NASA TECHNICAL NOTE

NASA TN D-3363

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NASA TN D-3363

COMPARATIVE MEASUREMENTS OF MAN'S WALKING AND RUNNING GAITS IN EARTH AND SIMULATED LUNAR GRAVITY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1966

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Technical Film Supplement L-896 available on request.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A study was conducted to evaluate the effect of lunar gravity on man's walking and running gait characteristics by comparing results of tests conducted in earth and simulated lunar gravity. The lunar tests were conducted by using a modified version of the Langley reduced gravity simulator described in NASA TN D-2176 and the corresponding earth gravity tests were performed by using a portion of asphaltic concrete road of a length equal to that provided by the modified simulator. The test subjects wore lightweight flight coveralls and boots.

The subjects walked and ran at various speeds up to their maximums for both gravity conditions. The data were obtained by using a high-speed motion-picture camera stationed 150 feet (46 m) normal to the center line of the track.

The results of this study, which are useful primarily as base-line information, indicated that reduced gravity does have a definite effect on the angular movements of the hip, knee, and ankle joints and on the inclination of the body with walking and running. Maximum walking and running rates at simulated lunar gravity were found to be approximately 60 percent of those in earth gravity. A loping gait at about 10 feet per second (3 m/sec) in lunar gravity was, according to the test subjects' comments, the most natural method of self-locomotion.

INTRODUCTION

Since the inception of the Apollo lunar mission project, there has been much discussion of the use of man in performing the exploration of the lunar surface. It has been generally recognized that the low gravitational field of the moon would probably have an appreciable effect on the explorer's ability to walk, run, and perform other self-locomotive tasks which would comprise the exploration activities; however, there has been very little factual data available to substantiate these expectations. This dearth of corroborative information has been due primarily to the lack of a convenient means of duplicating or simulating the low lunar gravity under conditions suitable for a man to perform self-locomotive tasks here on earth. Recently a new simulation technique developed at the Langley Research Center was found to be practical and useful for this purpose and some brief exploratory studies demonstrated significant differences in man's self-locomotive performance, as reported in references 1 and 2. Consequently, a research program has been initiated at the Langley Research Center to evaluate these differences more fully.

This report summarizes the results of tests in which comparative measurements were obtained for both earth and simulated lunar gravity conditions to evaluate first-order effects of lunar gravity on man's walking and running gaits. These tests were performed by three experienced test subjects of different stature garbed in conventional summer-weight flying coveralls and wearing crepe-rubber soled boots. The lunar gravity tests are considered to duplicate closely the condition of a lunar explorer moving about within the confines of lunar-base housing. No attempt was made in this investigation to duplicate the constraints of a space suit; consequently, the test results are only indirectly applicable to the condition of the explorer moving across the lunar terrain where a suit would be mandatory. The results of this investigation are considered to be useful, however, in determining the applicability of currently available earth-gravity data to both types of lunar activity and in providing some insight relative to special requirements for space suits intended specifically for lunar self-locomotion.

SYMBOLS

Measurements for this investigation were taken in the U.S. Customary System of Units. Equivalent values are indicated herein in the International System of Units (SI) in the interest of promoting use of this system in future NASA reports.

δ_b back angle, angular deflection of reference line joining hip and shoulder joints relative to vertical, degrees (see fig. 1)

δ_h hip angle, angular deflection of thigh relative to back reference line, degrees (see fig. 1)

δ_k knee angle, angular deflection of calf relative to thigh, degrees (see fig. 1)

δ_a ankle angle, angular deflection of foot relative to calf, degrees (see fig. 1)

ω_h rate of change of hip angle, degrees per second (see fig. 1)

ω_k	rate of change of knee angle, degrees per second (see fig. 1)
N	stepping rate, number of steps taken by subject 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, $S = L + D$, feet (meters)
D	leg stroke, ground distance traversed during portion of stride when reference foot is in contact with ground, feet (meters)
L	leg swing, ground distance traversed during portion of stride when reference foot is free of ground, feet (meters)
η	locomotion index, ratio of leg swing to leg stroke, L/D also $\frac{S - D}{D}$
g	gravitational unit, relative to acceleration produced by earth gravitational field
T	time, seconds
V	velocity, feet per second (meters per second)

Subscript:

max	maximum value

TEST EQUIPMENT

The tests were conducted at an outdoor site beneath a multipurpose gantry structure by using an enlarged and modified version of the Langley reduced gravity simulator described in reference 1. The simulator supports the test subject on his side in an inclined attitude of about 9.5° from the horizontal plane by a series of cables attached to an overhead trolley unit which is free to move along a track parallel to a walkway on which the subject stands and moves. The subject is free to walk, run, jump, and perform other self-locomotive tasks in a more-or-less normal manner even though he is constrained to move essentially in one plane. Because of the inclination angle, this plane contains the component of earth gravity equal to the lunar gravity, that is, one-sixth of earth gravity. A sketch of the simulator is illustrated in figure 2. The plywood-surfaced walkway was 175 feet (53 m) long and the monorail trolley system was 150 feet (46 m) above the center line of the walkway. Details of the present sling supports for the subject are shown in figure 3. The leg bar used in these current studies was enlarged from that used originally to permit greater leg travel and was linked to the back of the test subject to minimize interference with movement of the subject. The top edge of the runway was marked in 1-foot (0.3-m) increments to facilitate measurements of the subject's motion along the walkway. A 16-mm motion-picture camera, running at 24 and, at times, 48 frames per second, was mounted on a catwalk of the gantry structure 150 feet (46 m) directly over the middle of the walkway. A telephoto lens with 70-mm focal length on the camera was used to provide a full-frame image of the test subject. The camera was operated manually so that the subject was followed the full distance of the walkway.

Corresponding tests were made under earth-gravity conditions of the asphaltic concrete road running parallel to the gantry structure. The road was suitably marked off and the motion-picture camera was mounted on the ground at a distance of 150 feet (46 m) from the test strip to produce the same side view of the subject as that for the tests performed in the simulator.

FUNDAMENTAL TEST CONSIDERATIONS

A particular locomotive gait is characterized by a unique combination of sequential motions of the body members relative to each other and to the surface over which the subject is traveling. Because of the complexity of these motions, it is desirable to select a few specific motions which are most descriptive of a given gait; consequently, emphasis was given to those body movements generated by the subject, herein referred to as primary motion, which were necessary to produce locomotion. This primary category includes inclination of the torso relative to the vertical (back angle), angular deflections of the thigh relative to the torso (hip angle), and angular deflections of the calf relative to the thigh (knee angle). Some consideration was given to secondary motions which are a result of the primary movements and which provide balance and a smoothing action. This category includes movements of the arms and feet and swaying and twisting of the torso. The smoothing action tends to make the particular gait more comfortable and to minimize the net energy expenditure involved in producing locomotion, but this action is considered to have only a relatively small effect on the characteristics of the primary motions.

The principal locomotive gaits employed by man are walking and running, for which the generally accepted distinction is that in walking both feet are on the ground at sometime during any given stride, whereas, in running both feet are off the ground at sometime during any given stride. Based on this distinction a locomotive index η is used in this investigation to indicate the type of gait developed for each test. Values of η (as calculated from the test measurements) less than 1 indicate that the subject was walking and values greater than 1 indicate running. A further distinction can be made in the case of the running gait, namely, loping or sprinting. There is, however, no definite demarcation value of η for these two conditions whereas there is a distinction in η between walking and running. The differentiation between the lope and the sprint made herein is based primarily on subjective evaluation. At the lower running speeds the lope, or long leaping stride, is usually employed with a relatively low stepping rate, whereas, the sprint or fast stepping short stride is most often used to achieve maximum speed. The characteristics of the walking and running gaits for the earth and lunar gravity conditions are most conveniently illustrated by comparisons of stride, stepping rate, and locomotive index which are determined from measurements of the primary motions defined previously.

SUBJECTS AND TEST CONDITIONS

Three test subjects of different stature and in generally good physical condition participated in this investigation, and each was thoroughly experienced with the operation of the Langley reduced gravity simulator. The following table summarizes their pertinent characteristics:

Subject number	Age	Height	Weight
1	40 yr	6 ft 1 in. (1.85 m)	230 lb (1023 N)
2	30 yr	5 ft 11 in. (1.80 m)	185 lb (823 N)
3	22 yr	5 ft 6 in. (1.68 m)	140 lb (623 N)

Identical summer-weight cotton flying coveralls and crepe-rubber soled boots, weighing approximately 3.5 pounds (15.6 N), were worn for all tests. Ambient temperatures were generally moderate in the range of about 60° F to 80° F (290° K to 300° K). The lunar simulator walkway was smooth painted plywood and the surface used for earth gravity tests were made on smooth dry asphaltic concrete. The coefficients of sliding friction for these two surfaces with boots were about 0.73 for the plywood surface and about 0.96 for the asphalt surface.

Each subject was requested to move at several different speeds up to their maximum for both walking and running gaits. The first portion of walkway (from 10 to 35 feet or 3 to 10 m) was used by the subjects to accelerate to the desired speed; whereupon, they attempted to maintain a steady pace over the middle 100 feet (30 m) of walkway.

Sufficient time was allowed between runs to permit the subjects to regain their breath and to avoid becoming fatigued.

MEASUREMENTS

All tests were recorded by means of the motion-picture cameras operating at 24 and, at times, 48 frames per second. An observer using a stop watch obtained the time required to travel the 100-foot (30.5-m) distance in the middle portion of the walkway. This time was used to establish the average velocity for each test.

Measurements of the positions and rates of movement for the various body members relative to each other and to the ground were obtained from the projected images of the motion-picture film by using a motion-study projector. To facilitate the reading of the film, a special articulated device was developed. (See fig. 4.) The device was constructed by tracing properly sized projected images of the test subject on thin stiff fiberboard, cutting out portions representing the various body members, and joining these portions with rivets at the locations corresponding to the body joints. Appropriate angular scales were added to the resulting articulated figure which was mounted on a large stiff white board used as a projection screen. Reference marks parallel to the vertical and ground lines were drawn on this screen. The screen was set up at the proper distance so that the articulated device could be adjusted to match exactly the projected image from successive frames of the film. Horizontal movement of the subject was obtained by noting the displacement of the subject's image with respect to the 1-foot (0.3-m) reference marks on the walkway appearing in the projected image. In this manner measurements of the back, hip, knee, and ankle angles and the horizontal movement of the body relative to the ground could be obtained at a rate of about one film frame per minute. The accuracy of the angular measurements using this technique is considered to be about $\pm 2^{\circ}$ which is considered adequate for purposes of this investigation.

RESULTS AND DISCUSSION

Motion-picture film supplement L-896 illustrating some of the results of this investigation has been prepared and is available on loan. A request form and description of the film will be found at the back of this paper.

In carrying out the exploratory studies of references 1 and 2, the constraints imposed on the test subject by the simulation equipment were assumed, primarily on the basis of subjective evaluation, to have negligible effects on the performance of the test subject in the simulated lunar gravity. The assumption that the results of this current investigation would not be seriously distorted by the constraints of the modified equipment was checked and the results are presented in the appendix. The analysis showed that the relative magnitudes of these constraints are generally quite small; consequently, based on the stated purpose of this investigation to evaluate first-order effects of lunar gravity, the constraints imposed by the simulator were considered to be negligible.

Walking and Running Speeds

A plot of the locomotive index calculated from the data for all the subjects and test conditions as a function of average locomotive speed is presented in figure 5 in which curves are faired through the two sets of data points to denote general trends. Note that, although the two curves denote similar trends, they also show significant differences. The average lunar transition speed (the speed at which $\eta = 1$) for the three subjects was about 5 feet per second (1.5 m/sec) or about 60 percent of the 8.3 feet-per-second (2.5 m/sec) speed for the earth gravity condition. The location of the data points along the abscissa of figure 5 indicate that the maximum running speeds achieved by the test subjects for the lunar condition were approximately 13 feet per second (4 m/sec), which is about 60 percent of the 20 feet-per-second (6 m/sec) maximum running speed for the earth condition. Thus it is indicated that man not only will walk slower but also will run slower on the moon than on earth by about 40 percent. These two related effects are attributed to the reduced weight and corresponding loss of traction experienced in lunar gravity.

An analytical study of human locomotion in subgravity, reported in reference 3, indicates a trend similar to that just discussed but differs in some respects with the limits of the lunar gaits reported herein. The value of about 7.8 feet per second (8.5 km/hr) given in the referenced study for the earth gravity transition speed agrees fairly well with the value (8.3 feet per second or 9 km/hr) discussed here; however, the theoretical limit of about 0.91 feet per second (1 km/hr) for lunar gravity is very much lower than the value obtained experimentally, 4.9 feet per second (5.4 km/hr). Consequently, on the basis of these experimental findings the maximum walking speed apparently is not a direct function of gravity level as was assumed in the reference study. An analysis of the actual relation of gravity level to maximum walking speed indicated by these tests is beyond the scope of this investigation.

