sun. Insulation conductivity, 0.01 Btu-in./hr-ft²-° F; $\Delta x = 0.25$ in.; inner surface temperature $T_1 = 90°$ F. (AFTER WHISENHUNT AND KNEZEK.[344])

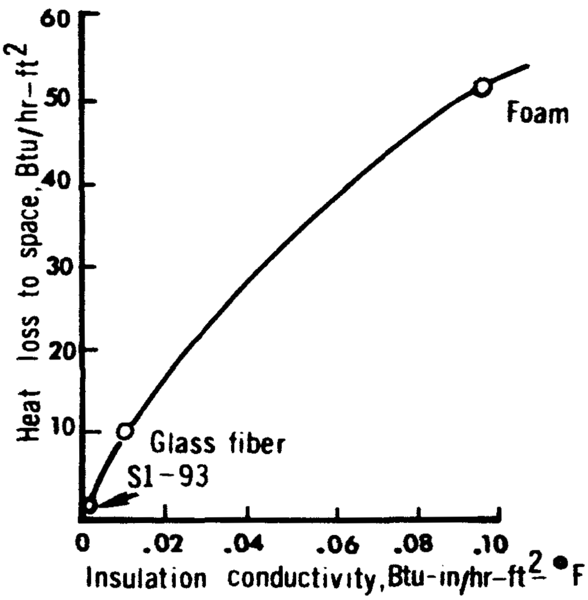


FIGURE 62.—Effect of insulation conductivity on heat loss to space. Insulation thickness, 0.25 in.; outer surface emissivity, 0.93; inner surface temperature, 90° F. (AFTER WHISENHUNT AND KNEZEK.[344])

Special consideration must be given to the critical areas that have been mentioned as well as to heat shorts such as seams and zippers. In the maximum heating environment, only 1 ft^2 of heat shorts would more than double the thermal heat load. The details of avoiding these shorts as well as the specific design of glove, helmet, and footgear are beyond the scope of this general discussion, but not beyond the realm of engineering possibility. It should be remembered that almost 40% of the external heat transport will be through these areas.

A similar calculation of the external heat loads on lunar suit air-conditioning systems has been presented by Del Duca et al.[83] They assumed a super insulation of 10 to 20 layers of foil with a total thickness of 1/4 inch, giving a total transmittance of 0.02 Btu/ft^2–hr–°F. For a suit of 25 ft^2 area they arrived at a 50 Btu/hr heat load on the subsolar point (fig. 1) with a suit surface temperature of 175° F and a 45 Btu/hr heat loss in the shade with a −10° F surface temperature. These thermal loads are of the same order of magnitude as in the Ling-Temco-Vought study. It should be pointed out, however, that heat shorts were not included in this study, nor was the added thermal load of being in a radiant focus of a lunar crater. It would seem from these two studies that reasonable thermal loads on the cooling system of a lunar suit may be about 100 to 200 Btu/hr.

It must be remembered that, as discussed in Chapter 1, abrasion or erosion of the suit surface by meteorites is a distinct possibility. An example of wear abrasion on the thermal properties of current space suits may be seen in the specifications for surface emissivity and absorptivity of the Project Mercury suit:[241]

A. Infrared spectral range emittance—6% (spectral range 0–7μ with surface fabric at 25° to 600° F)
B. Reflectivity (temperature 70° to 160° F)
  1. New material
    a. Near infrared (2,000 mμ)—88%
    b. Visible range (500 mμ)—84%
    c. Ultraviolet range (200 mμ)—87%
  2. After abrasion and wear
    a. Near infrared—82%
    b. Visible range—73%
    c. Ultraviolet—71.5%

Changes of this magnitude may well be critical under lunar conditions. The design of the outer layers is most critical. Choice of ideal surface material is difficult since factors other than absorptance/emission ratios influence the choice. Meteorite protection, for instance, may well dictate a heavier metallic shielding than current fabrics will offer. In any case it would appear that the functions of meteorite protection, radiant control, and insulation would best be relegated to an external garment which can be donned prior to exit to the lunar surface.

One must also consider such possibilities as designing convertible, imbricated coverings to allow optimum function in both the lunar day and night. The same surface cannot optimally reflect the infrared radiation from the lunar surface and also emit into space the internally generated heat in the same spectral region. As Schueller and Berner[291] point out, an imbricated system with one side of white, spectrally-selective surface can simultaneously reflect heat from the lunar surface, reflect direct solar input, and radiate body heat to space when optimally positioned. During the lunar night the shingles can be closed to prevent too large a heat loss from the white surface. With the possible need for meteorite protection, such an approach may well be worth the weight penalty.

PARTITION OF INTERNAL COOLING LOADS

It has been seen that the maximum daytime external heat loads presented to the internal air-conditioning system may well amount to 100–200 Btu/hr. The discussion in Chapter 3 indicates that the metabolically generated loads under 1 g conditions and at the very slowest locomotion (0.4 mph) on a flat, hard surface may entail a thermal input of 1,300 Btu/hr for 4 hours or more. It was pointed out that the combination of subgravity locomotion problems, faster walking speeds in emergency conditions, and a sand-dune environment may well boost the input to 5,000 Btu/hr for periods up to several minutes. It appears that the human thermal inputs are at least one order of magnitude larger than the external inputs. How well can current pressure-suit cooling systems handle these thermal loads?

It has recently become apparent that mathematical models of the interactions of the human thermoregulatory mechanism and ventilating garments are inadequate for precise prediction of such parameters as optimum configuration, gas flow, partition of sensible and latent heat transfer, and so on. Simultaneous variations appear in temperature, heat flux, surface wetness indices, and such critical flow parameters as distribution through suit channels and interstices, Reynolds numbers, Sherwood numbers, Smith numbers, and Lewis numbers. It is appropriate, however, to mention at this point that several excellent theoretical thermal analyses of ventilating garments have been presented by Spells and his coworkers at the Biophysics Laboratory of the RAF Institute of Aviation Medicine, Farnborough, England.[306, 307, 308, 309] Other recent studies of the theory and practice of ventilating-garment design have been presented by Mauch et al.,[228] Skilling et al.,[301] Webb and Veghte,[334] Webb and Klemm,[333] and Billingham and coworkers.[38, 39] Some earlier studies of the dehydrating effects of full-pressure-suit ventilating systems have been presented by Libber and his coworkers.[209, 210] These studies will not be reviewed because of the more recent advances to be discussed below.

Waste heat in man is normally dissipated by a combination of transfer processes including natural forced convection, radiation, conduction, and evaporation. The thermal energy (Q) balance of the body may be written:

$$Q_{metabolic} = Q_{work} + Q_{latent} + Q_{sensible} + Q_{stored} \quad (35)$$

The latent heat loss involves evaporation of sweat; the sensible loss is that lost through the other mechanisms. Any deficit in body cooling is accompanied by body heat storage. This partition of heat loss and storage factors in current suit design will now be discussed.

The first study to be discussed is that of the Garrett Corporation.[59, 243, 332, 352] Many of the data are previously unpublished and thanks are due Dr. James Waggoner and Dr. E. C. Wortz of the Garrett Corporation for their cooperation in discussing this material and permitting its publication in this report. The Navy Mark IV, Mercury, and International Latex Apollo suits were tested under the general thermal conditions described in Chapter 3 of this report. It is important to realize that in these studies the suits were *not pressurized.* Ambient gases and pressure in the altitude chamber were varied, as well as the methods of suit cooling. These partition data on thermal loads were obtained from analysis of inlet and outlet air parameters. Sensible heat load was determined from volume flow and difference between inlet and outlet dry-bulb temperatures. Latent heat flow was determined from volume flow and difference between inlet and outlet dew points. Total heat load is the summation of the two values.

The data shown in figure 63 are for several suit types. The suit outlet dry-bulb and dewpoint temperatures are shown as functions of metabolic rate for a constant ventilating flow of 15 ft³/min. It will be noted that the highest dewpoint temperature obtained in these tests is 72° F, as compared with a frequently used design value of 79° F (suit outlet relative humidity = 70%). The suit outlet dry-bulb temperature remains constant at 90° F, a fact observed in the testing of several different types of suits over a wide range of metabolic load, ventilating flow rate, and suit inlet conditions. The shape of the dewpoint curve appears to vary with ventilating flow rate, and may approach an asymptote at 70° F.

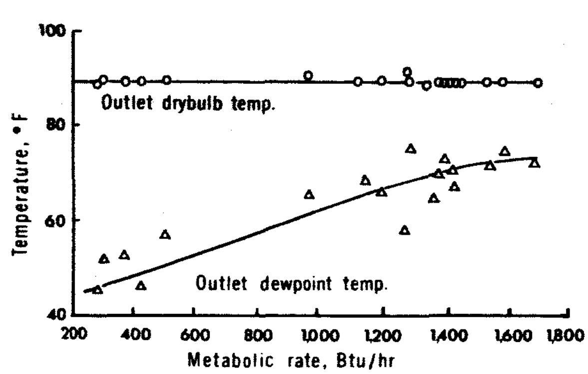


FIGURE 63.—Variation of suit outlet conditions with metabolic rate. Suit ventilating gas flow rate, 15 ft³/min. (AFTER GARRETT CORPORATION.[3])

Figure 64 shows the suit outlet conditions for different flow rates. It will be observed that the suit outlet dewpoint temperature peaks at approximately 80° F with a ventilating flow of 5 ft³/min, a flow condition obviously unsatisfactory from the standpoint of thermal adequacy. With increasing flow, the suit outlet dewpoint temperature falls off gradually.

