NASA TECHNICAL NOTE

NASA TN D-4464

NASA TN D-4464

EFFECTS OF PRESSURE SUITS AND BACKPACK LOADS ON MAN'S SELF-LOCOMOTION IN EARTH AND SIMULATED LUNAR GRAVITY

by Amos A. Spady, Jr., and Randall L. Harris

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1968

NASA TN D-4464

EFFECTS OF PRESSURE SUITS AND BACKPACK LOADS ON MAN'S SELF-LOCOMOTION IN EARTH AND SIMULATED LUNAR GRAVITY

By Amos A. Spady, Jr., and Randall L. Harris

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

EFFECTS OF PRESSURE SUITS AND BACKPACK LOADS ON MAN'S SELF-LOCOMOTION IN EARTH AND SIMULATED LUNAR GRAVITY

By Amos A. Spady, Jr., and Randall L. Harris
Langley Research Center

SUMMARY

Studies were conducted to evaluate the effect of a state-of-the-art full pressure suit on man's self-locomotion capabilities in earth and simulated lunar gravity. Separate tests, with subjects wearing lightweight coveralls, were also conducted in simulated lunar gravity to determine the effect on locomotion of carrying backpack loads of up to 500 earth pounds (2225 N). The simulated lunar tests were conducted on a modified version of the reduced-gravity walking simulator designed at the Langley Research Center and described in NASA TN D-2176 and TN D-3363. Tests in earth gravity were performed on a portion of asphaltic concrete road of length equal to that provided by the modified lunar-gravity simulator. The gait characteristics of the subjects were determined by having the subjects walk and run at various speeds.

The results obtained with the pressure suit indicated that pressurizing the suit to 3.7 psig $\left(25.5 \text{ kN/m}^2\right)$ did not appreciably affect the subject's self-locomotive gait characteristics in lunar gravity. The results of the load-carrying tests indicated that a subject, dressed in lightweight coveralls, could carry a backpack loaded with 500 earth pounds (2225 N) while walking, loping, and sprinting in lunar gravity.

INTRODUCTION

A general research program is being conducted at the Langley Research Center by utilizing the reduced-gravity walking simulator designed at the center to investigate the effects of lunar gravity on man's self-locomotion capabilities (refs. 1, 2, and 3). The results of the program to date indicate that man will be able to walk, run, jump, and to perform other self-locomotive tasks in lunar gravity; however, there are significant differences in man's performance in lunar gravity compared to that in earth gravity. Although most people can adapt quickly to simulated lunar gravity (refs. 1 and 3), a significant amount of experience is required to develop consistent gait characteristics.

As a continuation of the research program, tests have been conducted to investigate the effects of a state-of-the-art full pressure suit on man's lunar self-locomotive gait characteristics. Separate tests were also conducted in simulated lunar gravity with subjects wearing lightweight coveralls (shirt-sleeve condition) and carrying a backpack loaded to 500 earth pounds (2225 N).

The range of locomotive rates used in the present experiment included the maximum values achieved under ideal laboratory conditions. Since the lunar conditions will be considerably different from those which existed during the present experiment, these maximum values may not be achieved during actual lunar operations. However, the results of this investigation should be useful as background information for more extensive studies of the lunar exploration missions and in solving the problems of transporting moderate loads from place to place on the lunar surface.

SYMBOLS AND ABBREVIATIONS

Measurements for this investigation are expressed in U.S. Customary Units and equivalent values are indicated herein in the International System of Units (SI).

C_f	coefficient of rolling friction
D	leg stroke, ground distance traversed by hip joint during portion of stride when reference foot is on ground, feet (meters)
F_D	aerodynamic drag force at constant speed, pounds (newtons)
g	gravitational unit, relative to acceleration produced by earth gravitational field, $\left(1g = 32.2 \text{ ft/sec}^2 = 9.8 \text{ m/sec}^2\right)$
L	leg swing, ground distance traversed by hip joint during portion of stride when reference foot is free of ground, feet (meters)
m	mass of subject and equipment, slugs (kilograms)
N	stepping rate, number of steps taken during unit of time, steps per second
S	stride, ground distance traversed by hip joint during one stride cycle, which is completed when body members regain initial relative positions, L + D, feet (meters)
V	locomotive velocity, feet per second (meters per second)

δ_a	ankle angle, angular deflection of foot relative to calf, degrees (see fig. 1)
δ_b	back angle, angular deflection of reference line joining hip and shoulder joints relative to vertical, degrees (see fig. 1)
$\Delta\delta_b$	change in back angle, degrees (see fig. 29)
δ_h	hip angle, angular deflection of thigh relative to body reference line, degrees (see fig. 1)
δ_k	knee angle, angular deflection of calf relative to thigh, degrees (see fig. 1)
η	locomotion index, ratio of leg swing to leg stroke, L/D or $\frac{S - D}{D}$

Subscript:

max	maximum value

Abbreviations:

RHD	right heel down
RTO	right toe off ground
LHD	left heel down
LTO	left toe off ground

FUNDAMENTAL GAIT CONSIDERATIONS

The principal locomotive gaits employed by man are walking and running. The general distinction between the two gaits is that in walking both feet are on the ground at some time during any given stride whereas in running both feet are off the ground at some time during a given stride. For simulated lunar gravity a further distinction is made within the running gait, that is, sprinting and loping. (See ref. 3.) The distinction between the sprint and lope for a given speed is characterized by a relatively low stepping rate for the lope and by a relatively high stepping rate for the sprint.

The primary motions necessary to produce locomotion are defined in reference 3 as the inclination of the torso relative to the vertical (back angle), angular deflection of the upper leg relative to the torso (hip angle), and angular deflection of the lower leg relative to the upper leg (knee angle). (See fig. 1.) Secondary motions, such as movements of the arms, feet, head, and the twisting and swaying of the torso, are a result of the primary motions. A smoothing action is provided by the secondary motions that tend to make a particular gait more comfortable and minimize the net energy expenditure involved in producing locomotion. The secondary motions, however, are considered to have only a relatively small effect on the characteristics of the primary motions and consequently are not discussed in this report.

SUBJECTS AND EQUIPMENT

Subjects

The weight, height, and age of the two subjects used in this study are as follows:

Subject	Height		Weight		Age
	in.	cm	lb	N	yr
1	71	180	185	823	32
2	66	168	155	689	23

Both of the subjects have had many hours of simulated lunar gravity experience. Subject 1 participated in the investigations reported in references 1, 2, and 3 and in aircraft flights on $\frac{1}{6}$g trajectories. Subject 2 was a subject for the investigation reported in reference 3. During the pressure-suit tests, physiological responses were monitored to insure subject safety.

Equipment

Pressure suit.- Two state-of-the-art full pressure suits (AXIL) manufactured by the International Latex Corporation (fig. 2) were used by the two participating subjects in this program. Each suit weighed approximately 38 lb (169 N).

Life support equipment.- The Portable Life Support System (PLSS) weighed approximately 47 lb (209 N) fully loaded and was furnished by the Manned Spacecraft Center. The PLSS was capable of both cooling the subject and providing him with a breathable atmosphere in the suit for approximately 45 minutes at either vent flow, 0 psig $\left(0 \text{ N/m}^2\right)$, or pressurized, 3.7 psig $\left(25.5 \text{ kN/m}^2\right)$. The construction of the PLSS dictated its orientation with respect to gravity; consequently, for the simulated lunar gravity tests the PLSS was strapped across the subject's back as shown in figure 3.

Backpack loads.- For the load-carrying tests, which were performed only in the shirt-sleeve condition, a standard Army backpack was modified (fig. 4) so that lead sheets could be added in 100-lb (445 N) increments to increase the total weight to 500 lb (2225 N). Crotch straps were added to the backpack harness system to minimize any bouncing or shifting of the pack on the subject's back during the tests.

Simulator.- The reduced-gravity walking simulator (fig. 5) was used to test the subject's lunar self-locomotion capabilities. A complete description of the system can be found in reference 3. The only modification to the simulator required for these tests was the addition of a separate cable to support the PLSS or backpack from the trolley.

The motion constraints imposed on the subjects by the basic simulation equipment were evaluated and were found to be small, as reported in the appendix of reference 3. However, a further analysis of the constraints as affected by the additional cable required for the present tests is presented in the appendix of this report. This analysis showed that the loads or forces imposed by the additional cable did not appreciably alter the motion constraints reported in reference 3 and, therefore, were considered negligible.

The runway surface used for the simulated-lunar-gravity tests was smooth, painted plywood and for the earth-gravity tests was asphaltic concrete. The coefficient of friction between the subject's crepe-rubber-soled boots and the lunar and earth runway was measured to be 0.73 and 0.96, respectively. This difference is believed to have had little effect on the comparisons presented herein.

All tests were recorded with the use of a 16-mm motion-picture camera that operated at 48 frames per second. The camera was located 150 ft (45.7 m) normal to the center portion of the runway and was manually operated to track the subject. All measurements of the position and rates of the various body members relative to each other and to the ground, as well as stepping rate and stride length, were obtained from the film by using the technique described in reference 3. The accuracy of the angular measurements is approximately $\pm 2^{\circ}$, which is considered adequate for this investigation.

RESULTS AND DISCUSSION

The results of this investigation are presented and discussed mainly in terms of the maximum walking speed, maximum running speed, stepping rate, and stride length to reveal separately the effects of the pressure suit and the backpack loads on the gait characteristics of the subjects for the simulated lunar-gravity condition. Some results for earth-gravity conditions are also included for comparison. The relative motions of various body members and plots of maximum angular displacements are included to provide a better understanding of the locomotive gait characteristics for the various test conditions. The results of this study were obtained under test conditions that did not duplicate all operational aspects of an actual lunar mission. Consequently, care should be exercised in the application of the data. In some instances, the maximum performance achieved in these tests may not be realized because of overriding safety considerations.

Maximum Walking Speed

The parameter used in this investigation to determine the maximum walking speed is the locomotion index η. The speed at which $\eta = 1$ is identified as the speed of transition from walking to running and, therefore, designates the maximum speed at which both feet are in contact with the ground at some time during a stride.

Pressure suit.- A plot of η as a function of velocity is presented in figure 6 for the subjects in lunar gravity and wearing a pressure suit in both the pressurized and unpressurized condition. These data indicate that pressurizing the suit had no appreciable effect on the maximum lunar walking speed. In general, the transition velocity for both conditions of suit pressure is between 5 and 6 ft/sec (1.5 and 1.8 m/sec), as indicated in figure 6 by the hatched area labeled "transition range." The maximum walking speeds of from 5 to 6 ft/sec were obtained on a smooth, hard surface.

The earth results are somewhat in contrast with those obtained in simulated lunar gravity. Figure 7 shows the variation of η with the average locomotive velocity for the subjects in the pressurized and unpressurized suit in earth gravity. On the basis of the data, the average transition-velocity range for the unpressurized suit is between 8 and 9 ft/sec (2.4 and 2.7 m/sec) whereas the transition range for the pressurized suit is between 6.5 and 7.5 ft/sec (2.0 and 2.3 m/sec) – an average decrease of about 1.5 ft/sec (0.5 m/sec) due to suit pressurization.

In the interest of expediency values of η above 3.5 or for locomotive velocities greater than 14 ft/sec (4.0 m/sec) are not plotted in figures 6, 7, and 8. The data presented are sufficient to establish the maximum walking speeds for the conditions studied.

Loads.- The values of η obtained for the two subjects in shirt sleeves, carrying backpack loads weighing from 100 to 500 lb (445 to 2225 N), in simulated lunar gravity, are plotted against average locomotive velocity in figure 8. From the data presented there seems to be no consistent effect of loads on the locomotive velocity for transition from walking to running. The data indicate that transition occurs at a locomotive velocity of from 5 to 6 ft/sec (1.5 to 1.8 m/sec), which is the same range obtained for the zero-load data of reference 3. In general, the maximum lunar walking speed over a smooth surface apparently is not appreciably affected by backpack loads from 0 to 500 lb (0 to 2225 N).

Maximum Running Speed

The maximum running speed achieved in these separate tests corresponds to the steady-state speed attained when the subjects exerted their maximum effort in traversing the test distance of 100 ft (30 m). The maximum running speeds for the various test conditions can be obtained from figures 9 to 14, which are plots of stepping rate or stride length against velocity.

Pressure suit.- The maximum running speed achieved by the subjects in lunar gravity was approximately 15.5 ft/sec (4.7 m/sec) with the unpressurized suit and approximately 12.5 ft/sec (3.8 m/sec) with the suit pressurized to 3.7 psig $\left(25.5 \text{ kN/m}^2\right)$. (See figs. 9 and 10.) This decrease of approximately 20 percent is attributable to the effects of the pressurized suit. By comparison, the maximum speed achieved in earth gravity was approximately 18 ft/sec (5.5 m/sec) for the unpressurized suit and 14 ft/sec (4.3 m/sec) for the pressurized suit, also a decrease of approximately 20 percent. (See figs. 11 and 12.)

Loads.- The maximum running speeds achieved by the subjects in the shirt-sleeve condition, carrying weights from 100 to 500 lb (445 to 2225 N), ranged from about 12 to 14 ft/sec (3.7 to 4.3 m/sec). (See figs. 13 and 14.) This range is comparable to the maximum speed of about 13 ft/sec (4.0 m/sec) achieved by subjects in the tests with zero load reported in reference 3. Thus, loads up to 500 lb (2225 N) do not appreciably affect the maximum running speeds that are possible in lunar gravity. The subjects commented that the 500-lb load seemed to be approaching the maximum that they could control and carry with confidence while sprinting.

Stepping Rate and Stride Length

Data for both the stepping rate and stride length are presented in figures 9 to 14. However, because the subject's stride length S and stepping rate N are related to the average velocity V by the expression $V = \frac{NS}{2}$, this discussion deals primarily with the stepping rate.

Pressure suit.- The stepping rate and the corresponding stride lengths used by the subjects in simulated lunar gravity for both the pressurized and unpressurized suit conditions are plotted against the average locomotive velocity in figures 9 and 10, respectively. The stepping-rate data have been divided into three fairly distinct areas corresponding to the three types of lunar locomotive gaits used; that is, walking, loping, and sprinting. Curves are faired only through the walking and loping gaits because the scatter in the sprinting data made it difficult to distinguish trends for either the unpressurized or pressurized suit conditions. In figure 9, the trend shown for the walking-gait curve is a linear increase in stepping rate with increasing locomotive velocity, whereas the trend for the loping-gait curves is a constant stepping rate with increasing locomotive velocity.

Pressurizing the suit had no significant effect on either the walking or loping gait characteristics. The sprinting-gait data in figures 9 and 10 imply that increasing speed is achieved by changing both stepping rate and stride length. (See figs. 9 and 10.) The effects on the stepping rate of pressurizing the suit are inconsistent apparently because of differences in the individual sprinting styles used by the subjects.

The lines in figure 10 which show the variation of stride length with velocity for the lope condition were determined from the relationship $S = \frac{2V}{N}$ with values of N and V obtained from the lines faired by inspection through the measured values of N shown in figure 9. As can be seen, the lines in figure 10 are not the best representative lines for the measured data. This discrepancy can be attributed to inaccuracies in the measurements of stride length. The same reasoning holds true for subsequent figures that present the variation of stride length with velocity.

The stepping rates and corresponding stride lengths used by the subjects in earth gravity as a function of locomotive velocity are given in figures 11 and 12, respectively. Curves are faired through the data to indicate the general trends for both the unpressurized and pressurized suit. Even though the subjects attempted to lope in earth gravity, they were not able to achieve the low-frequency stepping rates and the corresponding long stride lengths characterized by the lunar lope. Therefore, in the earth-gravity test, the running-gait data cannot be separated into loping and sprinting regions as it can in the lunar-gravity tests. Pressurizing the suit in earth gravity, as shown by comparison of the curves, caused the average stepping rate to increase over the entire velocity range with the largest difference occurring at the higher locomotive velocities.

Comparison of the walking and sprinting results for lunar and earth gravity (figs. 9, 10, 11, and 12) indicates that for any given speed the lunar explorer will probably use lower stepping rates and correspondingly longer stride lengths than his earth counterpart.

Loads.- The stepping rate and the corresponding stride length used by the subjects in simulated lunar gravity plotted against the average locomotive velocity while carrying the various backpack loads are given in figures 13 and 14, respectively. These data, which are for the shirt-sleeve condition only, can also be divided into three fairly distinct areas, each of which corresponds to a given gait. For the walking gait, increasing the load from 100 to 500 lb (445 to 2225 N) does not appear to have any effect on the stepping rate (fig. 13) or stride length (fig. 14). The curves faired through the loping data indicate that increasing the load carried from 100 to 500 lb caused an increase in stepping rate (fig. 13) of approximately 30 percent at 7 ft/sec (2.2 m/sec) and 50 percent at 11 ft/sec (3.4 m/sec). Because of the amount of scatter in the sprinting-gait data, no definite trends due to increasing loads are evident.

Body Member Motions

As a matter of interest, histories of the relative motions of the body members of one subject for different test conditions are presented in figures 15 to 22. Although arm motions were not obtained during the present tests the arms were observed to play a relatively minor role in lunar walking and loping; only during maximum-effort sprint were the arms used in approximately the same manner as they were used in 1g. This observation was also reported in reference 3.

The relative motions of body members for one subject wearing a pressurized suit in the two gravity conditions are presented in figures 15 to 18. The data are presented for a slow walk at approximately 2.5 ft/sec (0.8 m/sec), a normal walk at approximately 4.5 ft/sec (1.4 m/sec), a lope at approximately 9 ft/sec (2.7 m/sec), and the maximum sprinting velocity for each test condition. The angular position of the various body members is plotted against percent of stride for one lunar stride, which begins and ends at the instant the right heel contacts the ground. Similar curves (shirt-sleeve condition only) are shown in figures 19 to 22, which present data for a slow walk at approximately 2.5 ft/sec (0.8 m/sec), a normal walk of approximately 5.0 ft/sec (1.5 m/sec), a lope of approximately 10 ft/sec (3.0 m/sec), and the maximum sprinting velocity.