In reference 3 the maximum lunar running speed was given as 13 kilometers per hour or about 12 feet per second, which is in good agreement with the experimental findings. It was stated in reference 3, however, that a greater speed of approximately 18 feet per second (19.8 km/hr) could possibly be achieved by a series of jumps. If it is assumed that these consecutive jumps have the same mechanics as the loping gait utilized in this investigation, then the experimental results do not agree with the theoretical predictions; that is, the maximum experimental jumping pace was actually much slower than predicted.

Stride and Stepping Rate

In spite of the type of gait employed and the obvious different physical characteristics of the three subjects, there was a fairly well-defined variation of the stride and stepping rate with velocity, as illustrated in figures 6 and 7 where the data for stepping rate and stride are plotted against average locomotive speed. There is somewhat less scatter of data for earth gravity tests as compared with the lunar gravity data points; the closer agreement is attributed to the subjects' greater familiarity with the condition of earth gravity and to the less constraining effects of lunar gravity which probably make the individual variations in locomotive gaits more apparent.

The trends of the gait parameters with speed of locomotion for the two gravity conditions as denoted by the shape of faired curves are similar (figs. 6 and 7); however, there are significant differences in the absolute values of the stride and stepping rate at any given speed. At practically all speeds, the subjects were able to take longer strides with corresponding lower stepping rates for the lunar condition than for the other; that is to say, they took fewer steps to cover a given distance. This effect was most pronounced in the range between 6 and 12 feet per second (1.8 to 3.7 m/sec) where the stride was greater and the stepping rate was lesser by a factor as large as 2. This difference is believed to be a very important fact pertaining to energy expenditures and will be discussed subsequently.

For the earth gravity tests, the loping gait was usually employed in the speed range of about 9 to 15 feet per second (2.7 to 3.7 m/sec) and sprinting produced substantially higher speeds up to about 20 feet per second (6 m/sec). Note that for the higher running speed range the stride did not change appreciably and the higher speeds were achieved primarily as the result of increased stepping rate. Although the highest speeds for the lunar condition also were achieved by use of the sprinting gait, practically no difference in the maximum loping speeds existed; also, there was a loss of stride with the sprinting gait as compared with that for the loping gait. This loss accounts for the break in the stride curve between 11 and 12 feet per second.

The stepping rate data obtained from reference 3 is shown for comparison with the current test data in figure 6. The reference data are for two values of friction coefficient, both of which are appreciably lower than that for the current tests. There appears to be very little correlation between these two sets of data other than the close match of the reference data with the 1g test data at the lower speeds. This agreement is explained by the fact that the analytical study assumed no difference between earth and lunar conditions for this speed range and that the curve was probably based on some earlier earth gravity tests.

Relative Motions of Body Members

Comparisons of the time histories of the relative motion of the body members of one of the subjects are made in figures 8 to 11 for the two gravity conditions and reveal some significant differences pertinent to lunar space suit design. The time histories of figure 8 are in the form of "stickmen" or line diagrams showing the relative positions of the body at time intervals of about 0.16 second and for a distance of at least one step as denoted by the solid horizontal bars at the ground lines. The comparisons are made for walking speeds of about 4 feet per second (1.2 m/sec) and loping speeds of about 10 feet per second (3 m/sec). The comparison for the sprinting gait is made for maximum running speed and, consequently, could not be made at the same speed; the sprinting speeds correspond to 19.8 feet per second (6 m/sec) for earth gravity and 13.1 feet per second (4 m/sec) for lunar gravity.

The time histories of figures 9 to 11 are in the form of curves showing the variations of the several angular measurements with time at approximately the same speed conditions as in figure 8. The curves are for the duration of one lunar stride, beginning and ending at the instant of right heel contact with the ground. The instants of other significant events are denoted by the symbols along the time abscissa.

Further comparisons are made in figures 12 to 16 in which data for the maximum back angle, hip angle, and knee angle, and angular rates for all three subjects are plotted against average locomotive speed. Curves have been faired through the data points of figures 12 to 16 to denote general trends.

The stickmen of figure 8 illustrate graphically several of the more evident differences in the locomotive gaits for the two gravity conditions. For instance, forward inclination of the body for the lunar condition is progressively larger as the speed is increased, whereas, for the earth condition, the forward inclination of the body is relatively small over the complete speed range. This difference can also be seen in figures 9 to 11 where, for instance, in figure 11 the back angle is seen to be 10° for the earth sprinting gait and greater than 60° for the lunar sprinting gaits.

Another difference evident in figure 8 is the manner in which the arms are carried with respect to the body. For earth conditions, the arms appear to play a very active role in achieving a coordinated and balanced gait as indicated by the swinging secondary motion in opposition to the primary motion of the leg member on the same side of the body. In contrast, the arms seem to play a relatively minor role in the case of the lunar gaits inasmuch as the arms are shown being carried high and forward with a minimum of swinging motion. It is noted for the lunar loping gait that the arms usually were used with a slight up-and-down pumping motion in unison with each jumping step. It is possible that some of the constraints of the body support cables for the lunar simulation tests (see appendix) might have provided compensating moments that would have been required otherwise from this type of secondary motion; consequently, the results of the simulation tests relative to arm motions are regarded as inconclusive.

During each step, the legs were carried farther forward with the lunar gaits than with the corresponding earth gaits as illustrated in figure 13 where the hip extension angles are larger for the lunar condition than for the earth condition. Note that the total travel of the thigh, that is, the difference between extension and flexion angle, is about the same for both conditions. This effect is attributed to the previously discussed difference in the inclination of the body; that is to say, with the body inclined farther forward the legs also had to be carried further forward as part of the process of maintaining balance. The accompanying action of the knees gave the subject the appearance of walking stiff-legged for the lunar activities; this effect is shown in figure 14 where the knee flexion angles for lunar gravity tests are shown to be somewhat smaller than for the corresponding earth tests. Although this knee action may be the result of a small restraint imposed by the support equipment of the lunar gravity simulator, it appears likely that the customary knee action is not needed when the weight carried on the legs is relatively low as is the case for lunar gravity.

As shown in figures 15 and 16, the maximum angular rates for both the hip and knee motions for lunar walking were less than one-half of those for earth walking, that is, for speeds below about 5 feet per second (1.5 m/sec).

An interesting phenomenon noted during these tests was the presence of an approximate 10 cycle-per-second uncontrolled oscillation of small amplitude superimposed on the motions of the foot and leg for the loping and running gaits, as seen in figures 10 and 11. This oscillatory motion is of about the same amplitude for both gravity conditions and appears to be the reaction to the kicking movements used with these gaits. Perhaps the most significant aspect of this apparently trivial phenomenon is the fact that its presence in the lunar tests seems to substantiate the assumption that the effects of the restraints imposed by the leg suspension system were neglibible. If it were otherwise, the frequency and amplitude of these very slight motions for the simulator tests should have been significantly different from those for the earth gravity tests.

Special Considerations for Energy Expenditure

General observations indicate that each person adopts a particular walking speed as a natural or comfortable pace. The work of reference 4 shows that for earth conditions such a natural pace corresponds very closely with the optimum speed for minimum energy expenditure, per unit distance traveled; therefore, for this discussion it is assumed that man has the ability to select the speed that will cost him the least amount of energy. For a normal male subject this particular speed was reported in reference 4 to be about 4.0 feet per second (1.2 m/sec) which is about 20 percent of the maximum earth gravity running speed measured in the current experiments. In the lunar gravity tests all three subjects, who had many hours of simulation experience, observed and commented that the walking gait was uncomfortable or seemed unnatural; they preferred to travel at higher speeds by using the loping gait characterized by long easy strides with a relatively low stepping rate. This gait, which was described as comfortable and not tiring, corresponds to the dip in the stepping-rate curve of figure 6 and the peak in the stride curve of figure 7 at about 10 feet per second (3 m/sec) or about 60 percent of the maximum lunar running speed. Consequently, based on these observations and the assumed minimum energy expenditure in a natural pace, it is concluded that the optimum rate of energy expenditure for lunar gravity conditions occurs at an appreciably higher speed than for earth conditions. Therefore, even though the maximum walking and running speeds are less on the moon than here on earth, as discussed previously, it is anticipated that the lunar explorer will find it much more natural to move at a faster pace (up to twice as fast) than that which he would normally use on earth. Of course, it is recognized that this conclusion would be true only if the lunar surface conditions and clothing constraints were comparable to those for the earth conditions.

One reason for the faster natural pace is that the low lunar weight of the subject makes it relatively easy to develop the long leaping steps which carry the subject distances up to about 28 feet (8.5 m) and which relieve him of the work of sustaining his own weight except during the very brief period when there is contact with the surface. Furthermore, the stepping rates for lunar walking and loping are comparable and, if it is assumed that the internal work expended by the subject merely to move his legs back and forth is a direct function of the stepping rate, then the work for the two gaits is nearly the same; consequently, the higher speed of the loping gait should cause it to be the more efficient of the two modes of lunar locomotion. One step further in this line of reasoning indicates that, since the lunar stepping rate is about one-half of that for the optimum earth walking speed, it is also possible that the total work required of a lunar explorer employing the loping gait will be appreciably less than that required to walk the same distance here on earth. These observations are in general agreement with similar comments reported in the analytical study of reference 3.

Application of Results to Space Suit Design and Mission Planning

If the assumption is made that the most efficient or ideal space suit is one which permits the wearer to have the same freedom of movement as he would have without the suit, then the results of this investigation can be applied in a general manner to design and development problems of a space suit of this type suitable for lunar locomotion.

Perhaps the most significant results of the tests pertinent to suit problems are those which show that the locomotive gaits for the two gravity conditions differ significantly in many respects. In the light of these differences, it is very possible that a suit developed only on the basis of earth gravity tests will not be optimized for lunar operation. Consideration therefore should be given to incorporating simulated lunar gravity tests into lunar suit development programs to supplement those tests normally performed.

In optimizing a suit for the loping gait, consideration should be given to the relatively large body inclination which requires the wearer to pitch his head back in order to see where he is going. Thus, the requirements for neck mobility and helmet field of vision should be evaluated. Also, the tendency to carry the upper leg far forward with the loping gait places emphasis on the development of a suit hip joint which has a minimum of restraint over a very large range of deflections. Inasmuch as this joint has been a source of development problems in current space suits, new designs for this joint may have to be developed before an optimum lunar suit can be produced. It is doubtful that the stiff-legged effect noted for lunar gravity condition will alleviate the knee joint design problem inasmuch as other mobility requirements such as kneeling require a flexible knee joint.

Earth gravity experience with current space suits has led some investigators to the conclusion that the lunar explorer's activities will be restricted to only a slow walking pace (in some cases, speeds of about 2 feet per second or 0.6 m/sec have been estimated). Also, the life support systems have been sized for the work loads measured in earth gravity tests. As a consequence, mission planners generally assumed that the lunar explorers would be restricted to very short excursions, generally less than a mile (1.6 km), because of the slow pace and the basic time limitations of the portable life-support system. The results of the present lunar gravity tests indicate, however, the possibility of two modes of lunar locomotion; walking and loping. As indicated previously, the loping pace may be the most efficient pace and, consequently, would permit a given distance to be covered in a much shorter period of time with maximum efficiency. However, this faster gait probably would be employed only over known and relatively smooth firm terrain and the explorer probably will employ the walking pace to perform the initial exploration over the unknown terrain, even though the progress would be slower and less efficient. The loping gait will be utilized in the return trip to his vehicle over the already explored terrain. In this manner, the explorer could explore a much greater area than could he if he utilized only the walking pace for the total trip.

SUMMARY OF RESULTS

The following summary presents the results of the comparative study of walking and running gaits in earth and simulated lunar gravity as performed on smooth firm surfaces by subjects wearing conventional clothing and crepe-soled boots:

1. The maximum lunar walking and running speeds were about 60 percent of those for earth gravity.

2. For most speeds, the lunar stride was greater and the stepping rate was lesser than the corresponding earth values by as much as a factor of 2.

3. The natural or most comfortable gait for the lunar condition corresponded to a loping gait at about 10 feet per second (3 m/sec) which is much faster than the natural earth walking gait of about 4.0 feet per second (1.2 m/sec).

4. Sprinting and loping in the lunar conditions produced about the same running speeds, whereas sprinting produced significantly higher speeds in earth tests.

5. The subjects leaned further forward and swung their legs further forward for lunar gravity tests than for corresponding earth gravity tests. Furthermore, the subjects tended to walk stiff-legged with very little flexing of the knees for the lunar tests.

On the basis of this investigation, it was concluded that there will be significant differences between the lunar walking and running gaits and the corresponding earth modes of locomotion and that these differences may play important roles in the design of space suits intended for lunar locomotion and in the planning of lunar missions and their logistic support. Also, it was noted that the most comfortable lunar gait corresponds to that requiring the least total expenditure of work and that the preferred lunar gait probably will be the loping gait which has a significantly faster speed than the most comfortable or natural pace on earth.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 28, 1966.