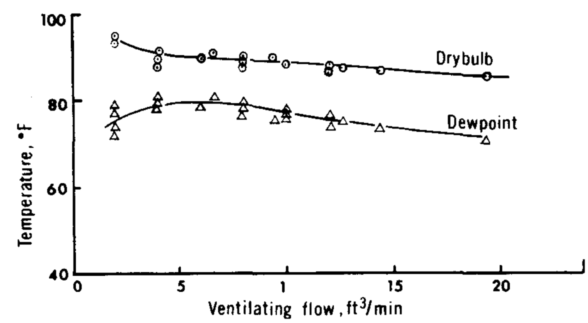


FIGURE 64.—Variation of suit outlet conditions with ventilating flow. Walking 2.0 mph; suit unpressurized; chamber pressure, 3.5 psia; inlet dry-bulb temperature, 50° F; inlet dewpoint temperature, 45° F. (AFTER GARRETT CORPORATION.[3])

Data were obtained on subjects walking horizontally at 2 mph (1,200 Btu/hr) in Mercury and International Latex Apollo suits, but for the sake of brevity only the Apollo suit data will be presented. Experiments were performed with the chamber at both 3.5 psi with 100% oxygen and at 7.0 psi with 50% oxygen and 50% nitrogen. At 3.5 psi it was found that at rest the total heat load removed was about 250–350 Btu/hr and with exercise this increased to about 700–800 Btu/hr. The latent heat load ran from 100 to 200 Btu/hr at rest, and from 600 to 800 Btu/hr with exercise, with much variation between subjects. As the gas flow increased from 8 to 14 ft³/min the sensible heat load increased from 85 to 180 Btu/hr, with little variation between subjects and with resting levels almost equal to exercising loads.

With an increase in air density to 7.0 psi (50% nitrogen and 50% oxygen) the total heat loads removed were slightly increased to 300–400 Btu/hr at rest and 800–900 Btu/hr with exercise. The latent heat loads again showed marked variation between individuals, with the levels about the same as at 3.5 psi. As would be expected from the doubled heat capacity, the sensible heat load was a little less than double that at 3.5 psi. The dry-bulb temperatures were about the same at both pressures.

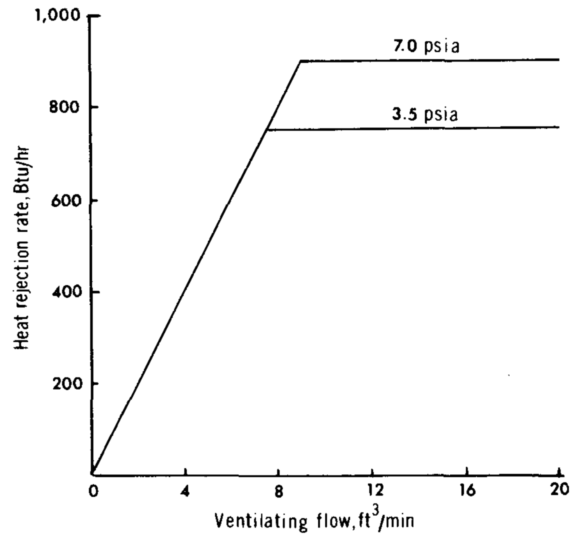


FIGURE 65.—Heat rejection rate. (AFTER GARRETT CORPORATION.[3])

Figure 65 compares the heat rejection rates at the two pressures in the Apollo suit. The Mercury suit figures were not remarkably different. It will be noted that the maximum heat rejection rate obtained at the 3.5 psia condition was approximately 750 Btu/hr, a value curiously close to the average heat removal rate of 750 Btu/hr obtained when the ventilating flow rate was held constant at 15 ft³/min and the metabolic rate was varied. The leveling off of the heat rejection rate could indicate the occurrence of thermal adequacy at a ventilating flow of 8 ft³/min. If an average metabolic rate of 1,200 Btu/hr and a net work output of 160 Btu/hr are assumed, this would require a net heat loss by radiation and convection of approximately 290 Btu/hr to avoid heat storage. Although a heat loss of this magnitude is certainly possible under the experimental conditions used in the tests, it is not possible in lunar daytime conditions where an added 100–200 Btu burden would be imposed. It is interesting to note that similar tests at 7.0 psia show a similar leveling off in heat rejection but at the higher rate of 900 Btu/hr. Tests run at sea-level ambient pressure indicate a maximum heat removal rate of 1,050 Btu/hr.

It is clear from these tests that thermal adequacy of a ventilating gas loop system must be demonstrated at the system design pressure level. These data also indicate that evaporative sweating accounts for more than 5 times as much heat loss as does convective cooling at high exercise rates in these suits. There was only a slight tendency for sweating to decrease as convective flow almost doubled and outlet dry-bulb temperatures remained constant. The increased rate of airflow apparently increased the latent heat loss by increasing the effective vapor-pressure gradients.

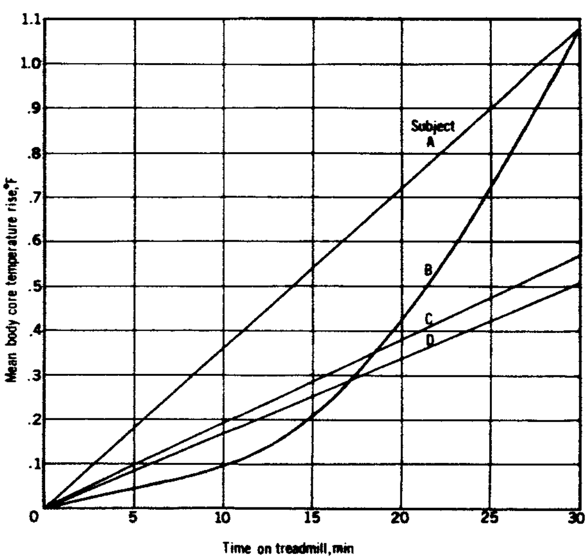


FIGURE 66.—Mean body temperature rise as a function of time on treadmill. Chamber pressure, 3.5 psia; Mercury and International Latex suits unpressurized; temperature rise determined by rectal probe. (AFTER BURRIS ET AL.[59])

A continuation of these studies in analysis of body temperature, fluid loss, and other factors indicates the moderately severe strain to which the body is subjected by these exercise loads in unpressurized suits. It was determined that with a ventilating gas flow of 14 ft³/min at 3.5 psi, the sweating mechanism removes from 82 to 87% of the heat generated. This requires from 0.75 to 1 lb of sweat per hour, a rate which is quite stressful when prolonged. Some of the pathological physiology of the heat-loss process which this state entails is briefly discussed in Chapter 5. As an index of the stress, figure 66 demonstrates how the mean body core temperature (heat storage) rises as treadmill time in an unpressurized suit at 3.5 psi increases.

It appears from the Garrett study that thermal control by ventilation alone is inadequate for lunar operations. Figure 67 outlines this inadequacy, pointing out the heat storage potential at higher metabolic rates even with high ventilation rates.

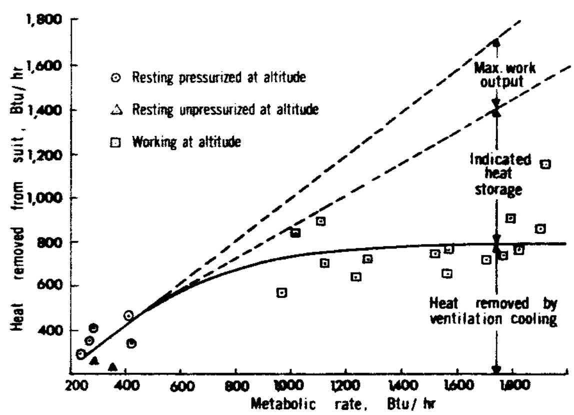


FIGURE 67.—Thermal inadequacy of ventilated suits. Chamber pressure, 3.5 psia; International Latex prototype Apollo pressure suit; suit pressurization, 3.5 psi; ventilating flow, 15 ft³/min. (AFTER GARRETT CORPORATION.[3])

Other investigators studying the ventilation cooling of Apollo suits are less pessimistic. Tests performed on the International Latex suit by the Hamilton Standard Division of United Aircraft Corporation have been reviewed by Lang.[205] A pre-prototype ventilating assembly for the International Latex NR–2 suit was tested for adequacy at 15 cu ft/min airflow and 1,600 Btu/hr thermal load. The studies were performed at the Moore Laboratory of Republic Aviation Corporation. The single subject, an F–105 test pilot, was denitrogenated for 2 hours prior to going to a chamber altitude of 35,000 ft. With the ventilation flow of the suit turned on for the 5 hours of preparations prior to flight, a total weight loss of 1.8 lb was recorded before the experiment even began. The rectal temperature started at a rather low value of 36.15° C and dropped to 35.6° C before the experiment began. At 14:22 hours the subject mounted a bicycle ergometer and set an external work pace of 250 Btu/hr, a level previously calibrated at sea level to produce a metabolic rate of 1,600 Btu/hr at 50 rpm pedal revolutions and 1.5 kg ergometer load. A rather brief review of the detailed results will be given since they present a closer review of subjective sensation and physiological parameters involved than do the protocols of the Garrett Corporation study. Figures 68 to 72 present the time flow of metabolic rate, mean body temperature, rectal temperature, ventilation stream and average skin temperatures, and finally heat flow partitions. The following general description of the events is taken directly from the report.