In order to illustrate more clearly some of the effects of suit pressurization and load carrying on body member motions, data similar to those presented in figures 15 to 22 were used to prepare figures 23 to 28. Presented in these figures are the maximum back angle $\delta_{b,max}$, hip angle $\delta_{h,max}$, and knee angle $\delta_{k,max}$ plotted against average locomotive velocity for both the pressure-suit and load tests. Curves have been faired, by inspection, through the data points to denote general trends.

Pressure suits.- The variation of maximum back angle $\delta_{b,max}$ with velocity (fig. 23) for the lunar-gravity tests with the suit unpressurized compares closely with the results obtained in shirt sleeves in reference 3; that is, $\delta_{b,max}$ becomes progressively larger with increasing speed (an increase of 21° from approximately 21° at 4 ft/sec (1.2 m/sec) to approximately 42° at 10 ft/sec (3.0 m/sec)). Whereas the same general trend was present for the pressurized-suit tests, the value of $\delta_{b,max}$ at 4 ft/sec (1.2 m/sec) was greater and the increase of $\delta_{b,max}$ with increasing speed was less and showed a change of only 11° for the same change in speed. In earth gravity the same general trends of back angle with speed were noted; however, the angles used were much smaller (by 50 percent or more) than those used in lunar gravity.

During the pressure-suit test, the legs were carried farther forward for the lunar gaits than for the corresponding earth gaits, as illustrated in figure 24, where the hip flexion angles are larger for the lunar conditions than for the corresponding earth conditions. However, the total angular travel of $\delta_{h,max}$, that is, the difference between extension and flexion angle, is approximately the same for corresponding velocities in both gravity conditions. This effect is attributed, as pointed out in reference 3, to the difference in $\delta_{b,max}$, that is, with the larger $\delta_{b,max}$ the legs also must be carried farther forward to maintain balance. The $\delta_{k,max}$ flexion and extension used (fig. 25) are not appreciably affected by changing the suit pressure or the gravity level.

Loads.- Increasing the load carried by the subjects, in shirt sleeves, caused them to increase their back angle δ_b while standing (zero velocity) so that the resultant center of gravity (body + load) remained over the feet. This increase in back angle was also noted for the low locomotive velocities (fig. 26). However, increasing the load being carried generally caused a decrease in the slope of the curve of $\delta_{b,max}$ with respect to locomotive velocity, so that for the maximum load there is little increase in $\delta_{b,max}$ over the entire velocity range. At the higher locomotive velocities the curves of figure 26 show less effect of load on $\delta_{b,max}$ than is seen at the lower locomotive velocities. Although no tests were conducted with various center-of-gravity locations for a given load, it stands to reason that the closer the combined center of gravity can be kept to the normal center of gravity of the body, the less initial body lean will be required and consequently the easier the load will be to control. No consistent trends due to increasing the load were noted for the maximum δ_h and δ_k (figs. 27 and 28).

GENERAL OBSERVATIONS

Pressure Suit

For the first two or three practice trials, in simulated lunar gravity with the suit pressurized, both subjects experienced difficulty in maintaining their balance while accelerating to the desired velocities. The subjects commented that the difficulty was due primarily to the stiffness of the suit in the waist region, which tended to restrict body lean. However, they were able to adapt to the situation and no further difficulty was noted. In fact, after the subjects had adapted they realized that less conscious effort was required to maintain fore and aft balance in lunar gravity than in earth gravity, probably because they were not overly concerned about the consequence of falling in lunar gravity. As a matter of fact, prior to the tests the subjects were required to fall to a prone position and regain a standing position in simulated lunar gravity. Neither subject suffered any injury or experienced any difficulty whatsoever in performing either task.

The effort required to accomplish identical tasks, in the opinion of both test subjects, was less in lunar gravity than in earth gravity. This opinion was partially verified when one test series conducted in earth gravity with the suit pressurized had to be terminated because the subject became overheated. The same subject completed an identical series in lunar gravity under the same ambient environment without a noticeable rise in either the suit temperature or the subject's temperature.

Loads

In general, the subjects were required to carry each load in lunar gravity for approximately 45 minutes while performing the various walking, sprinting, and loping tests. Although the subjects who performed these tests in only the shirt-sleeve condition did become tired, particularly with the maximum loads, they both thought that they could have continued for a significantly longer period. The load was found to be easier to control if it was securely strapped to the subject; however, care was taken to insure that the backpack straps did not impede the subject's respiration. In several incidents where the subject's respiration was impaired by the straps, headaches were experienced after leaving the simulator.

The subjects were able to fall to a prone position and then regain a standing position, with no difficulty even with the 500-lb (2225 N) load; however, the technique used depended on the load being carried. For the light loads it was not necessary for the subjects to use the arms for braking purposes when falling and they could regain a standing position, simply, by pushing the body upward with the arms. In contrast, for the heavy loads the arms were required to provide a braking action and the same technique was used to regain a standing position as is normally employed in earth gravity.

SUMMARY OF RESULTS

The effect of a state-of-the-art full pressure suit at 0 and 3.7 psig $\left(0 \text{ and } 2225 \text{ kN/m}^2\right)$ on a subject's lunar locomotive gaits can be summarized as follows: (1) Pressurizing the suit did not appreciably affect either the stepping rate or the maximum walking speed in lunar gravity, but it had a marked effect on both in earth gravity, (2) In general, the stepping rates were lower and the corresponding stride length longer in simulated lunar gravity than in earth gravity.

The effect of backpack loads on the lunar locomotive gait of subjects in shirt sleeves can be summarized as follows: (1) In simulated lunar gravity the subject could carry backpack loads of up to 500 earth pounds (2225 N) while standing, walking, loping, and sprinting, (2) The amount of load being carried did not significantly affect the lunar gait characteristics; however, the greater loads did increase the stepping rate of the lunar lope, (3) The subjects were of the opinion that the 500-pound load seemed to be approaching the maximum load they could carry with confidence while sprinting.

The results of the study discussed in this report were obtained under test conditions which did not duplicate all operational aspects of an actual lunar mission; consequently, care should be exercised in the application of the data.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 19, 1967,
127-51-03-02-23.

APPENDIX

PHYSICAL CONSTRAINTS ON SUBJECT'S PRIMARY MOTIONS CAUSED BY THE BACKPACK SUPPORT CABLE

A simplified analysis of the effect of the restraints imposed on the subject by the simulator was presented in the appendix of reference 3. The effects are the same for the present investigation, with the exception of the forces generated by the motions of the additional cables and loads. A brief analysis of the effect of these forces is presented as an addition to the analysis of reference 3 in order to verify the present data.

The forces generated by the motions of the additional simulator cables and weights consist of the friction of the trolley rolling on the track and the air drag of the cable and man. In reference 3, the coefficient of rolling friction was 0.004 (assumed as one-half the experimentally determined static coefficient of friction) and the air drag was reported to be 1.2 pounds (5.34 N) for the subject and 0.5 pound (2.22 N) for the support cables. The air drag of the additional 1/8-inch cable used in the present investigation at a running speed of 13 ft/sec (4.0 m/sec) is estimated to be 0.4 pound (1.78 N), by assuming a drag coefficient of 1.2. Thus, a total air drag of 2.1 pounds (93.4 N) is obtained.

As the subject travels at a steady pace, the average force acting through his center of mass in lunar gravity $\left(\frac{1}{6}g\right)$ in the vertical direction is $\frac{1}{6}mg$. (See fig. 29.) With the addition of drag to the subject, the resultant force rotates through a small angle. The back angle of the subject is assumed to rotate through this same angle $\Delta\delta_b$ which can be expressed as follows:

$$\tan \Delta\delta_b = \frac{\text{Retarding force}}{\text{Lunar weight}} \qquad (1)$$

where

$$\text{Retarding force} = F_D + C_f mg$$

and $C_f mg$ is the rolling friction of the trolley. Then $\Delta\delta_b$ can be obtained by use of the following equations:

$$\tan \Delta\delta_b = \frac{F_D + C_f mg}{\frac{1}{6}mg} \qquad (2)$$

$$57.3 \tan \Delta\delta_b = \Delta\delta_b \qquad (3)$$

$$\Delta\delta_b = 343.8\left(\frac{F_D}{mg} + C_f\right) \qquad (4)$$

APPENDIX

The change in back angle $\Delta\delta_b$ is plotted against the reciprocal of the total earth weight in figure 30 for three speeds: 5, 10, and 13 ft/sec (1.5, 3.0, and 4.0 m/sec). The graph shows that reducing the velocity decreases the back angle necessary to overcome the drag imposed by the simulation. The additional cable increased the slope of the curve slightly as seen by comparing the dash line from the data of reference 3 with the solid line for 13 ft/sec (4.0 m/sec). For the range of test variables in the current test series indicated in figure 30, the change in back angle varies from 2.4° to 5.4° for a locomotive velocity of 13 ft/sec. This change is small compared with the average body back angle of around 40° and can be considered negligible.

REFERENCES

1. Hewes, Donald E.; and Spady, Amos A., Jr.: Evaluation of a Gravity-Simulation Technique for Studies of Man's Self-Locomotion in Lunar Environment. NASA TN D-2176, 1964.

2. Spady, Amos A., Jr.; and Krasnow, William D.: Exploratory Study of Man's Self-Locomotion Capabilities With a Space Suit in Lunar Gravity. NASA TN D-2641, 1966.

3. Hewes, Donald E.; Spady, Amos A., Jr.; and Harris, Randall L.: Comparative Measurements of Man's Walking and Running Gaits in Earth and Simulated Lunar Gravity. NASA TN D-3363, 1966.

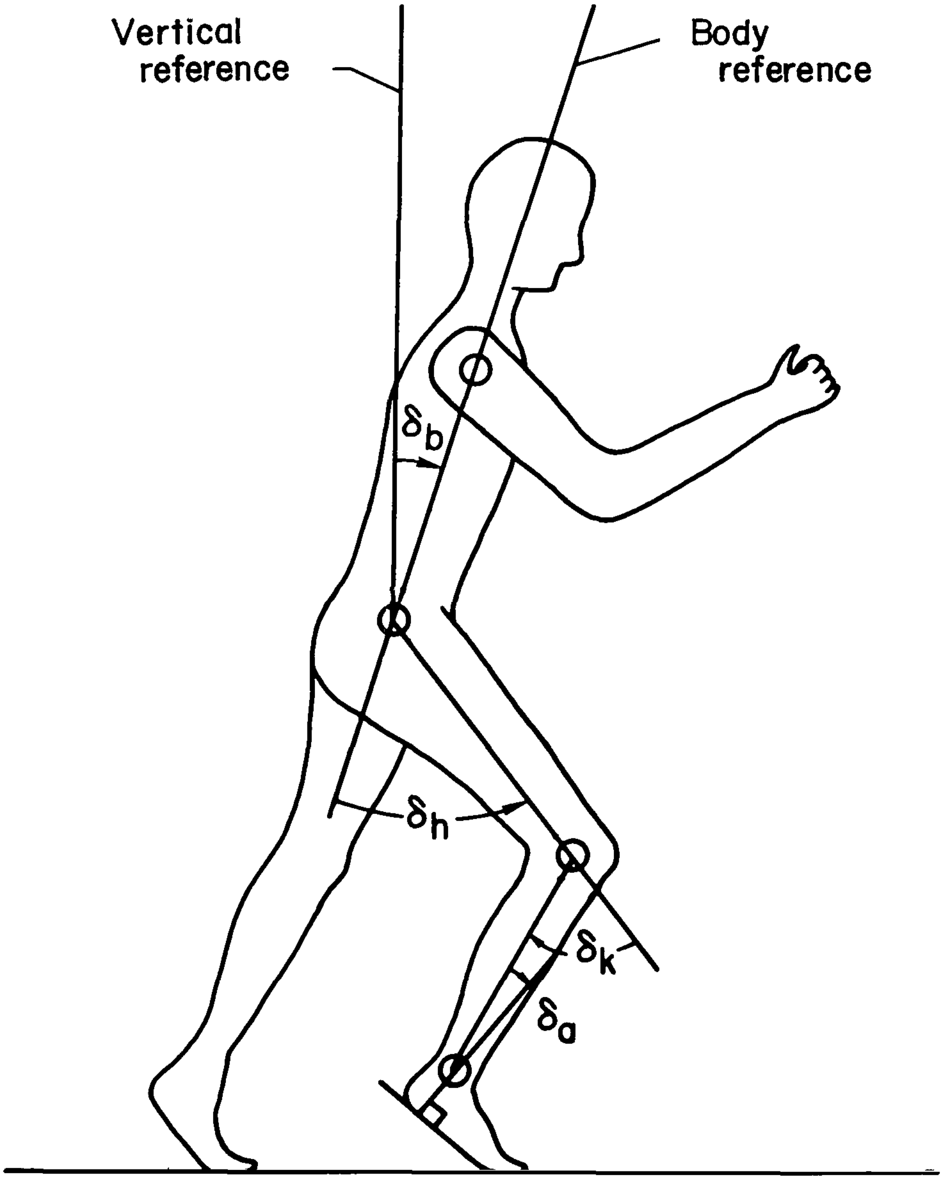

Figure 1.- Definition of body angles. All angles are positive as shown. Arrows for hip and knee angle indicate direction of flexion.

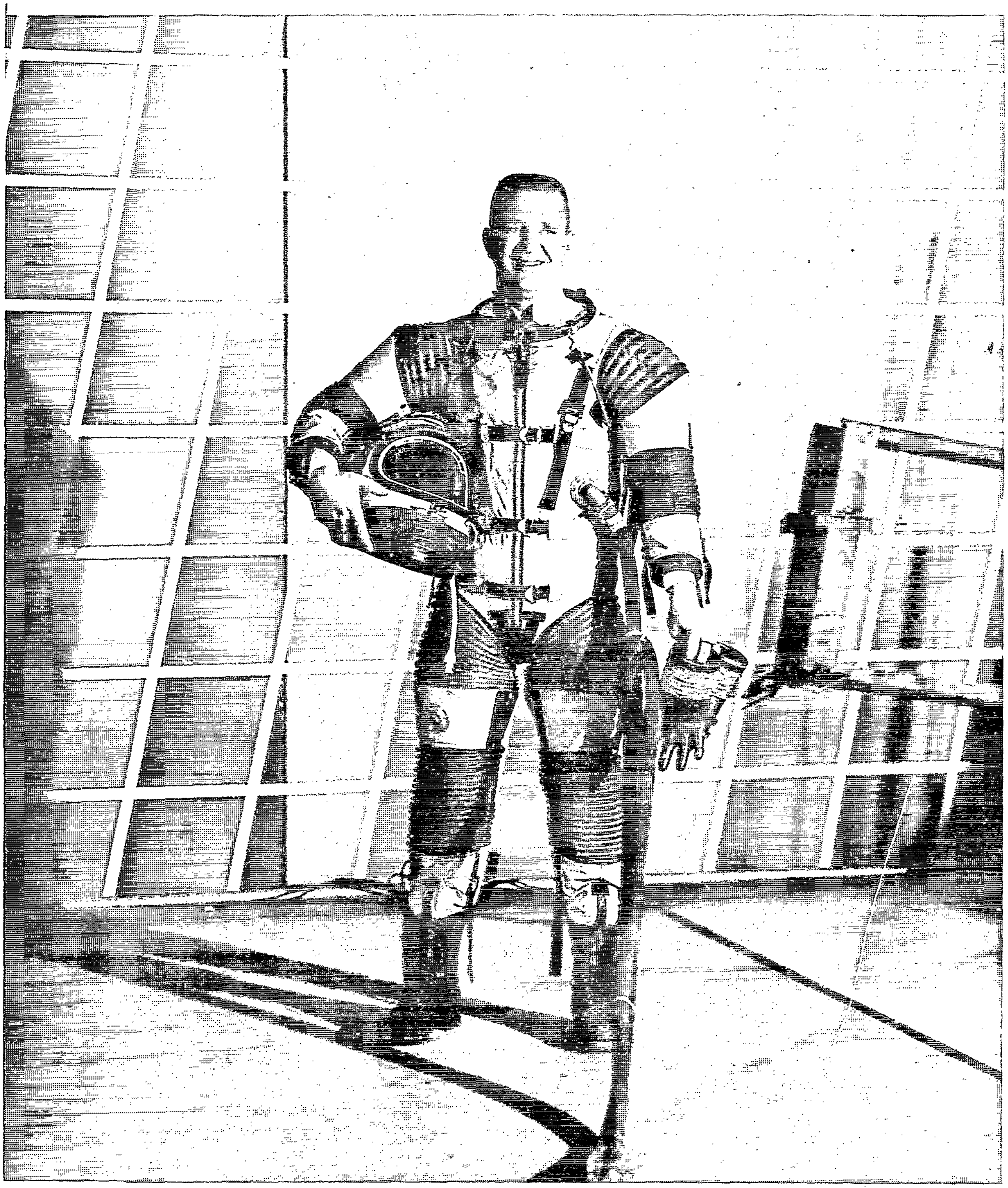

Figure 2.- Subject in state-of-the-art full pressure suit worn for tests. L-64-1663

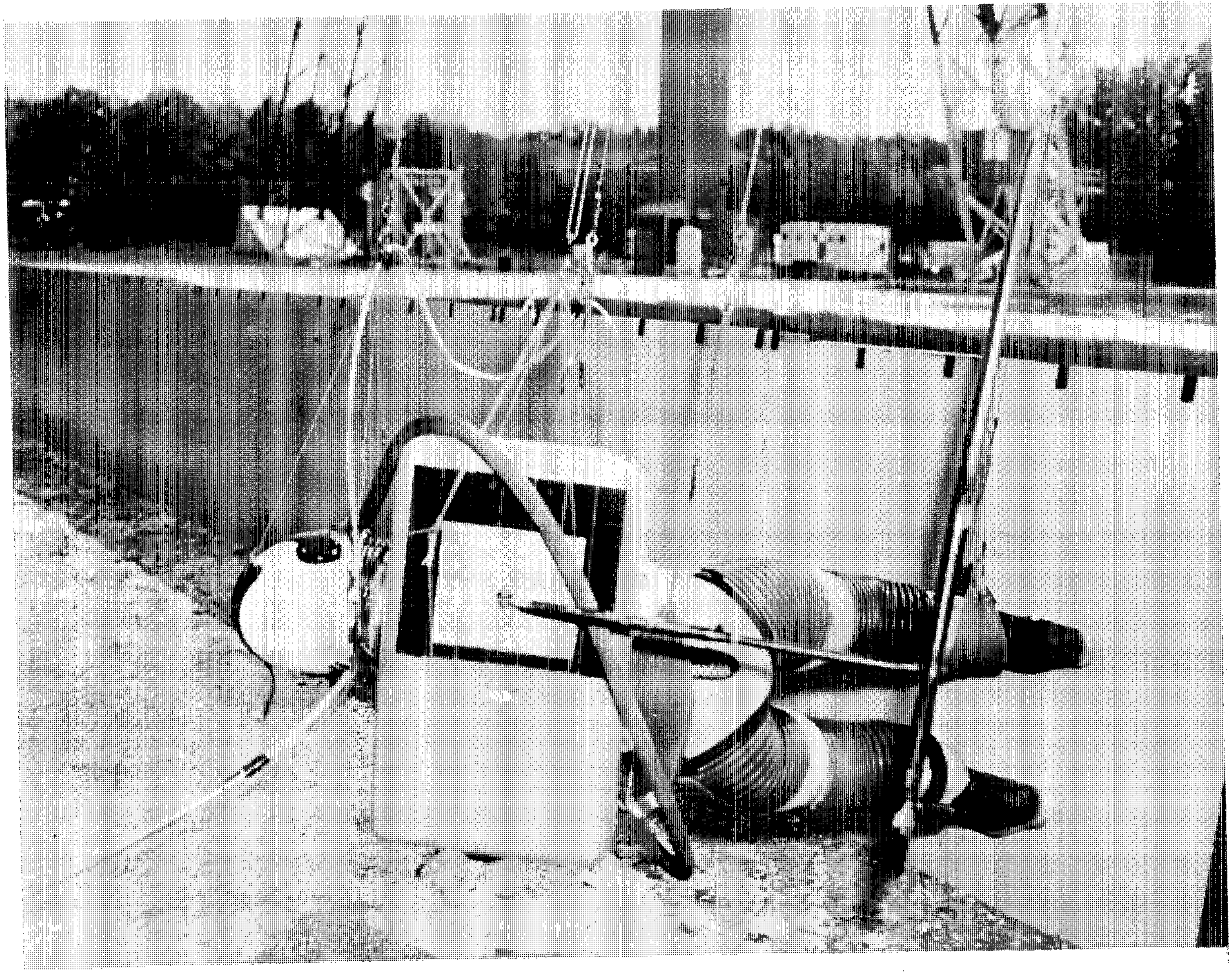

Figure 3.- Subject in reduced-gravity walking simulator, wearing full pressure suit and carrying PLSS.