APPENDIX

ANALYSIS OF PHYSICAL CONSTRAINTS ON TEST SUBJECT IN LUNAR GRAVITY SIMULATOR

In order to show that the results of the comparative study are not seriously distorted by the constraints which are unique to the lunar gravity tests, the following simplified analysis is made to define the types of constraints imposed on the test subject and to evaluate the relative magnitudes of the forces involved. The nature of the comparative study is such that only the most significant or first-order differences in the locomotive gaits for the two gravity conditions will be evaluated; consequently, small differences on the order of 10 percent or less are assumed to be negligible.

Analysis of Primary-Motion Constraints

The test subject is supported by a group of slings, cables, and a trolley which is accelerated by and moves along with the subject as he walks and runs. The constraints on the subject, therefore, consist of the additional weight or mass of the slings attached to the subject, the forces generated by the motion of the subject relative to the cables, and the forces generated by motion of the subject, cables, and trolley relative to the track and the atmosphere. For this analysis, the earth weight of the test subject fully clothed with boots and helmet is assumed to be 180 pounds (800 N) and the coefficient of friction for the boots on the test surface is taken as 0.8. The weight of one leg, foot, and boot of the subject is assumed to be 35 pounds (155 N), the center of gravity being 1.6 feet (0.49 m) below the hip joint, and the attachment point of the leg support sling being approximately 2 feet (0.6 m) below the hip joint.

The total weight of the support system including the trolley is 30 pounds (133 N), but the weight of the trolley (12 pounds or 53 N) is supported directly by the trolley track, as indicated in figure 17, and only about one-sixth of the remaining weight, or approximately 3 pounds (13 N), is supported directly by the subject; consequently, the additional weight, which is imposed on the subject by the equipment, is less than 2 percent of the subject's normal weight. The mass of the total support system must be accelerated by the subject to initiate the walk or run, but only a portion of the mass of the leg slings and cables is under continuous acceleration as the subject maintains a steady pace. This portion is equivalent to a mass weighing about 1.5 pounds (6.7 N) attached to the calf of the leg or about 4 percent of the mass of the leg.

The forces generated by motion of the subject relative to the cables are caused in part by motion essentially perpendicular to the walkway. This motion changes the inclination angle of the cables and, consequently, the gravity level. For the present tests, the subjects generally produced vertical motions of less than 1 foot (0.3 m) while walking and running. The curves of gravity gradient, given in figure 8 of reference 1, indicate a gradient value of less than 0.01 earth gravity units per foot (0.03g units per meter) for a cable length for the present suspension system (about 150 ft or 46 m). Consequently, the vertical motions of the subject during the tests produced force variations of less than 1 percent of his earth weight.

Striding motion of the legs causes the leg support cables to produce additional forces tending to return the legs to their position for a normal feet-together standing position, as shown in the diagrams of figure 18. The leg support cables are 25 feet long (7.6 m) and the weight of the legs produces a vertical component of the tension in each cable of about 27 pounds (120 N). If it is assumed that the cables are spread a maximum of 3.5 feet (1.1 m) apart (that is, 1.75 feet or 0.53 m from center) as the subject takes a large step, then the component of the cable tension in the plane of the leg motion is 1.9 pounds (8.6 N) resulting in a maximum torque of about 4 foot-pounds (5.4 J). Some simple tests were made with the three test subjects to evaluate the maximum torques which can be exerted by the subjects to produce the striding motion. The test consisted of raising one leg, as though the subject were taking a step with the knee stiff. A weight was placed on the foot, and the horizontal distance between the foot on the floor and the test weight when the leg was raised as high as possible was measured; the maximum torque exerted by the muscles of the upper leg was then calculated. An average total torque of about 70 foot-pounds (95 J) was determined on the basis of these tests; consequently, the torque imposed by the leg cables appears to be no greater than about 6 percent of the maximum torque the subjects are able to exert to produce the striding motion.

The forces generated by motions of the subject and support system relative to the track and the atmosphere consist primarily of the friction of the trolley on the track and the air drag of the subject's body and the cables. Some calibration tests were performed to measure the breakout friction for the trolley carrying a weight corresponding to the weight of a subject and it was found that a force of about 1.3 pounds (5.8 N) is required to initiate trolley motion. It is assumed that the rolling friction is about one-half of this value or approximately 0.7 pound (3.1 N). The maximum lunar running speed of 13 feet per second (4 m/sec) under the test conditions produced a dynamic pressure of about 0.2 pound per square foot $\left(0.9 \text{ N/m}^2\right)$, consequently, the air drag acting on the subject is estimated to be 1.2 pounds (5.3 N), on the basis of an assumed flat-plate drag area of 6 square feet $\left(0.56 \text{ m}^2\right)$. Likewise, the air drag of the cables is found to be about 0.5 pound (2.2 N) on the assumption of a drag coefficient of 1.2 for 130 feet (40 m) of 1/8-inch (0.32-cm) diameter main cable and 175 feet (53 m) of 1/16-inch (0.16-cm) cable used to support the individual body members. Therefore, the total force which has to be overcome by the subject in running at the maximum speed is estimated to be 2.4 pounds

(10.7 N), which is less than 2 percent of his earth weight. To overcome a force of this magnitude while running at maximum speed, the test subject must lean forward by an angle of approximately 5° greater than the angle that he would develop at the same maximum speed in the absence of the trolley and air drag forces. For a speed of one-half of the maximum speed, the additional angle would be reduced to about 2°. In the foregoing portions of this analysis, the constraints have been related to known characteristics of the test subjects and the results of this portion of the analysis are summarized as follows:

Type of constraint	Estimated maximum constraint		Pertinent characteristic	Relative magnitude of constraint, percent
Equipment weight	3 pounds	(13.3 N)	Body weight	2
Accelerated weight	1.5 pounds	(6.7 N)	Leg weight	4
Cable support (vertical motion)	1.8 pounds	(8.0 N)	Body weight	1
Cable support (leg motion)	4 foot-pounds	(5.4 J)	Maximum leg torque (stride position)	6
Air drag and trolley friction	2.4 pounds	(10.7 N)	Body weight	2

Inasmuch as the relative magnitudes of these constraints appear to be of the second order, it is considered that the results of the comparative investigation of the primary motions are not seriously distorted by these particular constraints.

Analysis of Secondary-Motion Constraints

Two constraints appear to be of concern for this category. The first is the torsional restraint imposed by the slings at the hips and the chest as a result of the twisting motion of the body associated with walking and running. This motion generally is only a few degrees in amplitude and generates a shearing action between the subject's body and the wide fabric straps supporting the subject. The shearing forces are considered to be very low because of the rolling or sliding of the skin relative to the body structure and also because of the yielding of the loose clothing and soft sponge rubber in the support straps. Experience of the test subjects shows that it takes very little effort to purposely twist the body through small angles; consequently, the effect of this torsional constraint is assumed to be negligible.

The second constraint, the suspension cables which support the subject in the inclined attitude, produces a lateral constraint which tends to limit the normal lateral swaying motion associated with the walking and running gaits; this motion is indicated in reference 5 to be about ±0.9 inch (±2.3 cm). Measurements of the suspension cable elongation under load indicate that the spring constant of the cables was 60 pounds per inch $(414\ kN/m^2)$. The cables would therefore produce a maximum restraining force of about 53 pounds (235 N) if the swaying motion in the simulator were not affected by the cables. Inasmuch as this is an appreciable force relative to the subject's weight, the effect of the cables on the swaying motion undoubtedly is quite large. However, because the emphasis of the current investigation is on the primary locomotive motion, the lateral constraint of the cable is considered to not affect the results discussed in the body of this report. It is pointed out in this appendix, that for some applications of the simulator, other than that of this investigation, this type of constraint may be significant and steps should be taken to minimize its effect. One possible scheme for doing so would be to utilize a "soft" springy link in the cable suspension system such as bungee chord or springs. It is estimated that by reducing the spring constant of the cable to about 10 pounds per inch (175 N/m) the constraint could be reduced to a negligible level.

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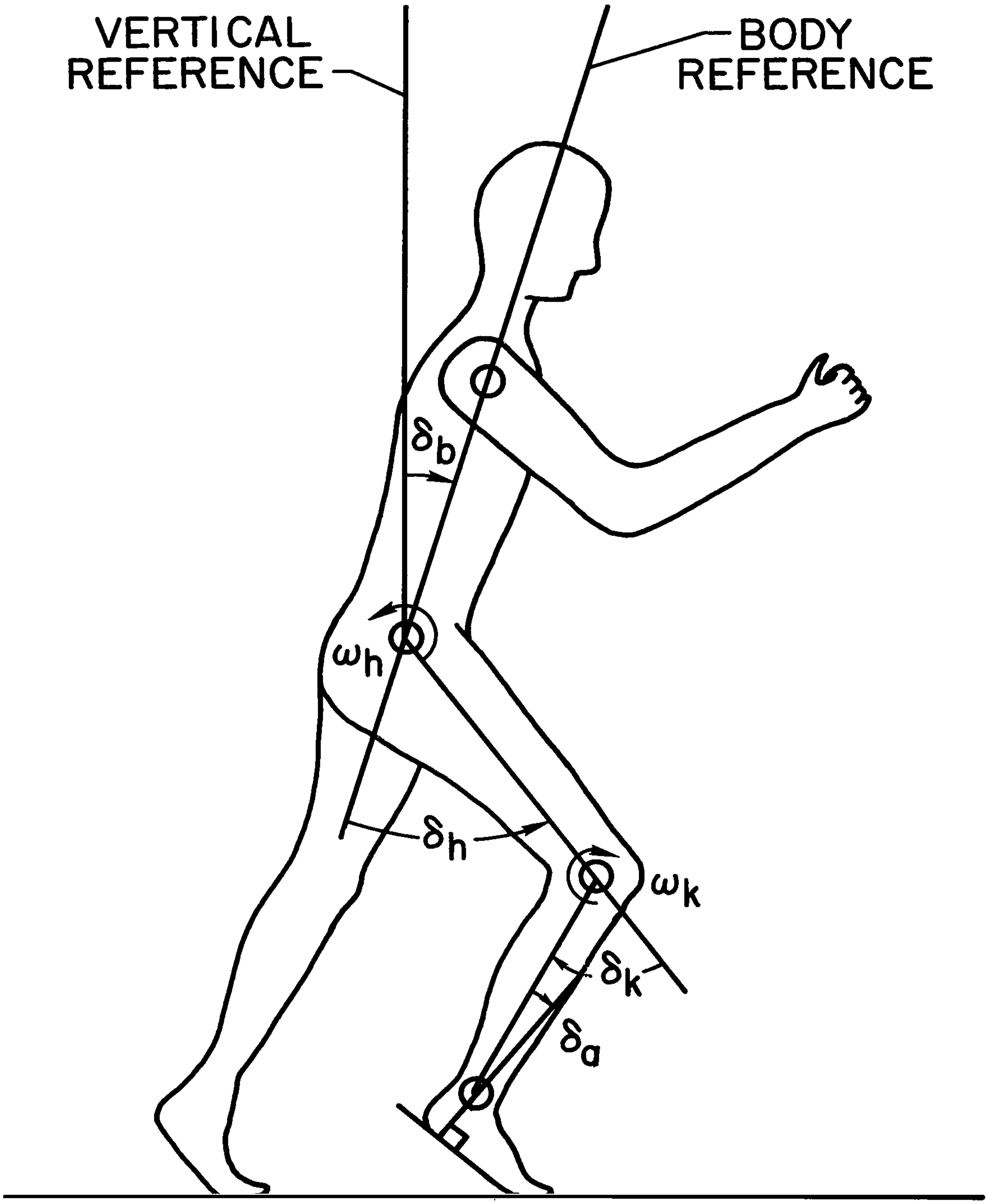

Figure 1.- Illustration of location of various body angles. All angles are positive as shown.