After the beginning of hard exercise, the heart rate increased from 116–132 to 116–170 beats/min. The rectal temperature showed a gradual increase from 35.60° C to 36.84° C. Initially, the subject noticed a general warming effect. The coolest parts of his body were his feet. After about 10 minutes, he noticed sweating on his back and then over his entire body, including the forehead. He described the heat load as similar to the sea level run, but with more sweating. He was aware of hot breath coming back into his face. After 30 minutes, his feet and calves became tired and later had a heavy feeling. Throughout the exercise period, he was not aware of ventilation below the elbows or knees. There were no other localized hot spots and the noise level remained unchanged. When he momentarily stopped his pedaling so that an outflow reading could be taken, there was better ventilation over his back area. At 15:16 the exercise level was reduced to 167 Btu/hr useful work output corresponding to a metabolic rate slightly below 1,200 Btu/hr. Ergometer pedal speed was still 50 rpm and ergometer load was reduced

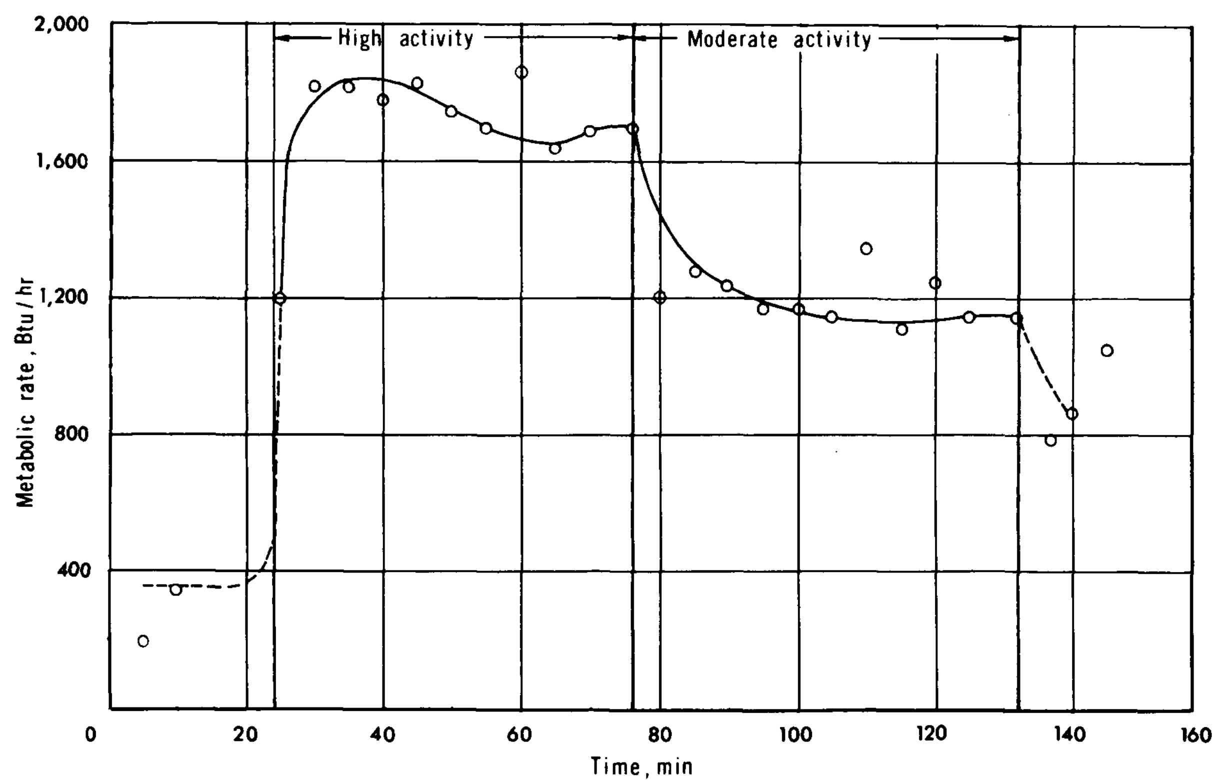


FIGURE 68.—Metabolic rate based on carbon dioxide production. Ventilation test of International Latex full-pressure suit (MR-2). (AFTER LANG.[205])

to 1 kg. The heart rate decreased from 170 to 150 beats/min. The rectal temperature showed a gradual decrease from 36.85 to 36.68° C.

Initially, there was moderate cooling, then an absence of sweating, a comfortable feeling, less fatigue, and no heaviness in the feet or knees. After 20 minutes, there was a slight increase in warmth followed by a slight increase in cooling effect, at which time skin temperatures showed an increase; subject reported slight increase in warmth and had noticed a gradual onset of sweating. Again there was no change in the ventilation to the feet and hands. At 16:12 exercise level was further reduced to 84 Btu/hr output corresponding to a metabolic rate of approximately 800 Btu/hr. The heart rate dropped to around 140 beats per minute, and rectal temperature decreased from 36.68° C. The subject did not notice any sweating and reported that he was quite comfortable throughout this period of exercise. After 13 minutes at this setting the test was terminated.

The analysis of the results is as follows:

1. *Heat balance:* The metabolic rate pattern is recorded in figure 68. In figures 69 and 71 it can be seen that the mean body temperature was approaching equilibrium at 45 minutes; the skin temperature at 35 minutes. The rectal temperature (fig. 70) behaved similarly. The role of the previous cooling, prior to the run, obscures somewhat the significance of rate of temperature rise and time to reach equilibrium but probably does not affect equilibrium levels. Experimental time constants which describe the response of rectal and mean body temperature with a step change in activity from rest to high activity were graphically determined from the data of figures 69 and 70. The mean body and rectal temperature time constants were 21 minutes. The average skin temperature readings were too erratic for time-constant analysis.

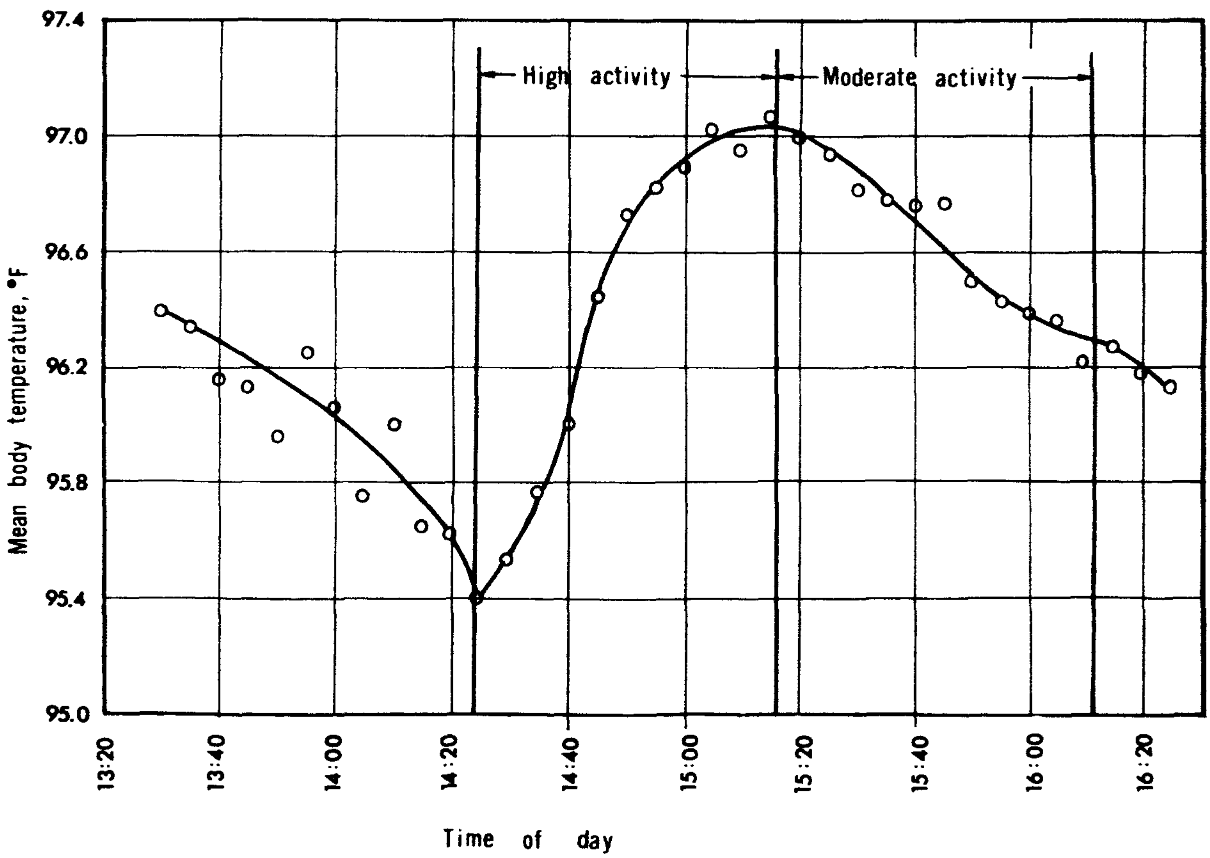


FIGURE 69.—Mean body temperature. Ventilation test of International Latex full-pressure suit (MR–2). (AFTER LANG.[205])