L-65-6583

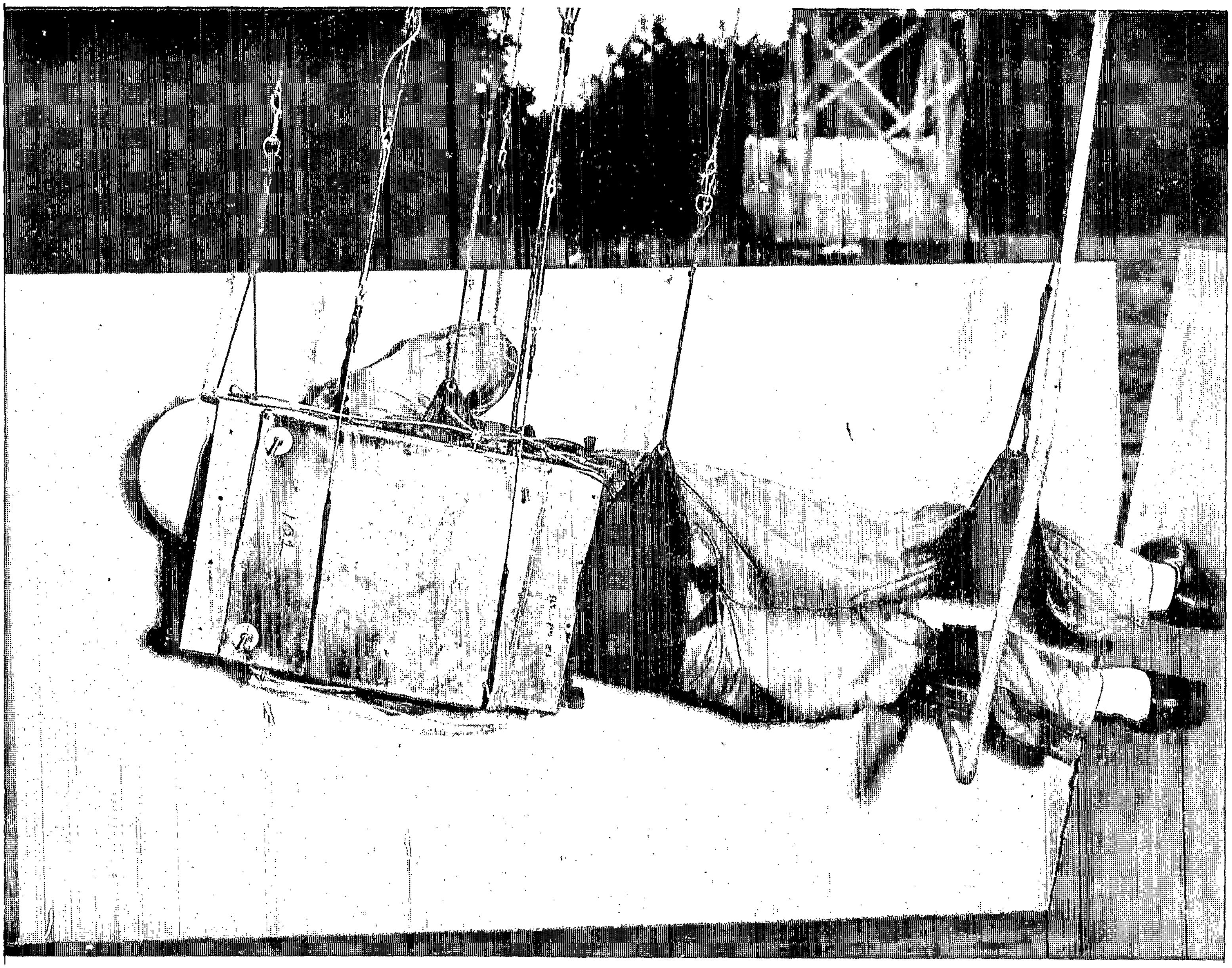

Figure 4.- Subject in reduced-gravity walking simulator, carrying backpack with 100-lb (445 N) load.

L-64-7425

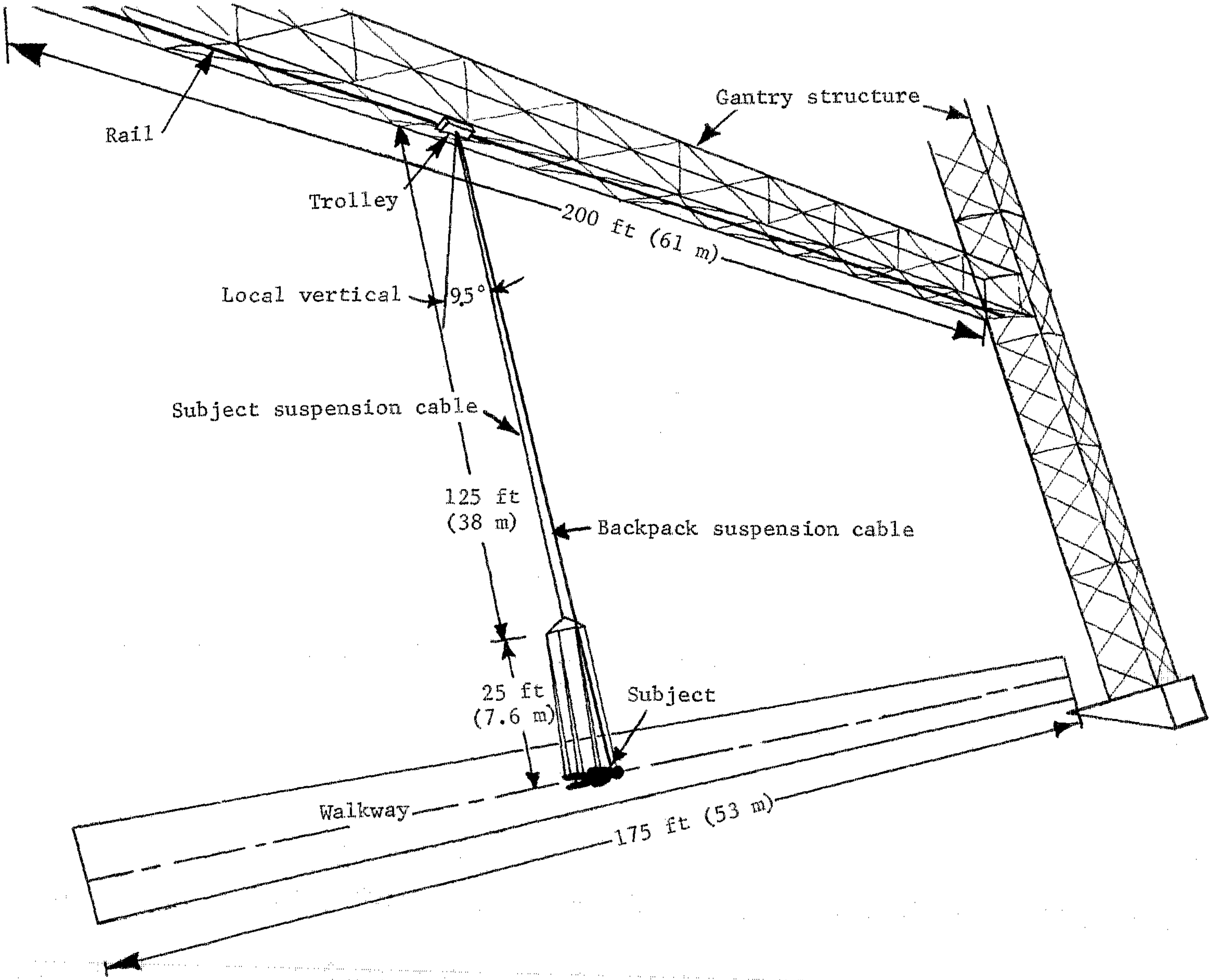

Figure 5.- Illustration of reduced-gravity walking simulator used for tests.

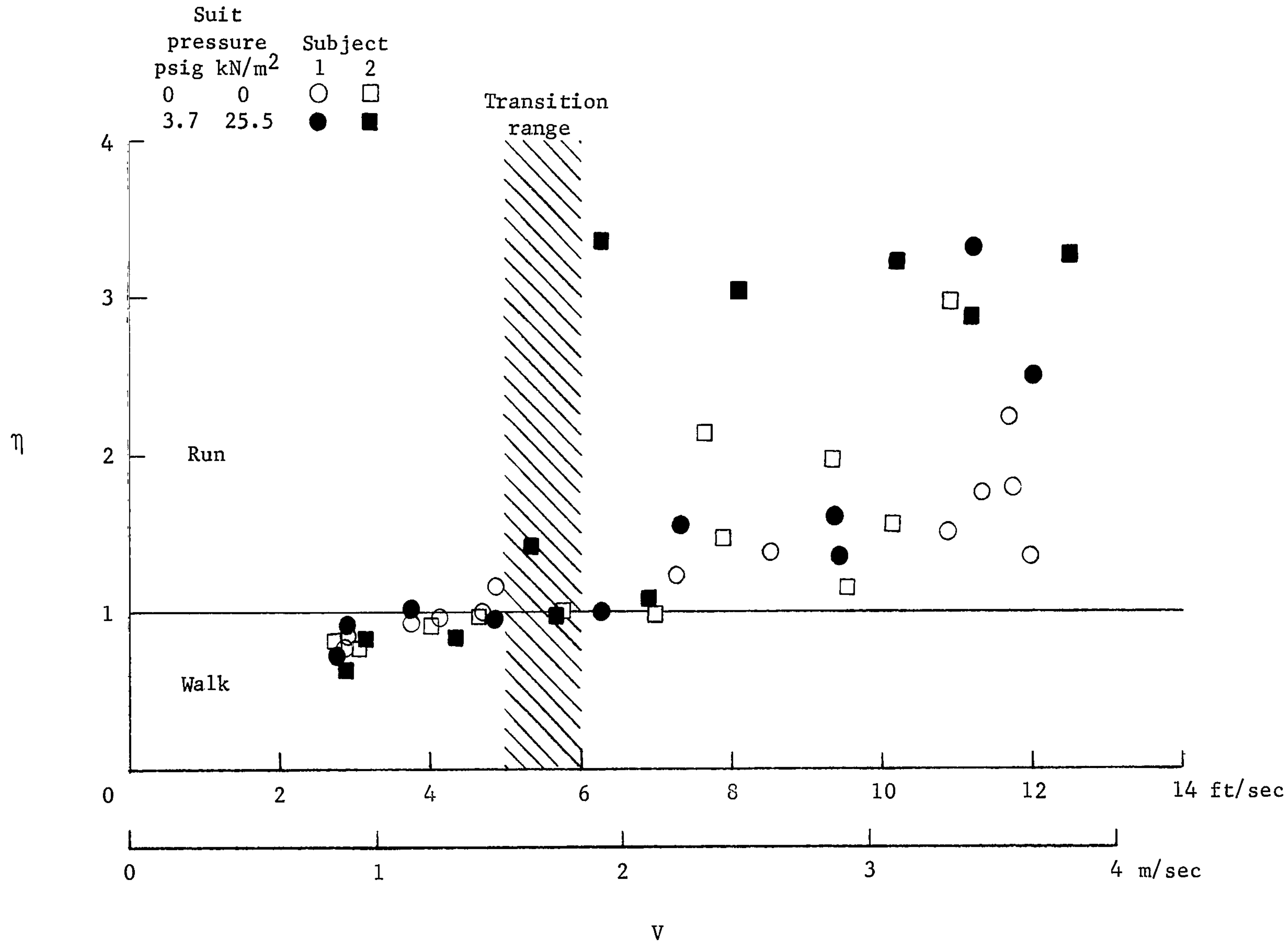

Figure 6.- Locomotion index plotted against average locomotive velocity. Pressure-suited subjects; simulated lunar gravity.

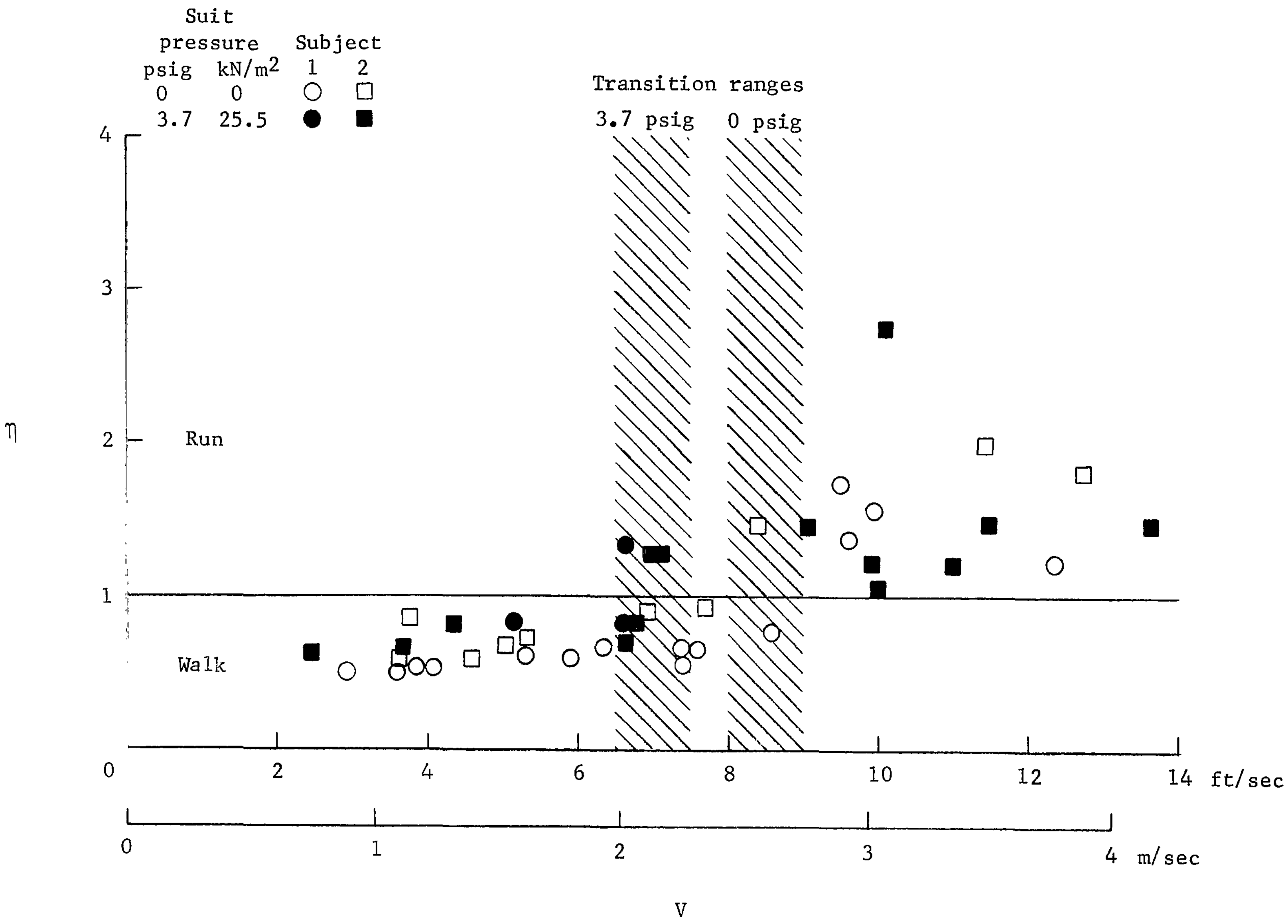

Figure 7.- Locomotion index plotted against average locomotive velocity. Pressure-suited subjects; earth gravity.