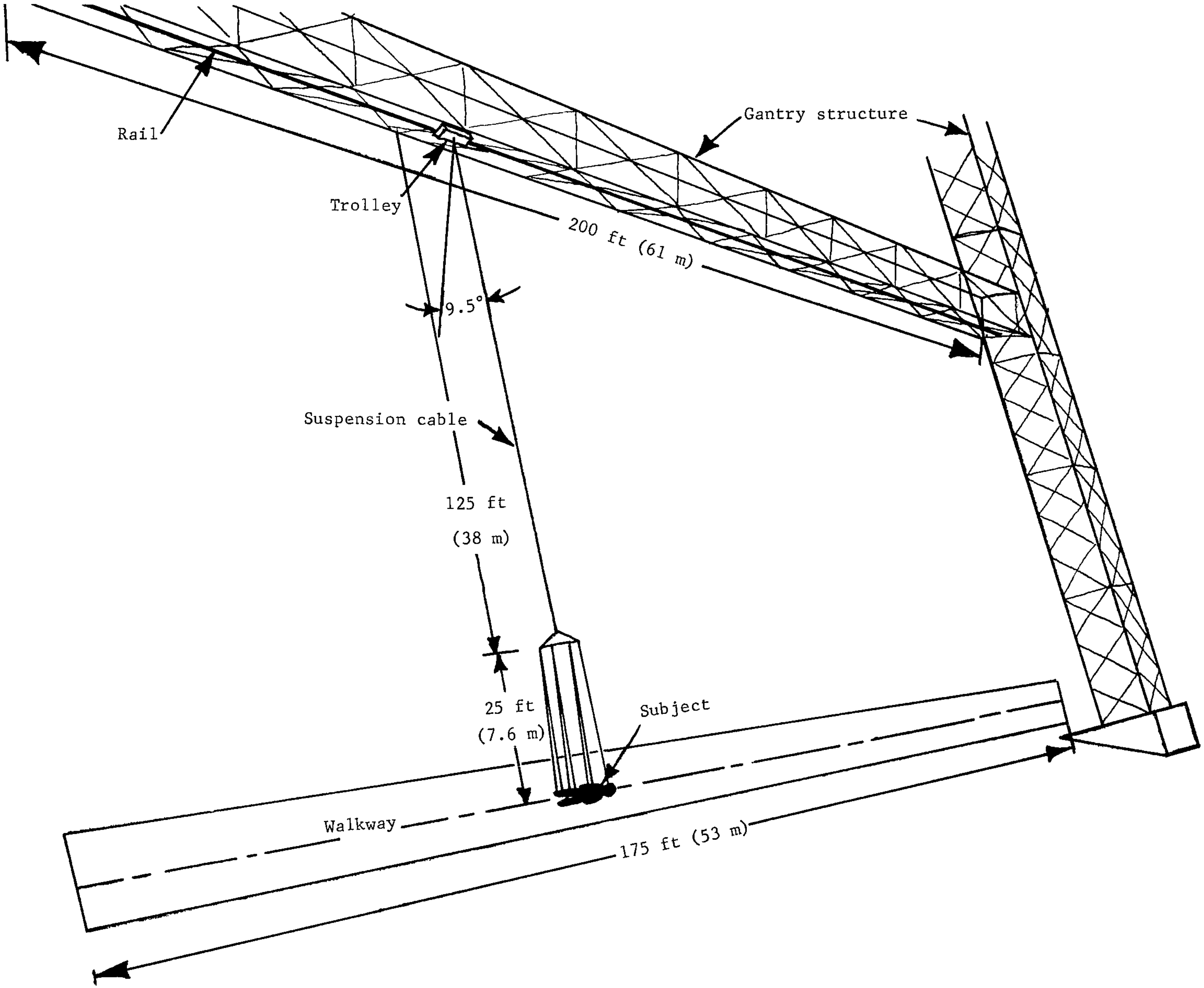

Figure 2.- Illustration of Langley reduced gravity simulator used for these tests.

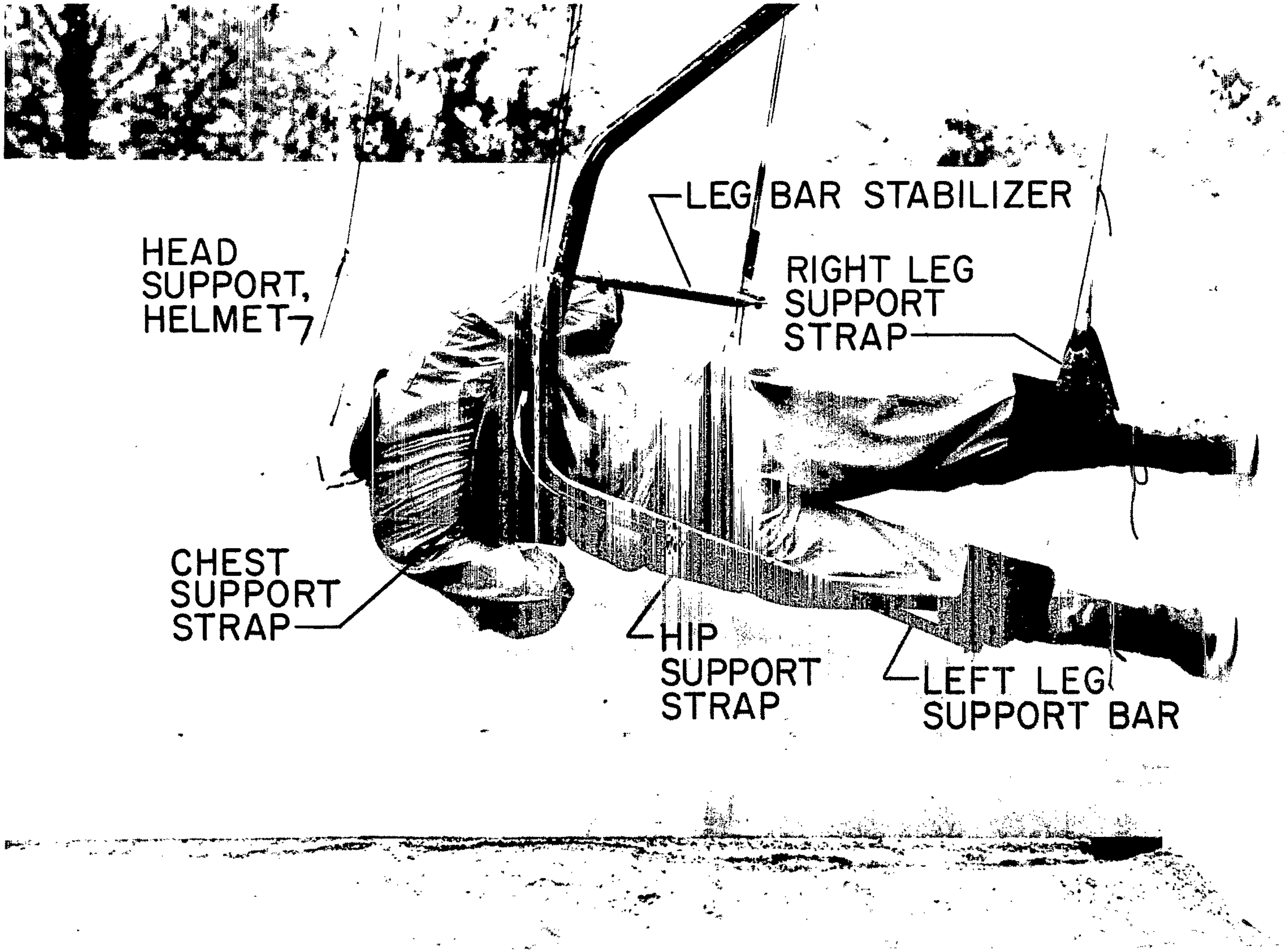

Figure 3.- Details of simulator sling supports.

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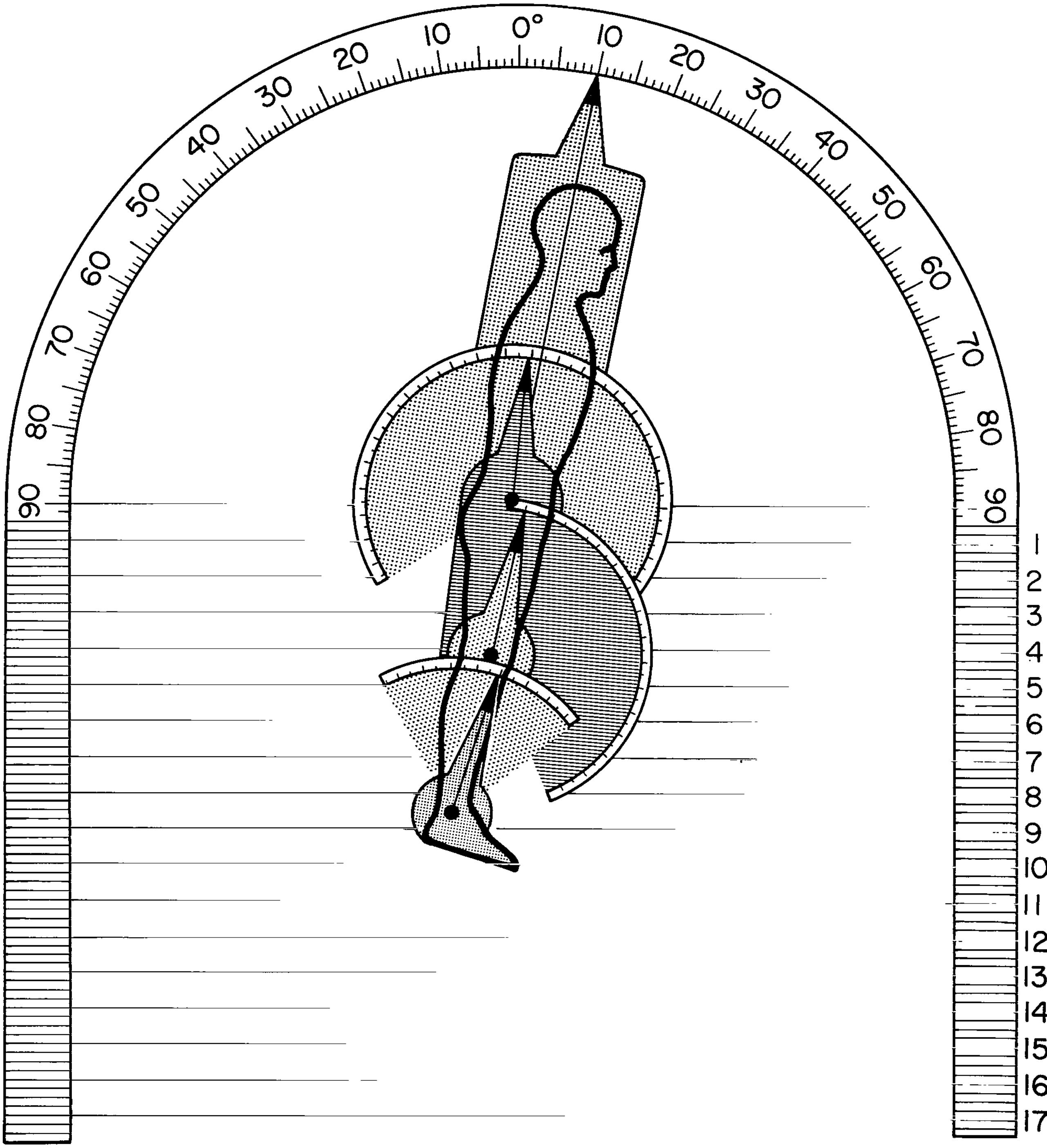


Figure 4.- Articulated device used to determine angular positions.

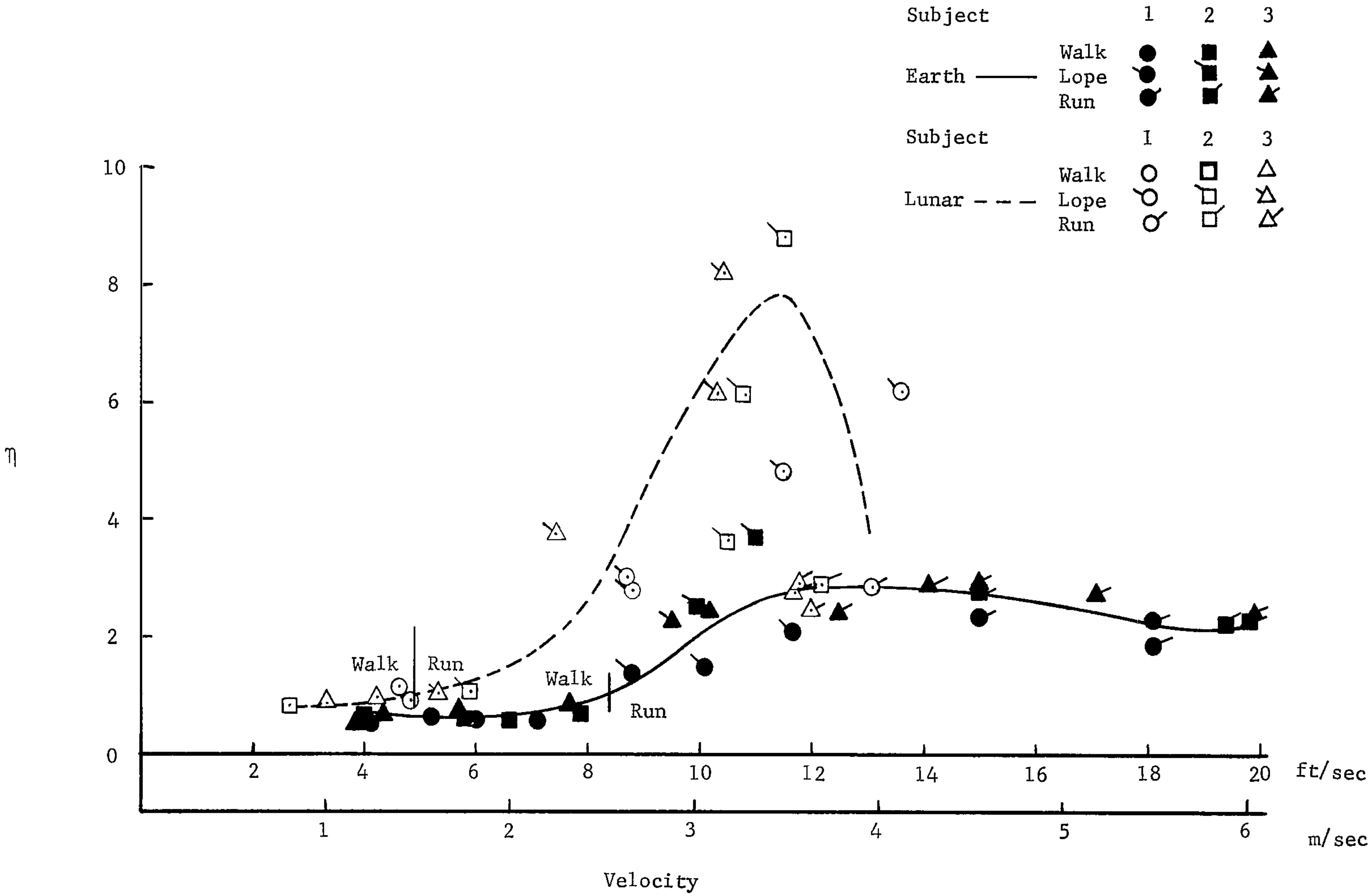


Figure 5.- Locomotive index plotted against velocity at 1g and 1/6g.