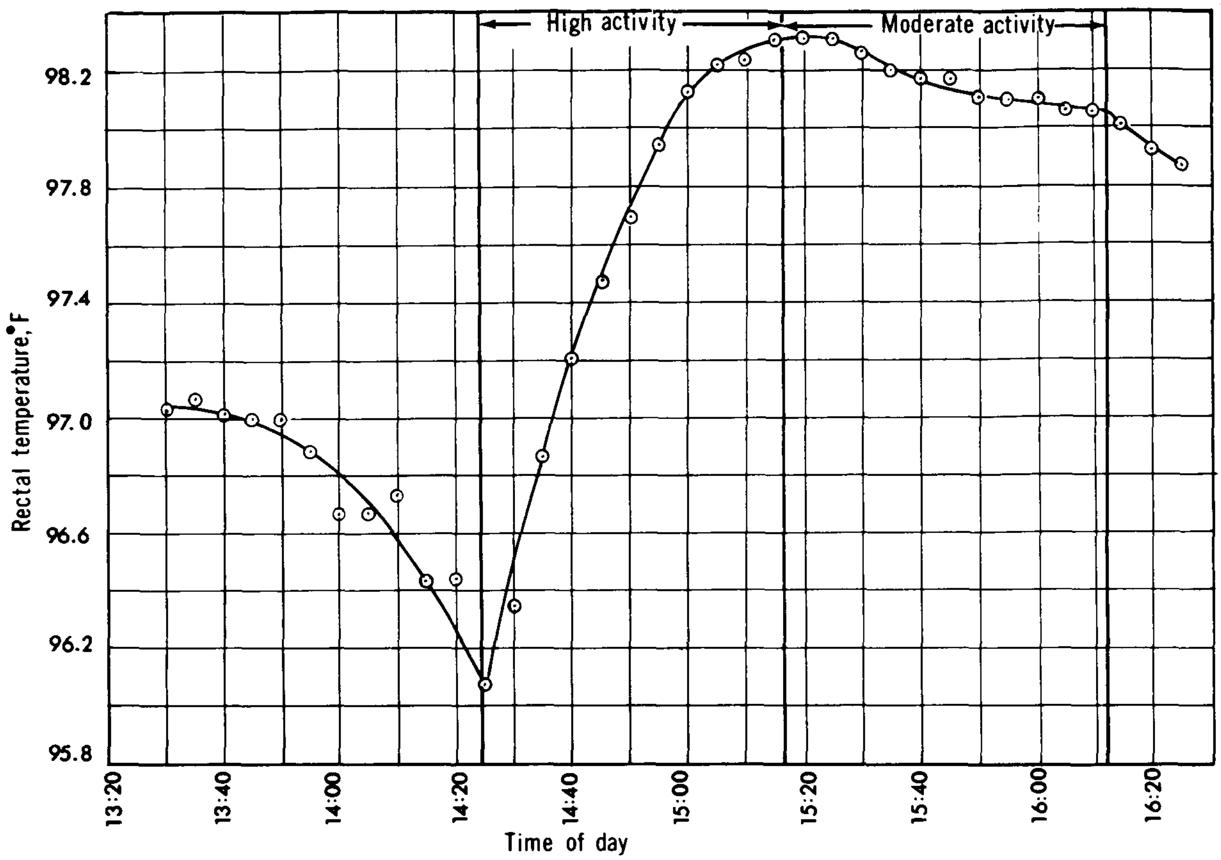


FIGURE 70.—Rectal temperature. Ventilation test of International Latex full-pressure suit (MR–2). (AFTER LANG.[205])

The possibility of heat storage exists, as seen in figure 71, when the temperature of the ventilation stream exceeds average skin temperature. The heat leakage into the suit was approximately constant at 50 Btu/hr. The sensible capacity of the ventilation stream is approximately 130 Btu/hr for an exit temperature of 90° F. With an increase in metabolic heat output, it would be expected that the skin temperature rise would lead the stream temperature rise because the heat originates in the muscles. If, however, a leakage over and above the capacity of the stream were to exist, then the stream exit temperature would rise, placing a greater load on the body. This would cause more sweating and possibly some additional body heat storage. These are the possible reasons for the overlap of the curves in figure 71 just after the occurrence of body heat storage.

However, there appears to be one red herring. Because of malfunction of the sensors, the thigh readings were not used in the determination of average skin temperature. Since the thigh muscles do much of the work, thigh skin temperatures were probably high. Therefore, the average skin temperature was higher than the values plotted. Furthermore, if area-weighted temperatures were used, an additional rise would be expected. If the average skin temperature, then, was found to be 2° in error, the overlap in figure 71 would not exist and no storage need be hypothesized.

There is another interesting point. The continual reduction in ventilation-stream exit temperature adds credence to the hypothesis that there is excess capacity in the stream. Evaporation was occurring, which caused the stream to cool at a faster rate than the skin.

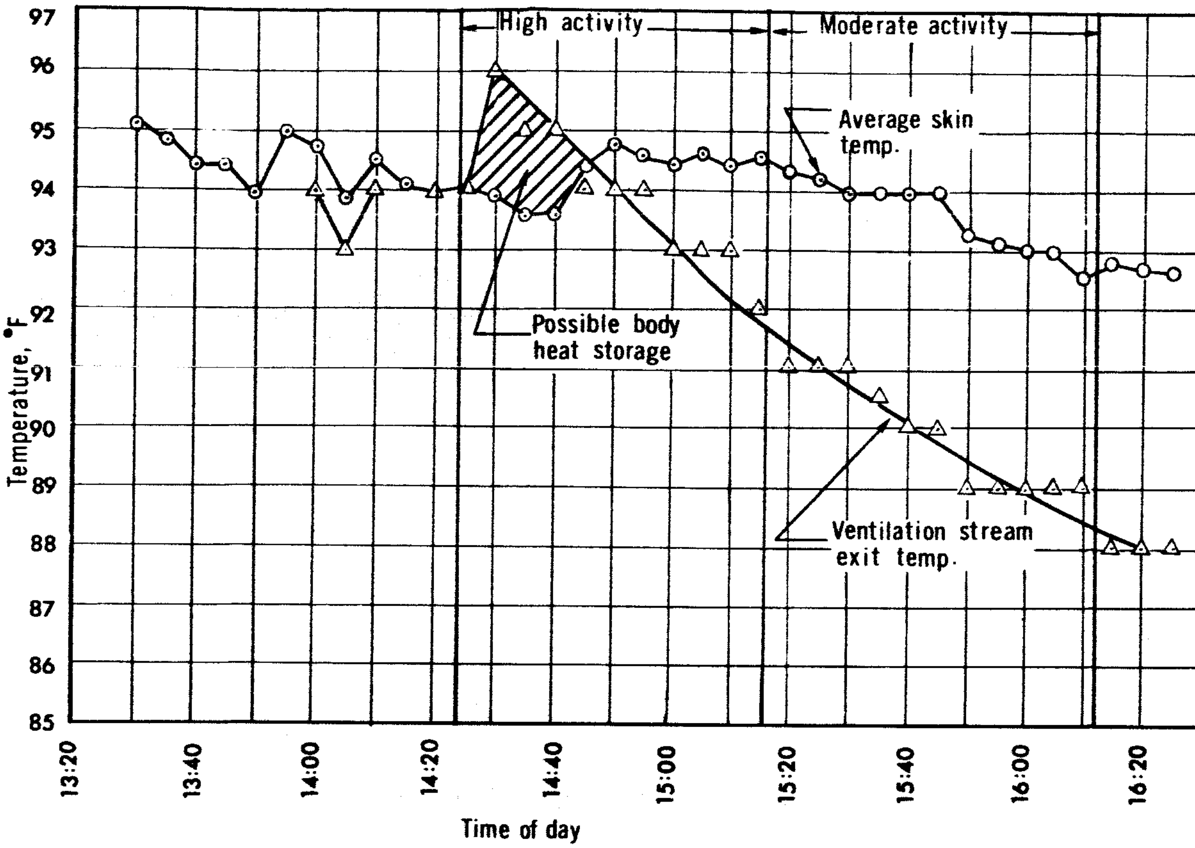


FIGURE 71.—Ventilation stream temperature and skin temperature. Ventilation test of International Latex full-pressure suit (MR-2). (AFTER LANG.[205])

The graphical representation of the system heat balance is found in figure 72. In Lang's interpretation of the data, the total instantaneous heat removed by the stream is compared with the total heat available to it. This heat available (curve E) was found by subtracting the heat equivalent of ergometer work from the sum of metabolic and leakage heat. The agreement obtained at the equilibrium point (76 minutes) was within 3%. Curve D was taken as a straight line although the plot of instantaneous work loads as a function of activity (fig. 68) is not actually a straight line. It was believed that the metabolic rate corresponding to the equilibrium CO_2 production rate most accurately describes the effort, inasmuch as the ergometer setting was held constant. It should be noted that the stream flow during most of the test was just under 15.5 cu ft/min. This value is approximately 5% greater than the design point inlet volume flow of 14.7 cu ft/min. Actual inlet temperature was also 15° F warmer than the design inlet temperature. From curve A the heat-response time constant for the step change in activity from rest to hard work was graphically determined to be 10 minutes.

2. *Subjective impression of subject:* The impression of the subject was noted as follows:

> The subject demonstrated that he could perform a very strenuous exercise for nearly an hour without being strained. To be sure, he was tired and he sweated considerably, but he continually reported that he felt fine. The limitation imposed on the system, then, was the physiological limitation of the subject and not the capacity of the ventilation stream.
>
> When the scheduled activity was dropped to a moderate level (approximately 1,150 Btu/hr) the subject reported that he stopped sweating. Actually, this indicates that