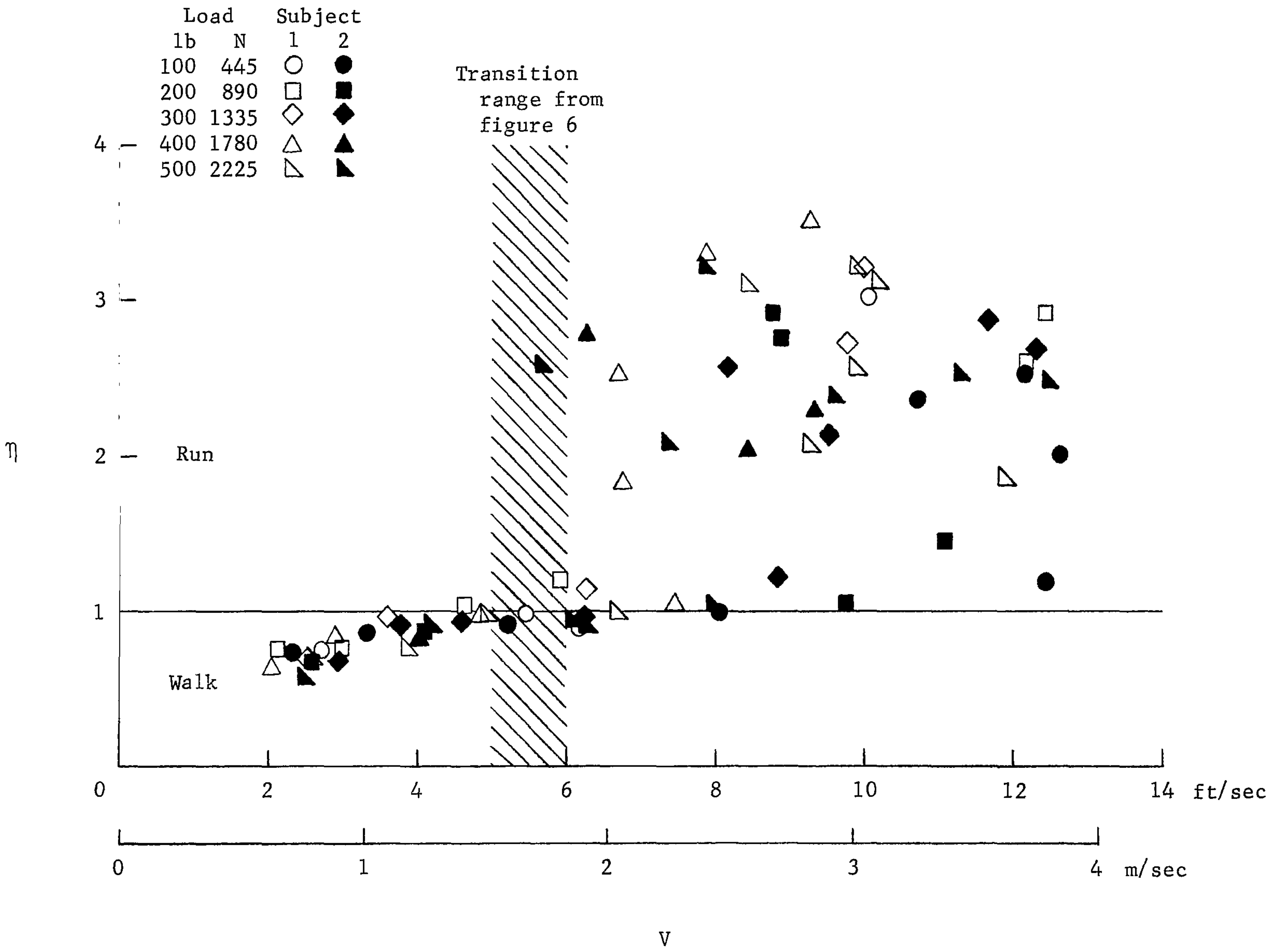

Figure 8.- Locomotion index plotted against average locomotive velocity. Shirt-sleeve condition; with backpack loads; simulated lunar gravity.

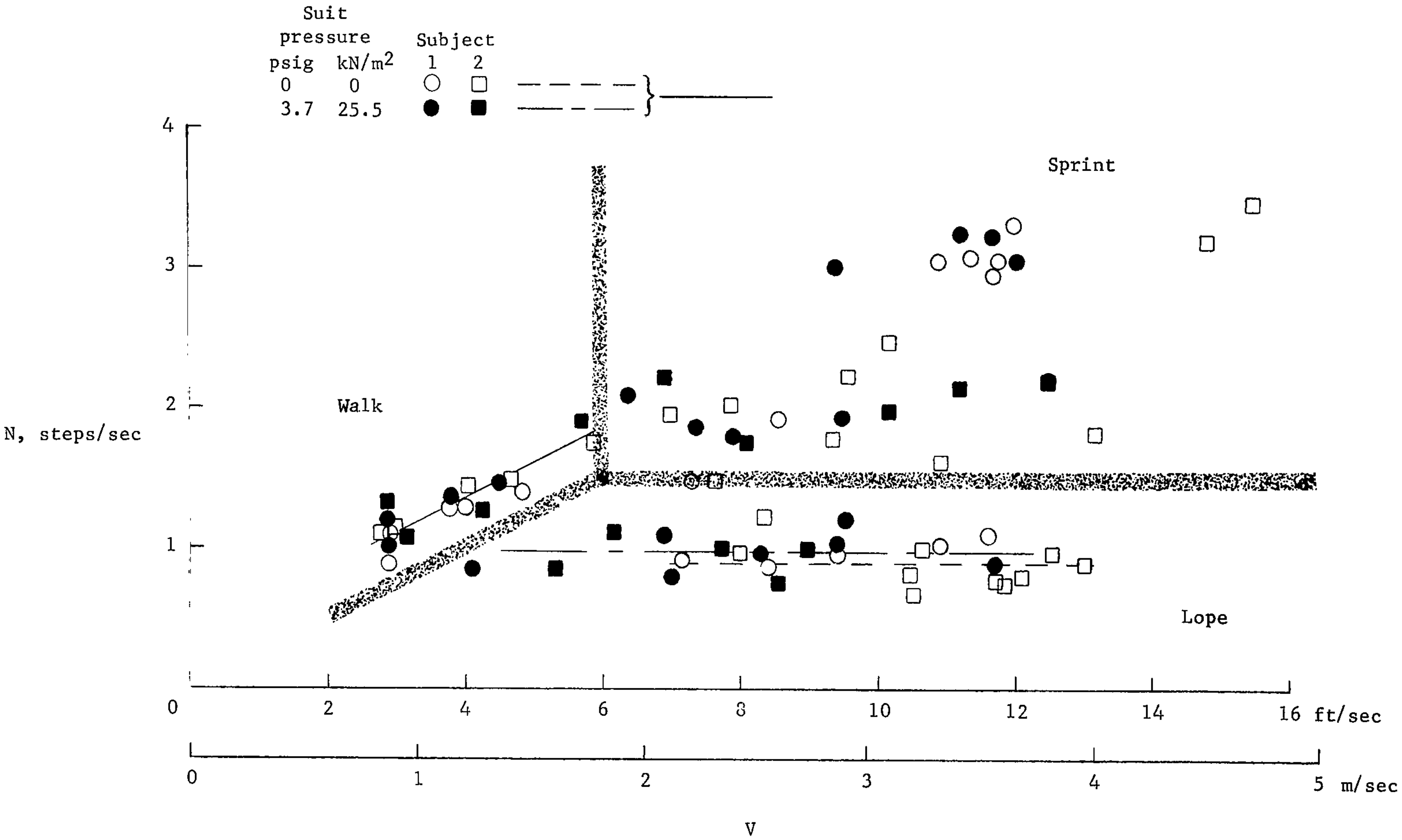

Figure 9.- Average stepping rate plotted against average locomotive velocity. Pressure-suited subjects; simulated lunar gravity.

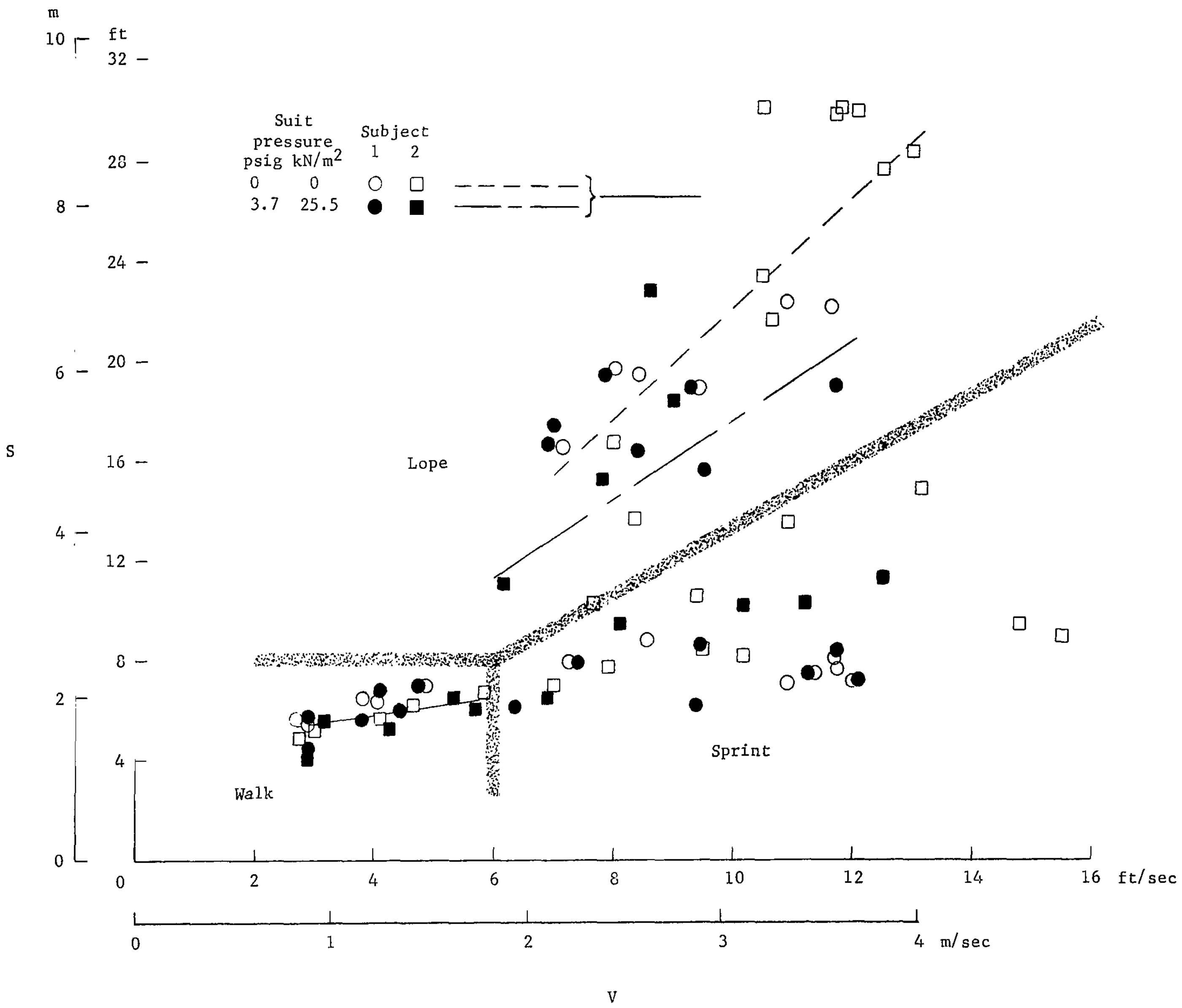

Figure 10.- Average stride length plotted against average locomotive velocity. Pressure-suited subjects; simulated lunar gravity.

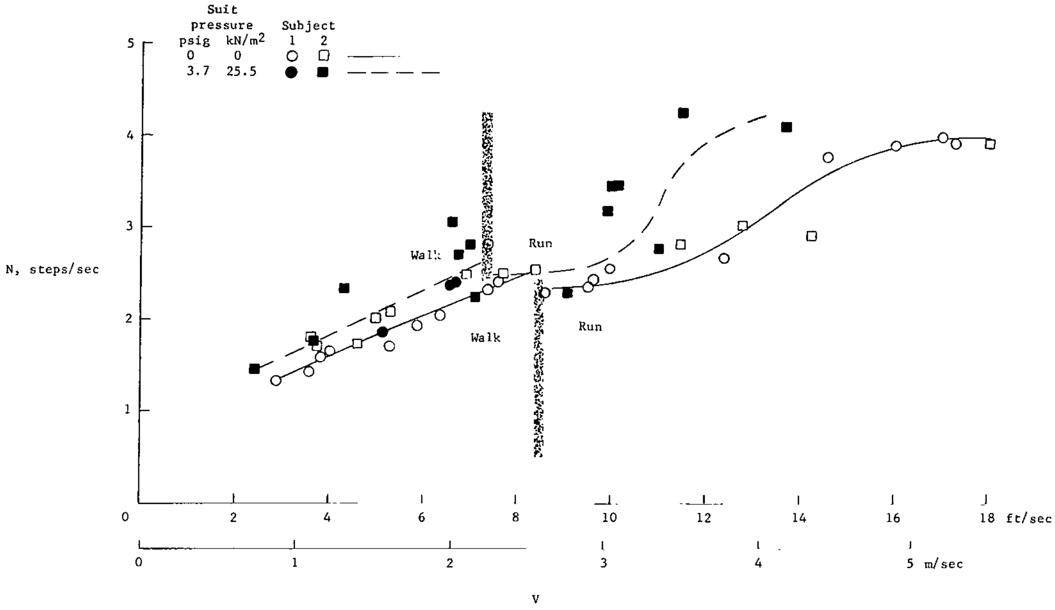

Figure 11.- Average stepping rate plotted against average locomotive velocity. Pressure-suited subjects; earth gravity.

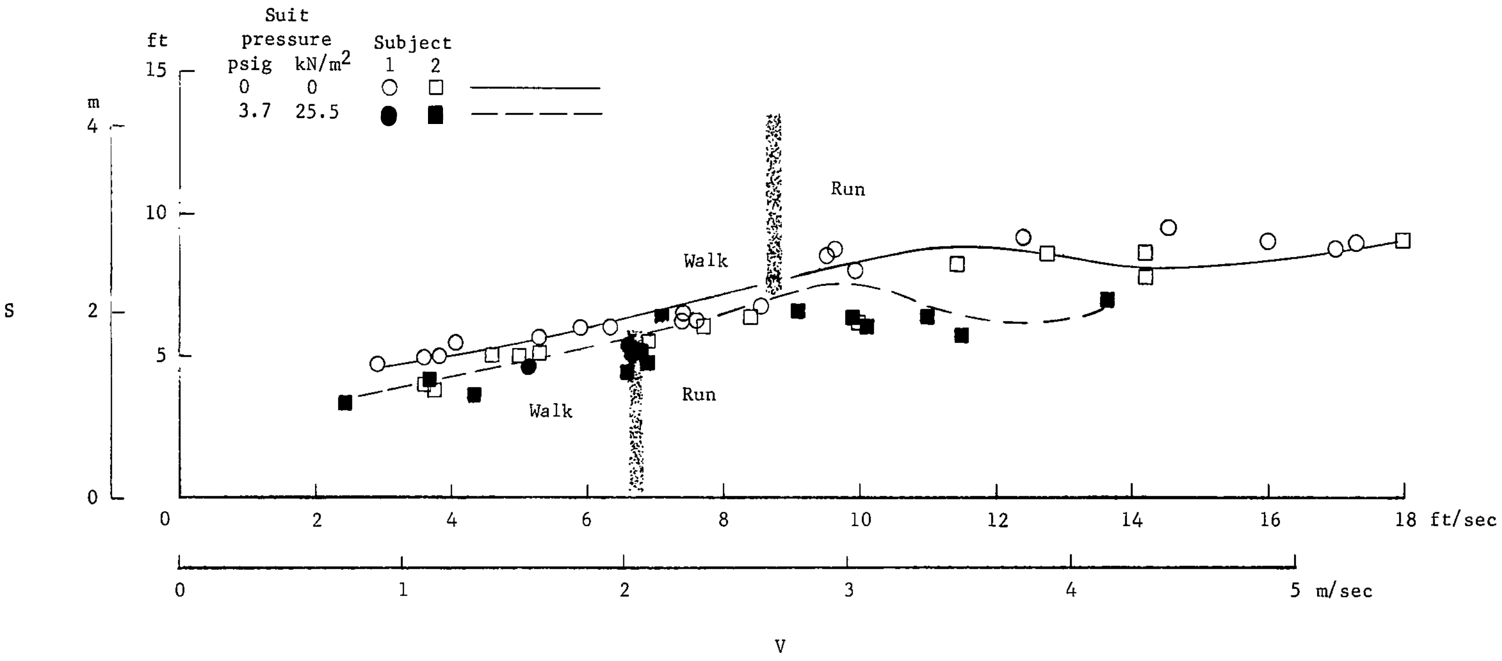

Figure 12.- Average stride length plotted against average locomotive velocity. Pressure-suited subjects; earth gravity.