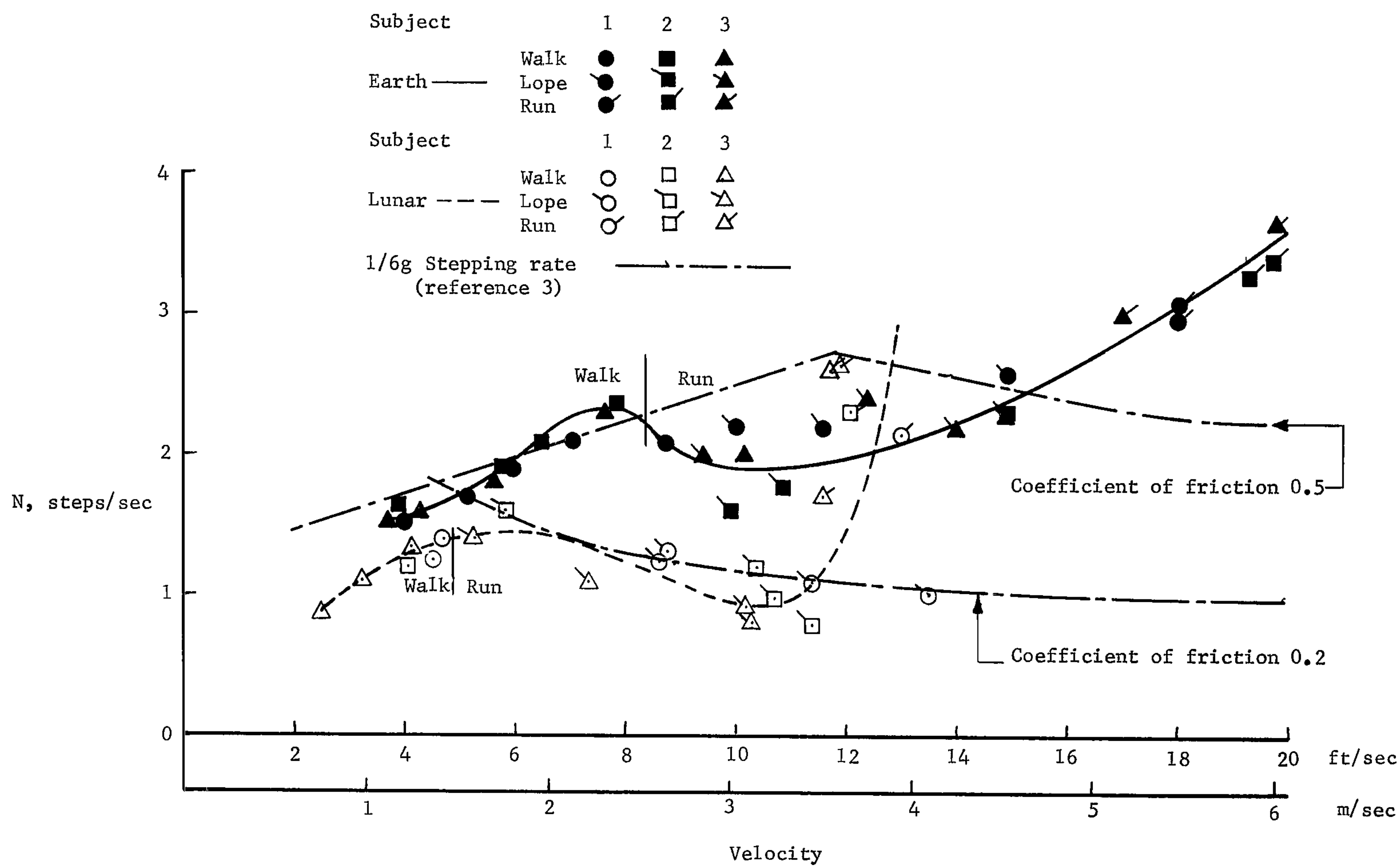


Figure 6.- Average stepping rate plotted against velocity at 1g and 1/6g.

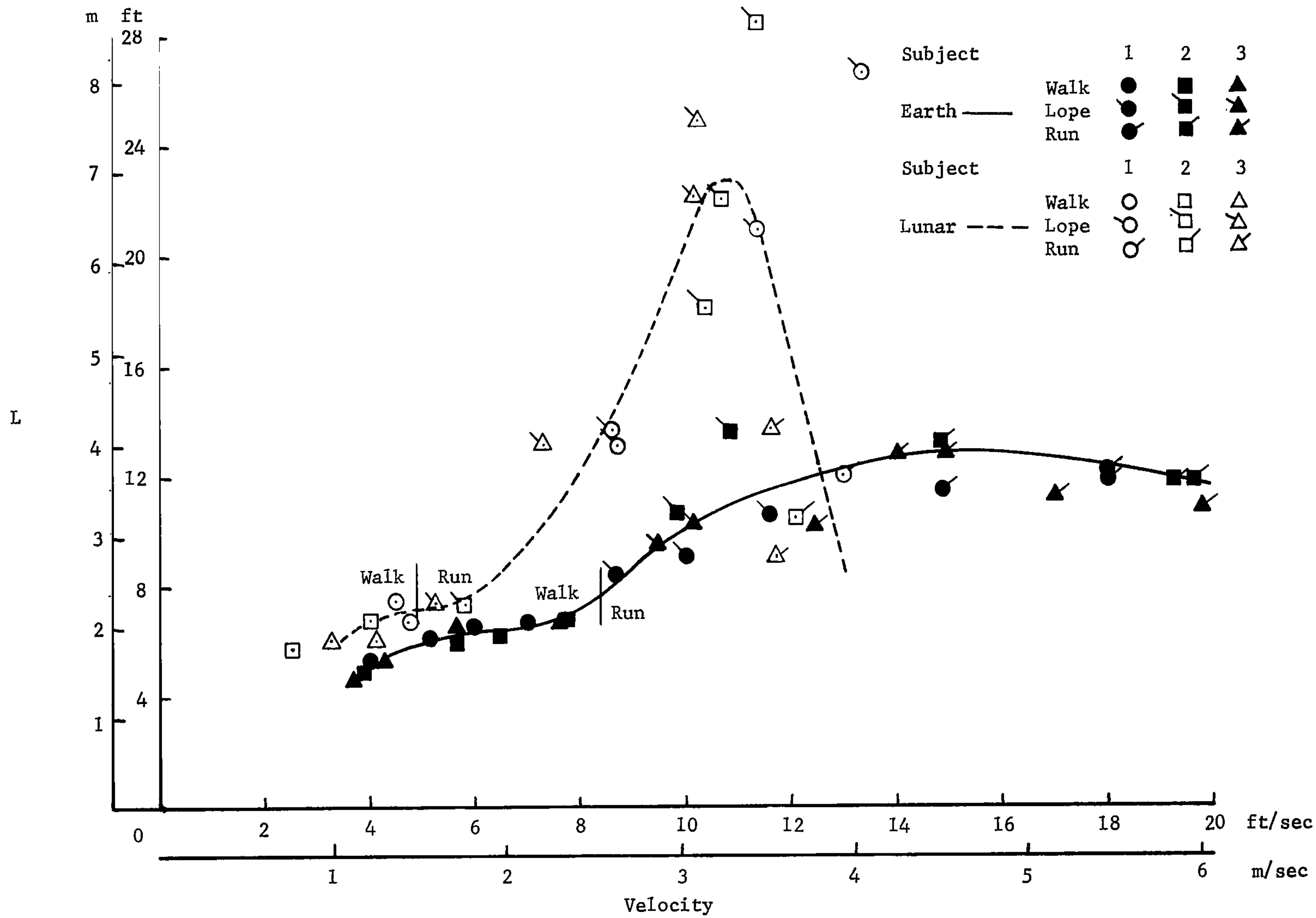
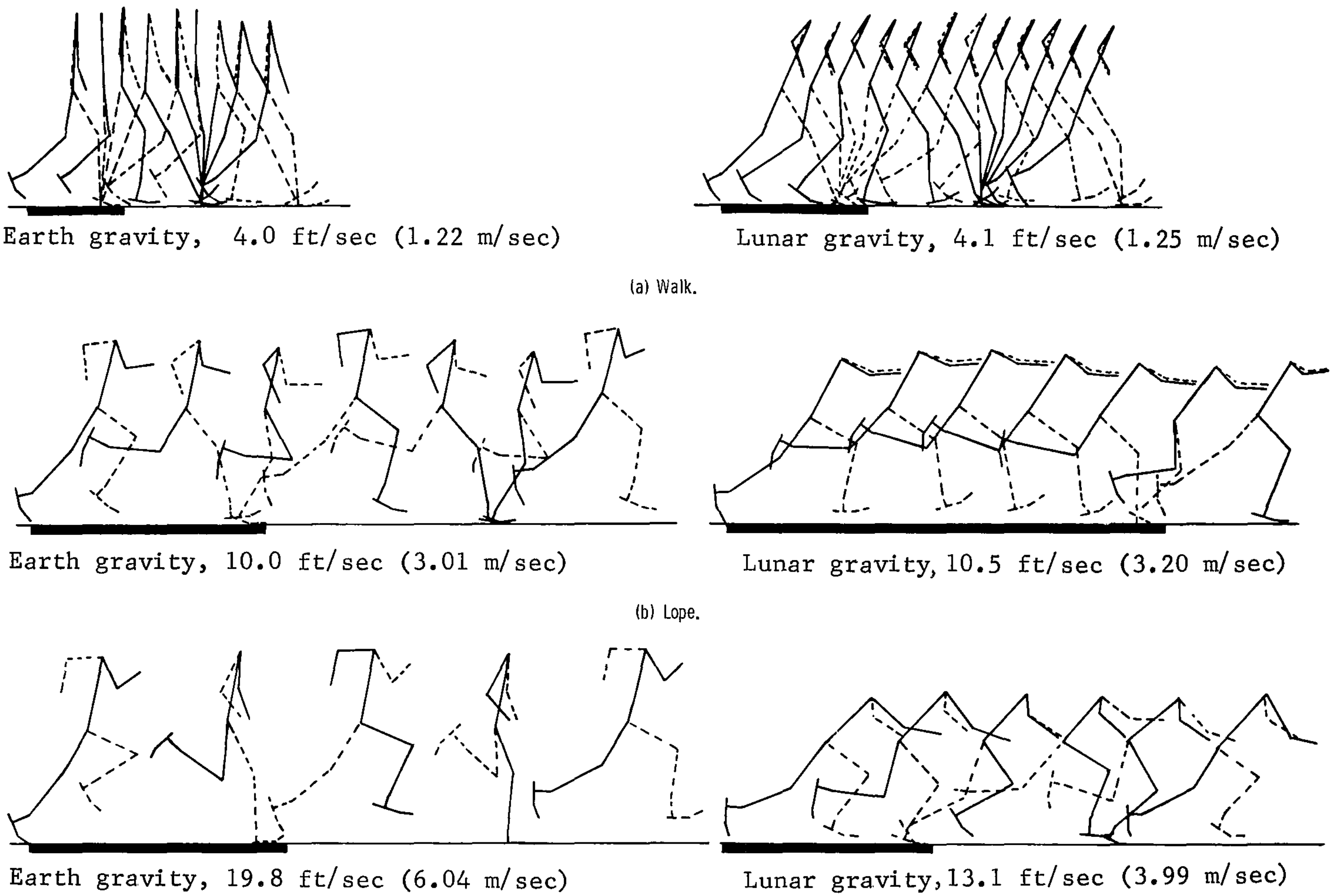


Figure 7.- Average stride plotted against velocity at 1g and 1/6g.



(c) Sprint.

Figure 8.- Stickman representation of typical walk, lope, and sprint in earth and lunar gravity. Length of bar at ground line denotes distance of one step. Dashed line denotes position of left arm and leg. Time interval between each figure is 0.16 second.