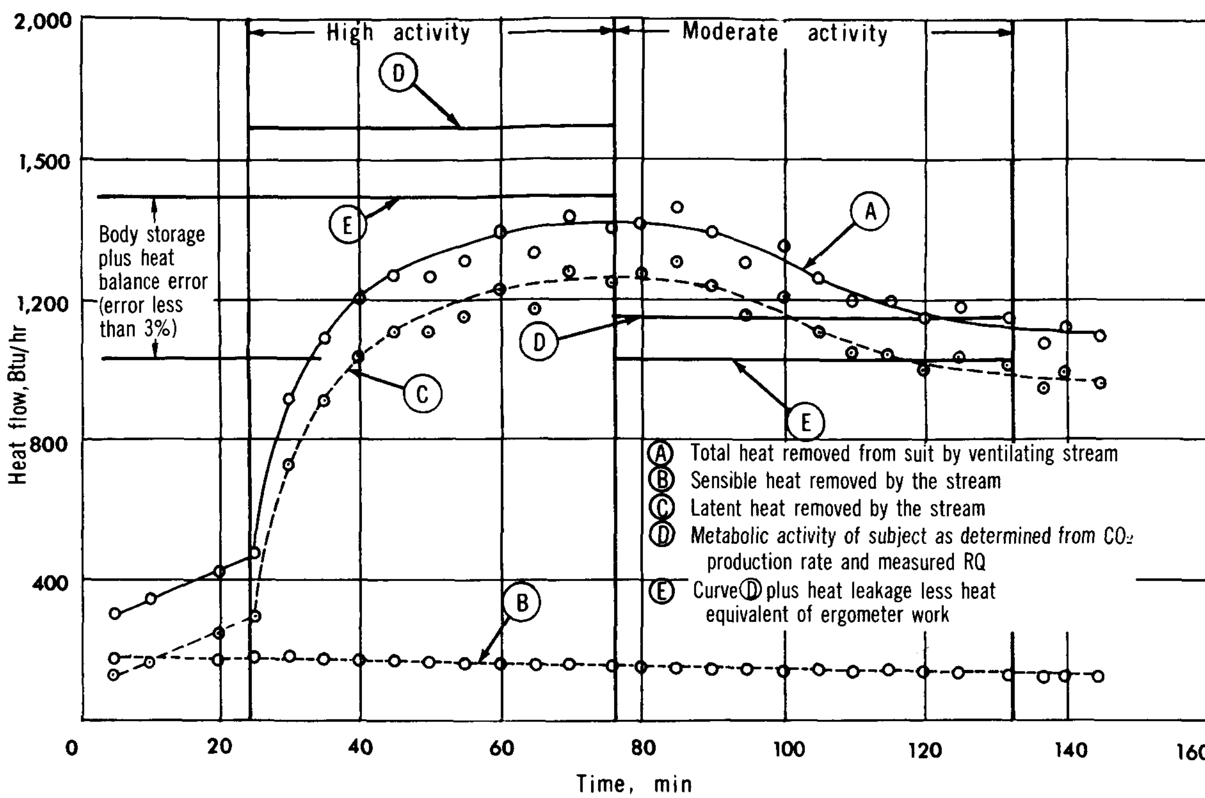


FIGURE 72.—Evaluation of data from ventilation test of International Latex full-pressure suit (MR-2). Time zero is 14:00 hours; heat leak into suit system is constant at 50 Btu/hr. (AFTER LANG.[205])

sweating, while it must have continued, became unnoticeable. During this entire run, the subject's mean body temperature was decreasing which indicates that the body was giving up stored heat to the stream. There is no doubt that, at this activity, the stream had excess capacity. Moreover, this conclusion was also reached by the doctors and physiologists who were present at the test. The heat leakage that occurred during this test is of the same order of magnitude that is anticipated for the Apollo mission design point. It is interesting to note that the unsuited attendant in the chamber lost more weight than the test subject despite the fact that he did not do any exercise.

3. *Water balance:* The following comments were made with regard to the water balance:

Because the weigh-in of the subject was made long before the actual test started (approximately 5 hours) it was not possible to relate directly, the total weight lost to the metabolic activity. It was, therefore, necessary to estimate, by deductive reasoning, the probable order of magnitude of water loss prior to the activity portion of the test. This was done by the attending physiologist and the writer. During this time it is estimated that the subject lost 1.82 lb. From the test data, instantaneous rates of water removal were calculated for each point and plotted versus time. From such curves drawn for the high, moderate, and low activity levels, it was possible to determine the integrated value of water removed for each. The total amount for the three periods was computed to be 2.07 lb. For the entire test, then, the calculated value of subject weight loss is $2.07+1.82=3.89$ lb. Although some of the weight measurements were found to be in error, there is reasonable confidence in the before and after nude weights of the subject. The difference between these weights was 3.84 lb. Thus, it is seen that a system water balance is obtained.

One can conclude along with Lang that the 15 cu ft/min inlet flow was probably adequate for handling the cooling of this subject working at 1,600 Btu/hr on an ergometer in an unpressurized suit for 1 hour. The time constant for mean body-temperature rise for this system is 20 minutes, with 48 minutes before equilibrium is reached. There was also no obvious controlling effect of stream exit temperature by the average skin temperature. The data indicated that exit stream temperature dropped sharply with the onset of sweating.

While skin temperature also dropped, there was a greater lag in skin temperature after a step change in activity. Inasmuch as the slope of the ventilating stream temperature-time curve was always steeper than that of the skin temperature-time curve it appears that the ventilating stream responds more rapidly than the skin to temperature changes caused by changing evaporation rate.

Body heat storage was much less than predicted by the Garrett Corporation study. The cause of the difference is not obvious. It must be pointed out, however, that even at 1,600 Btu/hr, a level of work far lower than the 2,500 Btu/hr suggested as a maximum heat rate in Chapter 3, the subject was being excessively strained. The rate of more than 1 pound of sweat per hour during the period of high activity would appear to be excessively dehydrating for 4-hour missions. Sodden skin with its impaired sweat production and increased likelihood of skin infection should be avoided in the lunar mission. For the proposed upper design limit of 2,000–2,500 Btu/hr lasting several hours, the present cooling system under study appears to be inadequate. What are the alternatives to the air-cooled suits?

NEW APPROACHES TO LUNAR-SUIT COOLING

There have been several new approaches to the reduction of sweat loss in lunar suits. The first was originated by Dr. E. C. Wortz of the Garrett Corporation and developed by that company.[3, 59] The technique involves the insertion of several air-to-liquid heat exchangers inside the pressure suit. General placement of the exchangers is shown in the schematic diagram in figure 73. Testing of this cascade system was carried out in a Navy Mark IV suit with a Mercury helmet. Glycol/water coolant lines passed through a Mk IV G-suit connector. Metabolic heat was studied by spirometry. Heat-balance studies showed a 40 to 60% loss through the suit, which was reduced to 12% loss by a coating of aluminized Mylar.

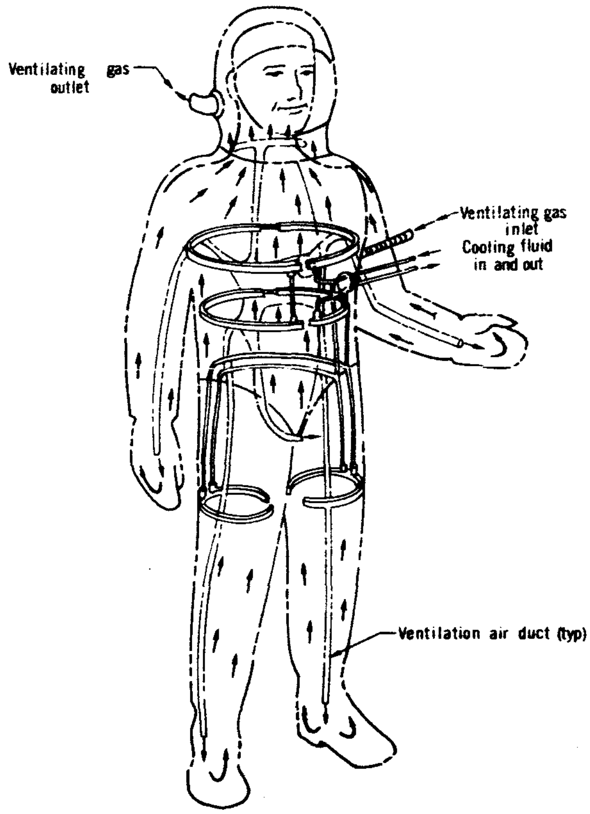


FIGURE 73.—Cascade suit cooling system. (AFTER BURRIS ET AL.[59])

Four basic types of heat absorbers were tested with coolant flow rate, coolant temperature, ventilating gas flow rate, and metabolic rate varied parametrically to obtain basic heat-transfer data for the various heat-absorber designs. The ventilating gas was conditioned to maintain constant inlet dry-bulb temperature of 50°F and a constant inlet dewpoint temperature of 45°F. The suit inlet and outlet dewpoint and dry-bulb temperatures were measured continuously during the test; for a given set of test parameters, equilibrium was reached in ventilating gas outlet conditions in about 60 minutes. Coolant inlet temperatures were varied over a range from 40° to 65°F. Coolant flow was varied from 0.9 to 9.0 lb/min, with the flow divided and monitored in three circuits in the suit.

Figure 74 shows typical test results for a high-effectiveness heat-transfer surface providing less than 20% coverage of the body.

In this series of tests, it was noted that the heat-removal rate of the liquid loop is relatively sensitive to coolant flow. At the highest coolant flow rate of 6.0 lb/min, approximately 80% of the metabolic heat load is removed by the liquid loop. In other studies it was shown that thermal adequacy is obtained for the low ventilating flow rate of 4 cu ft/min with coolant flow rates in excess of 3.5 lb/min for metabolic rates up to at least 1,200 Btu/hr. Based upon these data, thermal adequacy would be expected for metabolic rates up to approximately 1,600 Btu/hr.

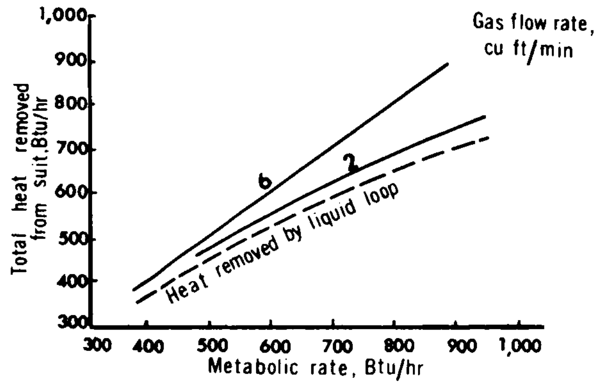


FIGURE 74.—Liquid-loop suit cooling. Coolant flow rate, 6 lb/min. (AFTER GARRETT CORPORATION.[3])

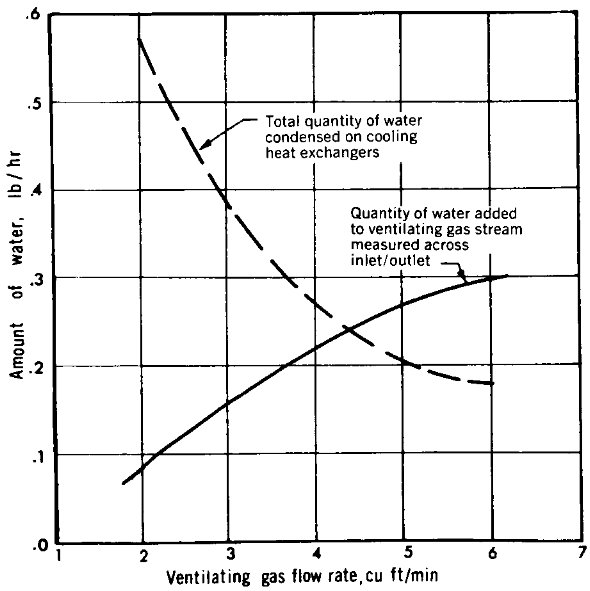


FIGURE 75.—Rate of addition of water (sweat) to ventilation stream during space-chamber tests. Mark IV full-pressure suit; 100% oxygen at 7 psi. (AFTER BURRIS ET AL.[59])