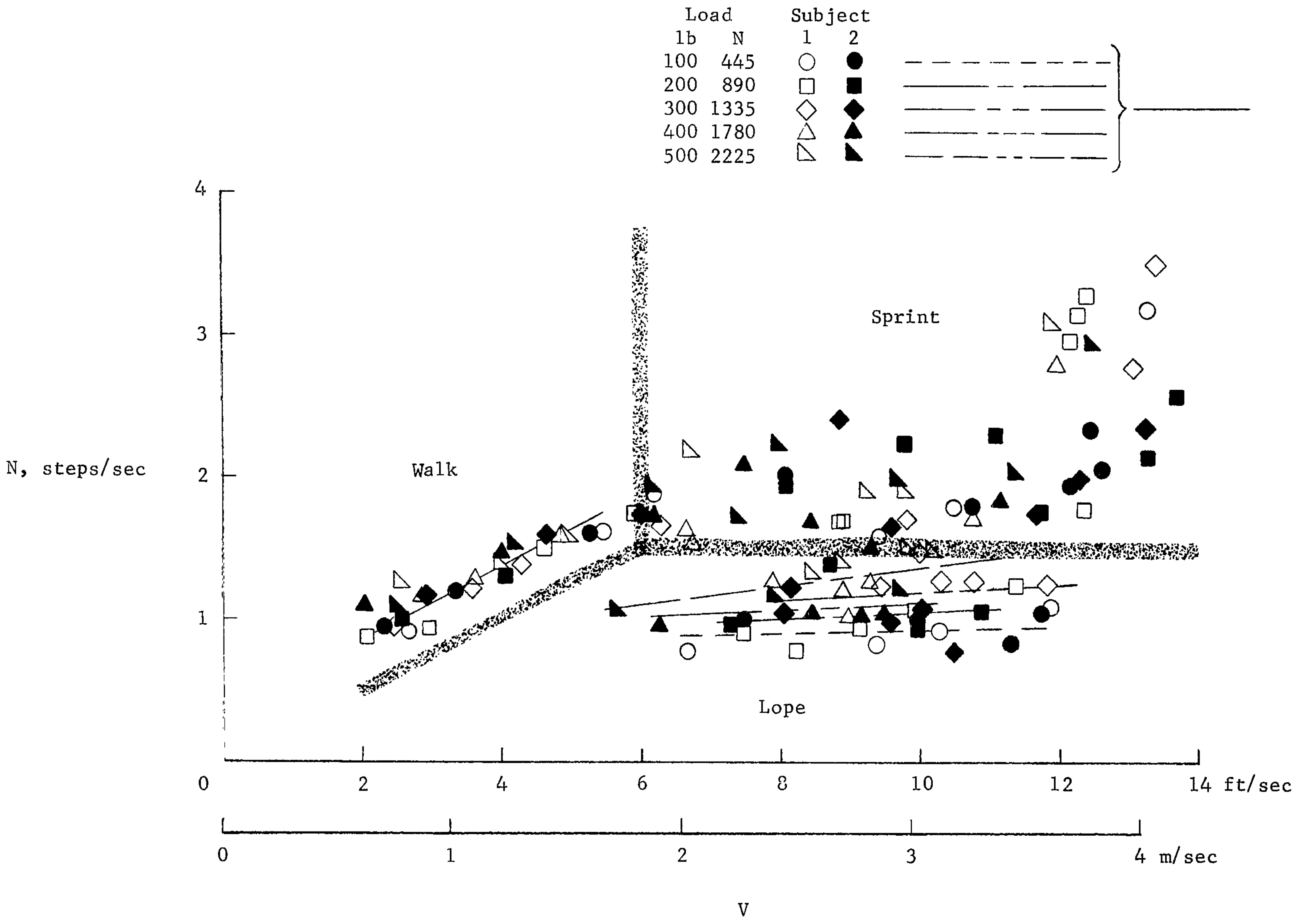

Figure 13.- Average stepping rate plotted against average locomotive velocity. Shirt-sleeve condition; with backpack loads; simulated lunar gravity.

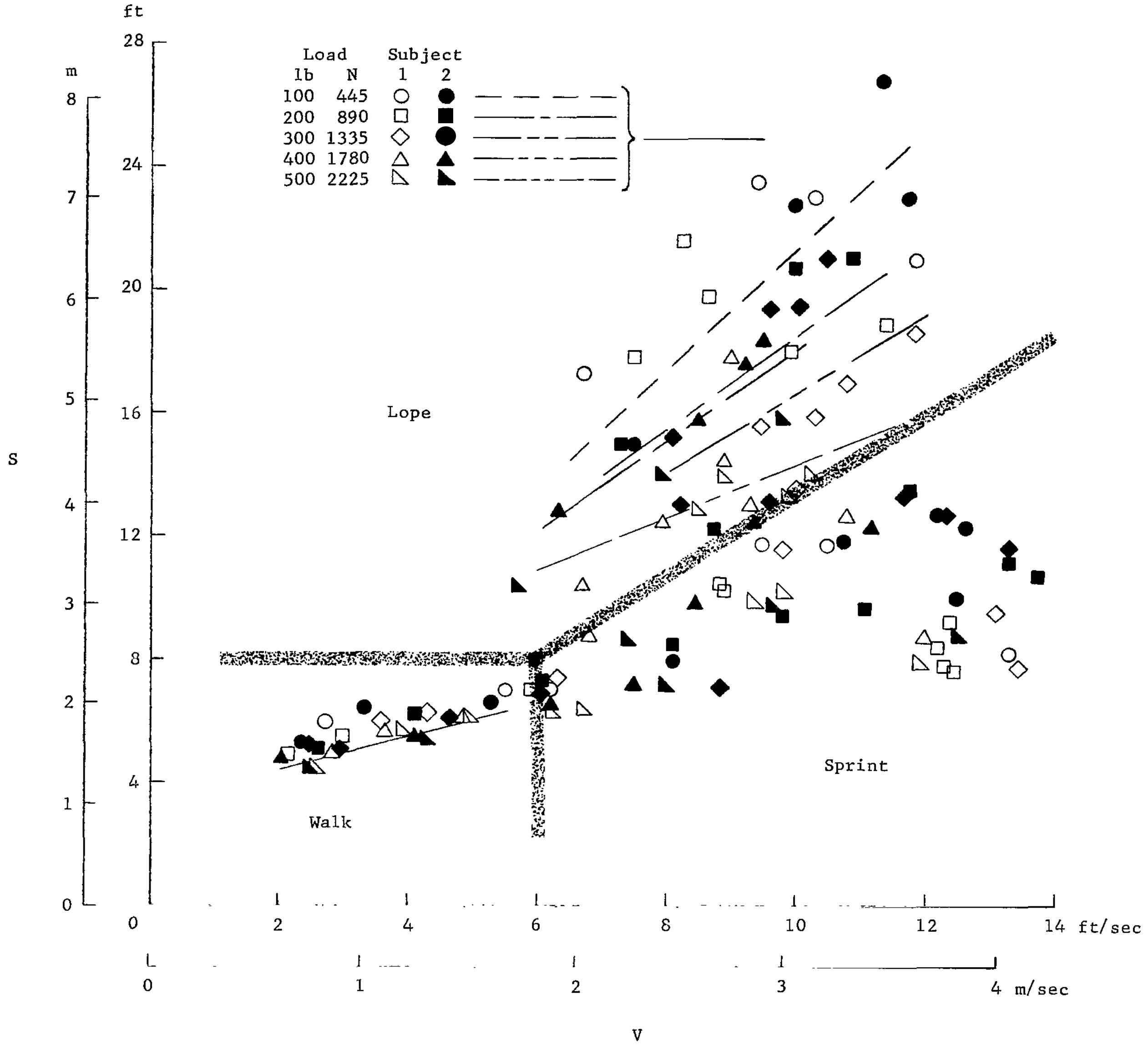

Figure 14.- Average stride length plotted against average locomotive velocity. Shirt-sleeve condition; with backpack loads; simulated lunar gravity.

	V		S		N	RHD	RTO	LHD	LTO	
	ft/sec	m/sec	ft	m	steps/sec					
1 g	2.5	0.8	3.6	1.1	1.4	♦	⬟	◆	▲	——
$\frac{1}{6}$g	2.9	.9	4.3	1.3	1.3	◊	⌂	◇	△	------

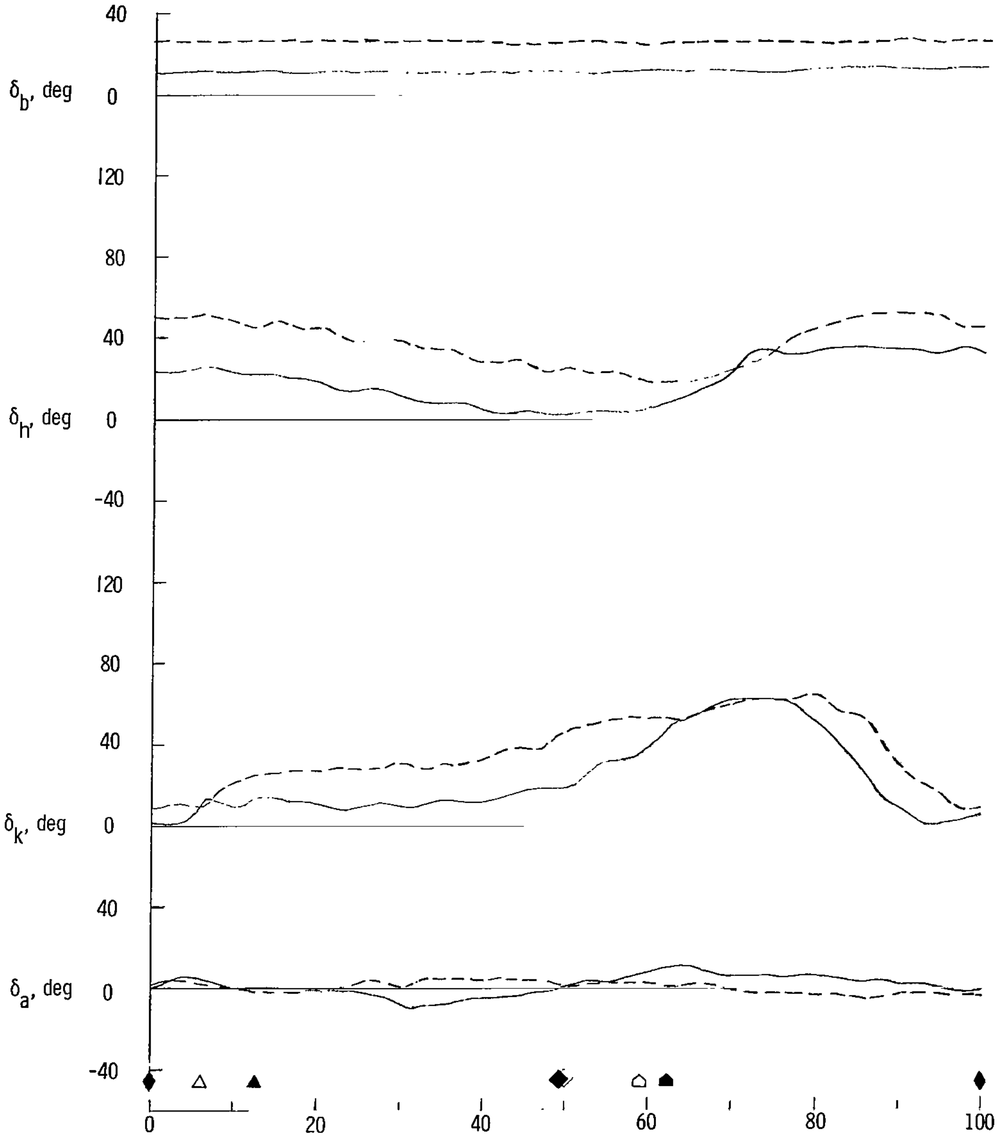

Figure 15.- Relative motions of various body members during one stride. Pressure-suited subject walking slowly; earth and simulated lunar gravity.

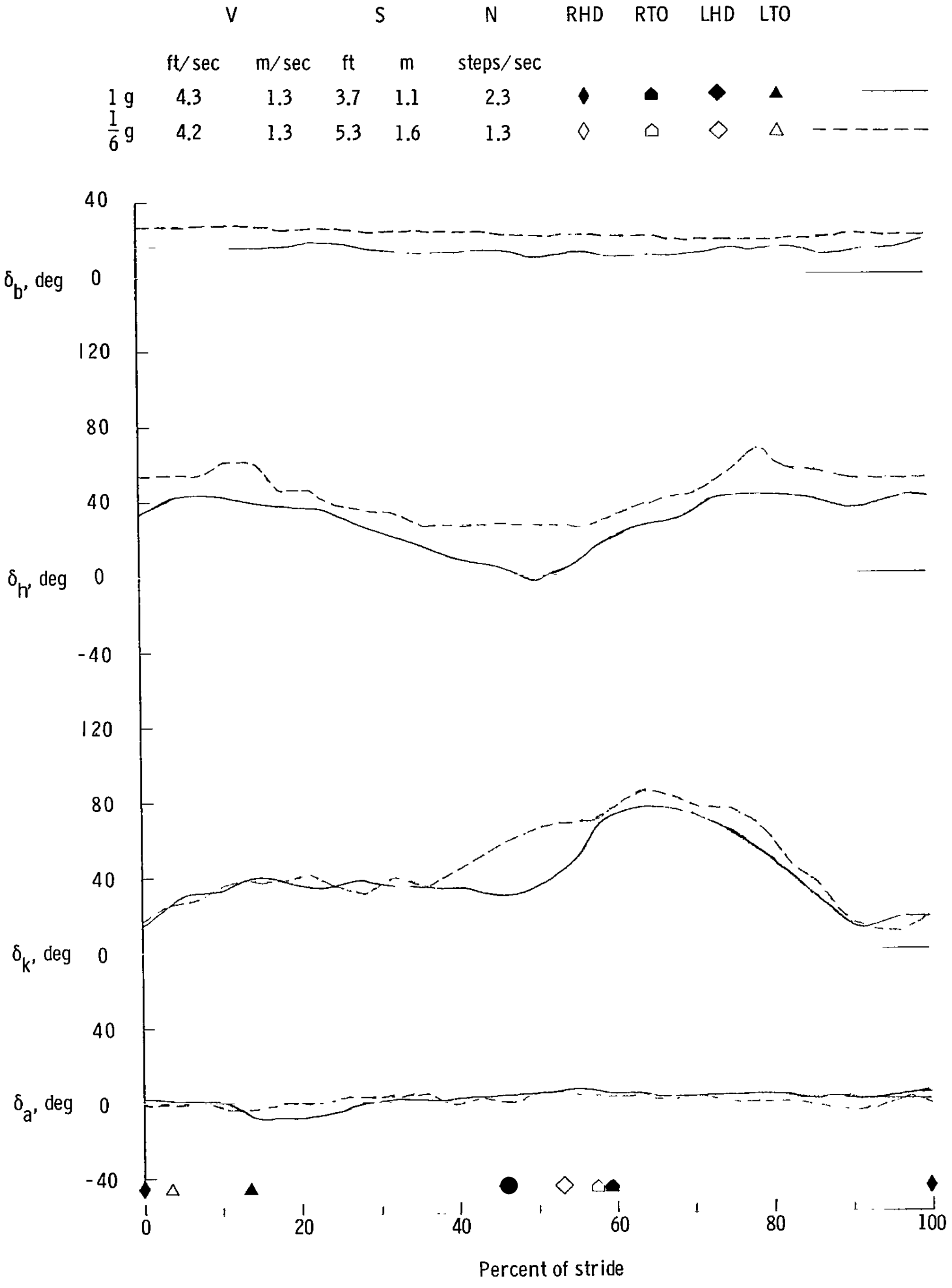

Figure 16.- Relative motions of various body members during one stride. Pressure-suited subject walking at normal speed; earth and simulated lunar gravity.

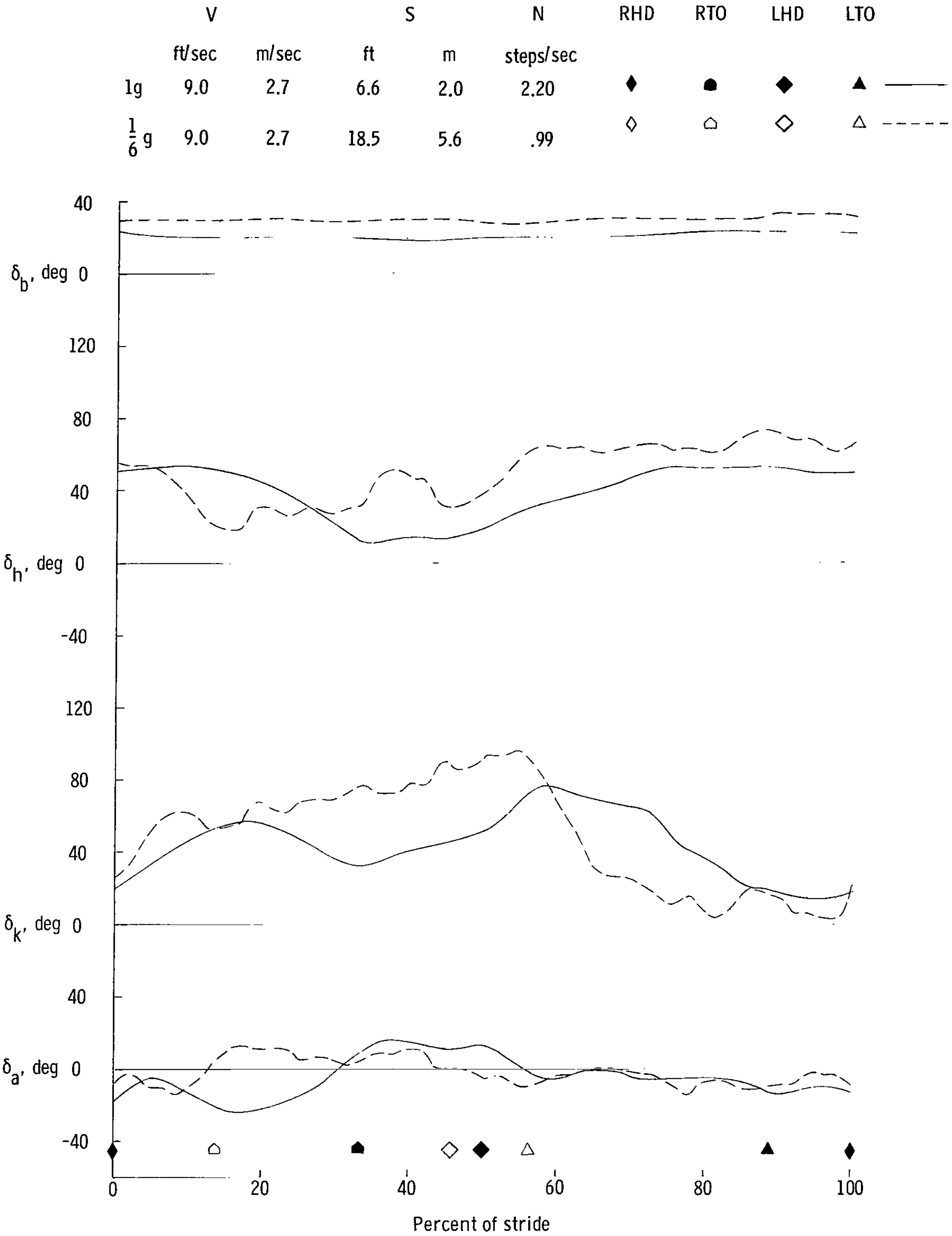

Figure 17.- Relative motions of various body members during one stride. Pressure-suited subject loping; earth and simulated lunar gravity.