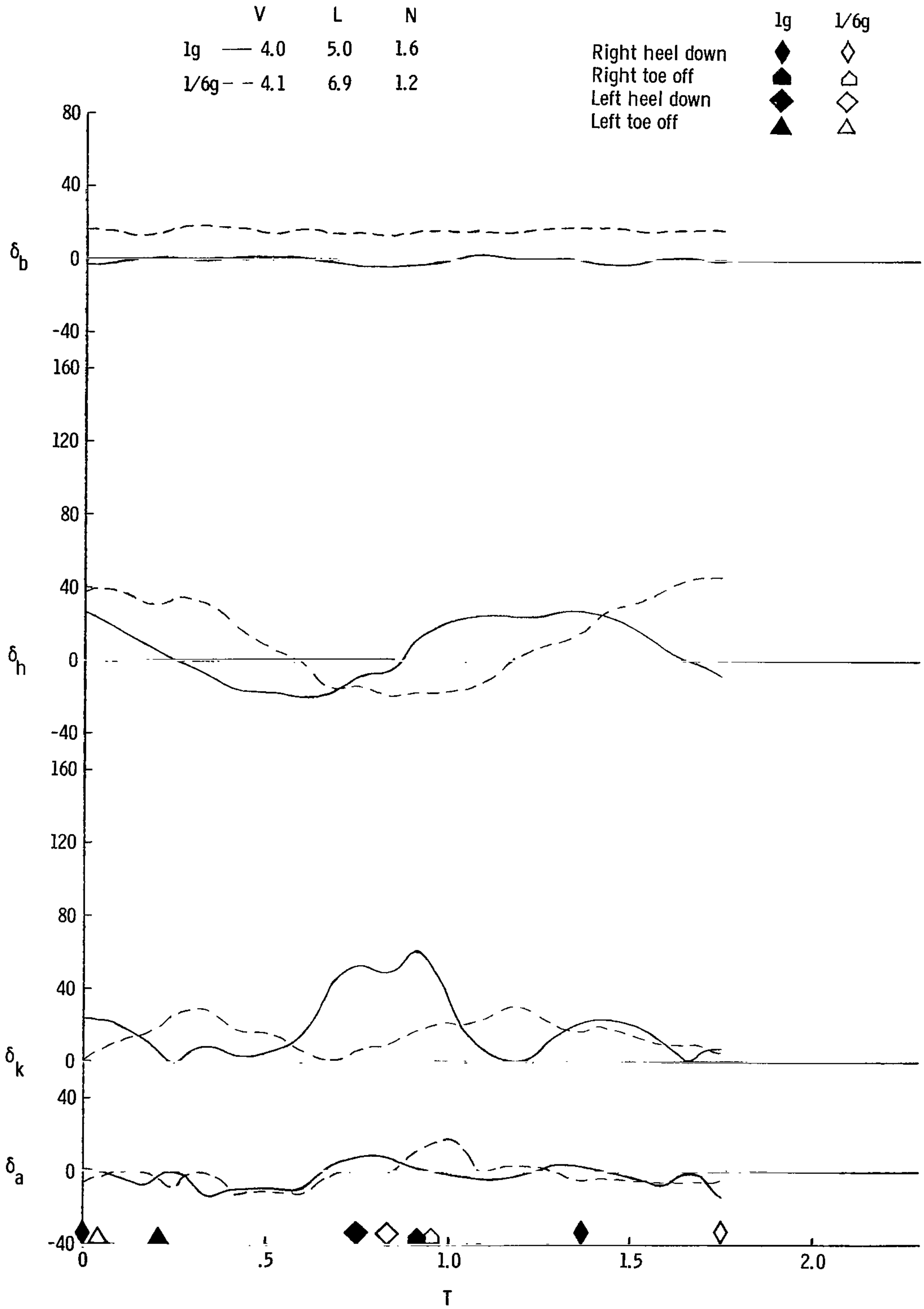


Figure 9.- Time history of relative motion of various body members while walking in earth and lunar gravity.

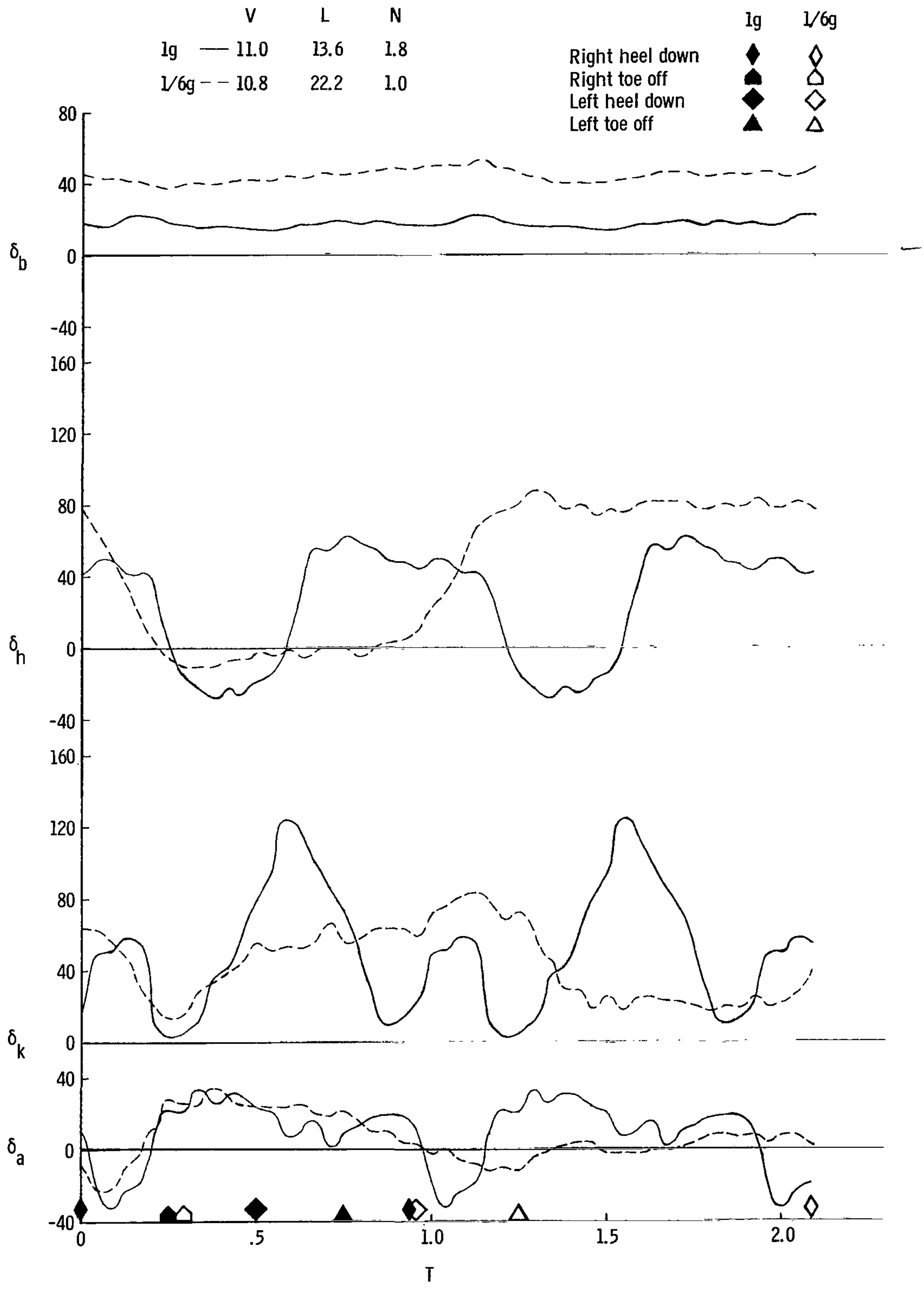


Figure 10.- Time history of relative motion of various body members while loping in earth and lunar gravity.

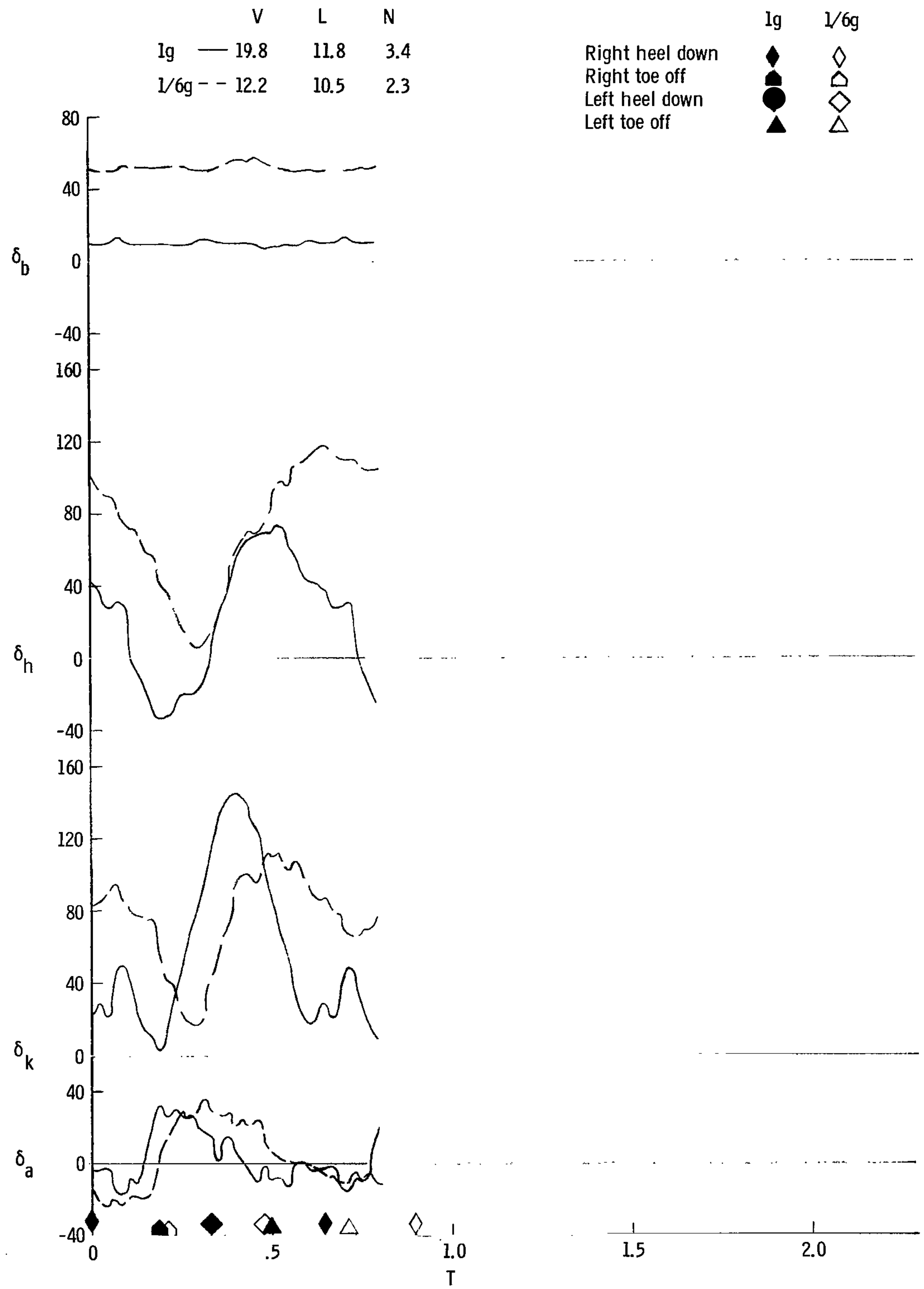


Figure 11.- Time history of relative motion of various body members while running at maximum velocity in earth and lunar gravity.