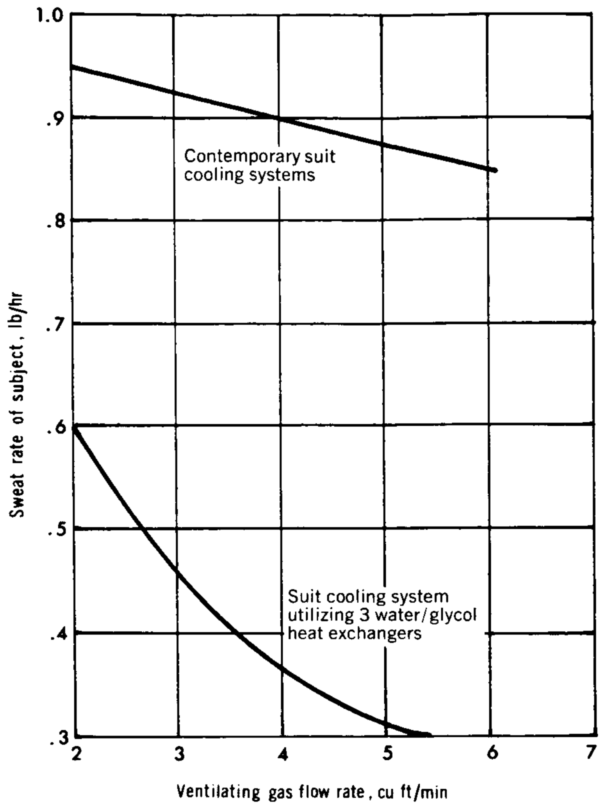


FIGURE 76.—Sweat rate with cascade cooling system and with contemporary cooling techniques. (AFTER BURRIS ET AL.[59])

In order to establish the actual amount of vapor condensed, excess heat removal attained by condensation was used to determine the effects of the gas stream across the condensers. Figure 75 indicates that as the flow rate increases, the quantity of water added to the gas stream increases, suggesting a cycle of skin evaporation, coil condensation, and subsequent reevaporation. This "cascade system" can be viewed as follows: As the gas flow increases there is a concurrent reduction of water condensation requirement for adequate heat transfer to the coolant circuit and an increase in total sweat evaporated. This occurs because (1) as flow increases, sensible cooling increases, and (2) the reevaporation of water from coils gives a large cooling effect without additional sweating—that is, the original sweat water is reutilized in another cycle. Figure 76 indicates that simply placing three small exchangers in thighs and trunk reduces the sweat rate of a subject to about ⅓ that in a pure gas-cooled suit system. From a thermodynamic analysis of the cascade system presented by the Garrett Corporation, it appears that an increase in the number of condensers per cooling cycle will lead to a much lower sweat evaporative rate. Table 35 suggests a possible placement and heat-removal breakdown for a 1,100 Btu/hr load. In the five cooling cycles no condensing occurs on the ankle exchangers, but 40% of total sweat rate is condensed on the thighs and is reevaporated for the waist exchanger. About 60% of total sweat rate can then be condensed on the waist exchanger (40% from legs and 20% from abdomen); and, likewise, 75% of total sweat rate can be condensed on the chest condenser. It can be seen from figure 76 that only about 0.3 lb/hr total sweat need be evaporated to attain adequate cooling.

TABLE 35.—*Breakdown of System Heat Removal* [AFTER BURRIS ET AL.[59]]

Heat-exchanger location	Percent flow	Sensible heat removed, Btu/hr	Heat removed by condensing, Btu/hr	Total heat removed, Btu/hr
Ankles (2)	80	35.9	0.0	35.9
Thighs (2)	80	35.9	127.0	162.9
Waist	80	35.9	192.0	227.9
Chest	80	35.9	240.0	275.9
Arms	20	8.9	32.0	40.9
Oxygen stream (from suit)	100	52.5	330.0	380.5
Total				1124.0

It is obvious that for any ratio of liquid coolant flow to gas flow, a trade-off exists between the glycol/water loop weight and power and the gas-blower weight and power. These relationships must be worked out in detail before an optimum system is attained. Even though a systems analysis of the entire air-conditioning system of the back pack should be involved in this study, it would appear appropriate to present current estimates for gas-loop and cascade-type liquid-loop cooling systems (table 36).

In both systems it is assumed that the work output (400 Btu/hr) is dissipated externally to the suit system, leaving a metabolic heat load of 1,600 Btu/hr to be removed by the cooling system. Assuming suit ventilating-gas outlet conditions of 90° F dry-bulb and 70° F dewpoint, a ventilating-gas flow rate of 25 cu ft/min at 3.5 psia would be required to provide thermal adequacy, where ventilating cooling alone is used. It should be emphasized that this estimate is an extrapolation of present experience and that no heat-balance tests have been conducted at ventilating flow rates this high. With a liquid-loop system, the ventilating flow of 6 cu ft/min used in table 36 should be adequate with respect to carbon dioxide removal. This gas flow requires the liquid transport loop to remove only 1,240 Btu/hr.

TABLE 36.—*Comparison of Cooling Systems* [AFTER GARRETT CORPORATION.[3]]

	Gas-loop cooling	Cascade liquid-loop cooling
Metabolic rate, Btu/hr	2,000	2,000
Metabolic heat load, Btu/hr	1,600	1,600
Ventilating flow, cu ft/min	25	6
Suit ΔP, in. H_2O	13	1.7
Coolant flow, lb/min	0	6
Isentropic vent. power, watts	59	2
Isentropic pump power, watts	0	0.4
Battery weight, lb	20	2
Sweat rate, lb/hr	1.2	0.3

Perhaps the most significant difference in system design, aside from the reduced sweat rates and the question of thermal adequacy, results from the great reduction in power requirement with the liquid-loop system. As emphasized by Burton and Collier,[60] the first approximation to power required for heat transfer may be expressed by

$$\frac{\text{Heat transferred}}{\text{Power required}} = 2{,}500 \frac{\Delta T}{\Delta P} \rho C_p \quad (36)$$

where

ΔT temperature gradient, °C
ΔP pressure gradient, lb/ft²
ρ density, lb/ft²
C_p heat capacity, Btu/lb

For temperature and pressure gradients required for suit cooling, this ratio is 3 orders of magnitude greater for water cooling than for air cooling. The indicated 18-lb reduction in battery weight (4-hr mission) for a portable life-support system is partially offset by the 8-lb weight increase due to the liquid-transport loop and heat absorber. Because of the smaller gas flows with a liquid-loop system, it would be somewhat more compact than a gas-loop system.

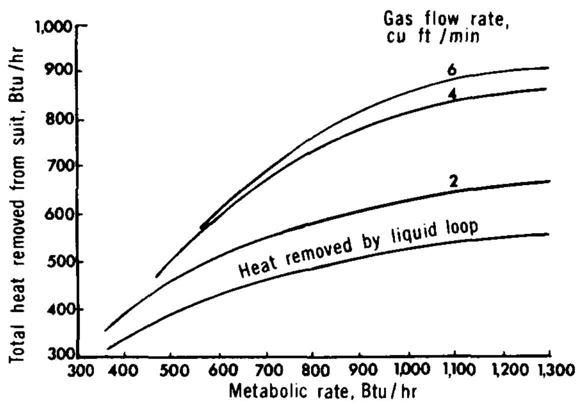


FIGURE 77.—Liquid-loop suit cooling (40% coverage) with vinyl tubing heat absorber. Coolant flow rate, 1.5 lb/min. (AFTER GARRETT CORPORATION.[3])

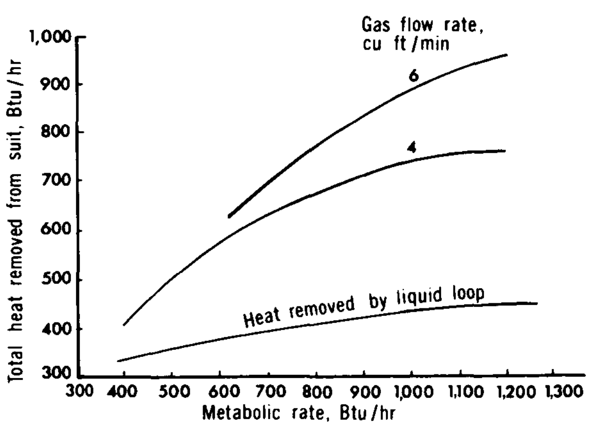


FIGURE 78.—Liquid-loop suit cooling (40% coverage) with "capillary tubing" heat absorber. Coolant flow rate, 0.9 lb/min. (AFTER GARRETT CORPORATION.[3])

Another approach tested by Garrett is to increase the surface area covered in a one-stage heat exchanger. Data shown in figures 77 and 78 were obtained with heat-absorber designs providing approximately 40% coverage of the body. Because of the low heat-transfer effectiveness in comparison with the local-coverage heat absorber previously discussed, only a 10 to 20% increase in heat removal rate was obtained with the extended-area heat absorber. It should be noted that the data given for the extended-area heat absorbers were obtained at relatively low coolant flow rates of 0.9 and 1.5 lb/min, as compared with a coolant flow of 6.0 lb/min in figure 74.