	V		S		N	RHD	RTO	LHD	LTO	
	ft/sec	m/sec	ft	m	steps/sec					
1 g	13.7	4.2	6.9	2.1	4.1	♦	⬟	◆	▲	———
$\frac{1}{6}$ g	12.5	3.8	11.4	3.5	2.2	◊	⌂	◇	△	- - - - - -

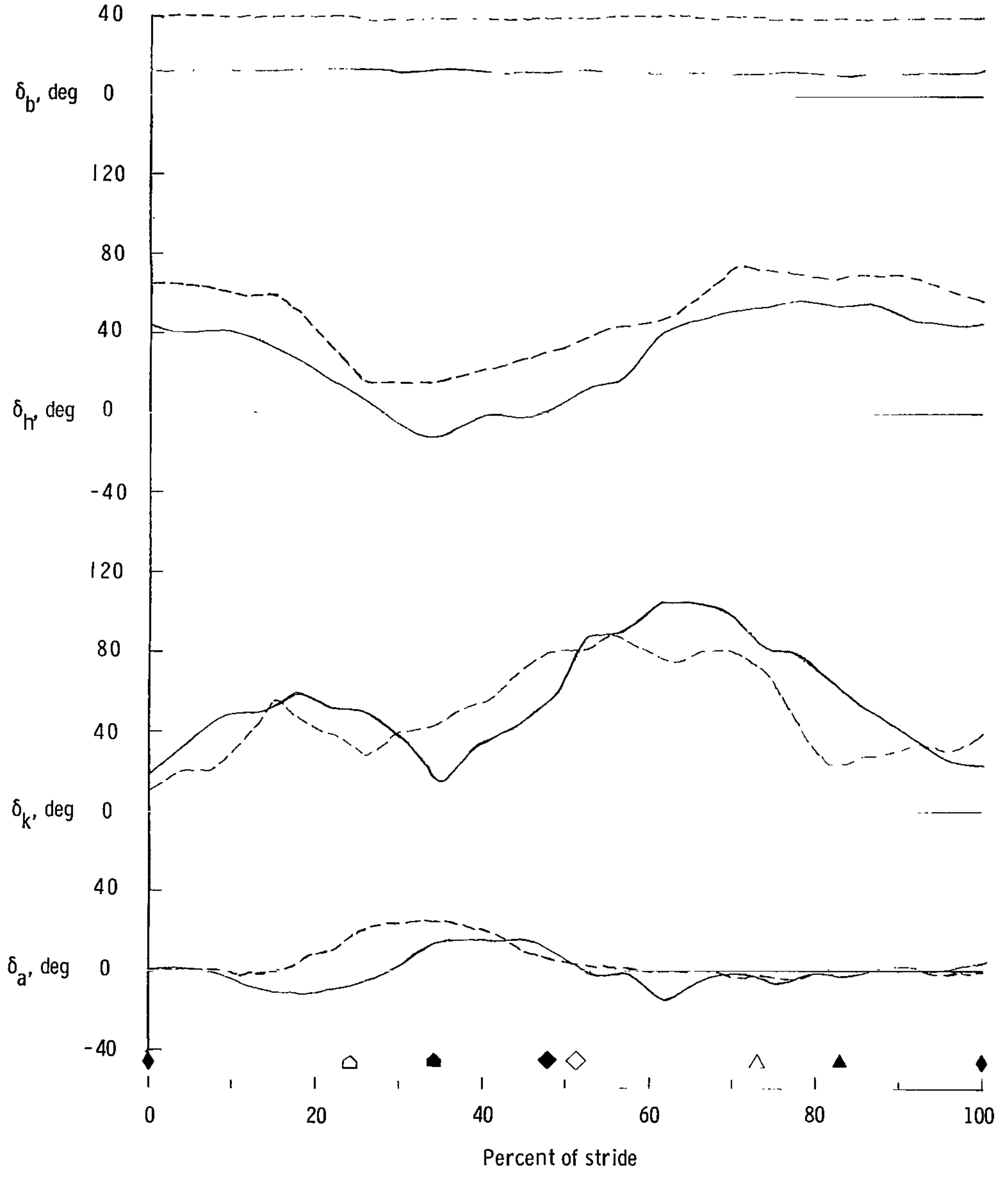

Figure 18.- Relative motions of various body members during one stride. Pressure-suited subject sprinting; earth and simulated lunar gravity.

Load		V		S		N	RHD	RTO	LHD	LTO	
lb	N	ft/sec	m/sec	ft	m	steps/sec					
100	445	2.7	0.8	6.0	1.8	0.9	□	□	■	■	— — —
200	890	3.0	.9	5.5	1.7	.9	◇	◇	◆	◆	— — — —
300	1335	2.5	.8	5.2	1.6	1.0	△	△	▲	▲	—— - ——
400	1780	2.9	.9	5.0	1.5	1.2	◺	◺	◣	◣	—— · · ——
500	2225	2.6	.8	4.5	1.4	1.1	⌂	⌂	⬟	⬟	— — — — —

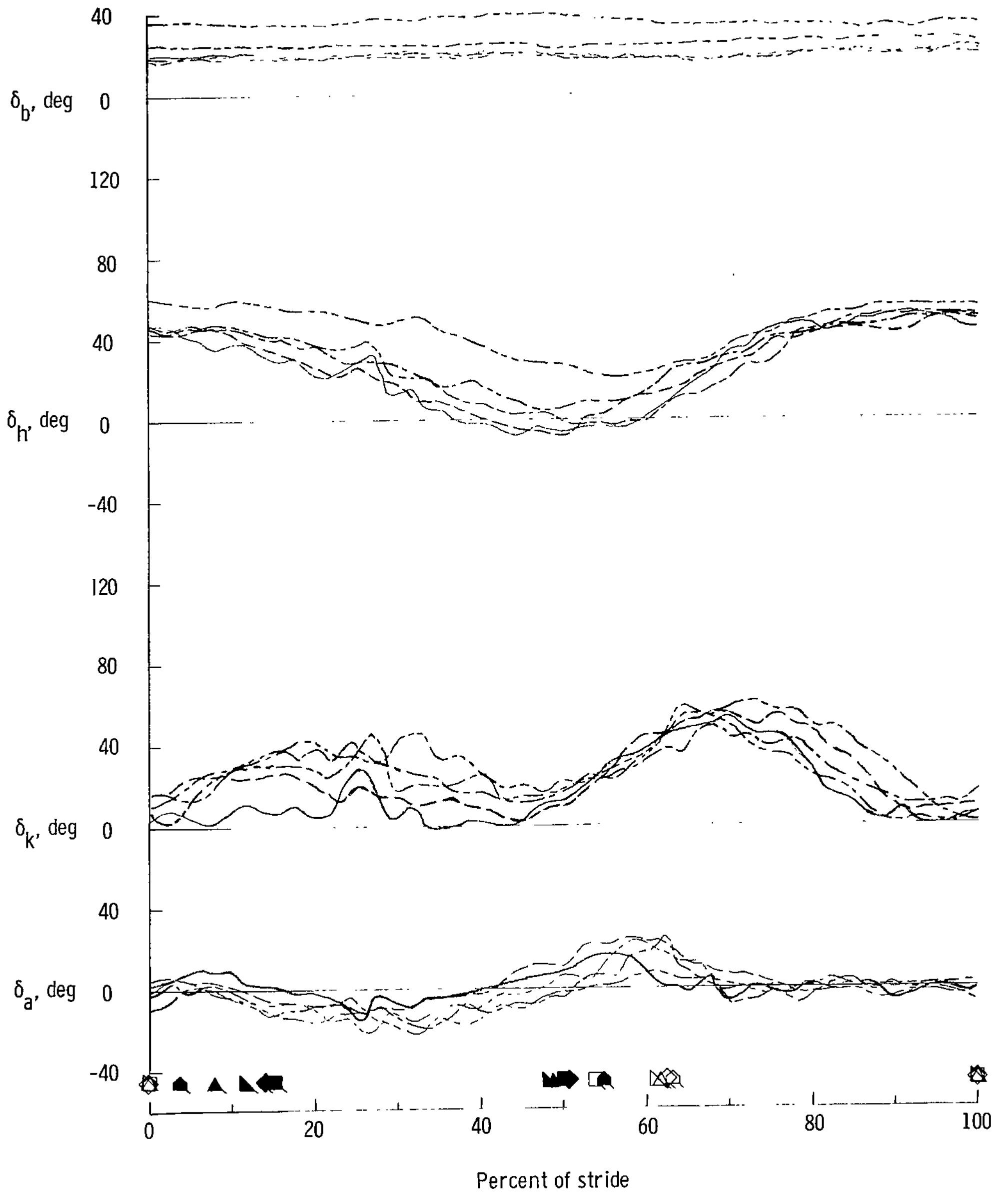

Figure 19.- Relative motions of various body members during one stride. Shirt-sleeve condition; with backpack loads; subject walking slowly in simulated lunar gravity.

Load		V		S		N	RHD	RTO	LHD	LTO	
lb	N	ft/sec	m/sec	ft	m	steps/sec					
100	445	5.5	1.7	7.0	2.1	1.6	□	□	■	■	———
200	890	4.7	1.4	6.1	1.9	1.5	◇	◇	◆	◆	— — —
300	1335	4.3	1.3	6.3	1.9	1.4	△	△	▲	▲	- - - —
400	1780	4.9	1.5	6.1	1.9	1.6	◺	◸	◣	◣	- — - —
500	2225	4.9	1.5	6.1	1.9	1.6	⌂	⌂	⬟	⬟	—- - - —

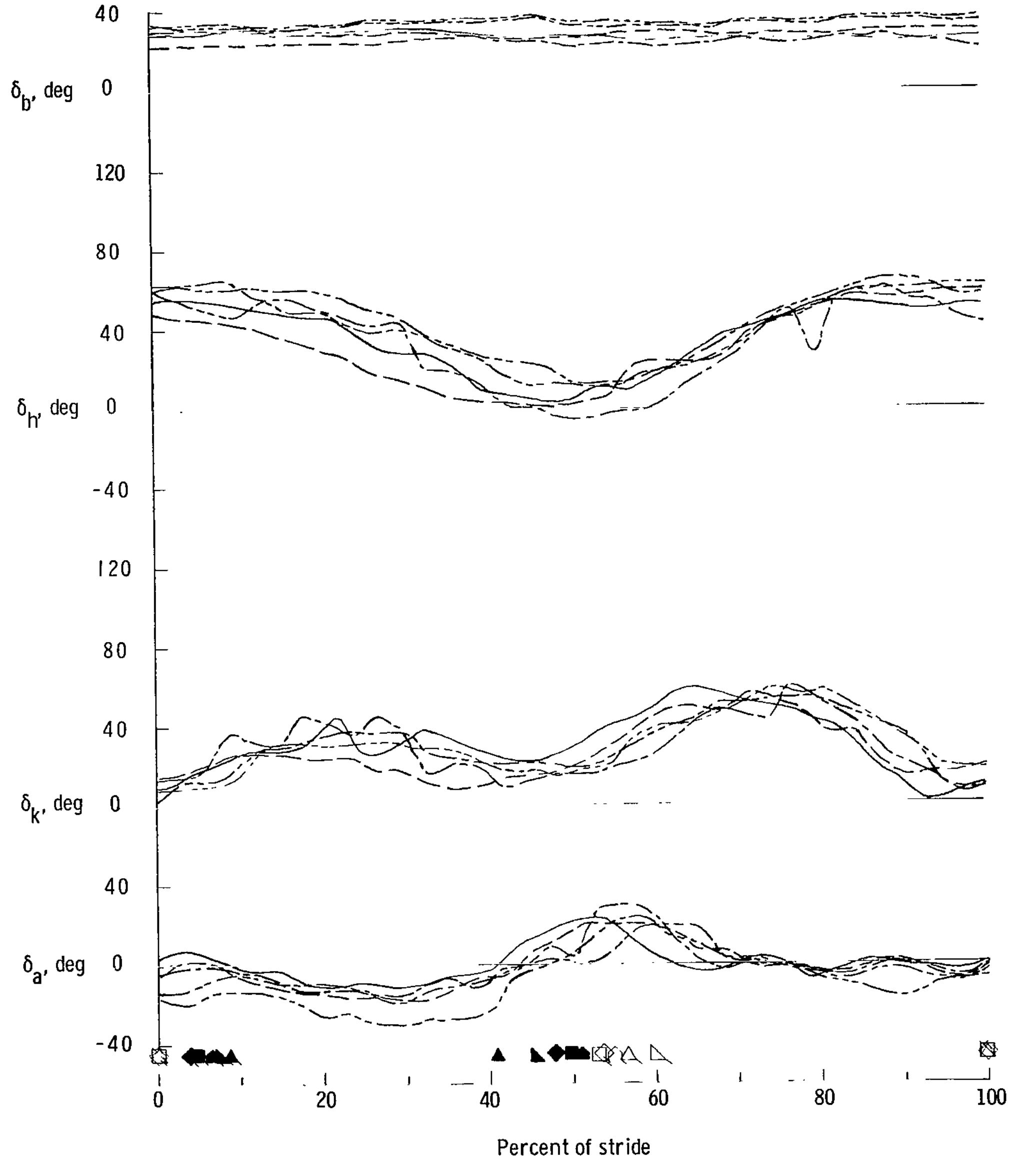

Figure 20.- Relative motions of various body members during one stride. Shirt-sleeve condition; with backpack loads; subject walking at normal speed in simulated lunar gravity.

Load		V		S		N	RHD	RTO	LHD	LTO	
lb	N	ft/sec	m/sec	ft	m	steps/sec					
100	445	10.3	3.1	23.0	7.0	0.9	□	□	■	■	———
200	890	9.9	3.0	18.0	5.5	1.1	◇	◇	◆	◆	— — —
300	1335	10.8	3.3	17.0	5.2	1.3	△	△	▲	▲	—— - ——
400	1780	10.8	3.3	12.6	3.8	1.7	◺	◺	◣	◣	—— - - ——
500	2225	10.2	3.1	14.0	4.3	1.5	⌂	⌂	☗	☗	—— - - - ——

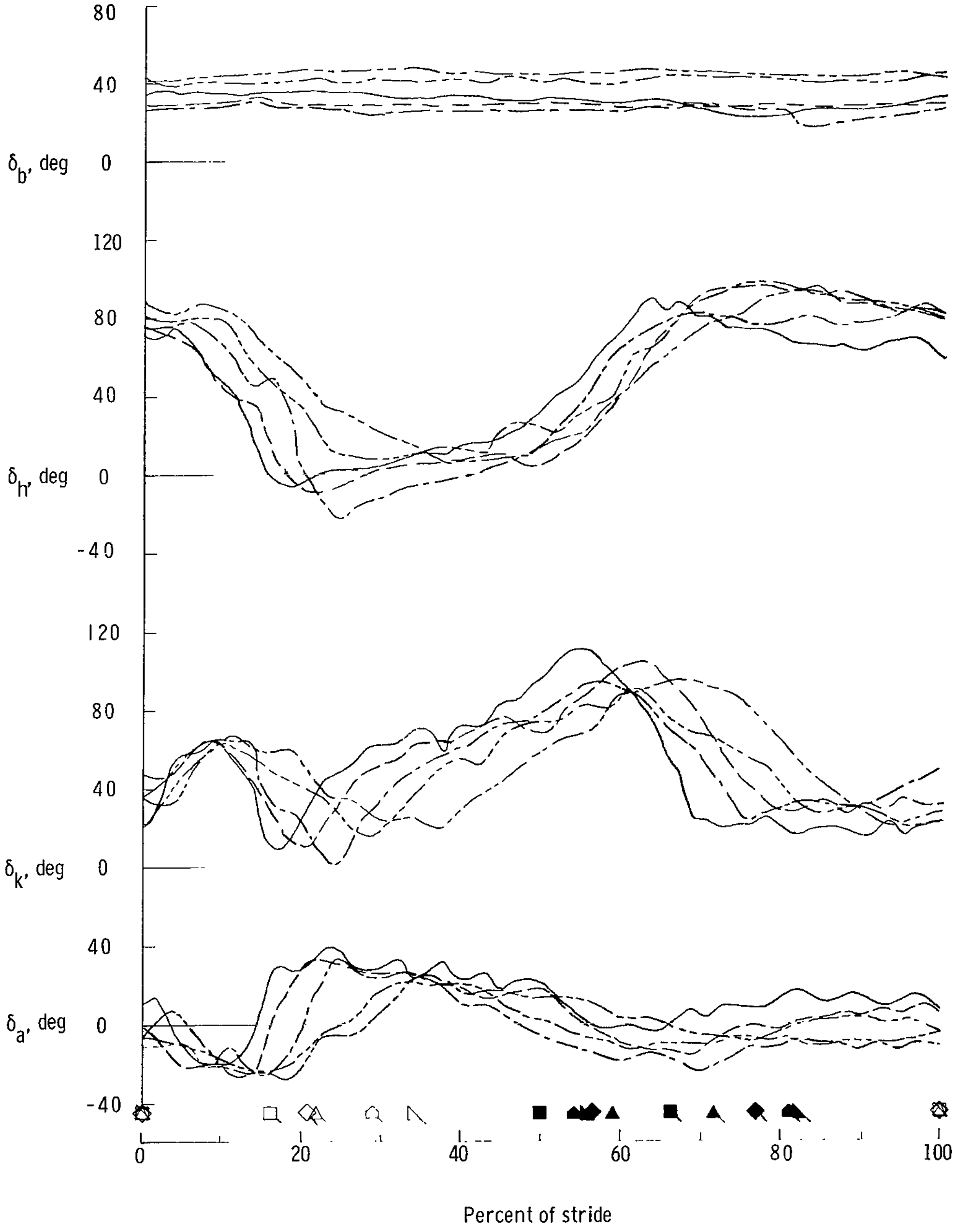

Figure 21.- Relative motions of various body members during one stride. Shirt-sleeve condition; with backpack loads; subject loping in simulated lunar gravity.