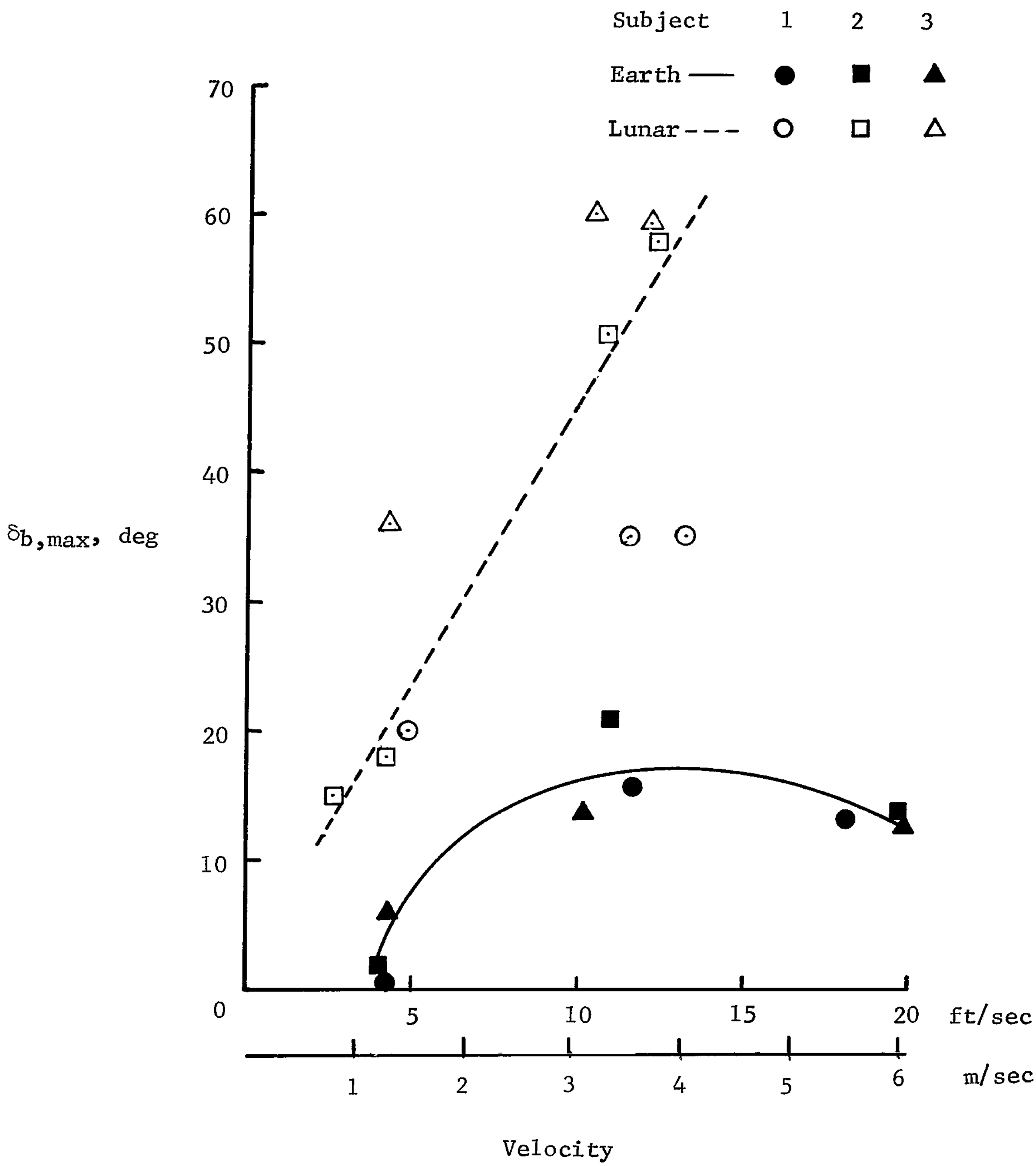


Figure 12.- Maximum body angle plotted against velocity at 1g and 1/6g.

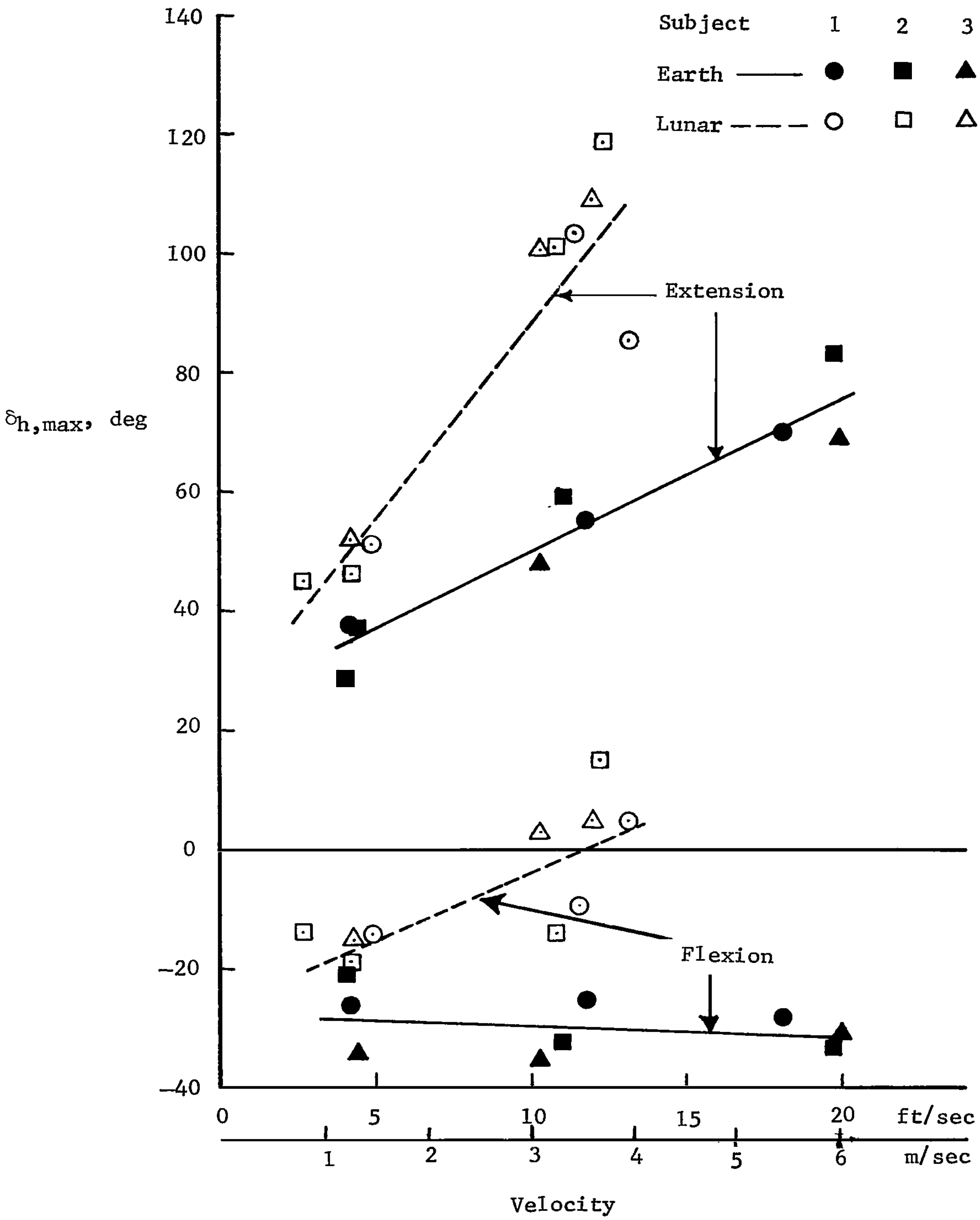


Figure 13.- Maximum hip flexion and extension angles plotted against velocity at 1g and 1/6g.

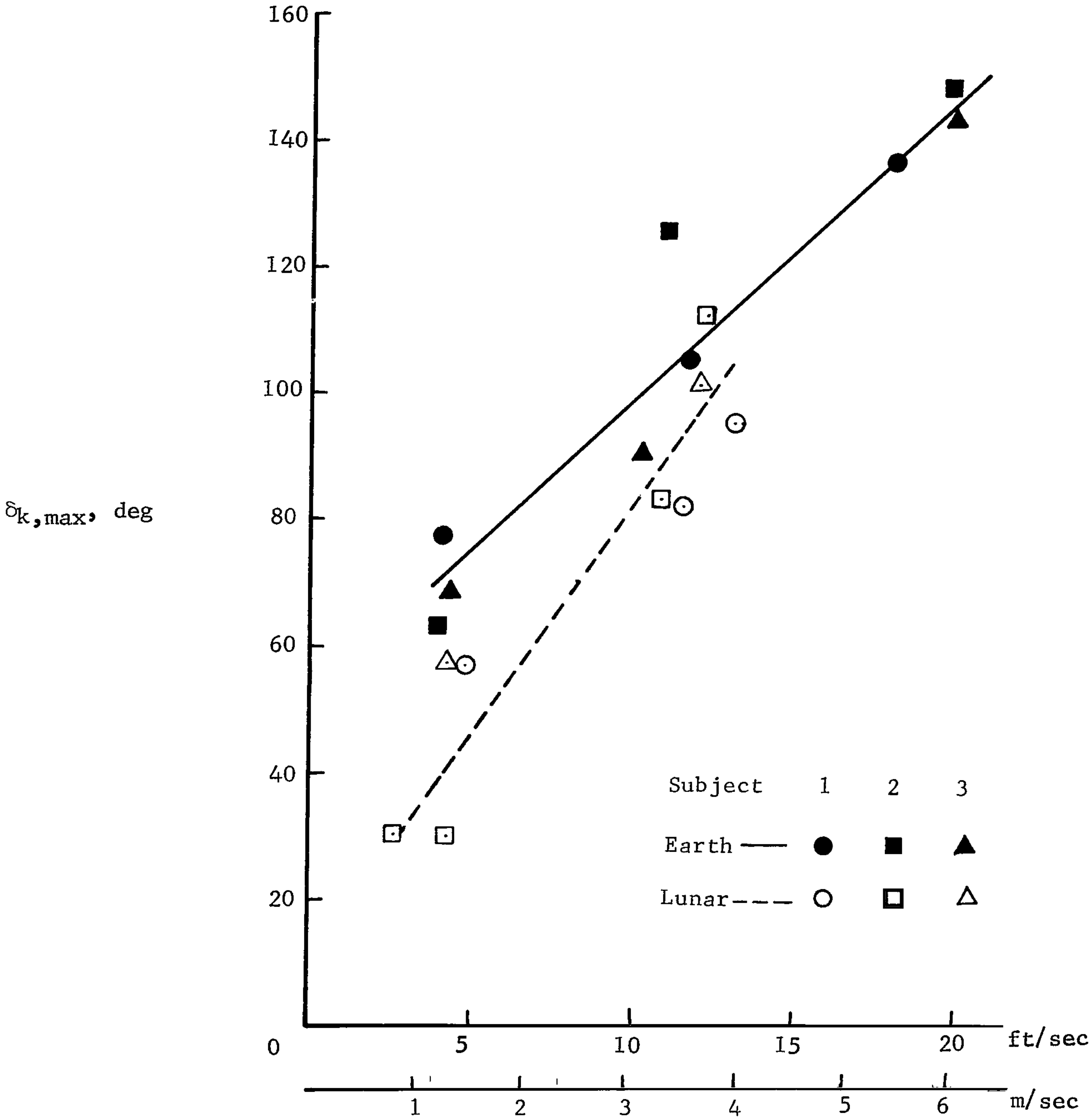


Figure 14.- Maximum knee flexion plotted against velocity at 1g and 1/6g.

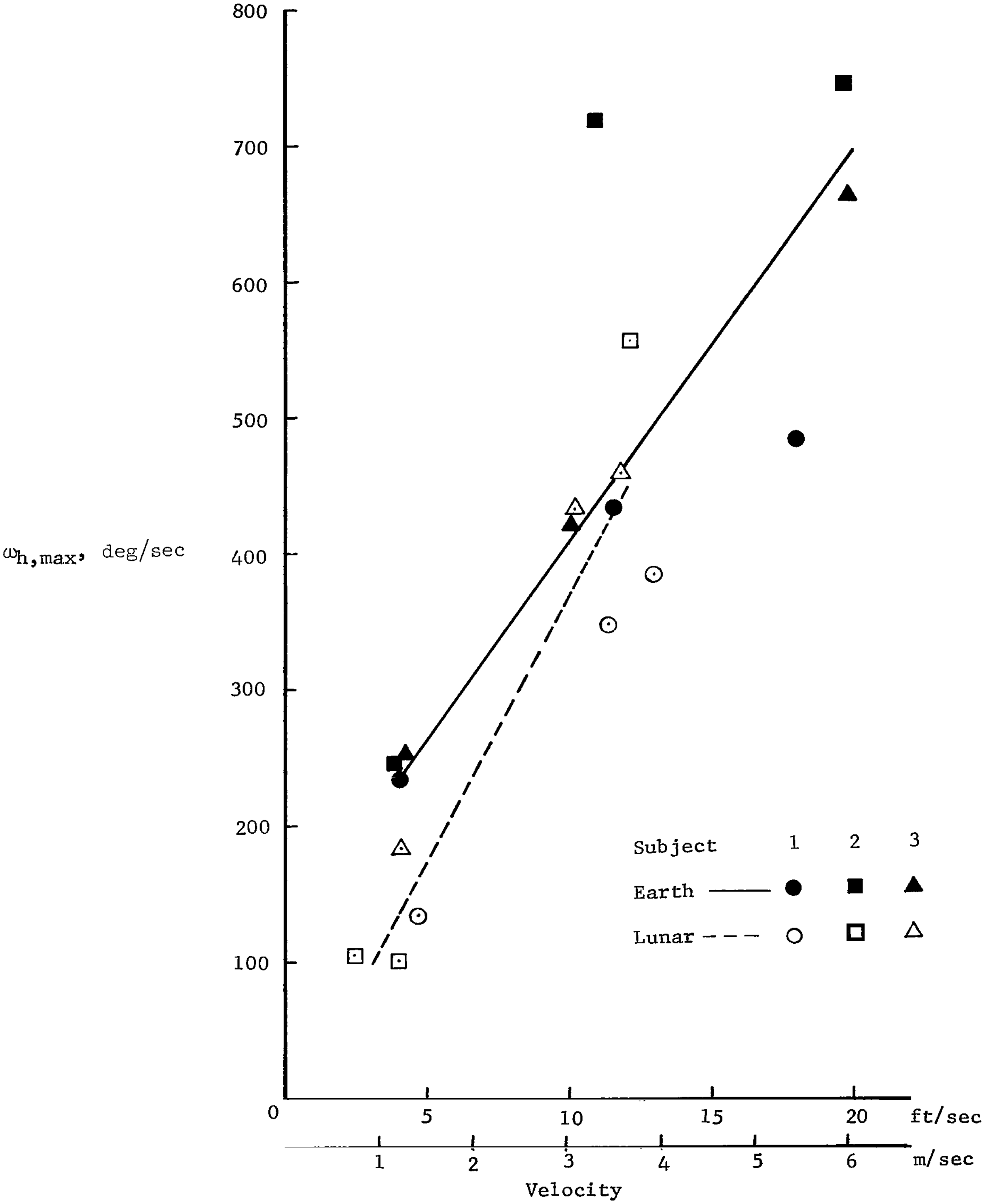


Figure 15.- Maximum angular rate of hip joint plotted against velocity at 1g and 1/6g.