These systems have not yet been optimized with regard to placement, materials, or general exchanger design. Elastomeric materials have thermal conductivities about 1/1000 that of metal. Inclusion of metal powders in materials should increase this crucial factor. The high flow resistance of the large-area tube-type exchangers does increase the pump power requirements any may be limiting.

A second approach to the augmented cooling system has been presented by Burton and Collier.[60] These investigators at the Royal Aircraft Establishment in Farnborough, England, took advantage of the much lower power requirement of a water cooling system and designed an entirely water-cooled undergarment weighing 2 lb 6 oz. Several prototypes have been tested with encouraging success in approximating theoretical heat-transfer goals. The heat is transferred directly from the skin to a network of polyvinyl chloride tubes of 1.67 mm bore. With flow rates of less than 50 lb/hr, heat extractions were obtained of about 75 Btu/ft^2-hr-°C, which was 1 order of magnitude better than the theoretical whole-body heat-transfer coefficient of 3.6 to 14.8 Btu/ft^2-hr-°C. These extraction rates were obtained with less than 1 ft^2 of effective contact area and differences between deep body temperature and water temperature of only about 10° to 20°C. In spite of the fact that cooling pathways were not perfectly matched to segmental body cooling rates, there was little problem with undercooling or "strip" cooling along the tubes. The garment was also used under exposure suits in cold water and allowed heating rates of 1,700 Btu/hr with no discomfort.

This approach to cooling and heating appears quite promising. The cooling flow rates obviously require augmentation for lunar operations. Trade-off studies between optimized liquid cascade cooling and total-body cooling systems should prove interesting. In both types, attempts will have to be made to match more closely the segmental sweating and skin-temperature rates. The data compiled by Kerslake [185] and Burton and Collier [60] which cover these basic points most adequately are given in table 37. It must be remembered that these systems must be optimized for the local conduction-convection relationships that exist between blood, skin, cooling tubes, and air. That local temperature changes in the skin do modify the blood flow, sweating pattern, and general thermal homeostasis is well known.[32] The recent study of Stromme et al.[318] on combinations of exercise and skin cooling is especially pertinent. Suit systems must be designed with these subtle changes in mind.

Another approach to the problem has recently been presented by the Northrop Company in a classified report to Wright-Patterson AFB. These investigators [247] have attained liquid-loop heat removal rates up to 1,000 Btu/hr with a heat absorber design providing a large area coverage of the body.

TABLE 37.—*Segmental Body-Heat Transfer.* [AFTER KERSLAKE [185] AND BURTON AND COLLIER.[60]]

Region	Preferred temp., °C	Heat loss, kcal/hr	Area, m^2	Skin conductance,[a] kcal/m^2–hr–° C
Head	34.6	4.0	0.20	7.55
Chest	34.6	8.2	.17	18.20
Abdomen	34.6	4.5	.12	14.16
Back	34.6	12.4	.23	20.35
Buttocks	34.6	8.3	.18	17.40
Thighs	33.0	12.0	.33	8.55
Calves	30.8	14.6	.20	11.30
Feet	28.6	10.0	.12	9.65
Arms	33.0	8.4	.10	19.80
Forearms	30.8	8.6	.08	16.70
Hands	28.6	16.0	.07	26.40
Total body	33.0 (Mean)	107	1.80	14.00 (Mean)

[a] Deduced from previous columns, assuming a deep body temperature of 37.25° C.

CHAPTER 5

Hyperthermia and Dehydration Problems

FROM THE DISCUSSION in Chapters 3 and 4, it is obvious that thermal overloads and water loss will be prominent dangers in lunar exploration. Current pre-prototype suits and their ventilating systems appear inadequate for the actual lunar exploration mission. Though the basic problems are not beyond solution, there is always the danger of malfunction. It is not the purpose of this closing chapter to present an exhaustive review of hyperthermia and dehydration, or even to discuss recent controversy in the theoretical aspects of the problem. An attempt will be made to define the problems at hand and to indicate current work which may aid in a clearer understanding and solution of the problems.

THERMOREGULATION AND HEAT STRESS

The body gains and loses heat by several mechanisms at various rates which depend on both external and internal conditions. The partition of heat gain and loss mechanisms into radiation, evaporation, convection, and conduction has been reviewed in great detail by Hardy.[158] The appropriate thermal-transfer equations are well defined in his report. These cover the high emissivity and absorptive properties of human skin for the infrared. The radiation parameters are emissivities of radiant source and background, radiation intensities, and body surface temperature and emissivity. Convection parameters are body surface area and temperature, as well as the temperature, heat capacity, and rate of movement of the gaseous environment. Evaporative losses depend on percent of body area wetted, relative humidity, and rate of movement of the gaseous environment, as well as the barriers to diffusion of water vapor between man and his gaseous environment. These evaporative factors have been shown in Chapter 4 to be the most prominent route of heat loss in ventilation of space suits, 0.58 kilocalories of heat being lost per gram of water evaporated. Conductive pathways are generally unimportant in most situations. However, the problem of heat shorts in lunar suits and water cooling of suits does increase the importance of this transport mechanism.

The homoiothermic animals depend on the feedback control of these routes of heat transfer by homeostatic mechanisms. Vasomotor control as well as the metabolic heat produced by muscle activity and general body metabolism are set against external factors that tend to lower the body temperature. Sweating and vasomotor control of peripheral vessels counter the factors that tend to raise the body temperature. Hardy[156, 157] and Wissler[351] have recently attempted to define the critical parameters of heat transfer and the feedback loops in a mathematical model of the thermoregulatory system. Electrical analog models of the system have been made.[77] Benzinger[33, 34] has reviewed the problem of the thermostat and the role of sensors in the feedback loops. An overall detailed review of current thinking in biothermal science has recently been published and should be of great value to all interested in these problems.[158]

Should any of these customary heat-transfer mechanisms be compromised by suit failure, the body may store or lose heat. In the lunar suits, heat storage appears to be the major problem. One can, however, visualize destruction of the passive insulation of the suit by various traumata, with ensuing heat-loss problems in shaded areas.

The compensatory effects produced by excessive heat storage define the pathological physiology of hyperthermia. A study of the degradation of human performance by excessive heat storage has been most adequately reviewed in the classic treatise on the prediction of human tolerance for heat in aircraft by Blockley et al.[42] Numerous physiological indices of strain have been presented in the past. Recent reviews of these indices include those of Carlson and Buettner,[63] Hall and Polte,[151,152] McCutchan and Isherwood,[218] Hall,[150] and Hatch.[161] Problems in the specific degradation of physiological performance and mental well-being have been reviewed by Peplet[257] and Givoni and Rim.[132] A bibliographic survey of this subject is available in a recent WADD report by Wing and Touchstone.[347] Finally, the complex interaction of exercise workloads and the thermal environment has been reviewed in detail by Buskirk and Bass[61] and Suggs and Splinter.[320]

DEHYDRATION AND HEAT STROKE

Closely related, of course, to the problem of thermal overloads is that of dehydration. It appears from the discussion in Chapter 4 that space suits utilizing only airflow mechanisms will impose on the lunar explorer severe loss of water in "normal" as well as emergency operation. The problem of dehydration is well worth discussing in this light. In the past, there have been many adequate reviews of the problem of excessive sweating and the pathological physiology of dehydration. The study of Robinson[276] on the physiological adjustments to heat has a very adequate review of the general problem. In this paper it is reported that in well-acclimatized individuals as much as 4 liters/hr of sweat may be produced for short periods of time. Eight liters have been produced during a 4-hour exposure to 38°C dry-bulb, 34.8°C wet-bulb conditions.[277] In most natural climatic conditions such severe sweating is not found. Coal miners often sweat 8.5 liters during a 5-hour shift.[238] Acclimatized desert workers often produce 10 to 12 liters of sweat in a day.[86, 87, 235]

As Robinson points out, the sweating mechanism is fatigable. Men's ability to sweat at high rates declines significantly during long exposures to heat stresses near the limits of tolerance. Gerking and Robinson[127] reported that the average rate of sweating declined by 10 to 80% in 6-hour exposures of working man from an average initial rate of 1.4 kg/hr. The amount of decline was found by Robinson and Gerking[277] to be greater in humid than in dry heat. They report:

> It was not dependent upon falling skin or rectal temperatures, not upon dehydration, salt deficiency, or lack of acclimatization. It increased with the initial rate of sweating, and with the mean level of skin temperature maintained during the exposure. . . .The declines of sweating did not occur in moderate heat stress where the mean skin temperature was below 35°C and the rate of sweating only 0.4 kg/m^2/hr. In hot dry atmospheres (50°C, with 18% relative humidity), if the men were working with a metabolic rate of 190 Cal/m^2/hr, the decline of sweating proved to be the limiting factor in their tolerance for the prolonged exposures because they maintained thermal equilibrium from the second through the fourth hours and then began to accumulate body heat rapidly because evaporation dropped below the amount required for heat regulation. This failure of sweating which occurs with long sustained high skin temperature and high rates of sweating is undoubtedly related to the more complete failure of heat regulation occurring in heat stroke. The subjects apparently recovered within forty-eight hours from the worst of the six-hour fatigue experiments. The fatigue of the sweating mechanism under these conditions may be considered as a useful adaptation in case of water shortage in a hot environment because it would assure an economical dispensation of water reserves and delay the development of dehydration.

In view of these studies, the more than 1 liter/hr of sweat produced by subjects in air-ventilated suits at 1,600 Btu/hr would appear excessive over periods of 4 hours in individuals not chronically exposed to these conditions.

The factors concerned in the regulation of sweating have been reviewed by Kerslake.[185] This paper pointed to deep skin receptors as key sensors supplementing the hypothalamic sensors in sweat control.[33, 34] A recent report on the regulation of sweating response to work in man[229] sheds some light on the mechanism of excessive sweating associated with exercise. It was concluded that

> ... sweating was regulated in these experiments by reflex effects originating from thermal receptors in the working muscle or in the veins draining the muscles, summated with reflexes originating from cutaneous thermal receptors, both acting through the hypothalamic center, the excitability of which was increased in proportion to its own temperature.