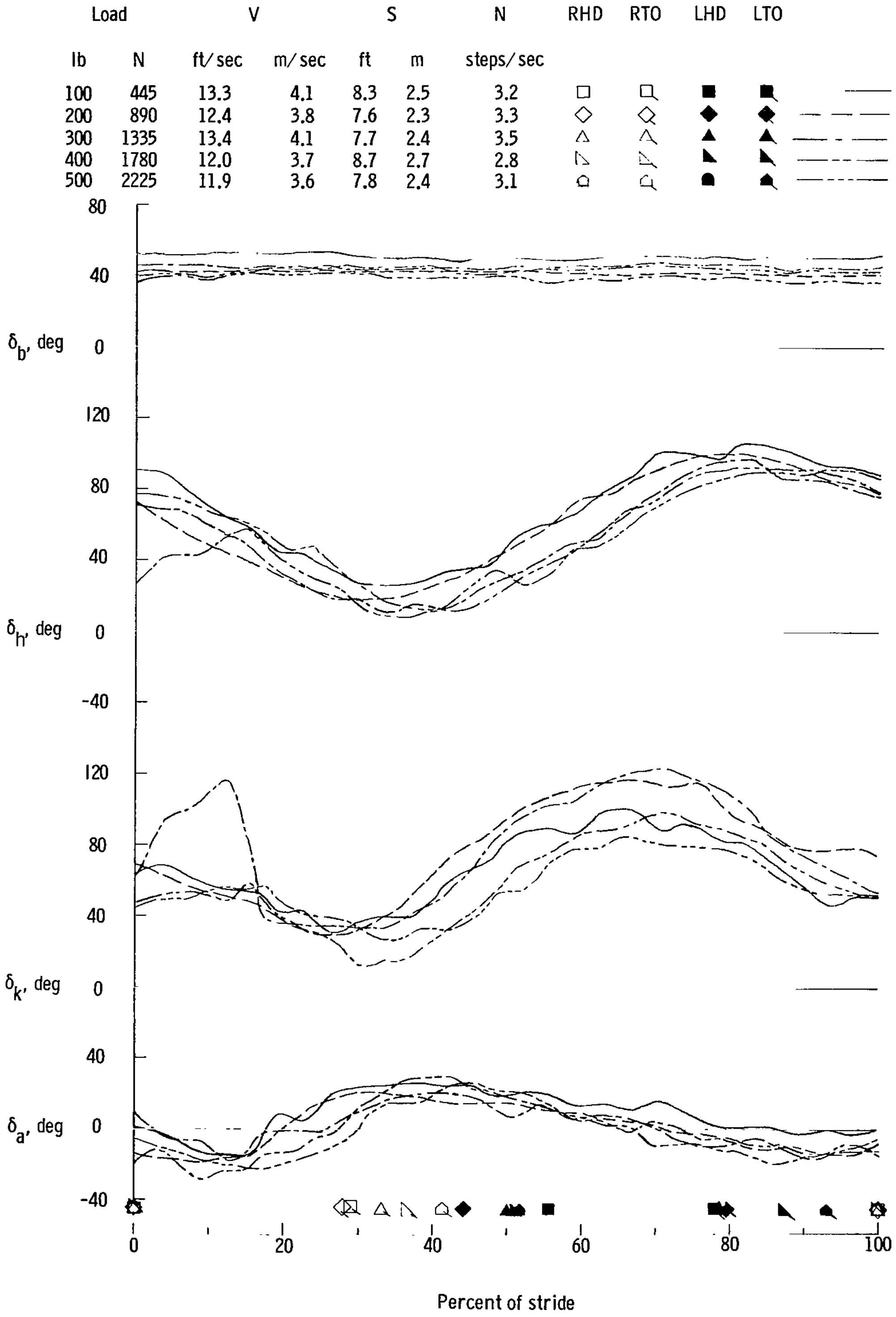

Figure 22.- Relative motions of various body members during one stride. Shirt-sleeve condition; with backpack loads; subject sprinting in simulated lunar gravity.

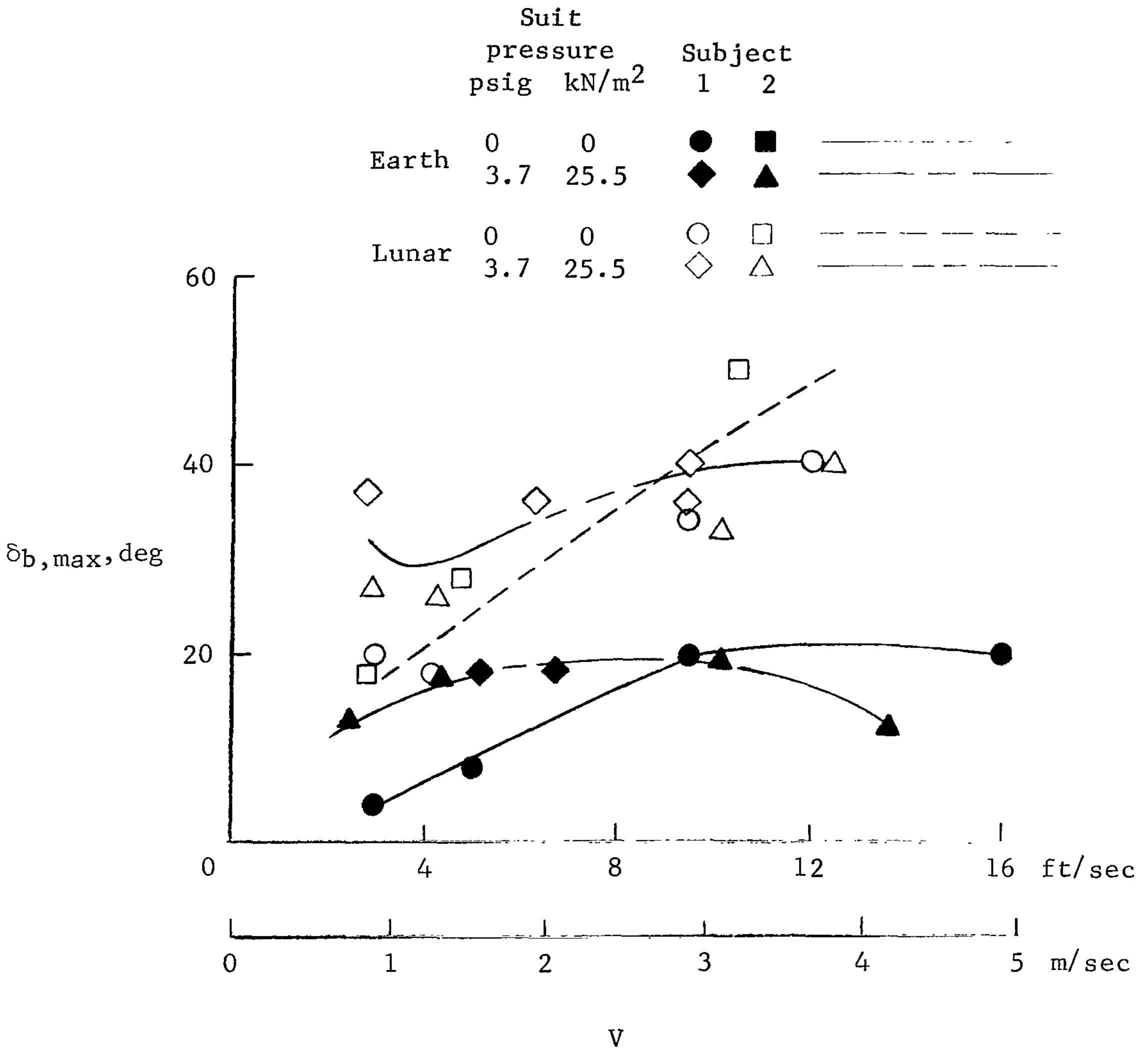

Figure 23.- Maximum back angle plotted against average locomotive velocity. Pressure-suited subjects; earth and simulated lunar gravity.

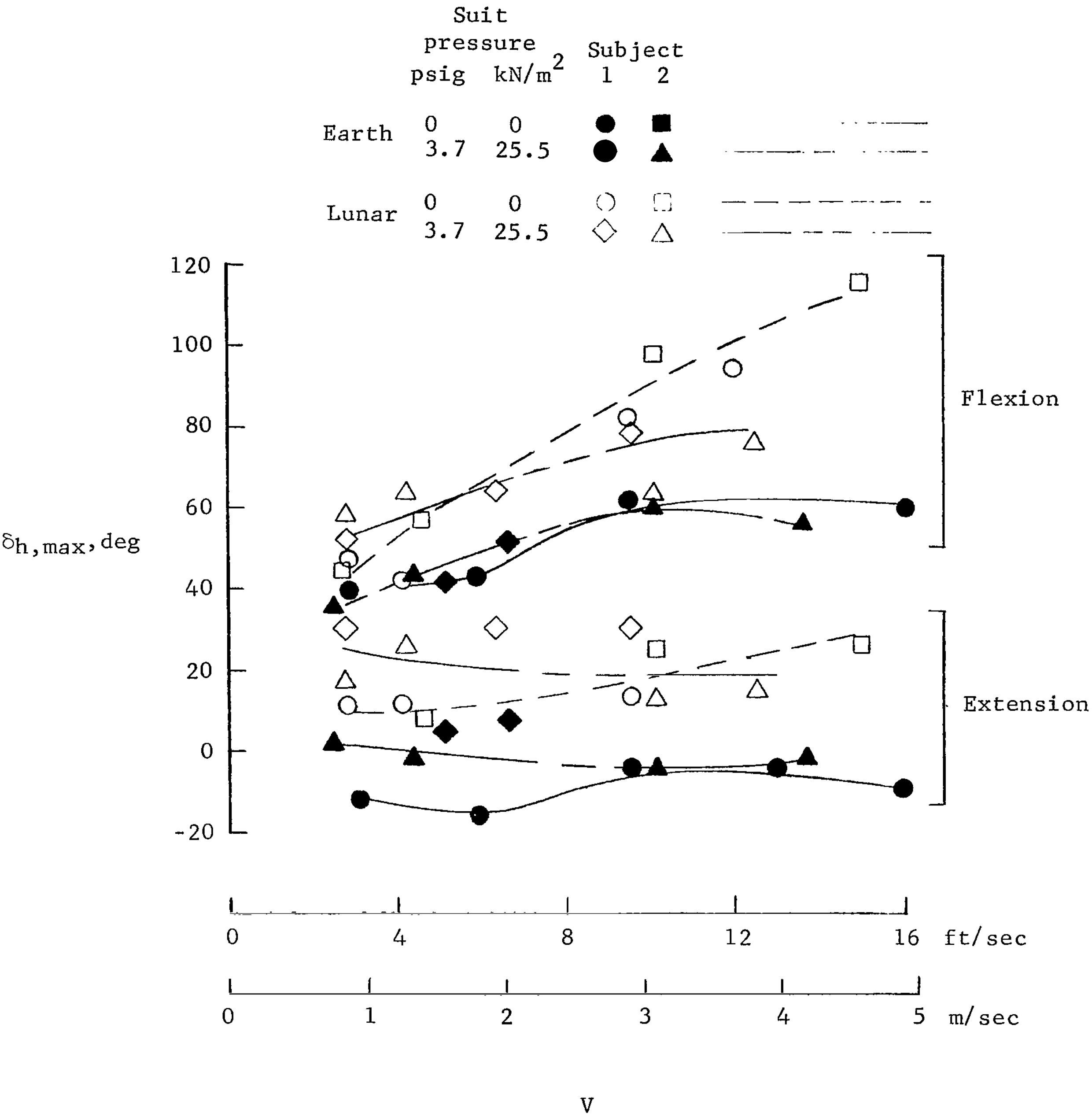

Figure 24.- Maximum hip flexion and extension angles plotted against average locomotive velocity. Pressure-suited subjects; earth and simulated lunar gravity.

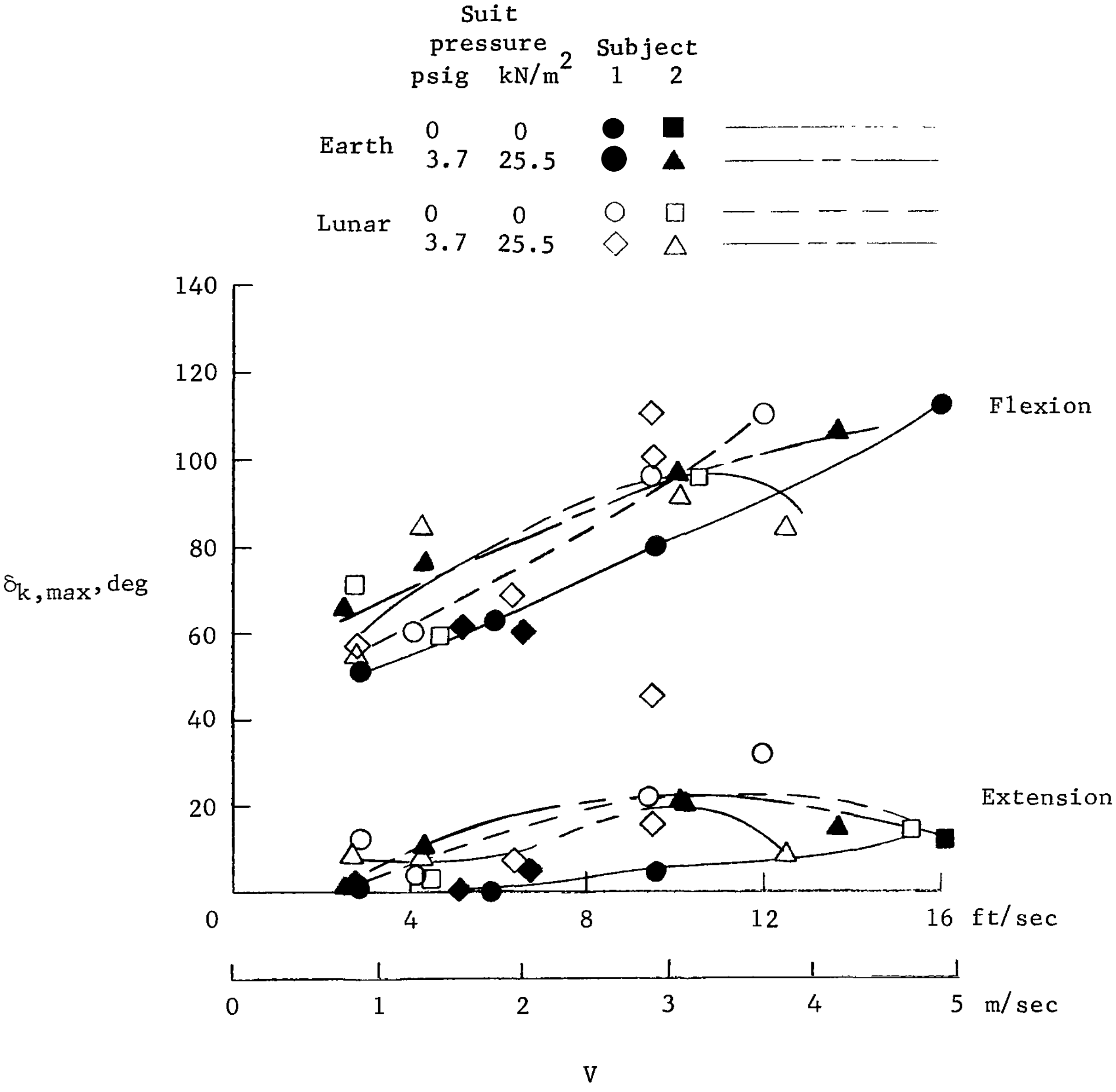

Figure 25.- Maximum knee flexion and extension angles plotted against average locomotive velocity. Pressure-suited subjects; earth and simulated lunar gravity.