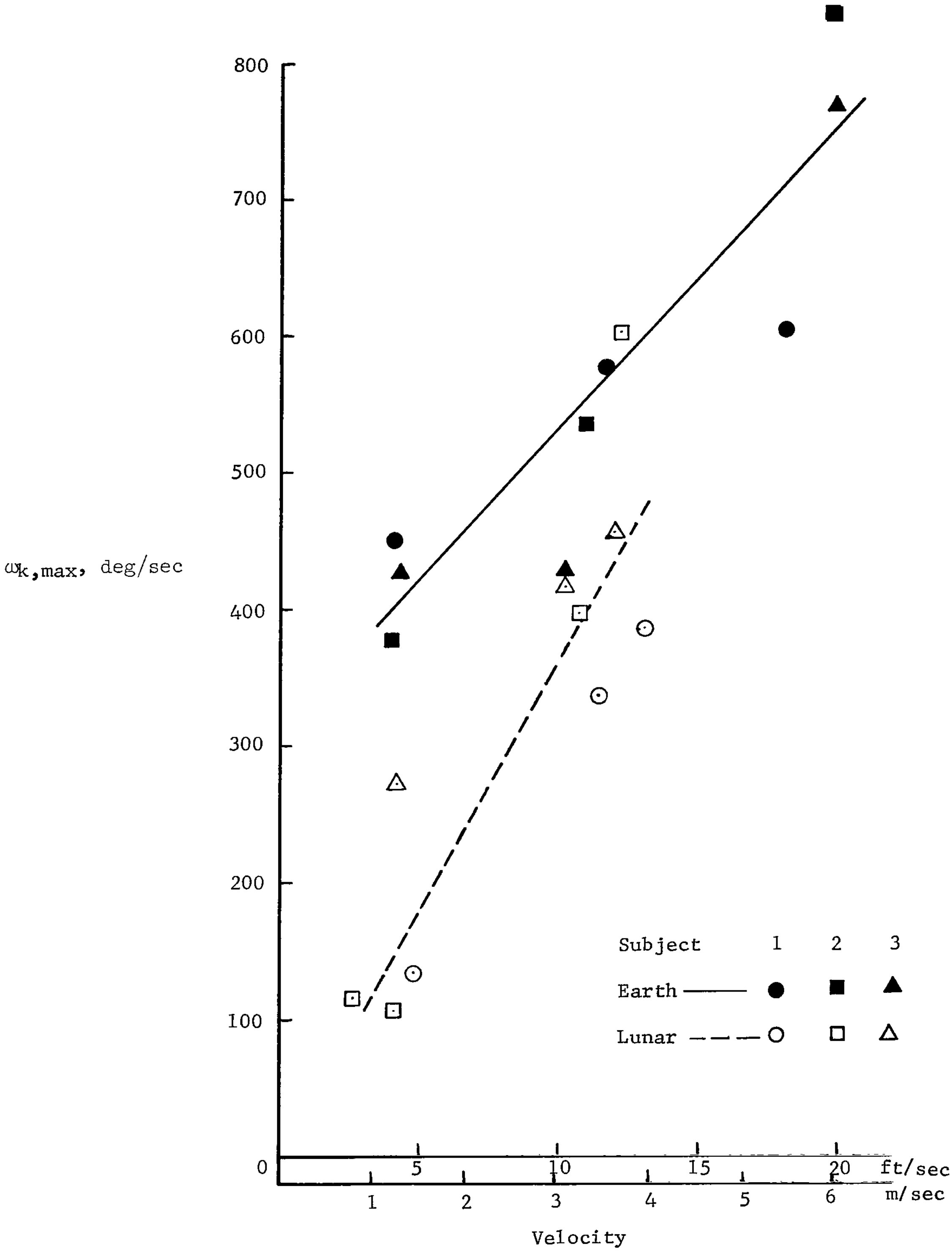


Figure 16.- Maximum angular rate of knee joint plotted against velocity at 1g and 1/6g.

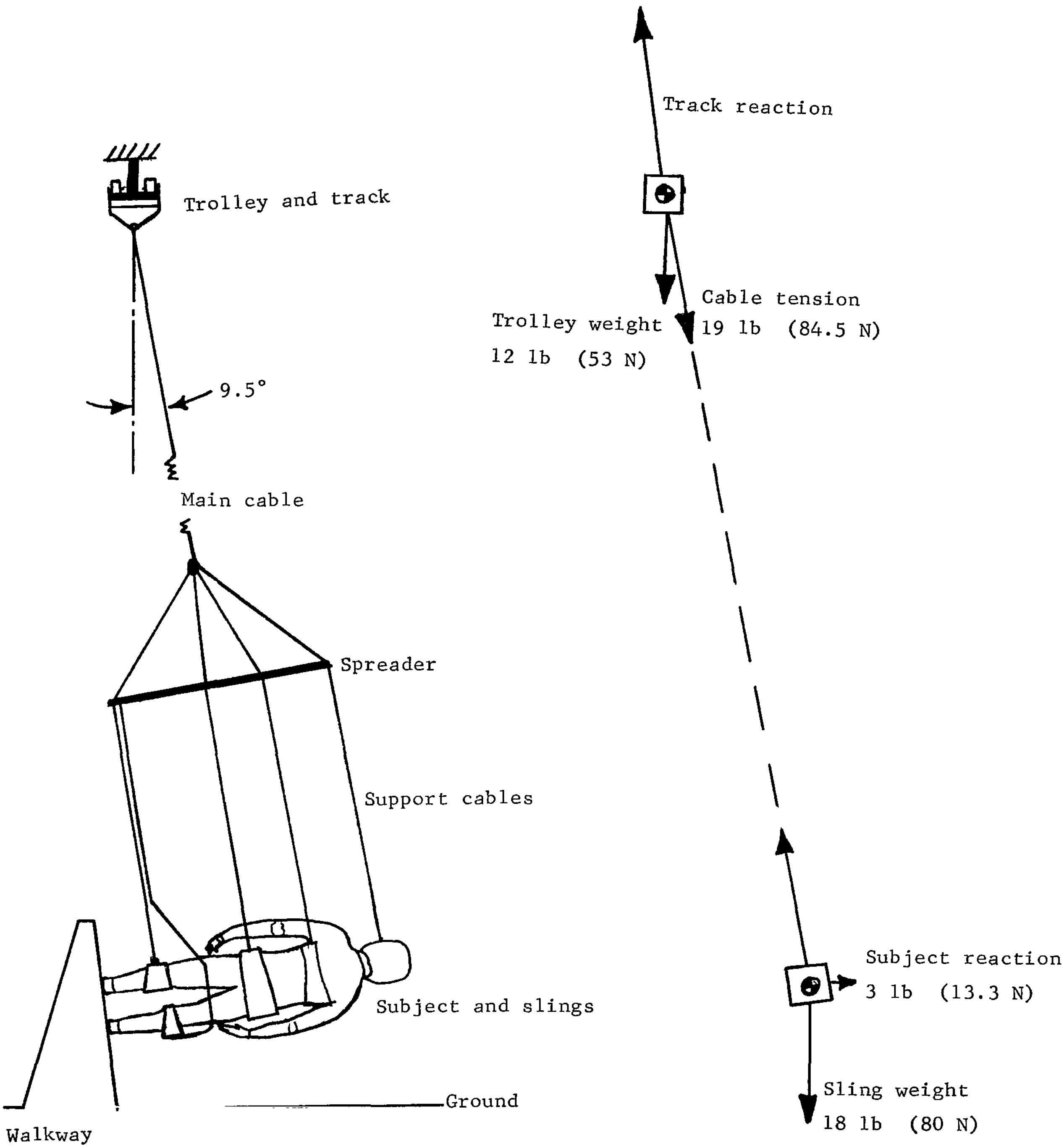


Figure 17.- Schematic diagrams illustrating effect of support system on weight supported by test subject.

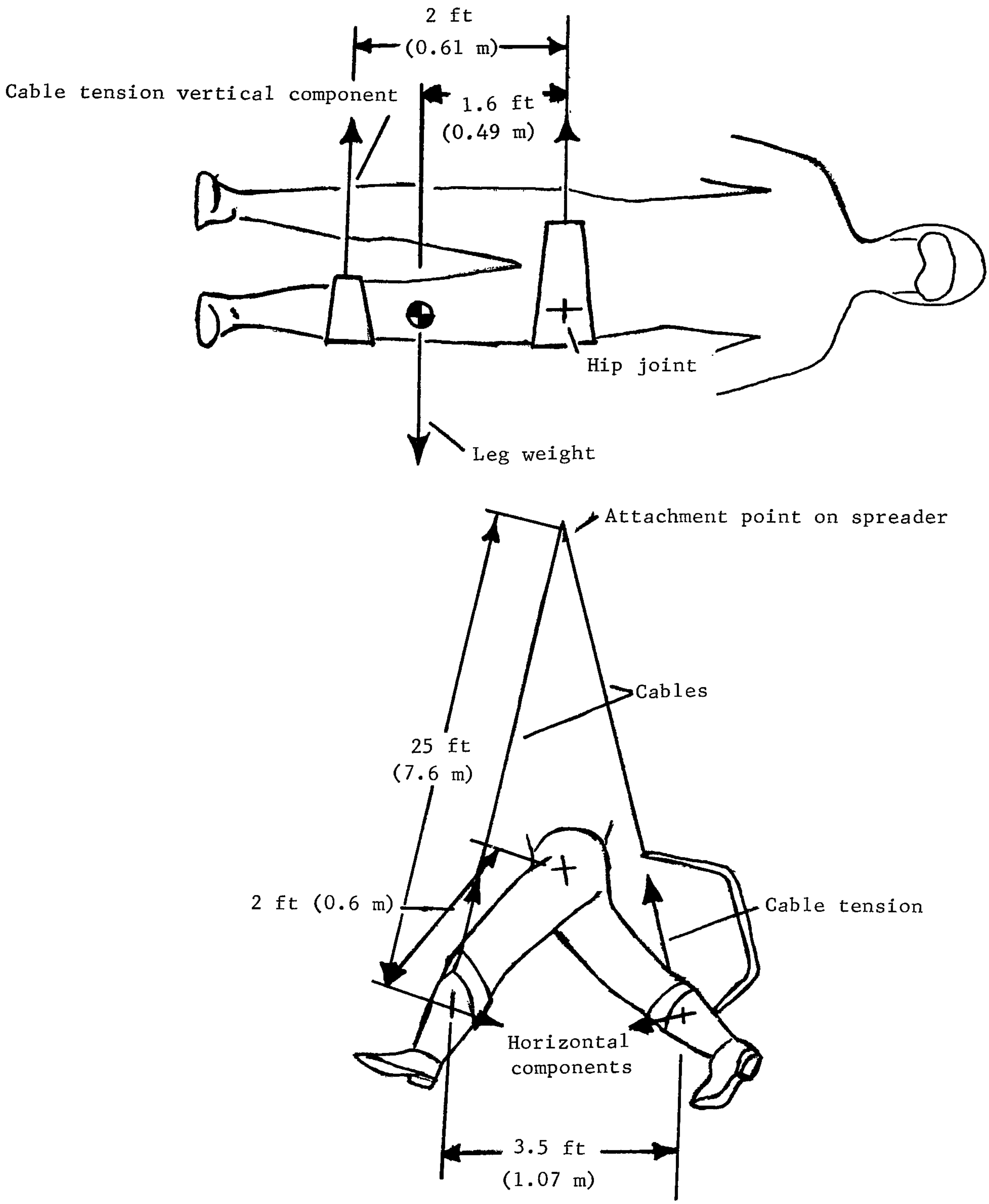


Figure 18.- Schematic diagrams illustrating effect of leg suspension cables on striding motion of legs.

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