The role of the thermal receptors in or about the muscles has not been hitherto so well demonstrated. Finally, the recent report of Bass and Henschel[24] covers most adequately the response of body fluid compartments to heat loading.

In view of the possibility of heat stroke resulting from severe hyperthermia in lunar emergencies, it appears worthwhile to discuss some of the latest concepts regarding this interesting syndrome. In an excellent paper on the development of heat pyrexia, Gold[135] has reviewed the pathological physiology of heat stroke as determined from more than 250 observations. His description of the general symptomatology as viewed subjectively by a patient with concomitant degradation of judgment and mental capacity is well worth quoting. It indicates the subtle onset in an individual preoccupied with a routine mental task.

> After the first half of a "tolerance" exposure (in which a subject is run close to his collapse point) is over, he first becomes conscious of an aura of impending physiological deterioration which has insidiously descended on him. Up to this point he has had a feeling of well-being, despite the intense heat. But now he is definitely aware that his time of heat exposure will be limited. At this point, also, he notices that his ability to concentrate has begun to wane, in that, for example, he cannot concentrate on and read an ordinary magazine article without taking frequent breaks, even though he is interested in its contents. At these breaks, moreover, he becomes increasingly aware of how hot it is. He then returns to his article and is somewhat taken aback to find that he is now looking only at the pictures and turning the pages rapidly, hardly caring what is in them.
>
> As time goes on he notices that his sweat rate has begun to diminish. His face feels dry and hot, and he thinks he can find a film of dried salt on his cheeks and forehead and especially in the corners of his mouth, which also have begun to feel raw; his hand has become somewhat redder, and it, too, is dry and seems to be getting hotter; and he no longer feels drops of sweat rolling down his trunk under his clothing. Suddenly and abruptly, he feels much worse. He leans forward in his seat in an effort to expose the sweat-soaked clothing on his back more fully to the air, which he hopes will result in a cooling effect due to increased evaporation. It does, but he is somewhat shaken to find that his slightest movement now results in a large increase in heart rate which he can bodily feel. Moreover, he has begun to notice that he is becoming lightheaded, especially when he moves his trunk. It is now that the first inkling of the possibility of fainting settles on him; he is certain that he cannot tolerate the heat much longer.
>
> At this point, if he tries to return to the magazine, he will probably throw it to the floor and find himself in a state of utter irritability. He will actually be fully aware of this irritability but will be unable to do anything about it, even should he want to. The goals of the experiment will no longer seem important to him, and he is likely to resent the periodic inflation of the blood pressure cuff on his arm, or being called on to assume a certain position. But he will want to finish the experiment because of high motivation—so as to cause no injury to his self-esteem. Soon he begins to feel the development of paresthesias, particularly in the hands, wrists, feet, ankles, and forelegs. At this point he realizes that he is becoming even more light-headed and that he must terminate the experiment.
>
> Until this time his face has been pinkish-red in color, but abruptly it has turned almost ashen grey. The subject is always removed from the chamber at this point. However, were he not, he would become stuporous, faint, and eventually lapse into the coma of heat stroke. His rectal temperature would be over 104°F (40°C) and skin temperatures would be equally high or higher.

Gold obtained data on body heat storage, sweat rate and replacement, blood pressure, venous pressure, oxygen consumption, blood gases, hemoconcentration, osmolarity changes, cardiac output, and other cardiovascular parameters. His findings can be generally summed up as follows:

> During extreme heat exposure there was an increased venous pressure and operational arteriovenous shunt (or its functional equivalent) in the presence of cardiac failure. It is postulated that (1) the primary event in the circulatory collapse of heat pyrexia is high-output cardiac failure, (2) the cessation of sweating is a result of rising venous pressure, (3) older persons are more susceptible because of irreversible circulatory changes and (4) an effective treatment may be the intravenous administration of saline solution together with rapid digitalization.

The finding that the increase in venous pressure probably triggers the cessation of sweating, the use of digitalis to supplement rapid cooling to about 102°F, and administration of fluids in the treatment of the syndrome are distinct contributions to our understanding of this problem. The possible use of digitalis autoinjector syringes in the emergency kit of a lunar suit appears to be worth considering.

ACCLIMATIZATION TO HIGH TEMPERATURES

In looking at the preventive aspects of hyperthermia and dehydration, there appear to be two basic approaches available for supplementing space-suit cooling systems. The first is the selection of candidates who have a great tolerance to heat stress and the second is a program of acclimatization to heat.

Gold[136] has recently reviewed the indices for heat tolerance in an attempt to define an improved system for selection of heat-stress candidates. He evaluated past experience in this area and suggested a new approach to the problem. Since most complicated indices of heat stress involve several factors related ultimately to the capacity of the cardiovascular system to keep ahead of body heat storage, Gold suggested that accumulative strain on the circulatory system in terms of heart rate alone should be the ideal criterion. When combined with evaluation of effective heat storage in an individual already fully equilibrated with the test heat chamber, the criterion gives not only the extent of an individual's capacity to dissipate heat, but the price he pays for it (strain). It would appear that such an approach will be superior to past efforts in selecting optimum candidates from a group of very healthy individuals.

The other approach is that of acclimatization. In a superb review of the subject, Bass et al.[25] have outlined the basic physiological mechanisms and effectiveness of acclimatization to heat. Their coverage of the water, salt, and adrenal mechanisms sheds much light on this controversial subject, and is a fine supplement to the previous studies of Robinson and his coworkers[276, 277] and Bean, Eichna, and coworkers.[26, 99] The problems of rapid acclimatization have been covered by Robinson[277] and Brebner et al.[51] Blockley has recently been working on a method of quantitating acclimatization to heat,[41] but no data were available in time for this report.

The basic questions for the lunar explorer are: How effective is acclimatization in increasing sweating capacity? How easy is it to initiate? How easily can it be maintained? Does it conflict with cold acclimatization? The first two questions have been answered. The maximal ability of men to sweat does increase with acclimatization brought about by repeated exposures to severe heat stress.[99, 174, 277, 325] There are wide variations in the amount and rate of the increase, which are dependent upon individual variations and the severity of the daily exposures to heat. Horvath and Shelley[174] observed an increase in the average rate of sweating of 16 men from 1.5 kg/hr to 2.0 kg/hr in 15 daily 1-hour work periods in an air temperature of 120°F with a wet-bulb temperature of 93°F. Further increase in the capacity to sweat can be gained by continuing the period of acclimatization for several weeks, and by this means men have been acclimatized to sweat in excess of 3 liters/hr by Eichna et al.[99] and by Ladell.[203] Ladell's group has found that with successive exposure of men to heat, the sweat rate at a given rectal temperature is increased and sweating is initiated at lower body temperatures. The latent period in the initiation of sweating is shortened with acclimatization to heat, being significantly shorter in summer than in winter.[201]

In apparent contrast to the above reports that the capacity for sweating increases with acclimatization, there are numerous reports that sweating is more profuse during marches of new soldiers in warm climates than in similar marches after the men become acclimatized to the heat. In this case, where the stress is moderate, the evaporative requirement for thermal equilibrium evidently becomes lower as the efficiency of the men in the work improves with training and with reduced body temperatures resulting from acclimatization.[278] It thus appears that the efficiency, rate, and total volume of sweating are favorably improved by acclimatization.

Vascular and other acclimatizations are also quite important. The summary of Eichna et al. on what acclimatization really accomplishes is worth quoting: [100]

> Deep tissue temperature is returned to the normal level set by the metabolic rate of the task in a cool environment, but neither total body temperature nor mean skin temperature are returned to their levels in the cool environment. Mean skin temperature is adjusted to a level which permits thermal equilibrium between the body and the environment on the one hand, and on the other, maintains an internal thermal gradient which permits the transport of the deep heat to the surface without overtaxing the circulation . . . These conditions were attained almost wholly as a result of the increased evaporative cooling which an increased sweat secretion produced.

The question of initiation and maintenance of acclimatization has been studied by Bean and Eichna.[26] They found that three or four exposures to heat of 3 to 4 hours' duration with one or two 1-hour work periods during each exposure will produce a considerable degree of acclimatization. These exposures may actually be separated by intervals of 2 days in a cool environment. Acclimatization is well retained for 1 to 2 weeks, after which it is lost at a variable rate. Most men lose the major portion of their acclimatization in 1 month—a few are able to retain it for 2 months. Men who remain in good physical condition retain their acclimatization best. Repeated exposures to heat are required at intervals not exceeding 1 month, if a high degree of acclimatization is to be maintained for long periods of time. The more recent studies of Fox and his co-workers [116] on the use of elevated body temperature rather than elevated air temperature as an acclimatization mechanism may prove of great value.

As to the question of conflicts in the simultaneous acclimatization to heat and cold, Stein et al.[314] have found that fully acclimatized men retain acclimatization to heat during 14 days of severe cold exposure (5½ hours per day at −20° F). Conversely, Davis [82] has recently suggested that artificially or seasonally acquired "cold acclimatization" is unaffected by a 21-day heat exposure. These findings do not conclusively prove but only suggest that heat and cold acclimatization are not mutually exclusive; they can coexist in an individual, and the loss of one usually occurs not as a result of the other, but as a result of the absence of an adequate acclimatizing stimulus. No serious conflicts between heat acclimatization and acclimatization to other stress parameters of lunar flight are apparent, though studies on these combined adaptations are distinctly limited. Much remains to be done in this area.

It would thus appear that a schedule of acclimatization to both heat and cold for the lunar explorer should be considered for further study. Exposure to heat and exercise during the flight to the Moon is not considered a prerequisite for maintenance of this acclimatization, but probably could be arranged if found to be so for the individuals involved. It must be cautioned, in closing, that the possibility of minimizing the effects of accidental exposure to heat and dehydration should not be a deterrent to the development of lunar suits which reduce to a minimum the chances of exposure.

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