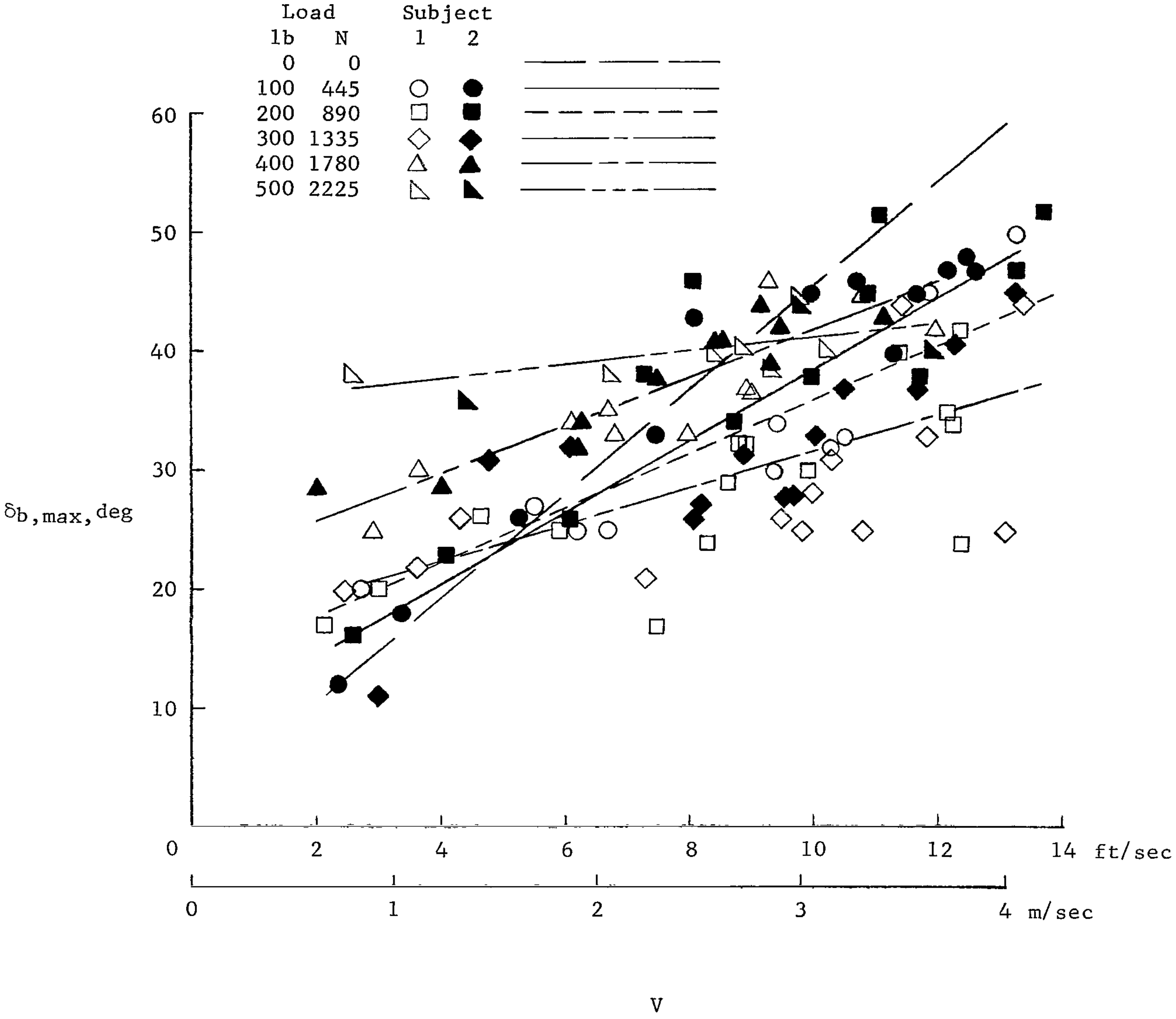

Figure 26.- Maximum back angle plotted against average locomotive velocity. Shirt-sleeve condition; with backpack loads; simulated lunar gravity.

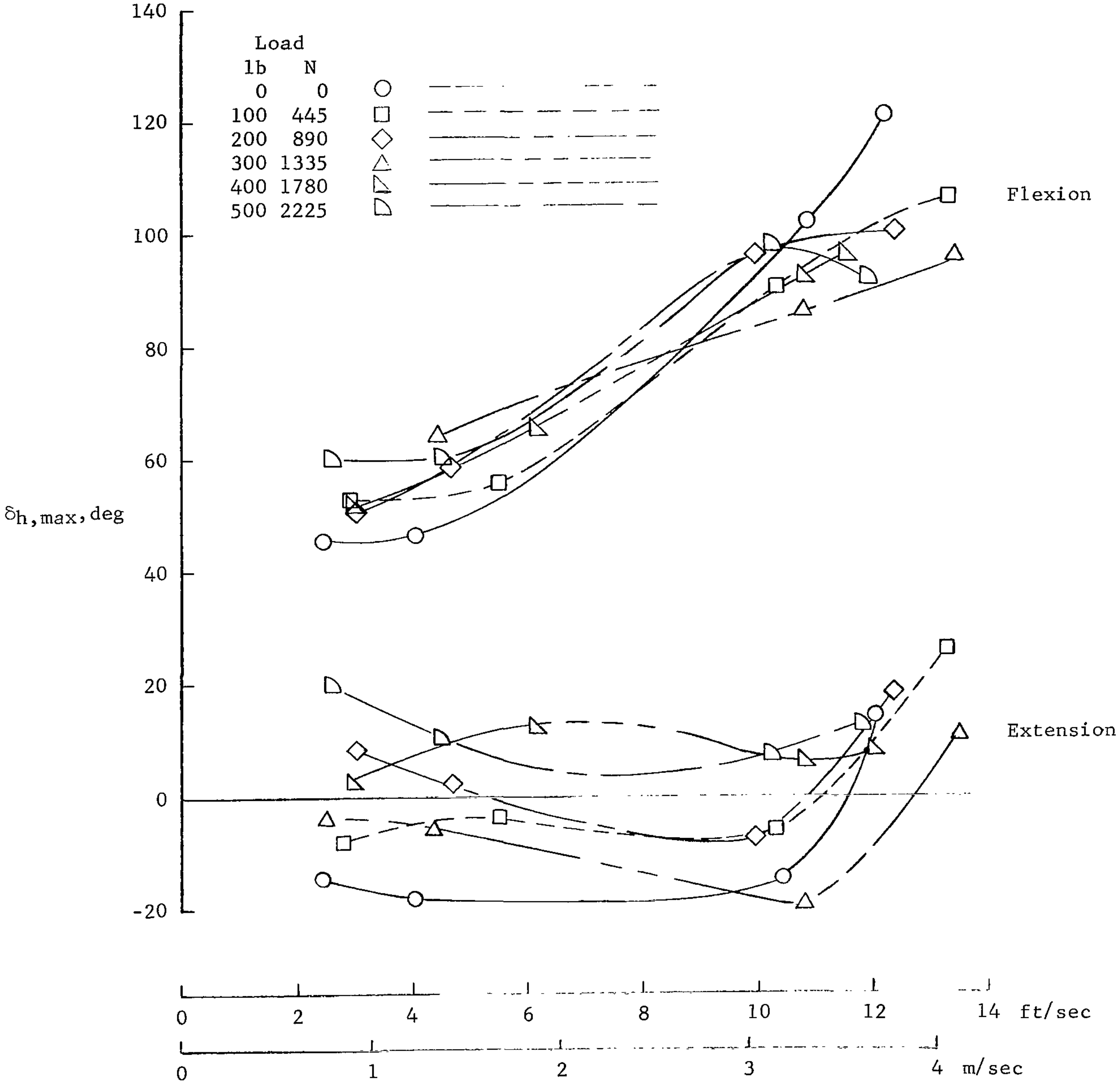

Figure 27.- Maximum hip flexion and extension angles plotted against average locomotive velocity. Shirt-sleeve condition; with backpack loads; simulated lunar gravity.

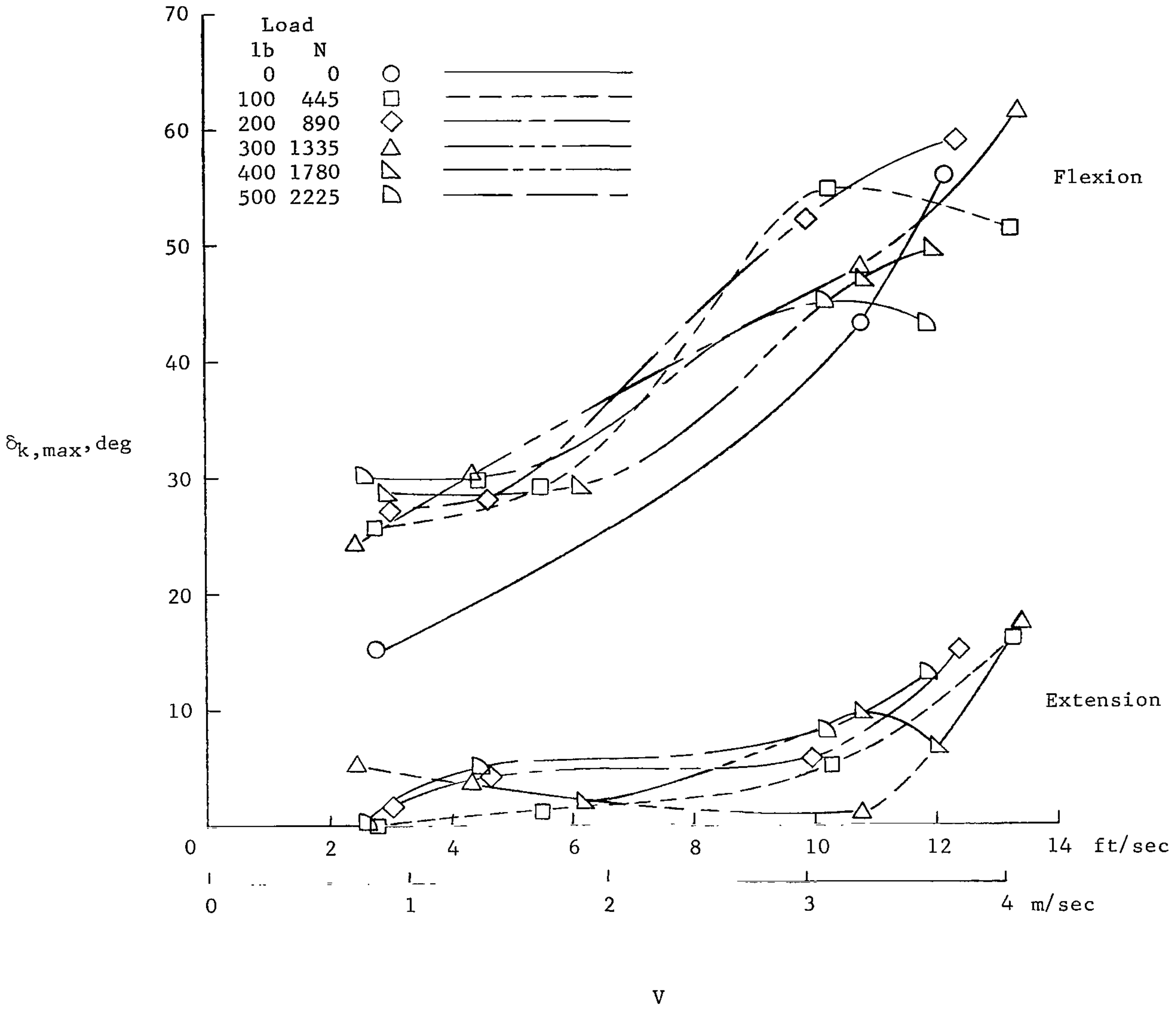

Figure 28.- Maximum knee flexion and extension angles plotted against average locomotive velocity. Shirt-sleeve condition; with backpack loads; simulated lunar gravity.

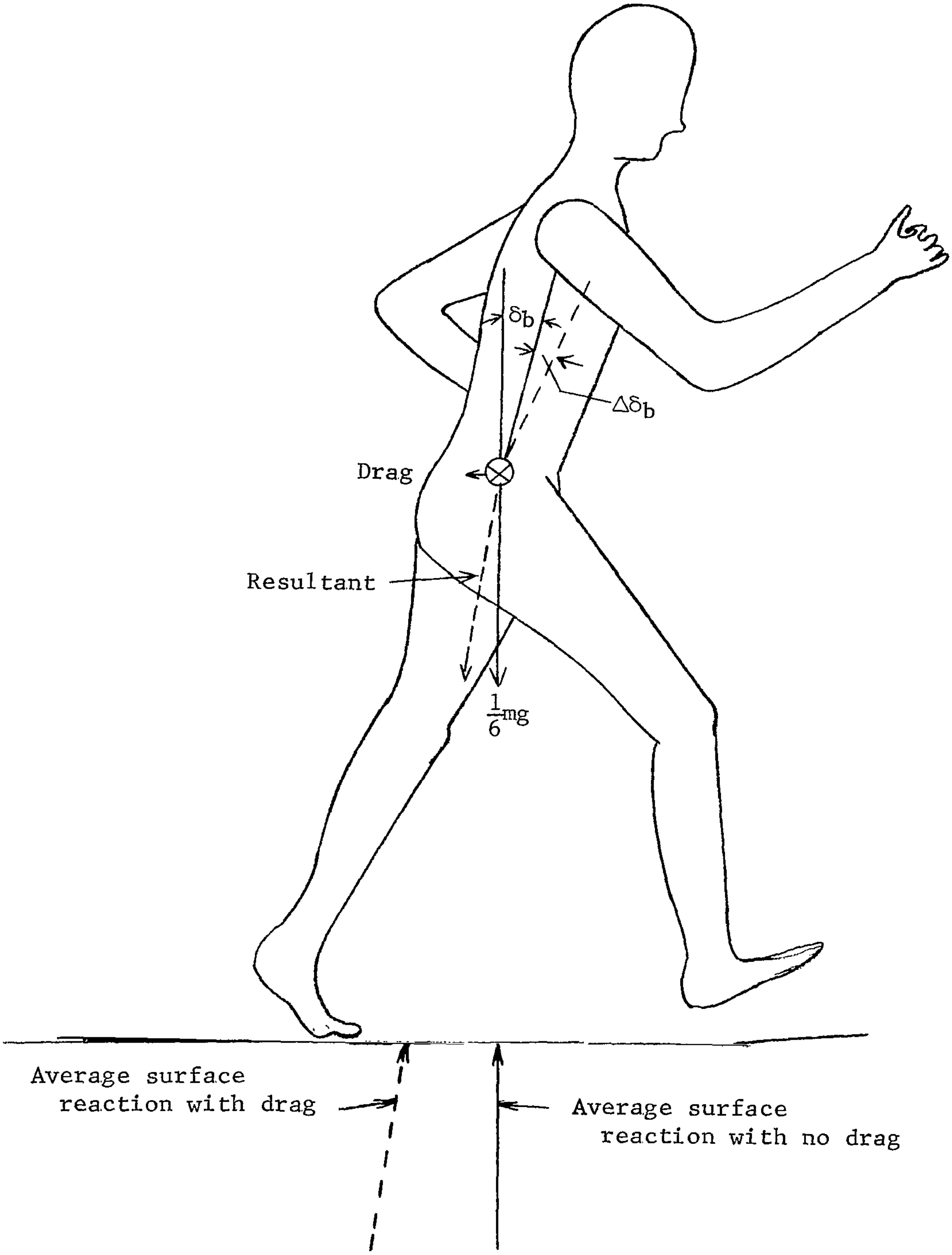

Figure 29.- Average forces and back angle with and without system drag.

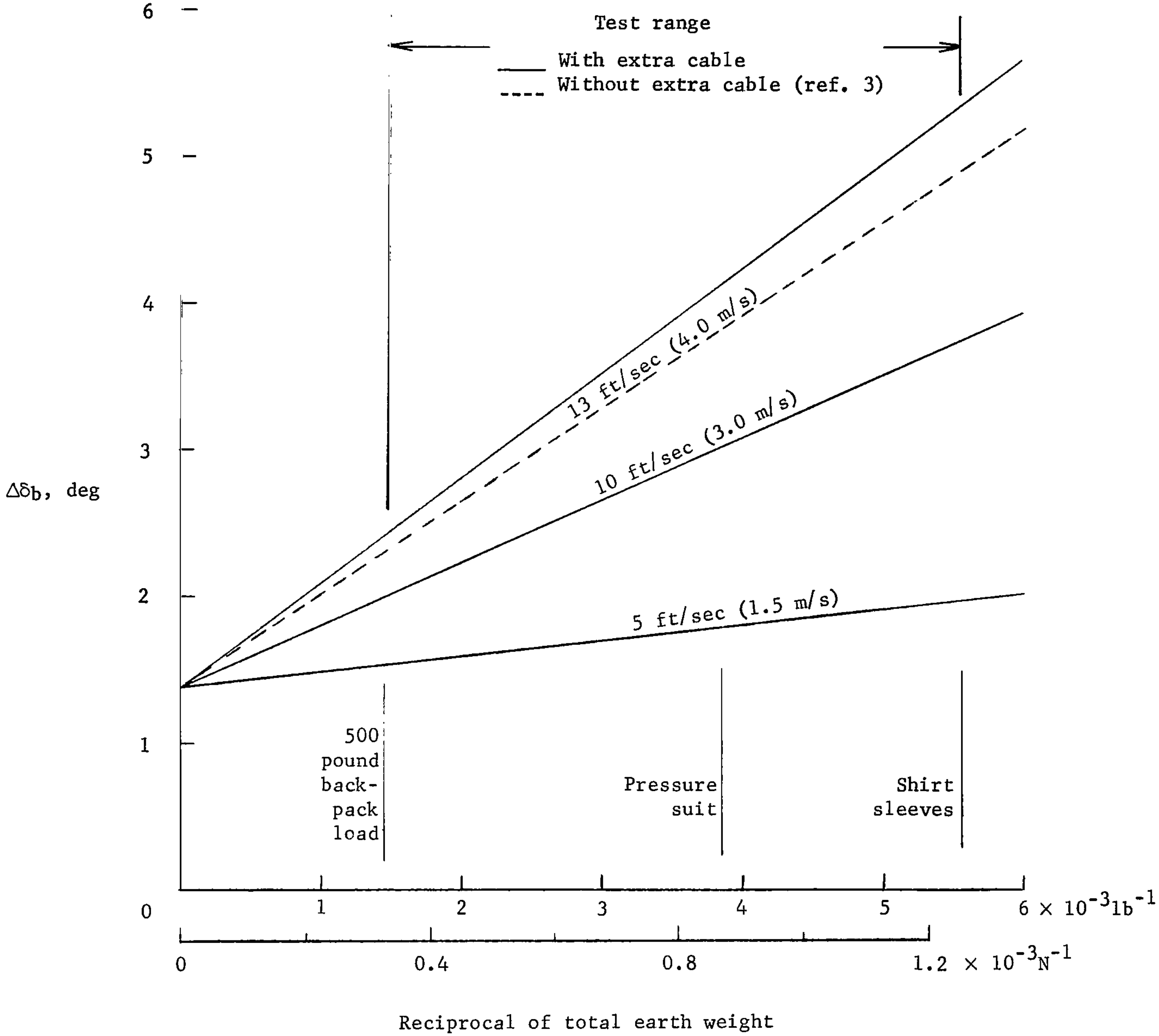

Figure 30.- Change in back angle needed to overcome system frictions.

NASA-Langley, 1968 — 5 L-5049

National Aeronautics and Space Administration
WASHINGTON, D. C.

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AN
SPACE ADMINISTRATION

09U 001 30 51 3DS 68074 00903
AIR FORCE WEAPONS LABORATORY/AFWL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 87117

ATT MISS MADELINE F. CANOVA, CHIEF TECHNI
LIBRARY /WLIL/

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Retur

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546